SLAC-PUB-7929
September 1998
(T/E)

THE TRANSFORMATION OF PHYSICS, FROM THE PARIS SHED TO THE 21ST CENTURY

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As Presented to the
International Conference
"The Discovery of Polonium and Radium –
Its Scientific and Philosophical Consequences,
Benefits and Threats to Mankind"

17-20 September 1998, Warsaw, Poland

[1] Work supported by the U.S. Department of Energy, contract DE-AC03-76SF00515.

I. INTRODUCTION

In the last decade of the nineteenth century, a small band of scientists created a revolution that profoundly changed our view of the physical world and that led to a technological revolution that has changed all of our lives. One of these revolutionaries was Marie Sklowdowska-Curie whose work we celebrate here. She was an unlikely revolutionary, born in 1867 in Russian-occupied Poland at a time when a foreign power rigidly controlled Polish education and at a time when women everywhere were seldom educated beyond the domestic arts.

The scientific community knows in detail of her great accomplishments and of their significance. Society knows her as the discoverer of radium. That she became one of the leaders of a scientific revolution is in itself a tribute to an intellect and a determination, both of which are rare and necessary elements to a successful career in science.

When I was young, I knew that I wanted to understand how the universe worked. Most doors were open to me, and I needed only my own abilities to walk through them. Maria Sklowdowska must have also decided as a child that she wanted to know those things. All of the doors were closed to her, and she had to use her ability and determination to open them as well as to walk through them. Open and walk through them she did.

The ferment among the middle and upper classes in Poland in her time created the climate in which she moved. The failed January 1863 uprising in Poland led to a Russian repression, but emigrés from that uprising created in Paris a center of Polish cultural life to which she could later escape. The Polish positivists' influence led to support among the intelligentsia for women's rights and education. When she finished Gymnasium at age 15, the clandestine "flying university" of Jadwiga Dawidowa was available to further the education of women. Her continued self-education during her years as a governess culminated in her move to Paris in 1891 at age 23 where she enrolled in the Faculty of Sciences at the Sorbonne. It was very rare to have a woman in science in 1890's France (and it still is more rare everywhere than it ought to be). Then, even in educated Paris, a woman's role was to be subservient; to be in a separate sphere from a man. When Marie enrolled in the Sorbonne there were 23 women out of 1,825 students in the Faculty of Sciences. It must have been a considerable surprise to the faculty when she scored first on the Licensées exam in Science in 1893 and second in Mathematics in 1894.

Her marriage to Pierre Curie in 1895 began a scientific partnership that lasted until his tragic accidental death in 1906. She began her research in what she came to call radioactivity in 1897, and in 1898 the Curies announced the discovery of polonium in July and of radium in December. She shared the Nobel Prize in Physics with Pierre in 1903, becoming the first woman to receive it and the only woman to do so until Irene, her daughter, received it in 1935. She received the Nobel Prize in Chemistry in 1911, and is one of only three people to receive two Nobel Prizes (the others being Pauling in Chemistry and Peace, and Bardeen both in Physics), and was showered with innumerable scientific honors. However, she only became a professor at the Sorbonne after Pierre died, and was the first woman to teach there.

Marie Curie has to be doubly honored for overcoming the obstacles of her time to achievement by a woman and for her achievements in science.

II. THE REVOLUTION – OPENING SHOTS

It all began in 1895. The view that people hold now of what might be called the pre-revolutionary classical period is that there was general satisfaction with the state of science, and that the scientific community felt that only the fine points needed elucidating. It was not that way at all. While in the area of mechanics Newton's laws were everywhere triumphant, there were serious problems in thermodynamics, electricity and magnetism, and the structure of matter, all of which turned out to be connected.

The opening shots of the revolution completely changed the view of the structure of matter that had been a subject of philosophical debate for 2500 years. Since ancient times, there had been two different views; the continuum theory of Anaxagoras and Aristotle, and the atomic view of Democritus and Lucretius. The continuum theory held that matter was infinitely divisible while the atomists held that there was a smallest thing, the atom; that there were a limited number of varieties of atoms; and that the atom and empty space were the only eternal immutable objects. The continuum theory won out on the basis of philosophical rather than experimental arguments, and held force for 2000 years. Even as late as the early 1600s, Descartes said that no piece of matter was indivisible.

Starting soon after the time of Descartes, evidence began to pile up that the atomists were correct after all. A kind of atomic theory was used by Bernoulli (1700-1780) to explain gas pressure in a container, by Dalton (1766-1844) to explain chemical reactions, by Avogadro (1776-1856) to explain the weight of a fixed volume of different kinds of gasses, by Clausius (1822-1888) to explain the different phases of matter, etc. While atoms came to be regarded as real, they were still believed to be indivisible and eternal.

In the 1800s, however, intractable problems arose in connection with electricity. Faraday had shown that electric forces were caused by electric charges at rest, and that magnetic forces came from charges in motion (currents). Ordinary matter carried no charge; where did the charge come from? Faraday also showed in his law of electrolysis that the deposition of a gram molecular weight of any material required the same amount of charge independent of the material (for monovalent systems). Maxwell, in his Treatise on Electricity and Magnetism (1873), was forced to assume the existence of a kind of molecule of electricity, but he added that, "It is extremely improbable that when we come to understand the true nature of electrolysis we shall retain in any form the theory of molecular charges….. ." Von Helmholtz, in his 1881 Faraday lectures said with regard to Faraday's law of electrolysis, "If we accept the hypothesis that the elementary substances are composed of atoms, we cannot avoid concluding that electricity also, positive as well as negative, is divided into definite elementary portions which behave like atoms of electricity." The picture of an atom as an eternal and immutable object was in deep trouble. Somehow these atoms of electricity had to come and go from these eternal and immutable atoms, and no one knew how that could be.

The revolution began in 1895 when Roentgen discovered x-rays. X-rays came as a total surprise. He was trying to understand how electricity could be conducted in a dilute gas when he found, coming from his discharge tube, some kind of ray that could cause a phosphor to glow, could blacken photographic film, and could penetrate soft matter. Nothing like it had ever been seen before. His x-ray picture of the bones in his wife's hand caused a sensation, and within a year physicians were using x-rays to diagnose human problems. (Figures 1 and 2)

In 1896, Bequerel discovered what he called uranium rays. He too was looking for another effect. The experiment required sunlight and, because of bad weather in Paris, he left his sample of uranium on a piece of film for several days and discovered that the film had become blackened. Uranium, an ordinary material, spontaneously emitted some kind of mysterious radiation.

In 1897, J. J. Thompson, who had spent many years studying the so-called cathode rays (electrical discharges in a gas), discovered the electron, the long-sought "atom" of electricity.

In 1898, the Curies announced the discovery of two new elements, polonium and radium, that emitted Bequerel's uranium rays with much higher intensity. They christened the phenomenon "radioactivity." In 1899, Rutherford showed that radioactive elements emitted two kinds of rays called alpha and beta, and that the beta rays were identical to Thompson's atoms of electricity. In 1900, Marie Curie tentatively advanced the hypothesis that radioactivity was an atomic phenomenon and that in the process one atom changed into another. She could not prove it, but Rutherford and Soddy did prove it in 1902. Incidentally, in 1903 Marie Curie received her Ph.D. at the Sorbonne and the Nobel Prize (with Pierre Curie and Bequerel), a very good year for a graduate student.

In 1900, Max Planck solved a problem that had been troubling physicists for years, the spectrum of blackbody radiation. If an object is heated, it emits radiation (like filaments in light bulbs or the glow of a coal in a fire, for example). All attempts to derive a formula that gave the intensity of the light as a function of frequency (color) failed. Planck guessed the formula and, when detailed experiments proved him right, he had to derive it from some physical principle. He showed that his formula was a natural consequence if, and only if, the matter in the walls of the body could exist in discrete energy states related to their frequency of oscillation. Thus the quantum hypothesis was borne and it was even more revolutionary than radioactivity, but just how revolutionary it really was took years to appreciate.

In 1905, Albert Einstein took the quantum hypothesis a step further when he explained the photoelectric effect, proposing that light was not continuous but composed of discrete particles, photons, and that the relation between the energy and frequency of a photon was the same as that given by Planck. Light was known to have wave-like properties, and Einstein's explanation of the photoelectric effect showed it had particle-like properties as well. As an encore in the same year, Einstein published the special theory of relativity that superceded Newton's laws when velocities were large.

The last two discoveries of the revolutionary era occurred in 1911. Rutherford showed that almost all the mass of an atom was concentrated in a tiny nucleus about a ten-thousandth the size of the atom. Niels Bohr proposed his "Bohr atom" which made sense of Planck's quantized walls in a black body by requiring that Thompson's electrons circulating Rutherford's nucleus could only have angular momenta that were integral multiples of Planck's quantity of action. Thus, they could have only discrete energy states.

The first Solvay conference (Figure 3) took place in Belgium in 1911 and brought together many of the principal revolutionaries. While there was still a long way to go to understand the new phenomena, the new concepts (the instability of certain atoms, the quantum of electricity, subatomic particles, quanta, relativity) were in place and formed a foundation for the development of science in the rest of the century.

III. A LEAP TO TODAY

Today, physics is completely transformed from what it was when the revolution began. This transformation is, in itself, a great story of brilliant insights, painstaking experiments and the development of technologies that enabled all of science and that affected all of our lives. The development in the 1920s of quantum mechanics (Schroedinger and Heisenberg), and its relativistic generalization that is the foundation of quantum electrodynamics (Dirac), as well as the nuclear physics of the thirties, laid the groundwork for a tremendous post-World-War-II expansion of science. Both the worlds of condensed matter and subatomic particles were illuminated by this post-war expansion, and, in my own field, the construction of particle accelerators that themselves are technological marvels have transformed our view of the subatomic world. Today, powerful symmetry arguments illuminate physics on all scales from the atomic to the elementary particle.

The physics community expanded enormously in the process as governments and industry realized the role that science plays in the development of technologies. For example, The American Physical Society was founded in 1899 by 38 physicists; today, The American Physical Society itself has more than 40,000 members, and The American Institute of Physics, which contains The American Physical Societies and nine other societies ranging from lasers to geophysics, has over 100,000 members. Similar expansions occurred in Europe and Japan.

Physics, indeed all of real science, is based on one certainty; today's models are only an approximation of a deeper truth and are valid in the domain accessible to science today. This is the essential skepticism that keeps all of science moving ahead and it is the antithesis of fundamentalism which believes, with certainty, in the absolute and eternal truth of some revealed knowledge.

Physics is unabashedly reductionist. Richard Feynman used to say he only worked on simple problems. I used to respond, “Dick, perhaps simple to Leonardo.” But the real truth behind Feynman’s statement is that physicists seek an underlying simplicity in apparently complex situations. We find invariance principles that imply conservation laws and vice versa. For example, the invariance of equations of motion to a uniform coordinate transformation implies the conservation of momentum. Rotational invariance implies the conservation of angular momentum. Invariance under time displacement implies the conservation of energy. Minimization of the action solves the problems of optics, as well as giving the Feynman path integral formulation for quantum electrodynamics. Two simple assumptions lie behind special relativity: the velocity of light is the same constant whether or not the observer is moving uniformly, and Maxwell's Equations are valid in any uniformly moving coordinate system. Add a third hypothesis, that you cannot tell the difference between a gravitational field and a uniform acceleration, and you get general relativity.

With quantum mechanics and relativity, the basics of the physical world are understood from the macroscopic scale down to distances as small as 10^{-18} meter. That is not to say all of the problems are solved, for some calculations, particularly in many-body systems, are too complicated to be solved directly from the basic equations, and good enough approximations for the behavior of complex systems are still needed at all scales. There are also still surprises like quantized flux, the two-dimensional quantized Hall Effect, Berry’s Phase, etc., but they are quickly brought into the main stream with what we already know.

On the subatomic front, of the constituents of the atoms known at the end of the revolution of 1895 to 1911, only the electron is still thought to be a fundamental entity. The atomic nucleus is a composite of protons and neutrons that are, themselves, composites of quarks, which may indeed be fundamental. The quarks and leptons that are thought of as today’s fundamental entities are organized into three families for reasons that we do not understand, and what used to be three independent forces, the electromagnetic, the weak and the strong, are now two with the Weinberg-Salam-Glashow electro-weak unification. There are in all 18 seemingly arbitrary constants, too many for a group of staunch reductionists, and gravity remains intractable at very short distances.

With all of this goes what is called the Standard Model that can explain all phenomena up to energies of about 100 GeV (down to distances of about 10^{-18} meter), but the Standard Model itself is known to be incomplete. While nature might even have 18 arbitrary constants, the Standard Model makes predictions that violate causality when extrapolated to energies a mere five to ten times those presently accessible with accelerators. There is much more still not understood related principally to high-energy short-distance phenomena that manifests itself through those 18 constants and the strange things we observe about the early universe.

IV. Science and Technology

Science has been in a relatively privileged position since the end of World War II. Support by governments has been generous, and those of us whose careers have spanned the period since World War II have, until recently, seen research funding increasing in real terms, and even the need for big facilities to advance science did not unduly stress the system. Our support rested on two assumptions: science would improve the lives of the citizens and, particularly in the case of physics, science would make us secure in a world that seemed very dangerous because of the US/USSR confrontation.

The world situation has changed radically, and economic concerns loom much larger. With this has come a re-examination of many of the assumptions about priorities for government activities. Being re-examined is not very comfortable for those under the microscope, for we are in effect being asked to rejustify our existence in terms of the relevance of our work to the problems that society perceives to be most immediate.

To the scientist this is strange, even unfair. The scientific revolution and the technology spawned from it have transformed the world. A person brought somehow from only a hundred years ago, the time we celebrate here, would find today's world shockingly different. Then, the average life span was shorter, infant mortality was much greater, and disease carried off more people than did old age. Communications were primitive, only crude telephones existed and there was no radio or television. The average person knew little of the rest of the world. Transportation was slow and there were no autos or airplanes. There was no knowledge of the subatomic world, no computers, etc. Indeed, most of the work that people do today is in areas that did not exist back then. It is based on the technologies derived from the continuing scientific revolution.

Industry, not science, turns long-term research into things that are used in the society. Typically, in industry today, the product-development cycle runs for three to five years. The research that lies behind the technologies incorporated by industry into new products, however, almost always lies much further back in time – twenty or more years. It is true that today's high-tech industry is based on the research of yesterday. For example, lasers and fiberoptics coming from research in the 1960s and 1970s have revolutionized telecommunications. The Global Positioning System (GPS) that allows precise location of anything and anybody anywhere is based on ultra-precise atomic clocks developed for research starting in the 1950s. Biotechnology is based in large measure on recombinant-DNA techniques developed in the 1970s. The explosive growth of the Internet is the result of four decades of work by a worldwide research community culminating in the development of the World Wide Web by the high-energy physicists at CERN in Europe.

Twenty and more years ago much new technology came from long-term R&D done in industry – in the U.S., one thinks of the glory days of Bell Laboratories, and the IBM, General Electric, and RCA research laboratories; and in Europe, of Phillips and Siemans. But, the world economic system has changed, and international competitive pressures have driven most of the long-term research out of industry. Today it is exceedingly rare to find an R&D program in industry whose time horizon is longer than three to five years to a product. We may regret this change, but it is real and it has come about because of deregulation and competition. If one's rivals don't spend money on research, in the short term they are going to have a better bottom line and our economic system, indeed the economic system of all of the developed world, rewards short-term results and punishes those who don't do as well as their competitors. Thus, changes in society have made the government investment in such long-term research much more important than before.

Since today's high-tech industry is based on the research of yesterday, and that research was funded at a time when high-tech industry made up a much smaller fraction of GDP than it does today, and, since high-tech industry is a much larger fraction of GDP today than yesterday and will be even larger tomorrow, the fraction of the government investment in long-term research should also be larger. It is shortsighted in the extreme that the converse is true, for tomorrow's high-tech industry will be based on today's research.

Politicians have often asked me about the worth of basic research. While I can cite many specific examples of things that have come from my lab and ones like it, my favorite response is a story that goes back to the 1850s when much of the fundamental work on electricity and magnetism was being done. In England, Michael Faraday was one of the giants of this work and made many of the basic discoveries linking electricity and magnetism. He is said to have been visited at his laboratory by the then Chancellor of the Exchequer, Gladstone (eventually Prime Minister). After looking at Faraday's work and his rather untidy laboratory, Gladstone said to Faraday, "This is all very interesting, but what good is it?" Faraday is said to have replied, "Sir, I do not know, but someday you will tax it."

V. THE 21ST CENTURY

Physics continues its rapid advance on all fronts. I want to mention briefly an emerging area before going on to discuss what will be happening in elementary-particle physics. The *Physical Review Letters* (PRL) now has a new section in its index called Biological Physics. The molecular-biology revolution began with its discovery of the atom and physics will play a vital role in understanding how biological systems function. The number of physics papers on such things as protein folding, for example, is what has led the editors of PRL to create this new index section. The problem of protein folding is a very difficult one; the potential energy of the long polymer as it is folded has many local minima that could give rise to a misfolded metastable state. The tools of statistical mechanics and thermodynamics are being used to understand the folding process, including how one gets in a very short time to the ultimate stable state.

Unraveling the structure of complex biological systems requires the use of x-ray diffraction and high-resolution nuclear magnetic resonance. Once a system is fully analyzed its functions can be understood; if it is a pathogen, methods can perhaps be found to interfere with it. This is the process used to develop the HIV protease inhibitors where, once the structure was found by x-ray diffraction, the chemists and biologists designed drugs to interfere with the virus' ability to synthesize the essential protease. At my own laboratory, the Stanford Linear Accelerator Center, the structure of cholera toxin is being unraveled and the hope is that new treatments can be developed based on understanding the system at the atomic level. Biological physics will be of increasing importance as we move into the next century. It will involve the experimenters and the theorists to study and understand interactions at all scales from the atomic level to the ensemble level.

In my own area, elementary particle physics, the big question is what lies beyond our Standard Model. The Standard Model was formulated in the 1970s and has withstood more than twenty years of experimental tests. In spite of its successes, it is known to be incomplete, has too many arbitrary constants, no source for the masses of the elementary entities, and makes impossible predictions on certain reactions when extrapolated to higher energies than now accessible. There are several alternative extensions to the Standard Model, and the job of the experimenter is to determine which, if any, of them is the correct new direction.

This situation is not unlike that in the 1960s before the Standard Model was fully formed. At that time, the Fermi model of the weak interactions explained the process of beta decay, but predicted that cross sections for the interactions of neutrinos with nucleons would rise without limit as the neutrino energy increased and would exceed the unitarity bound at a center-of-mass energy of around 300 GeV (Figure 4). That is not possible; it is equivalent to having a reaction probability greater than one. The Standard Model itself solved that problem with its introduction of the finite-mass carriers of a weak interaction, the W and Z bosons, while leaving the Fermi model perfectly useful in the low-energy regime. With the Standard Model, the neutrino-nucleon cross section would turn over and begin to fall as the energy increased, the transition point depending on the mass of the carriers of the weak force. The Standard Model itself has the same kind of problem. At an energy of approximately 1 TeV, the cross section for W-W scattering in certain polarization states will exceed the unitarity bound.

Sorting out which of the alternatives fix the Standard Model will happen early in the next century (perhaps sooner). The new accelerator being built at CERN, the LHC, is designed to achieve an energy where, with high probability, new phenomena will be uncovered that point the way out of the difficulty. The new facility will collide counter-rotating beams of 7-TeV protons, and thus reach 14 TeV in the proton-proton system. The proton has a substructure and it is the hard collisions of the constituents of the protons that are the most important, however, and there the energy is about 1.5 TeV. Construction of the machine is underway with participation beyond the 19 CERN member states including Canada, Japan, Russia, the U.S. and others. The new facility should begin operating in the year 2005.

A complementary facility using electron-positron colliding beams will be needed to sort things out. For decades, experiments of proton and electron colliders have given a kind of stereoscopic view of the fundamental particles and forces, and a full understanding of the TeV scale will require both. A worldwide collaboration on the R&D required for the next big step in electron accelerators has been going on for many years. The new machine will be an electron-positron linear collider, a technology that was pioneered at my own laboratory, SLAC. The main centers for the work are the DESY laboratory in Germany, the KEK laboratory in Japan and SLAC in the U.S., with contributions from many other countries, particularly France and Russia. Detailed designs for alternate approaches are being worked out now, and construction could begin as soon as 2003, with the start of physics research at the end of 2008.

High-energy physics and cosmology are intimately related. The phenomena of high-energy physics governed the evolution of the early universe, and thus some of the conditions in the early universe can be studied in the laboratory. The qualitative picture (Figure 5) is of an initial rapid expansion and cooling after the Big Bang, where what began as a maelstrom of ultra-high-energy quanta and particle-antiparticle pairs was transformed into what we see today. The later parts of this expansion are reasonably well understood; the earlier parts are still a mystery. Experimental information from cosmic rays, accelerators, telescopes, and satellites is continually bringing new information, sometimes confirming parts of the picture and sometimes forcing modifications.

The COBE satellite gives a picture of the temperature fluctuations in the cosmic microwave background radiation. This radiation was emitted 300,000 years after the Big Bang, about 15 billion years ago, when the temperature of the early universe dropped below that required to ionize hydrogen. In the blink of a cosmic eye, the mean free path for light went from a very short distance to a very long distance as the electrons condensed around the nuclei, turning a fog into a clear light. The observed fluctuations in temperature mark fluctuations in density that, under the influence of gravity, produce the distributions of galaxies and clusters of galaxies seen now. The angular resolution of the COBE instrument is not good enough to allow critical tests of the theory behind these fluctuations, but the next satellite will give more detailed information against which our models can be tested.

Only in the last month evidence came in from the Super Kamiokande experiment in Japan that neutrinos seem to have an intrinsic mass. The Super K detector uses 50,000 cubic meters of water to study the interactions of neutrinos generated by cosmic rays in the atmosphere, and finds clear evidence of a kind of neutrino oscillation where one neutrino turns into another, which is possible only if the neutrinos have an intrinsic mass. Our Standard Model has no mechanism to allow this mass, so we have further evidence that an extension to that Model is needed. Also, if the neutrinos have a mass, the amount of matter in the universe is changed, which affects its expansion rate and evolution.

When Albert Einstein developed general relativity the Hubbell expansion of the universe was not known, and the universe was assumed to be static. To allow a static solution to the equations of general relativity, he had to introduce a term called the cosmological constant, though he never liked it. Recent experiments on the number versus distance of super nova, a kind of standard candle, would, if confirmed, indicate that he was right after all to introduce the cosmological constant. The data seem to show an expansion that is speeding up as the mass density in the universe drops with expansion and the attractive force of gravity thus decreases compared to the pressure generated by the cosmological constant.

There are other peculiarities in the data as well. I believe the next century will bring answers to the questions raised by the effects mentioned here and the new questions that will be raised by experiments coming in the future. I will even hazard a prediction: the next century will solve the so-far intractable problem of integrating relativity quantum mechanics, and gravity.

A recent book, "*The End of Science*," by John Horgan, has as its thesis that physics is turning into metaphysics because the models it creates are not testable. That may eventually be true, but it is not true now. We are finding experimentally that Shakespeare had it right when Hamlet said, “There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy.”

VI. Science, Scientists, and Society

The construction of a theoretical model based on testable and falsifiable assumptions is at the heart of physics (indeed of all the physical sciences) and has been so since ancient times. Sometimes experiments uncover phenomena that have no place in the existing theory and the theory must be revised. Sometimes theory succeeds too well in explaining all of the observable phenomena and the experimenters have to find the cracks in the beautiful façade. Sometimes nature gives us a complete surprise, as with x-rays and uranium rays, and the experimenters and theorists must together struggle to explore it and fit it in. So far, we have succeeded by sticking with the rules: be skeptical, be careful, and explain only with testable and falsifiable hypotheses.

Not all so-called sciences use these rules. We have in the United States a movement called Creationist science, opposed to Darwin’s theory of evolution, that claims that all was brought into being a few thousands of years ago by an omnipotent, omniscient being. When confronted with the fossil record or stellar evolution, or the expansion of the universe, they claim their God made it so. This hypothesis is neither testable nor falsifiable: it is **not** science.

Some in society focus exclusively on practical outcomes from scientific research. That, however, is not what drives most scientists. It is the search for new knowledge for the sake of knowing more about the universe in which we exist and mankind’s place in it, for the joy and satisfaction of learning what no one has known before, or of doing something that no one has done before. It is that motivation that drives the young scientists to the typical 60- to 80-hour workweek, not the technologies that may come from his or her scientific work. This urge to understand is part of the human makeup and should not be ignored. We have a long tradition of exploring the unknown that goes back as far as recorded history. Governments have supported science for thousands of years. Alexander the Great took Aristotle on his marches through Asia. Today we launch space observatories like the Hubbell Space Telescope and support research aimed at revealing the ultimate structure of matter at laboratories like Fermilab and SLAC in the U.S. and CERN in Europe. The understanding that this exploration brings enriches our lives. It is sometimes said that such things are only the concern of the scientist, but I do not believe that to be so. The sale of books like Stephen Hawking’s “*A Brief History of Time*,” the audience for television shows on anthropology, biology and cosmology, the popularity of the science magazines, are all testimony that there is broad interest in new knowledge. Galileo’s work supporting the thesis of Copernicus that our earth was not the center of the universe changed fundamentally the way we think of ourselves, and that too is what science can bring to mankind.

Of course, we hope for practical benefits and that hope has been amply fulfilled. We should not, however, try to focus too narrowly on the practical, for that is to deny the needs of the spirit. To those very practical people who would deny the importance of the spirit, keep in mind the limits to our imagination. Remember Gladstone's question to Faraday, "What good is it?", and Faraday's reply, "Sir, some day you will tax it."

Finally, I want to confront a darker issue: is science an angel or a devil? There are those who say increasingly loudly that science and its derivative technology create more problems than they solve. This has been stated most eloquently by Vaclav Havel in an article in the New York Times of 1 March 1992, *"The End of the Modern Era."*

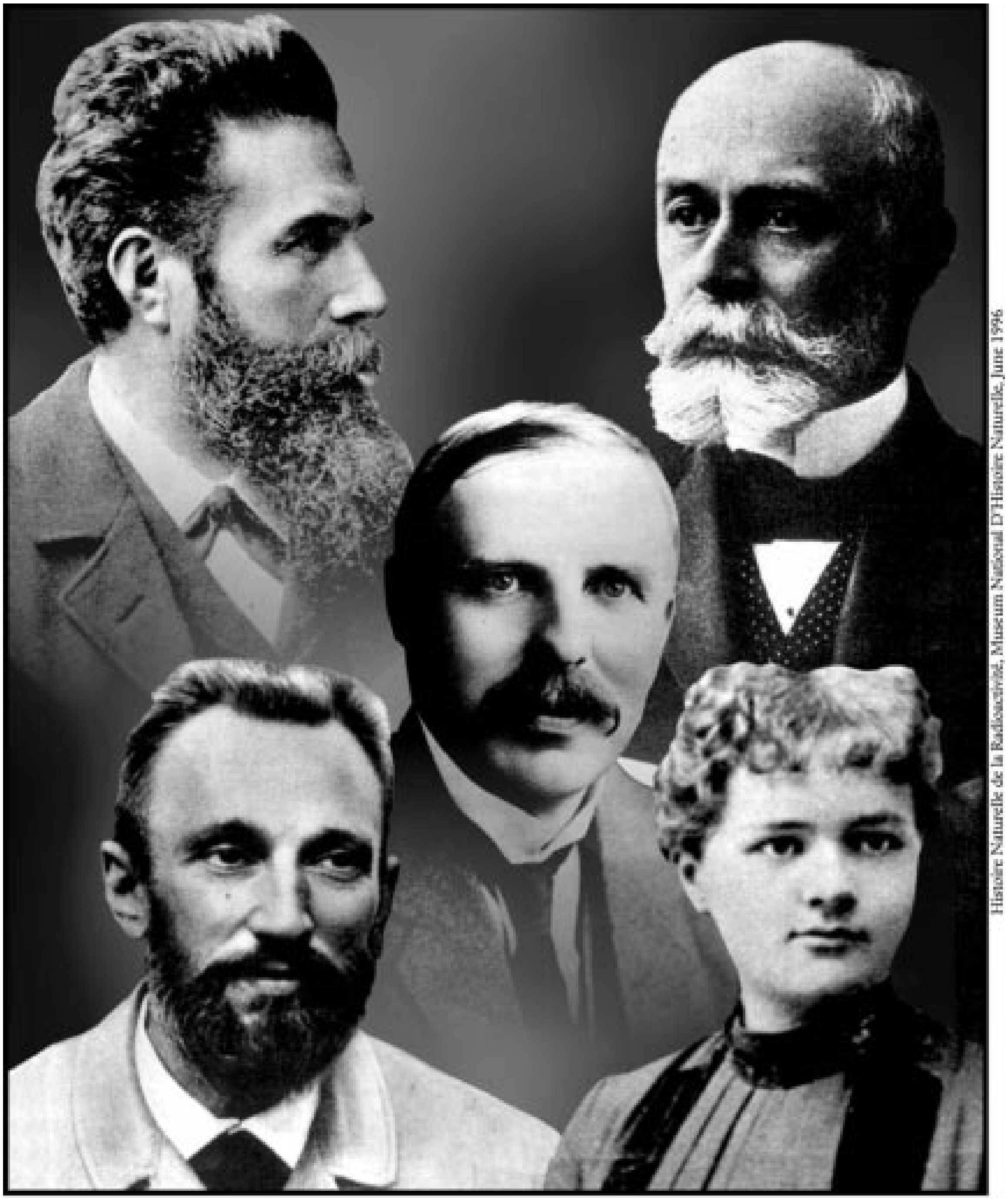
> *"…. This era has created the first global, or planetary, technical civilization, but it has reached the limit of its potential, the point beyond which the abyss begins. …. The traditional science, with its usual coolness, can describe the different ways we might destroy ourselves, but it cannot offer us truly effective and practicable instructions on how to avert them. …. We all know that civilization is in danger. The population explosion and the greenhouse effect, holes in the ozone, …. The threat of nuclear terrorism, …. All these, combined with a thousand other factors, represent a general threat to mankind. We are looking for new scientific recipes, new ideologies, new control systems, new institutions, new instruments to eliminate the dreadful consequences of our previous recipes, ideologies, control systems, institutions and instruments. We treat the fatal consequences of technology as though there were a technical defect that could be remedied by technology alone. We are looking for an objective way out of the crisis of objectivism.*

Is then science an angel or a devil? Havel does not say. I say that it is neither; it is the truth as we have learned it about our world and about nature. Truth can be extremely uncomfortable, creating both opportunities and risks. The truth uncovered in the scientific revolution of the last 400 years has made the world both better and more dangerous.

Havel's point is much deeper than the usual accusation that science does not solve problems as, for example, the disposal of nuclear waste. I interpret Havel's words as indicating the futility of seeking purely technical solutions to all problems. I fully agree. All too often, our leaders seek simple, low-cost, technical solutions to problems when science and technology have no simple, low-cost solutions. Yet science does have solutions to or palliatives for some of our most pressing problems if we but had the political will to implement them. The problems of the population explosion, nuclear waste disposal, energy efficiency, can all be attacked now, given the political will that we do not seem to have. The source of the lack of will lies in us. Some sacrifice is required and in the democracies, the acceptance of the need for sacrifice seems only to be triggered by a sense of crisis. Long-term problems require for solution consistent action over many years. That is difficult to achieve when eternity is the time to the next election. In parts of the world the problems are ignorance, tribalism, fanaticism, greed and the lust for power. There we can do little beyond palliative measures.

There seems to be a rising tide of anti-intellectualism in our society coming from frustration at science's apparent inability to solve the problems that Havel identified. It results in a retreat from reality and a yearning for an idealized past that never existed, or in blaming those different from the majority for the existence of the problems. We must get our political system to recognize that fundamental societal problems must be addressed using all the tools that we have. If we do not do so, nature will do so for us, and, while nature is not malicious, it is inexorable. It is alleged that Galileo, after his abjuration before the Inquisition of any concept of the earth as a moving body revolving around the sun, whispered, *"E pur si muove!" (But still it moves!)*. It does not matter how we wish things to be. Denial of the truth gets us nowhere. The task of the scientific community must be to help society get beyond denial.

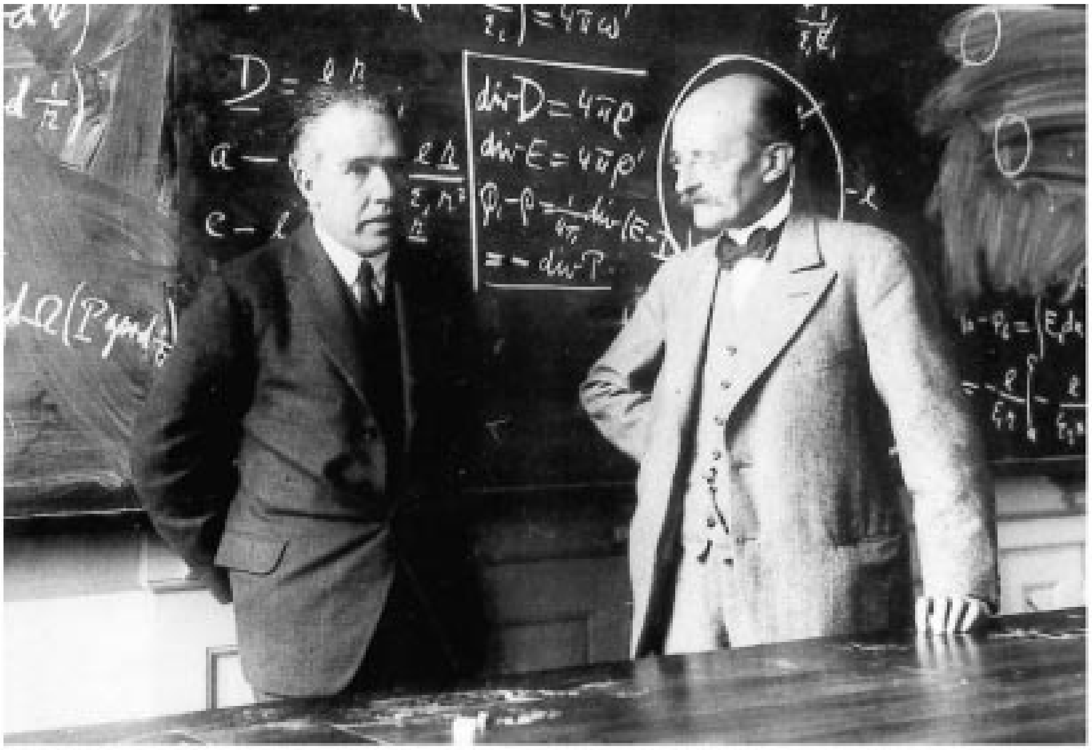
LIST PRESENTATION FIGURES



Wilhelm Roentgen *Ernest Rutherford* *Henri Becquerel*

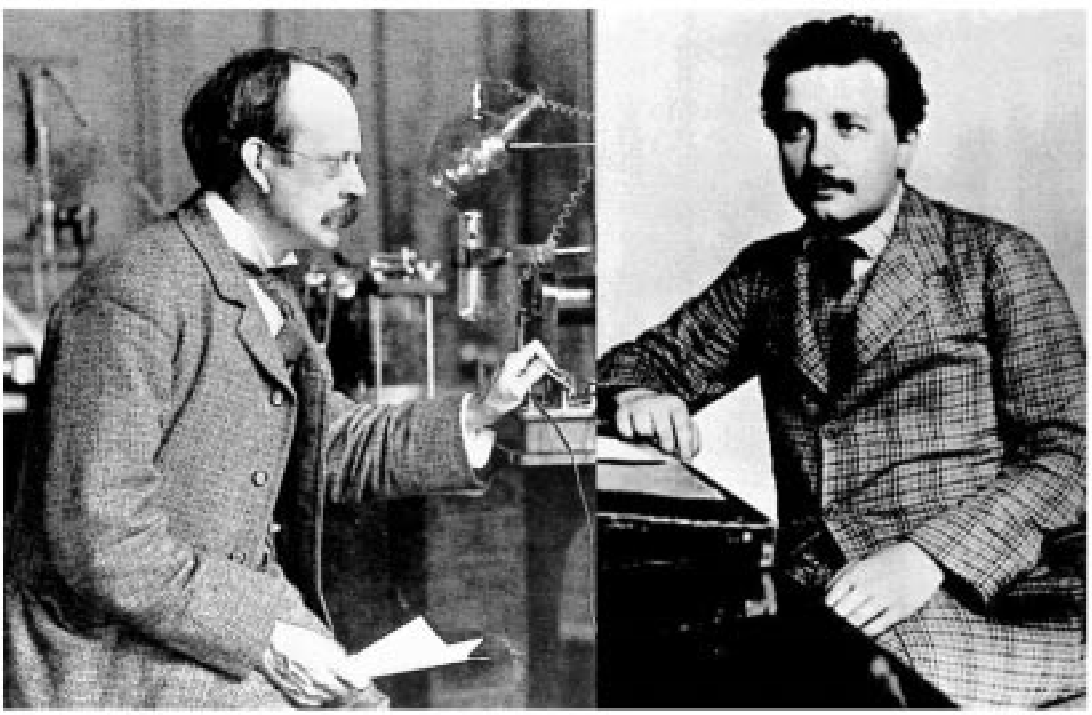
Pierre Curie *Marie Curie*

Figure 1



Courtesy AIP Emilio Segrè Visual Archives, Margrethe Bohr Collection

N. Bohr *M. Planck*



Courtesy Science Museum/Science & Society Picture Library, London

Courtesy of the Archives, California Institute of Technology

J.J. Thomson *A. Einstein*

Figure 2

Standing from left to right:
O. Goldschmidt, M. Planck, H. Rubens, A. Sommerfeld, T. Lindemann, M. de Broglie, M. Knudsen,
F. Hasenöhrl, H. Hostelet, T. Herzen, J. Jeans, E. Rutherford, H. Kamerlingh Onnes, A. Einstein, P. Langevin

Seated from left to right:
W. H. Nernst, M. Brillouin, E. Solvay, H. A. Lorentz, O. Warburg, J. Perrin, W. Wien, M. Curie, H. Poincaré

Figure 3

Neutrino – Nucleon Cross Section

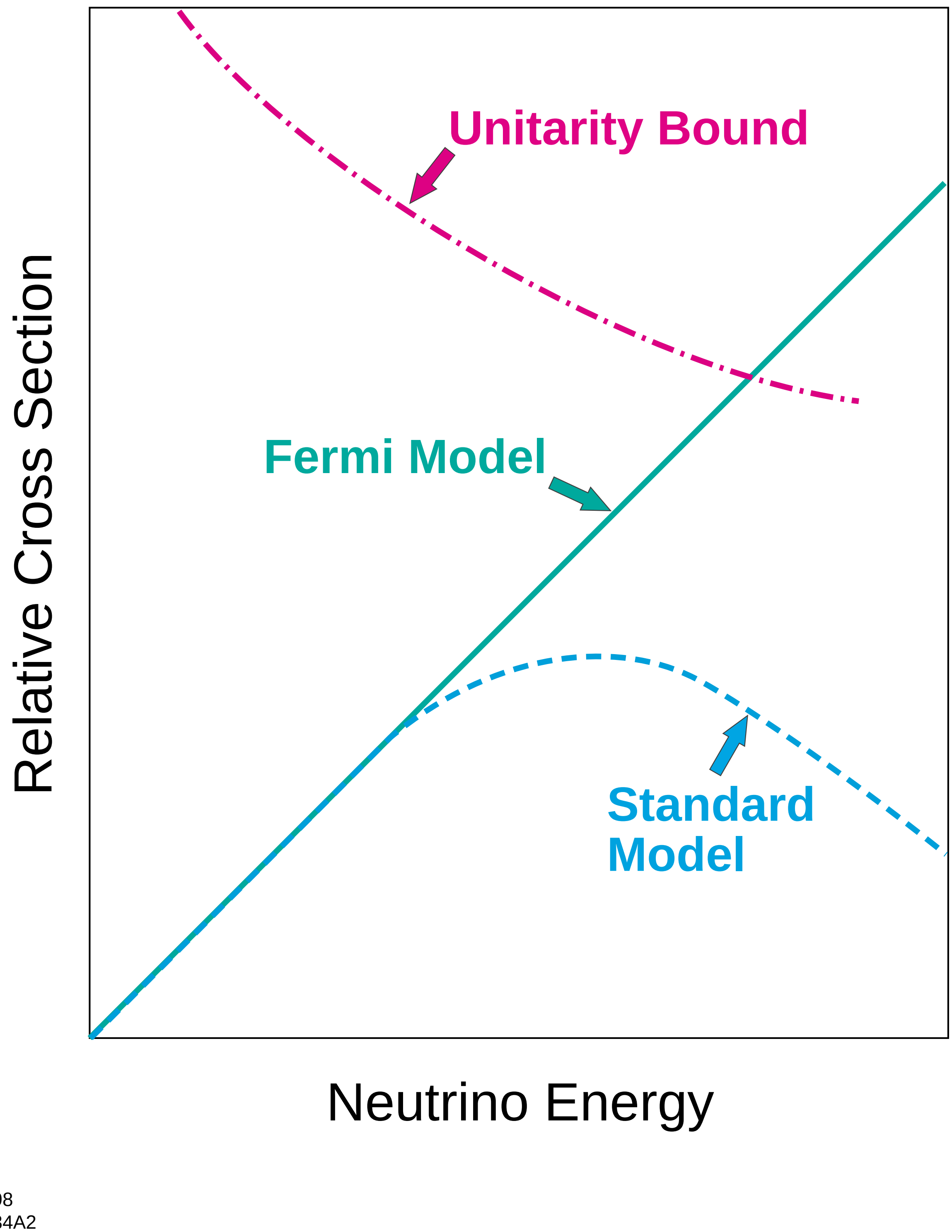


Figure 4

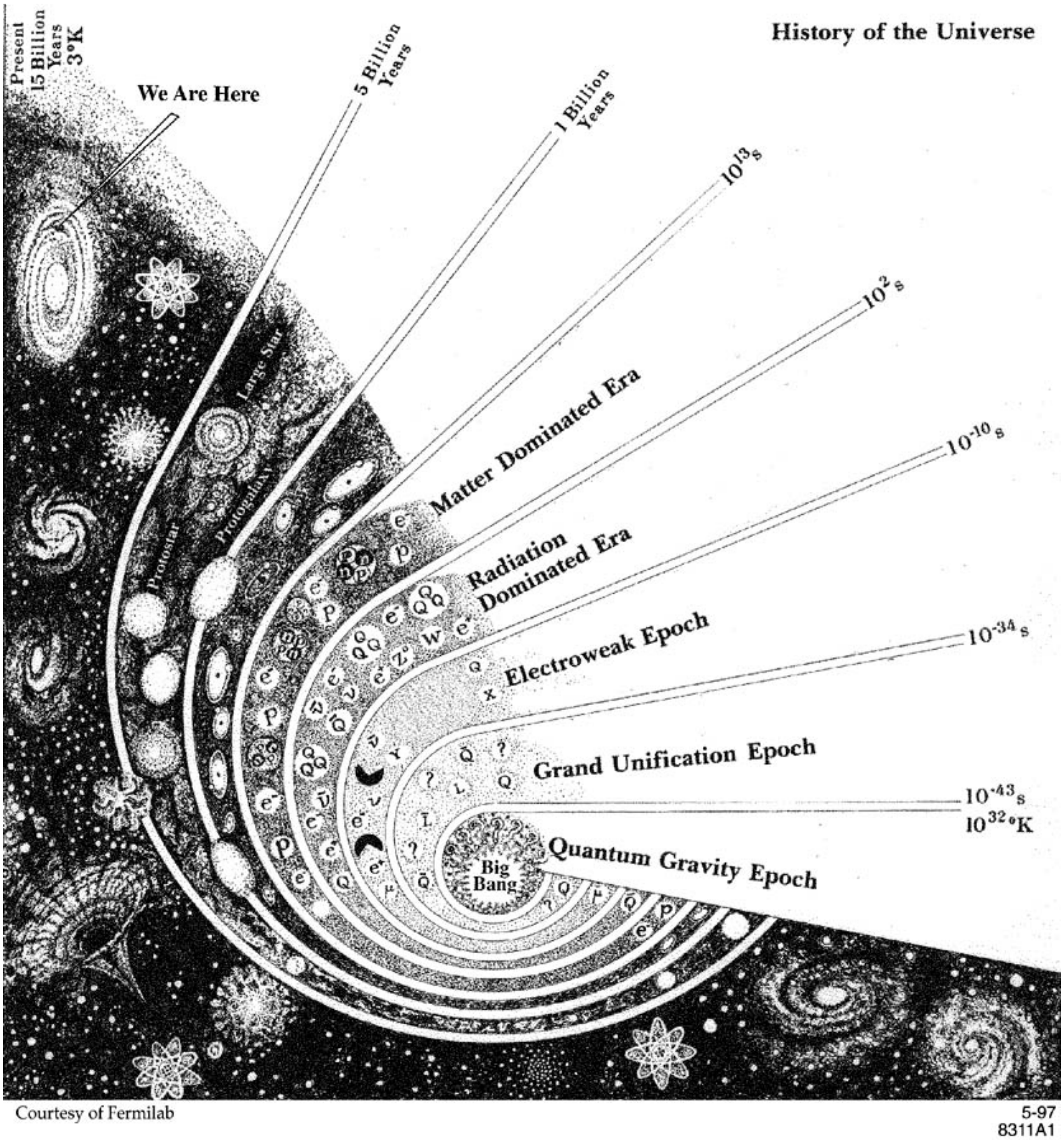

History of the Universe
Present
15 Billion
Years
3°K
We Are Here
5 Billion
Years
1 Billion
Years
10^13 s
10^2 s
10^-10 s
10^-34 s
10^-43 s
10^32 °K
Matter Dominated Era
Radiation
Dominated Era
Electroweak Epoch
Grand Unification Epoch
Quantum Gravity Epoch
Big
Bang
Large Star
Protogalaxy
Protostar
Courtesy of Fermilab
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Figure 5