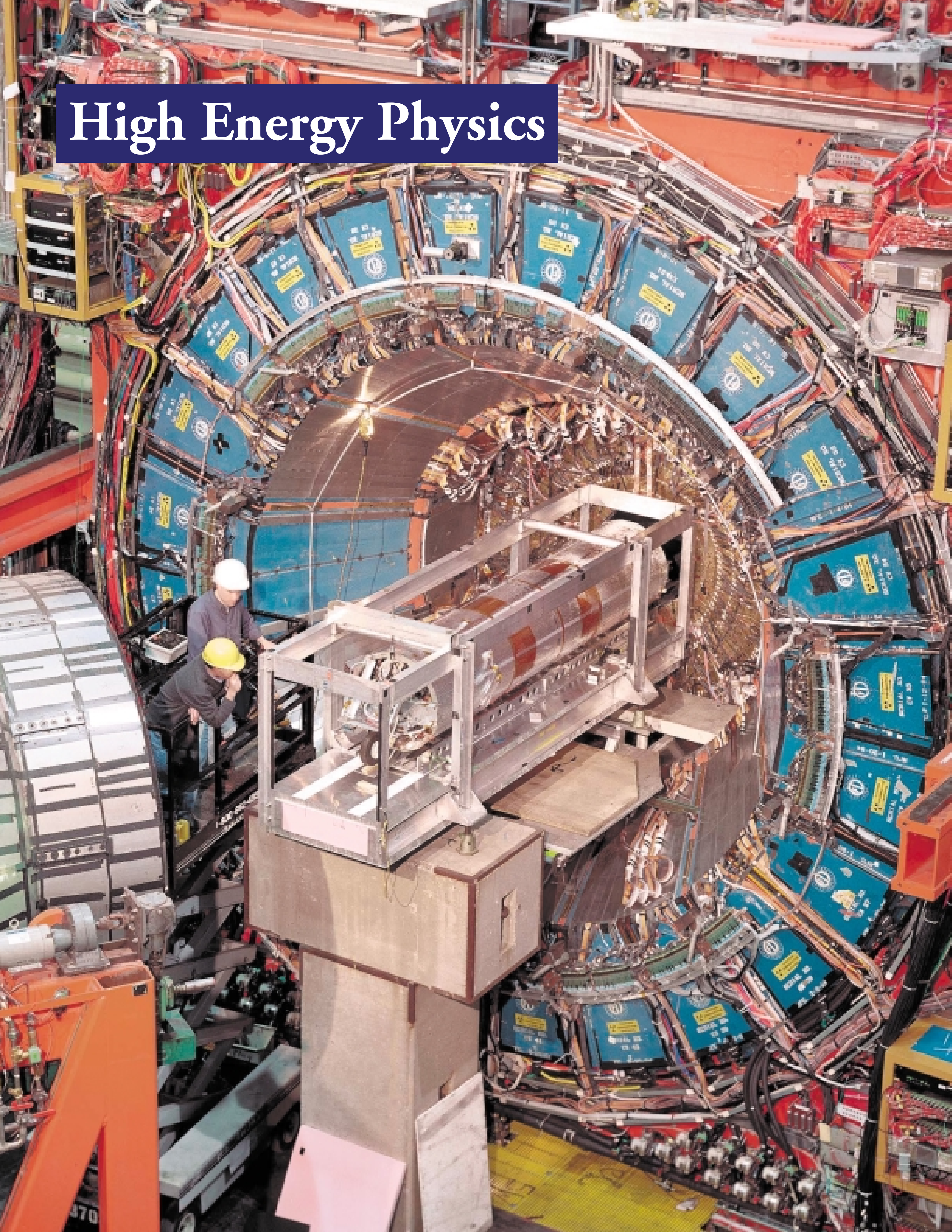
High Energy Physics



The Collider Detector at Fermilab (CDF): This experimental collaboration is committed to studying high-energy particle collisions at the world's highest-energy particle accelerator. The goal is to discover the identity and properties of the particles that make up the universe and to understand the forces and interactions between those particles.

SLAC

4 Explore the Fundamental Interactions of Energy, Matter, Time, and Space

Understand the unification of fundamental particles and forces and the mysterious forms of unseen energy and matter that dominate the universe, search for possible new dimensions of space, and investigate the nature of time itself.

Led by great physicists like Galileo, Einstein, and Heisenberg, we have learned much about the universe. In the early 20th Century, we learned that it is expanding and that space-time is curved. We discovered the quantum nature of matter, a profound advance with many practical benefits. We learned that all matter is built of just 12 types of particles interacting by four basic forces.

Nevertheless, we are continually humbled by what we do not understand. For example, we learned recently that the expansion of the universe is accelerating, not slowing down as we had thought. This astonishing fact is attributed to "dark energy" that accounts for nearly three-quarters of the energy of the universe.

Nearly a quarter of the energy is made up of another mysterious substance dubbed "dark matter." Only around 4% is ordinary matter.

These are a few of the basic questions yet to be answered:

- How were the patterns of particles and forces we see today unified in the early universe?
- What is the nature of dark energy? Of dark matter? Why do they make up most of the universe?
- Are there more than four dimensions of space-time? If so, how can we detect them?

Answering these questions will reveal much about the creation and fate of our universe. Computing resources that dwarf current capabilities will be unleashed on challenging calculations of subatomic structure, while new accelerators will be needed to investigate unification at high energies. Understanding unification and the cosmos is a challenge, but one that is well suited to the large-scale research teams and international partnerships that we bring together.

As an integral part of this Strategic Plan, and in *Facilities for the Future of Science: A Twenty-Year Outlook*, we have identified the need for four future facilities to realize our High Energy Physics vision and to meet the science challenges described in the following pages. Two of the facilities are near-term priorities: the **Joint Dark Energy Mission (JDEM)** and the **BTeV**. JDEM is a space-based probe, developed in partnership with NASA, designed to help understand the recently discovered mysterious "dark energy," which makes up nearly three quarters of the universe and evidently causes its accelerating expansion. BTeV ("B-particle physics at the TeVatron") is an experiment designed to use the Tevatron proton-antiproton collider at the Fermi National Accelerator Laboratory (currently the world's most powerful accelerator) to make very precise measurements of several aspects of fundamental particle behavior that may help explain why so little antimatter exists in the universe. All four facilities are included in our High Energy Physics Strategic Timeline at the end of the chapter and in the facilities chart in Chapter 7 (page 93), and they are discussed in detail in the *Twenty-Year Outlook*.

Our Strategies

In developing strategies to pursue these exciting opportunities, the Office of Science has been guided by long-range planning reports: *The Way to Discovery* (2002), High Energy Physics Advisory Panel (HEPAP); and *Connecting Quarks with the Cosmos* (2003), National Research Council.

4.1 Explore unification phenomena.

Unification is simplicity at the heart of matter and energy. The complex patterns of particles and forces we see today emerged from a much more symmetric universe at the extremely high energies of its first moments. Indications of this simpler world must occur at energies just beyond the reach of current accelerators. A principal strategy is to find out how our complex patterns merge into a unified picture at higher energies.

The Standard Model of particles and forces asserts that all matter is made of elementary particles called fermions. These are of two types: quarks and leptons, each of which comes in six "flavors." Four fundamental interactions are known: strong, weak, electromagnetic, and gravitational, which vary substantially in strength and range. The first three interactions are carried by another class of particles called gauge bosons. No quantum theory of gravity has been established and gravity is not included in the Standard Model.

At energies above one trillion electron volts (1 TeV), the electromagnetic and weak interactions are unified into the electroweak interaction, and two of its bosons are massless. At about 1 TeV, this electroweak symmetry is broken and the bosons acquire mass. The Standard Model attributes this to a new field called the Higgs, but the Higgs boson has not yet been observed.

Three of the leptons are neutrinos, which feel only the weak interaction, were thought to be massless, and barely interact with matter. Recent

Our History of Discovery…Select Examples

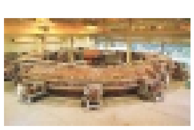
1950s
Discovered strange particles, nuclear antimatter, and nuclear resonances.

1962
Discovered the muon neutrino.
(1988 Nobel Prize)

1969
Found first direct evidence for quarks.
(1990 Nobel Prize)

1950 1960

1950s
Invented strong focusing, which led to higher energy accelerators (synchrotrons).



1956
Predicted parity violation in weak interaction.
(1957 Nobel Prize)

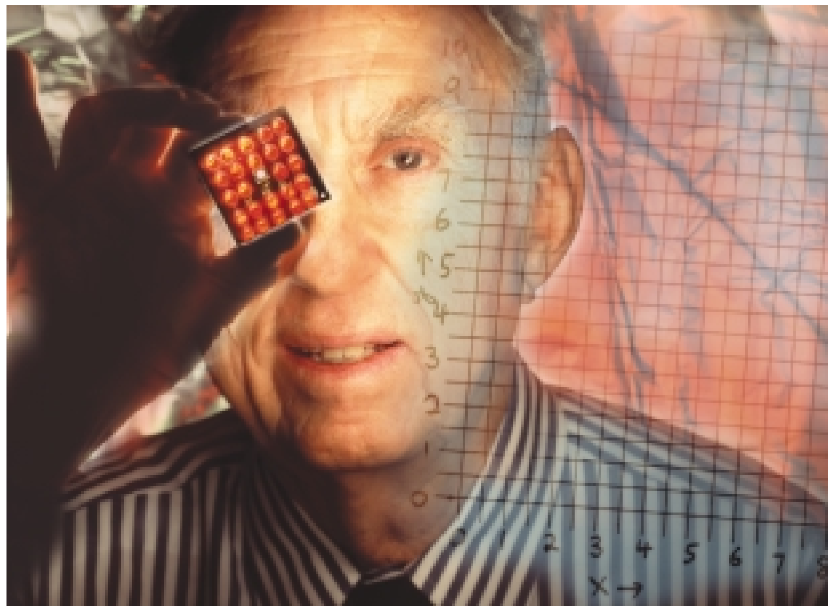
1964
Observed direct charge-parity violation, showing that matter and antimatter do not always behave symmetrically.
(1980 Nobel Prize)

experiments have shown that a neutrino produced in one flavor oscillates among all three flavors as it travels. This can only happen if neutrinos do have mass, which has important consequences for the Standard Model and for the universe.

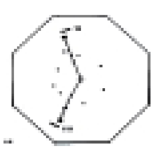
The Standard Model explains many observations at the energies our particle accelerators can reach today, but is known to have problems at higher energies. The theory requires 18 arbitrary and independent parameters whose values are unexplained. It is clear that the Standard Model must be substantially extended.

Physicists are striving to develop a quantum field theory for gravity, using "string theories," which explain particles as vibration modes of a tiny string-like bit of energy. String theories involve supersymmetry, a deep connection between fermions and bosons at high energies. Supersymmetry predicts that every known fermion has a boson partner and vice versa. Some of these partners must have masses low enough to be created at the TeV energy scale. Thus, our highest energy accelerators should be able to test supersymmetry by searching for the lightest supersymmetric particles.

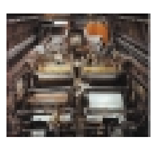
All string theories require several extra spatial dimensions beyond the three we now observe. These may be detected at accelerators by giving



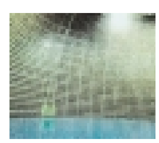
Constituents of matter: In the instant of collision, accelerated particles approaching the speed of light reveal their constituent parts. Martin Perl (above), at Stanford Linear Accelerator Center, discovered a new type of fundamental particle—the Tau lepton. This type of particle had not been observed prior to Perl's work and the discovery had crucial implications, providing new evidence of the third family of fundamental particles. His work inspired confidence in the Standard Model, the theory developed by physicists to explain matter and the forces of Nature, and for his efforts he was awarded the 1995 Nobel Prize in physics. Like many before him, and the many who will follow, his discoveries help shape our understanding about our physical universe, press the limits of theory and experimentation, and provide the intellectual content for a new generation of science education.



1977
Discovered the tau lepton.
(1995 Nobel Prize)



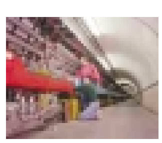
1977
Discovered the bottom quark.



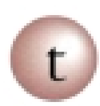
1998
Discovered neutrino oscillations, with neutrinos produced in Earth's atmosphere.
(2002 Nobel Prize)

1970 *1980* *1990* *2000*

1974
Discovered the charm quark.
(1976 Nobel Prize)



1986
Began operating the Tevatron, first accelerator with superconducting magnets.



1995
Discovered the top quark.

2000
Discovered the tau neutrino.

FNAL

Colliders and the science of matter: The Tevatron, operated by Fermi National Accelerator Laboratory since 1986, is a proton-antiproton collider that currently offers the world's highest energy particle collisions. With the tau neutrino observation in 2000, Fermilab has discovered three of the four particles of the third generation of the Standard Model: the bottom quark, the top quark, and the tau neutrino. Fermilab physicists and collaborators will now zero in on the mass of the undiscovered Higgs boson, one of the last crucial components of the theoretical framework of particle physics.

"When we try to pick out anything by itself, we find it is tied to everything else in the universe."

—John Muir (1838-1914), U.S. naturalist and explorer

particles enough energy that they feel the effects of extra dimensions. A direct discovery of extra dimensions would be an epochal event.

Our strategy includes the following emphases:

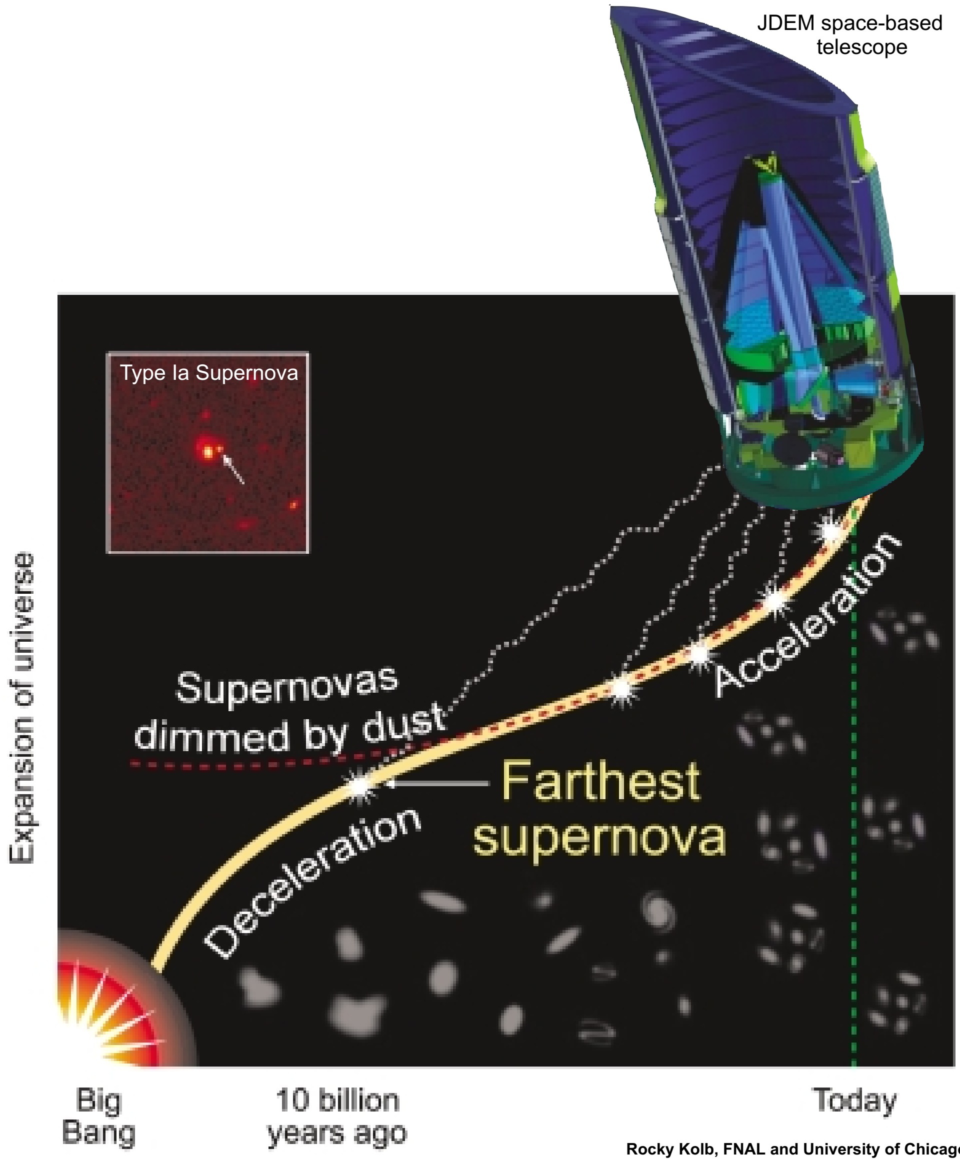
- Use the Tevatron proton-antiproton collider at the Fermi National Accelerator Laboratory to make detailed studies of the top quark discovered there in 1995.
- Search for evidence of unification at the Tevatron, such as the Higgs boson, supersymmetric particles, and extra dimensions.
- Use the B-Factory at the Stanford Linear Accelerator Center to improve our knowledge of the weak interactions of quarks.
- Study neutrino oscillation and double beta decay to learn more about lepton flavor mixing and neutrino masses.
- Develop a string theory that explains the observed particles and includes a quantum theory of gravity.
- Continue our collaboration with the CERN laboratory in Switzerland to complete construction of the Large Hadron Collider there and then use it to study unification. When it begins operations in 2007, this proton-proton collider will extend the energy frontier well beyond the reach of the Tevatron.
- Participate in the development of an international linear electron-positron collider for research at the TeV energy scale. Such a facility has been recommended by HEPAP and by expert panels in Asia and Europe as an essential tool for exploring unification.
- Pursue advanced accelerator development aimed at finding better ways to accelerate particles, with the promise of increasing their energies beyond one TeV.

4.2 Understand the cosmos.

The universe began in an extremely hot, dense condition and has undergone a tremendous expansion, greatly reducing its energy density. The early universe can be described by a unified picture of particles and forces. As it expanded and cooled, however, this simpler universe "froze out" into the complexity we see today.

In 1998, we learned that the expansion of the universe is now accelerating rather than decelerating. This means that some unknown source is producing an antigravity force stronger than gravity. This mysterious dark energy now composes 73% of the total matter and energy content of the universe. The second largest fraction, 23%, is called dark matter and it has not been identified either. Ordinary matter, including all the stars and galaxies, amounts to around 4%.

Since the science of the very large and the very small are intertwined, we will develop joint research programs with NASA and other partners to combine high energy physics research with related programs in astrophysics and cosmology.



Rocky Kolb, FNAL and University of Chicago

Amazing discovery in 1998 in studies of distant Type Ia supernovae: The Big Bang expansion of the universe is accelerating rather than decelerating. This expansion has been speeding up for the past few billion years, after a long period of slowing down. The source of the "antigravity" force pushing space outward is called "dark energy" and is still a profound mystery. Plans are underway to launch a space telescope, the JDEM, which could investigate the mystery by making more precise measurements of supernovae from many different times in the history of the universe.

Identify dark energy.

Explaining the dark energy that is pulling the universe apart is crucial for understanding its evolution. Our strategy includes the following emphases:

- Work in partnership with NASA to observe distant supernovae using a dedicated telescope in earth orbit. The JDEM will precisely measure the emission of light from supernovae located at a wide range of distances, providing a history of accelerating and decelerating periods in the life of the universe.
- Develop a theoretical understanding of dark energy. Our best attempts to calculate the vacuum energy density give results that are much too large.

Identify dark matter.

The nature of dark matter has not yet been determined, but we suspect that it consists of weakly interacting massive particles. A prime candidate is the lowest mass supersymmetric particle, left as a remnant of a very early stage of the universe. Our strategy includes the following emphases:

- Search for weakly interacting massive particles in cosmic rays.
- Search for supersymmetric particles produced in accelerator experiments.

Accelerator Technology for the Nation

Accelerators underpin virtually every activity of the DOE's Office of Science and, increasingly, of the entire scientific enterprise. From biology to medicine, from materials to metallurgy, from elementary particles to the cosmos, accelerators provide our window to the microcosm, forming the basis for scientific understanding and applications spanning countless fields.

Over the last century, particle accelerators have changed the way we look at Nature and the universe we live in and have become an integral part of the Nation's technical infrastructure. For example:

- 10,000 cancer patients are treated every day in the United States with electron beams from linear accelerators.
- Accelerators produce short-lived radioisotopes that are used in over 10 million diagnostic medical procedures and 100 million laboratory tests every year in the United States.
- Nuclear diagnostic medicine and radiation therapy together save countless lives and generate about $20 billion in business annually.
- The use of ion beams from accelerators to embed doped layers in semiconductors is essential to the multi-billion-dollar semiconductor industry.
- Ion implantation is also used to harden surfaces such as those of artificial hip or knee joints, high-speed bearings, or cutting tools.
- X-ray lithography with intense x-ray beams from synchrotron light sources is used to etch microchips and other semiconductor devices. Accelerators are also used for accurate, nondestructive dating of archeological samples and art objects.

DOE's Office of Science, like its predecessor agencies, has played the lead Federal role in developing these powerful tools and in establishing national accelerator facilities for scientific research. Among Federal funding agencies, the DOE Office of Science is unique in its stewardship of the development and operation of these large user facilities. Accelerator science is an interdisciplinary field spanning a range of technologies from applied superconductivity and microwave generation to high-performance computing. This is an area in which DOE is a recognized leader—bringing together diverse skills to tackle problems that can only be solved by a multidisciplinary approach.

As we look to the future, we project a need for an initiative in accelerator research and development to advance the frontiers of science, to expand collaborations, and to pursue educational opportunities.

The initiative will balance the full spectrum of needs for the Nation, including research and applications.

- Study the large-scale structure of the universe and infer the distribution of dark matter.

Explain the matter/antimatter puzzle.

There appears to be no antimatter in the universe now, although equal amounts of matter and antimatter should have been created in the early universe. This is one of the great mysteries of physics. Our strategy includes the following emphases:

- Use the SLAC B-Factory to provide sensitive measurements of a minute asymmetry in the weak interactions of quarks that may help explain the absence of antimatter.
- Conduct an experiment on the International Space Station to search for antimatter in cosmic rays.

Study the cosmic role of neutrinos.

Neutrinos permeate the universe and hardly interact with matter, yet play a key role in the explosion of stars. The recent discovery of neutrino mass has important consequences for these supernovae. Our strategic emphases in this section overlap with those listed in section 4.1, for exploring unification phenomena:

- Study neutrino masses and mixing in much more detail using new accelerator beams and detectors.
- Search for neutrino-less double beta decay to provide an absolute scale of neutrino masses.

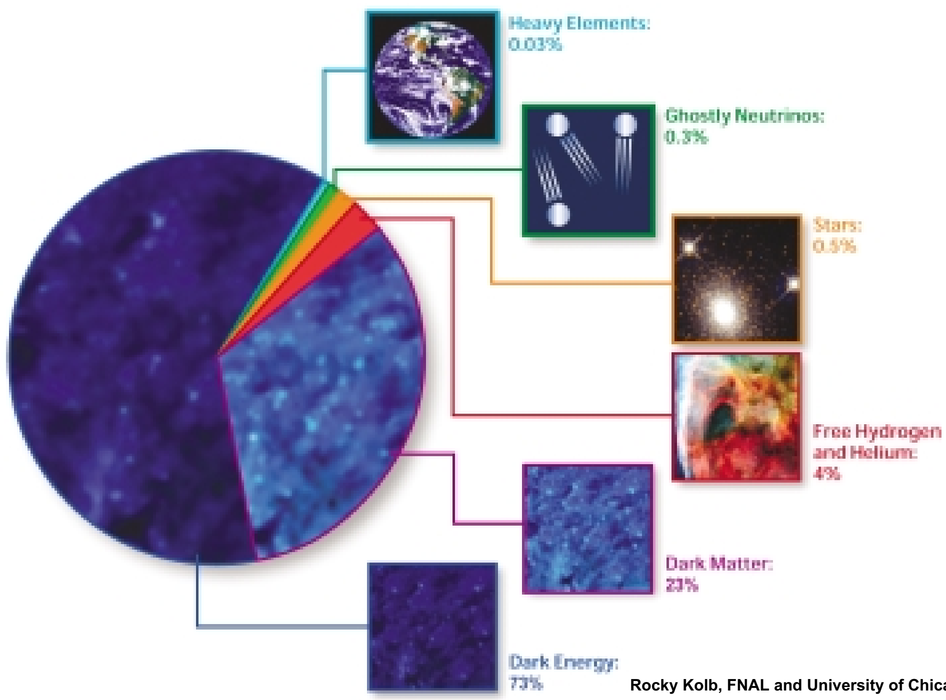
Investigate high energy astrophysics.

High energy physics research can help solve important problems in astrophysics—the origin of the highest-energy cosmic rays, core-collapse supernovae and the associated neutrino physics, and galactic and extragalactic gamma-ray sources. Our strategy includes the following emphasis:

- Develop detectors on the ground and in space that will be used to study high-energy cosmic rays and gamma rays.

"I have deep faith that the principle of the universe will be beautiful and simple."

—Albert Einstein



Rocky Kolb, FNAL and University of Chicago

Makeup of the universe: We do not know what makes up 96% of the universe. Current estimates are that 73% of the universe consists of dark energy and another 23% is dark matter, neither of which we really understand. The part we do understand, including all of the bright stars and galaxies in the sky, makes up only 4% of the universe.

Our Timeline and Indicators of Success

Our commitment to the future, and to the realization of **Goal 4: Explore the Fundamental Interactions of Energy, Matter, Time, and Space,** is not only reflected in our strategies, but also in our Key Indicators of Success, below, and our Strategic Timeline for High Energy Physics (HEP), at the end of this chapter.

Our HEP Strategic Timeline charts a collection of important, illustrative milestones, representing planned progress within each strategy. These milestones, while subject to the rapid pace of change and uncertainties that belie all science programs, reflect our latest perspectives on the future—what we hope to accomplish and when we hope to accomplish it—over the next 20 years and beyond. Following the science milestones, toward the bottom of the timeline, we have identified the required major new facilities. These facilities, described in greater detail in the DOE Office of Science companion report, *Facilities for the Future of Science: A Twenty-Year Outlook*, reflect time-sequencing that is based on the general priority of the facility, as well as critical-path relationships to research and corresponding science milestones.

Additionally, the Office of Science has identified Key Indicators of Success, designed to gauge our overall progress toward achieving Goal 4. These select indicators, identified below, are representative long-term measures against which progress can be evaluated over time. The specific features and parameters of these indicators, as well as definitions of success, can be found on the web at **www.science.doe.gov/measures**.

Key Indicators of Success:

- Progress in measuring the properties and interactions of the heaviest known particle (the top quark) in order to understand its particular role in the Standard Model.
- Progress in measuring the matter-antimatter asymmetry in many particle decay modes with high precision.
- Progress in discovering or ruling out the Standard Model Higgs particle, thought to be responsible for generating the mass of elementary particles.
- Progress in determining the pattern of the neutrino masses and the details of their mixing parameters.
- Progress in confirming the existence of new supersymmetric (SUSY) particles, or ruling out the minimal SUSY "Standard Model" of new physics.
- Progress in directly discovering or ruling out the existence of new particles that could explain the cosmological "dark matter."

Strategic Timeline for High Energy Physics

Strategic Timeline—

2003 2005 2007 2009 2011 2013

The Science

Explore Unification

- Begin studies of neutrino mass differences and flavor mixing with NuMI/MINOS to clarify neutrino's role in Standard Model of particles and forces (2005)
- Measure properties and interactions of the top quark to understand its role in Standard Model (2007)
- Use results from Tevatron Run 2 at energy frontier to discover or set better limits for Higgs boson, supersymmetric particles, and extra dimensions (2008)
- Begin research at Large Hadron Collider at CERN in Switzerland, guided by Tevatron results and extending frontier to substantially higher-energy (2008)
- Use computer simulations to calculate strong interactions between particles so precisely that theoretical uncertainties no longer limit our understanding of these interactions (2009)
- Determine the pattern of neutrino masses and details of neutrino mixing parameters (2011)
- Use early results from Large Hadron Collider to define initial physics objectives of Linear Collider (2012)
- Measure W boson mass with high precision to understand its relationship with the top quark and Higgs boson (2013)

Understand the Cosmos

- Begin using full array of detectors in Pierre Auger Observatory in Argentina to study origins of extremely high-energy cosmic rays (2005)
- Complete initial survey with Gamma-ray Large Area Space Telescope and use results to study high-energy gamma ray sources and astrophysical acceleration mechanisms (2009)
- Measure matter/antimatter asymmetry in quark sector with high precision (2013)

Future Facilities**

Joint Dark Energy Mission (JDEM): JDEM is a space-based probe, developed in partnership with NASA, designed to help understand the recently discovered mysterious "dark energy" that makes up more than 70% of the universe.

B-Particle Physics at the TeVatron (BTeV): BTeV is an experiment designed to use the Tevatron proton-antiproton collider at the Fermi National Accelerator Laboratory to make very precise measurements of several aspects of fundamental particle behavior.

***These strategic milestones are illustrative and depend on funds made available through the Federal budget process.**

****For more detail on these facilities and the overall prioritization process, see the companion document, *Facilities for the Future of Science: A Twenty-Year Outlook.***

High Energy Physics*

2015 | 2017 | 2019 | 2021 | 2023 | 2026

- Discover supersymmetric particles or rule out minimal supersymmetric Standard Model of new physics (2020)
- Measure neutrino masses from studies of double beta decay, helping to set energy scale for unification (2026)
- Discover extra dimensions or set limits on their extent (2022)
- Discover or rule out Standard Model Higgs boson, thought to be source of elementary particle mass (2014)
- Validate a theoretical model of relationships among top quark, W boson, and Higgs boson (2023)

- Determine the role of supersymmetric particles in dark matter (2020)
- Use knowledge of neutrino mass to clarify role of neutrinos in dark matter and stellar explosions (supernovae) (2026)
- With DOE/NASA Joint Dark Energy Mission, precisely measure expansion history of universe, to determine the nature of dark energy (2017)
- Using Super Neutrino Beam, begin measurements of matter/antimatter asymmetry in lepton sector (2021)

Linear Collider: The Linear Collider will allow physicists to make the world's most precise measurements of Nature's most fundamental particles and forces at energies comparable to those of the Large Hadron Collider (LHC).

Super Neutrino Beam: The Super Neutrino Beam will allow more comprehensive studies of the neutrino properties by producing a neutrino beam 10 times more intense than those available with current accelerators.