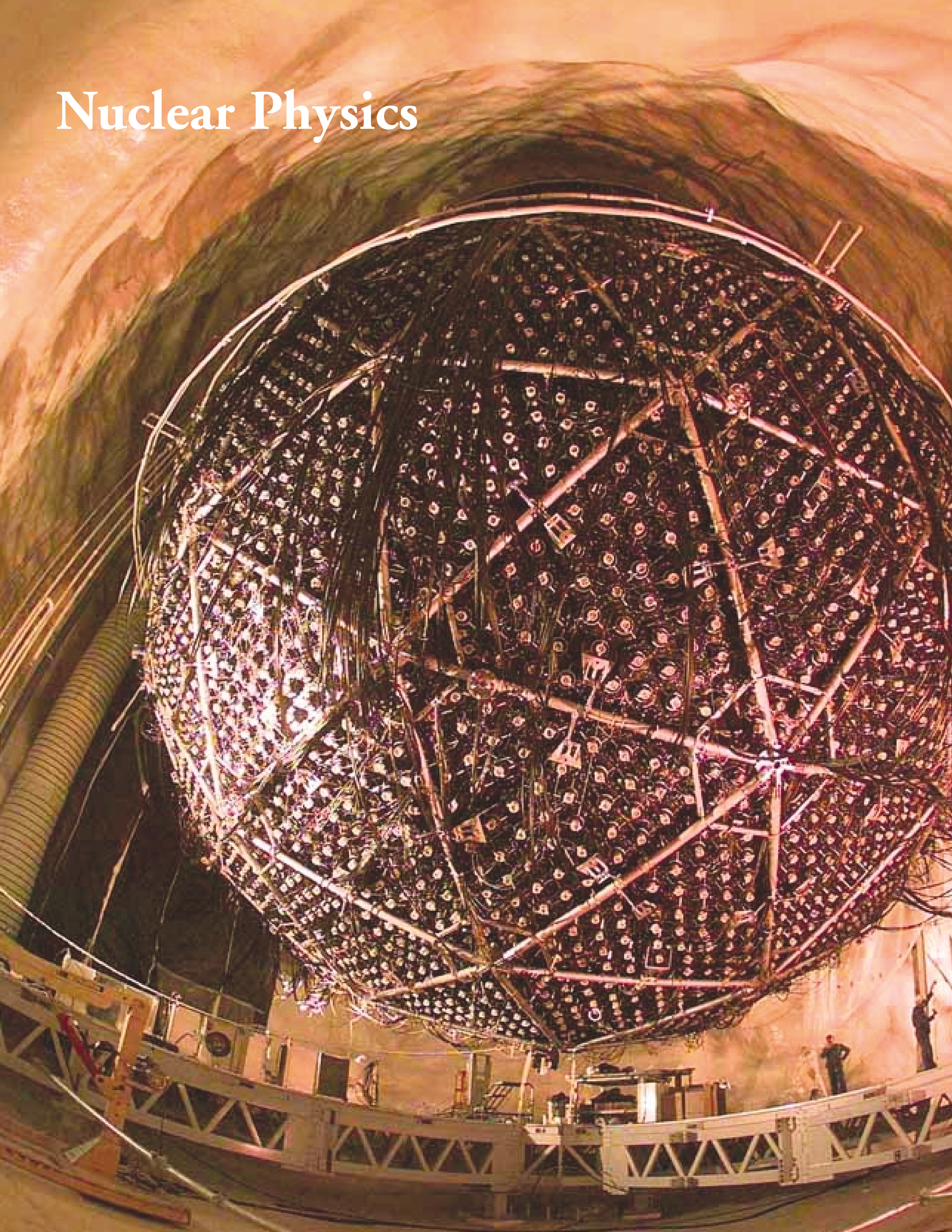
Nuclear Physics



The Sudbury Neutrino Observatory (SNO): This unusual observatory, built 6,800 feet underground in the Creighton mine near Sudbury, Ontario, Canada, is one of two international underground neutrino detectors in which the Office of Science is a collaborator. The other detector is KamLAND in Japan. These underground observatories were built to study neutrinos from the sun or from nuclear power reactors, and their combined research has recently determined that the mysterious elementary particle called the neutrino has mass and oscillates among three "flavors" as it travels through space. The 2002 Nobel Prize in physics recognized an Office of Science-supported scientist, Ray Davis, Jr., for his discovery of solar neutrinos in the late 1960s. His findings motivated the search for neutrino oscillations.

LBNL

5

Explore Nuclear Matter—from Quarks to Stars

Understand the evolution and structure of nuclear matter, from the smallest building blocks, quarks and gluons; to the elements in the universe created by stars; to unique isotopes created in the laboratory that exist at the limits of stability, possessing radically different properties from known matter.

Nucleons were born in the first minutes after the "Big Bang" and their subsequent synthesis into nuclei goes on in the ever-continuing process of nuclear synthesis in stars and supernovae. Nuclear matter makes up most of the mass of the visible universe. It is the stuff that makes up our planet and its inhabitants. Nuclear matter was once inaccessible for humans to study, but in the first half of the 20th Century, great strides in our understanding of nuclei and nuclear reactions were rapidly made, leading to such profound influences on society as the discovery of fission and fusion and the development of the now vast field of nuclear medicine.

Today, understanding nuclear matter and its interactions has become central to research in nuclear physics and important to research in energy, astrophysics, and national security. However, only with the development of the theory of the strong interaction, a strongly coupled quantum field theory called Quantum Chromodynamics (QCD), in just the last few decades, has a quantitative basis emerged to describe nuclear matter in terms of its underlying fundamental quark and gluon constituents. We have only recently acquired more sensitive tools to make the measurements and calculations needed to fully explore this quark structure of the nucleon, of simple nuclei, of nuclear matter, and even of the stars, opening an exciting new era in nuclear physics. The field of nuclear physics can be described in terms of five broad questions:

- What is the structure of the nucleon? Relating the observed properties of protons, neutrons, and simple nuclei to the underlying fundamental quarks is a central problem of modern physics.
- What is the structure of nucleonic matter? A central goal of nuclear physics is to explain the properties of nuclei and nuclear matter.

"The most incomprehensible thing about our universe, is that it can be comprehended."

—Albert Einstein

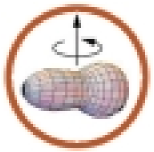
- What are the properties of hot nuclear matter? When nuclear matter is sufficiently heated, QCD predicts that the individual nucleons will lose their identities and the quarks and gluons will become "deconfined" into quark-gluon plasma; nuclear physicists are searching intensely for this new state of matter at high-energy density.
- What is the nuclear microphysics of the universe? How the nuclei of the chemical elements we find on earth were formed in stars and supernovae is a puzzle that relates to our very being.
- What is to be the new Standard Model (the current theory of elementary particles and forces)? Precision experiments deep underground and at low energies provide essential complementary information to searches for new physics in high-energy accelerator experiments.

Answering these questions will reveal important discoveries about how the visible matter of the physical world around us is put together, how the early universe developed from its initial extremely hot and dense state, the dynamics of stars and other cosmic objects, and how the very elements that we are made of came to be. Vast computing resources will be used to perform the challenging calculations of subatomic structure needed to address these questions, while new accelerators will be needed to study rare nuclei and nuclear reactions at high-energy densities. This research will primarily be performed by international research teams that are a hallmark of Office of Science physics, and will provide world leadership in all the major thrusts of nuclear physics.

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 five future facilities to realize our Nuclear Physics vision and to meet the

Our History of Discovery…Select Examples

1948-1955
Discovered that atomic nuclei have a shell structure analogous to the discrete electron orbits in atoms.
(1963 Nobel Prize)

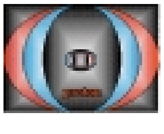


1950s
Discovery of the connection between collective motion and particle motion in atomic nuclei.
(1975 Nobel Prize)

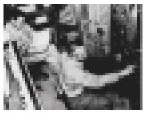
1956
Discovered the electron neutrino.
(1995 Nobel Prize)

1957
Discovery of CP (conservation of parity) violation with beta decay experiments, overturning one of the fundamental laws of Nature.

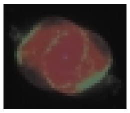
1950 1960



1950s
Discovered that protons and neutrons have a definite size and form, using new electron scattering techniques.
(1961 Nobel Prize)



1953
Discovery of the neutrino emitted from the core of a nuclear reactor.
(1995 Nobel Prize)



1950s-1960s
Demonstrated that nuclear processes in stars could manufacture all the elements, starting with just the hydrogen and helium produced in the Big Bang.
(1983 Nobel Prize)

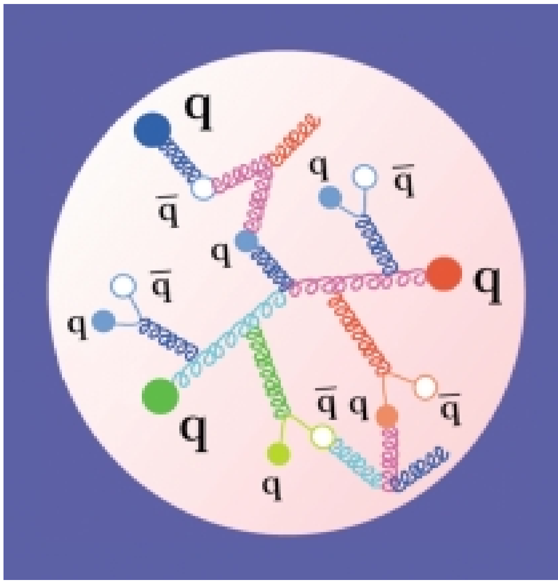
science challenges described in the following pages. Two of the facilities are near-term priorities: the **Rare Isotope Accelerator (RIA)** and the **Continuous Electron Beam Accelerator Facility (CEBAF) Upgrade**. The RIA will be the world's most powerful research facility dedicated to producing and exploring rare isotopes that are not found naturally on Earth. The upgrade to the CEBAF at Thomas Jefferson National Accelerator Facility (TJNAF) is a cost-effective way to double the energy of the existing beam, and thus provide the capability to study the structure of protons and neutrons in the atom with much greater precision than is currently possible. All five facilities are included in our Nuclear 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 the long-range planning report, *Opportunities in Nuclear Science* (2002), prepared by its advisory panel, the Nuclear Science Advisory Committee (NSAC); and by *Connecting Quarks with the Cosmos* (2003), a report prepared by the National Research Council Committee on Physics of the Universe.

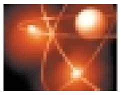
5.1 Understand the structure of the nucleon.

Protons and neutrons, collectively called nucleons, are the building blocks of nuclear matter and thus form the heart of every atom in the universe. But nucleons are themselves composed of quarks bound together by gluons, the carriers of the strong force. This strong force is responsible for the structure of nucleons and their composite structures, atomic nuclei, as well as neutron stars. The nucleus is an ideal system to study the strong interaction, which can be described by a strongly coupled quantum field theory called QCD. To understand nucleon structure, we will pursue several approaches.



Artist's impression of a nucleon: It contains three quarks (the large red, green, and blue disks). But a boiling sea of virtual quarks and gluons (the colored springs) are also shown: each of these appears for just a moment and then disappears, like bubbles in a tea kettle.

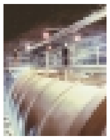
1967
Nobel Prize awarded for discovery of the energy source that powers the stars. Virtually all the energy produced by stars arises from nuclear fusion, in which the nuclei of hydrogen atoms are converted into helium.



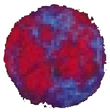
1985
Began operating TJNAF, world's first polarized, high intensity "electron microscope" to study the structure of the nucleon and the atomic nucleus.

1998-2000
Discovered neutrino oscillations, changing our picture of the universe and causing revisions of theory to include neutrino mass. Neutrino mass has important consequences for astrophysics and for the current theory of elementary particles and fields.

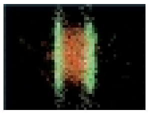
1970 1980 1990 2000



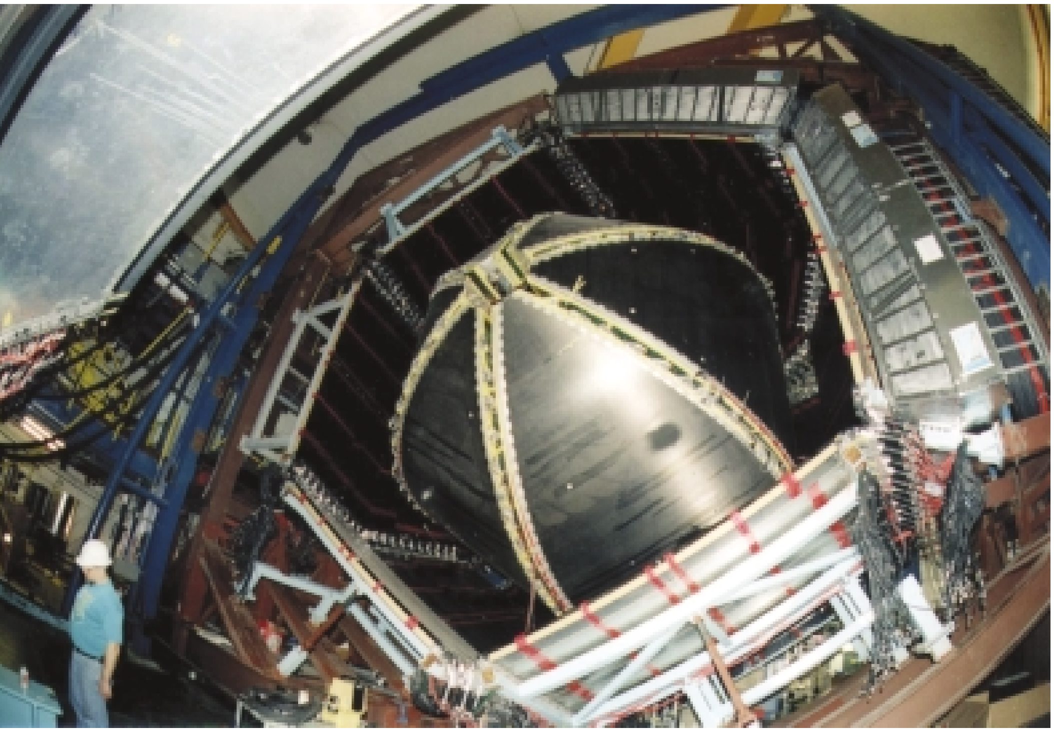
1968
Detection of solar neutrinos, ghostlike particles produced in the nuclear reactions that power the sun.
(2002 Nobel Prize)



1970s
Further substantiated the neutron-capture measurements theory of nucleosynthesis as the process of formation of the chemical elements in the universe.
(1983 Nobel Prize)



2000
Began operating RHIC, the world's only heavy ion collider, to study primordial matter in the universe. In 2002-2003, the first hot, dense nuclear matter was created at RHIC.



Probes for the composition of nuclear matter: The Continuous Electron Beam Accelerator Facility (CEBAF) Large Acceptance Spectrometer (CLAS) is a particle detection system at the Office of Science's Thomas Jefferson National Accelerator Facility. CEBAF enables scientists to explore the frontier of our understanding of the composition of nuclear matter.

Probe the mechanism of quark confinement inside the nucleon.

Although protons and neutrons can be separately observed, their quark and gluon constituents cannot, because they are permanently confined inside the nucleons. While the mechanism of quark confinement is qualitatively explained by QCD, a quantitative understanding remains one of our great intellectual challenges.

Our strategy includes the following emphases:

- Use high-intensity polarized electron beams at the TJNAF to measure properties of the proton, neutron, and simple nuclei for comparison with theoretical calculations to provide an improved quantitative understanding of their quark structure.
- Use high-energy polarized proton-proton collisions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory to determine the proton structure—how the quarks and particularly the gluons, the carriers of the strong force, assemble themselves to give the proton's properties.
- Upgrade TJNAF to provide higher-energy electron and photon beams to probe quark confinement and nucleon structure in a regime that will allow a more complete determination of the quark properties.

Search for gluon saturation.

Recent calculations suggest that, in high-energy collisions, nucleons and nuclei can behave in a completely new way, as if filled or "saturated" with many gluons. These gluons have remarkable properties, analogous both to spin glasses and to the Bose-Einstein condensates studied in condensed matter and atomic physics. This gluonic system may have universal properties, independent of the nucleus in which it resides, whose study could greatly increase our understanding of the quark-gluon structure of matter at high energy. Our strategy includes the following emphasis:

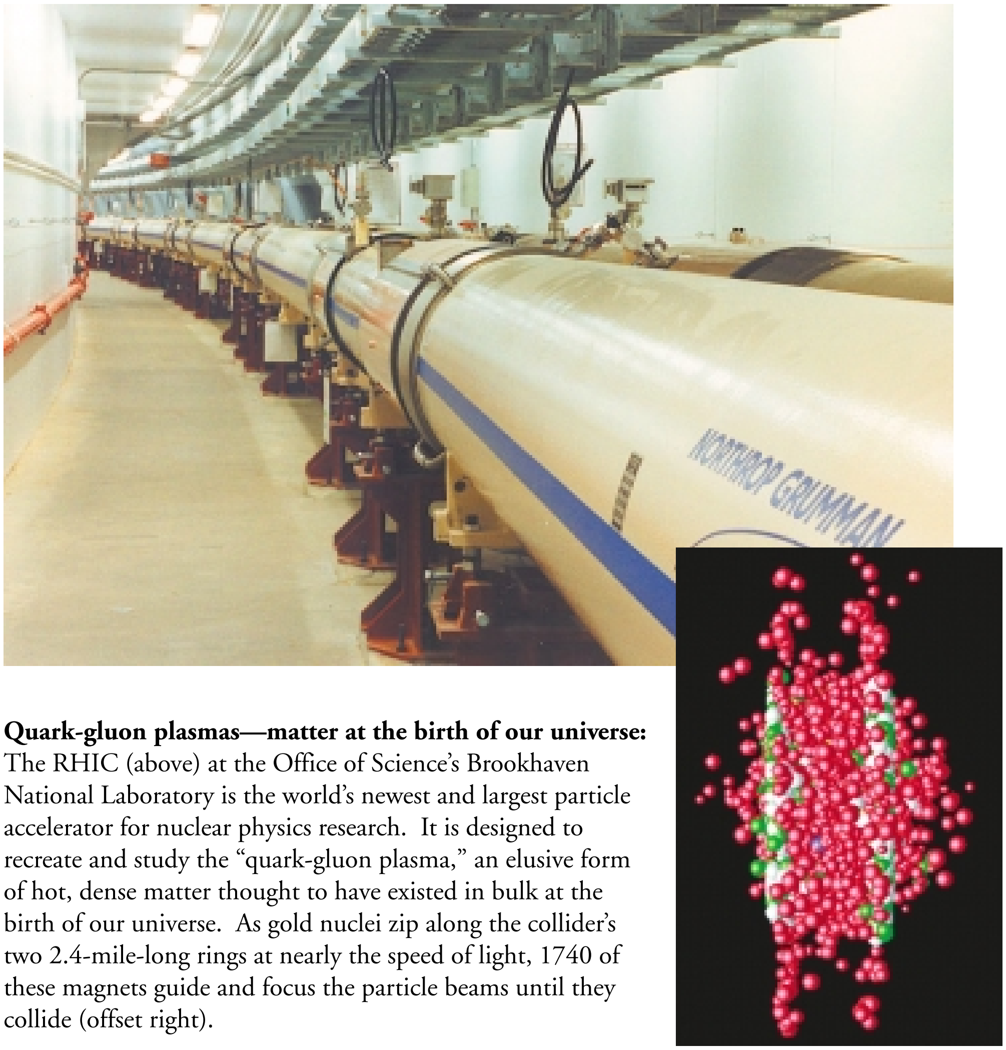
- Explore the development of an electron-nucleus collider that would allow the gluon saturation of nuclear matter to be seen.

5.2 Understand the structure of nucleonic matter.

Nuclei are the core of atoms and account for almost all the observable matter in the world around us. The naturally occurring stable nuclei are but a small fraction of the nuclei that can possibly exist. Most of the unstable nuclei (those that undergo radioactive decay) cannot be created for study by existing experimental facilities. Investigating these nuclei, and in particular those at the extreme limits of stability, offers a rich opportunity for major scientific discovery. Unbalanced neutron and proton numbers decrease the stability of a nucleus. For example, there is a limit to the number of neutrons that can be added to a nucleus of a given proton number (the nucleus of a given element). A similar stability limit for nuclei is reached if the number of protons is increased relative to a fixed neutron number.

Experiments have established which combinations of protons and neutrons can form a nucleus only for the first eight of the more than 100 known elements, but little is known about the limits of stability for the heaviest nuclei. The coming decade in nuclear physics may reveal nuclear phenomena and structure unlike anything known in the stable nuclei making up the world around us. New theoretical tools will be developed to describe nuclear many-body phenomena, with important applications to condensed matter and nuclear astrophysics. Our strategy includes the following emphases:

- Investigate new regions of nuclear structure and develop the nuclear many-body theory to predict nuclear properties.
- Develop a next-generation facility with forefront experimental instrumentation that will use beams of rare isotopes to study nuclei at the very limits of stability. This facility will provide the tools for understanding nuclear structure evolution across the entire landscape of the chart of the nuclides.



Quark-gluon plasmas—matter at the birth of our universe: The RHIC (above) at the Office of Science's Brookhaven National Laboratory is the world's newest and largest particle accelerator for nuclear physics research. It is designed to recreate and study the "quark-gluon plasma," an elusive form of hot, dense matter thought to have existed in bulk at the birth of our universe. As gold nuclei zip along the collider's two 2.4-mile-long rings at nearly the speed of light, 1740 of these magnets guide and focus the particle beams until they collide (offset right).

BNL

Gamma rays as windows to rare and exotic nuclear processes: Gammasphere (one-half shown here) is a spectrometer of unparalleled detection sensitivity to gamma rays due to its high resolution, granularity, and efficiency. It consists of a spherical shell of 110 large-volume, high-purity germanium detectors, each enclosed in a bismuth-germanate shield for increased sensitivity. This detector is the ideal device to study rare and exotic nuclear processes that are key to understanding the many facets of nuclear structure. Shown here, in the middle, is a plunger apparatus that can be used to measure extremely short nuclear lifetimes (1 to 1000 picoseconds).

5.3 Search for quark-gluon plasma.

The quarks and gluons that compose each proton and neutron are normally confined within these nucleons. However, if nuclear matter is heated sufficiently, quarks will become deconfined and individual nucleons will melt into a hot, dense plasma of quarks and gluons. Such plasma is believed to have filled the universe about a millionth of a second after the "Big Bang." The discovery and characterization of this new state of matter formed at extreme conditions never before available in the laboratory will yield new insight into the early phases of the universe. Our strategy includes the following emphases:

- Use colliding beams of atomic nuclei at RHIC to explore new states of matter at high-energy density, recreating brief, small samples of quark-gluon plasma and characterizing its properties.
- Increase the beam luminosities at RHIC and upgrade the detectors to allow more detailed studies of this primal state of matter. Investigate the emission of particles at high transverse momentum to better understand the behavior of jet transmission through the plasma, using the Large Hadron Collider.

5.4 Investigate nuclear astrophysics.

Nuclear physics research is essential if we are to solve important problems in astrophysics—the origin of the chemical elements, the behavior of neutron stars, core-collapse supernovae and the associated neutrino physics, and galactic and extragalactic gamma-ray sources. Almost all the chemical elements in the universe were generated by nuclear reactions in stars or in cataclysmic stellar explosions. Given the high temperatures and particle densities in stellar objects and explosions, the relevant nuclear reactions typically occur among radioactive or exotic nuclei. Our strategy includes the following emphases:

- Using exotic beams of nuclei that have many neutrons, study interactions in nuclear matter like those that occur in neutron stars and those that create the nuclei of most atomic elements inside stars and supernovae.
- Develop computer simulations for the behavior of supernovae, including core collapse and explosion, which incorporate the relevant nuclear reaction dynamics.

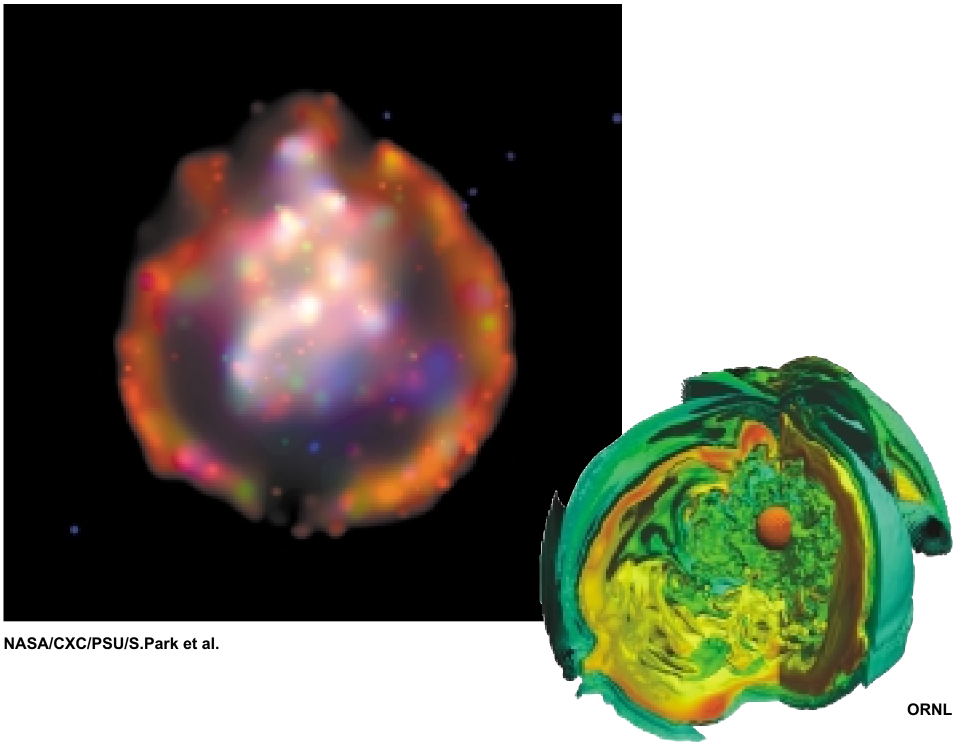
- Develop a unique next-generation facility with forefront experimental instrumentation that will provide new species of exotic beams at unprecedented intensities to advance science at the intersection of nuclear physics and astronomy. This facility is similarly described in section 5.2.

5.5 Investigate the fundamental symmetries that form the basis of the Standard Model.

Neutrinos are produced by nuclear reactions in the sun, in supernovae, and in reactors. Understanding their properties is essential for understanding stellar dynamics and supernova explosions. Studies with neutrinos generated in nuclear reactors are complementary to those produced by high-energy accelerators. Similarly, precise measurements of the weak (radioactive) decay of the neutron are complementary to measurements of weak interaction properties at high energies using particle accelerators. Both could require refinements of the Standard Model.

Our strategy includes the following emphasis:

- Further investigate neutrino mixing using neutrinos from the sun, cosmic-ray interactions, and nuclear reactors.
- Measure the decays of tritium nuclei and search for neutrino-less double beta decay to provide essential information about the absolute scale of neutrino masses.



NASA/CXC/PSU/S.Park et al.

ORNL

Understanding an exploding star: The striking Chandra image of a supernova remnant SNR 0103-72.6 reveals a nearly perfect ring about 150 light years in diameter surrounding a cloud of gas enriched in oxygen and shock heated to millions of degrees Celsius. The ring marks the outer limits of a shock wave produced as material ejected in the supernova explosion plows into the interstellar gas. When such a star explodes, its core collapses to form either a neutron star, or if massive enough, a black hole, and the material surrounding the core is propelled into interstellar space. The image on the right is a computer simulation of an exploding star (supernova). Obtaining a detailed understanding of supernovae explosions and the formation of new elements is a goal of the Terascale Supernova Initiative at the DOE Office of Science's Oak Ridge National Laboratory.

- Using new cold and ultra-cold neutron facilities at the Manuel Lujan Jr. Neutron Scattering Center and the Spallation Neutron Source, improve on existing measurements of the decay properties of the neutron and search for the electric dipole moment of the neutron.
- Using advanced laser trapping techniques, search for the electric dipole moment of radium-225.

Our Timeline and Indicators of Success

Our commitment to the future, and to the realization of **Goal 5: Explore Nuclear Matter—from Quarks to Stars**, is not only reflected in our strategies, but also in our Key Indicators of Success, below, and our Strategic Timeline for Nuclear Physics (NP), at the end of this chapter.

The NP 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 5. 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 realizing a quantitative understanding of the quark substructure of the proton, neutron, and simple nuclei by comparison of precision measurements of their fundamental properties with theoretical calculations.
- Progress in searching for, and characterizing the properties of, the quark-gluon plasma by recreating brief, tiny samples of hot, dense nuclear matter.
- Progress in investigating new regions of nuclear structure, study interactions in nuclear matter like those occurring in neutron stars, and determining the reactions that created the nuclei of atomic elements inside stars and supernovae.
- Progress in determining the fundamental properties of neutrinos and fundamental symmetries by using neutrinos from the sun and nuclear reactors and by using radioactive decay measurements.

Strategic Timeline for Nuclear Physics

Strategic Timeline-

2003 2005 2007 2009 2011 20

The Science

Heavy Ion

- Begin studies of rare processes in the formation of hot, dense nuclear matter (2004)

- Determine if quark-gluon plasma, the matter of the infant universe, can be made in the laboratory using colliding beams of atomic nuclei (2007)

- Begin measurements of the behavior of high-transverse-momentum particles through hot, dense, nuclear matter that is dominated by gluons (2011)

Medium Energy

- Obtain first polarized high-energy proton-proton data studying the proton spin (2006)

- Determine the strange quark content of the proton
- Begin search for an electric dipole moment of Radium-225 (2007)

- Determine gluon contribution to proton spin (2010)

- Establish basic properties of the proton, neutron, and simple nuclei using high-intensity polarized electron beams at 6 GeV (2012)

Low Energy

- Begin making precise measurements of the decay properties of the neutron to test the Standard Model of fundamental particles (2004)

- Quantify neutrino mixing using neutrinos from the sun, cosmic-ray interactions, and nuclear reactors (2006)

- Establish reaction rates for understanding how light elements are created in supernovae (2006)
- Develop three-dimensional computer simulations for the behavior of supernovae, including core collapse and explosion, which incorporate the relevant nuclear reaction dynamics (2006)

- Complete measurements in new regions of nuclear structure and develop the nuclear many-body theory to predict nuclear properties (2008)

- Begin studies of nuclei at the limits of stability using the new GRETINA gamma-ray detector, revolutionizing detector technology (2010)
- Launch next-generation neutron experiments studying decay of the neutrons (2010)

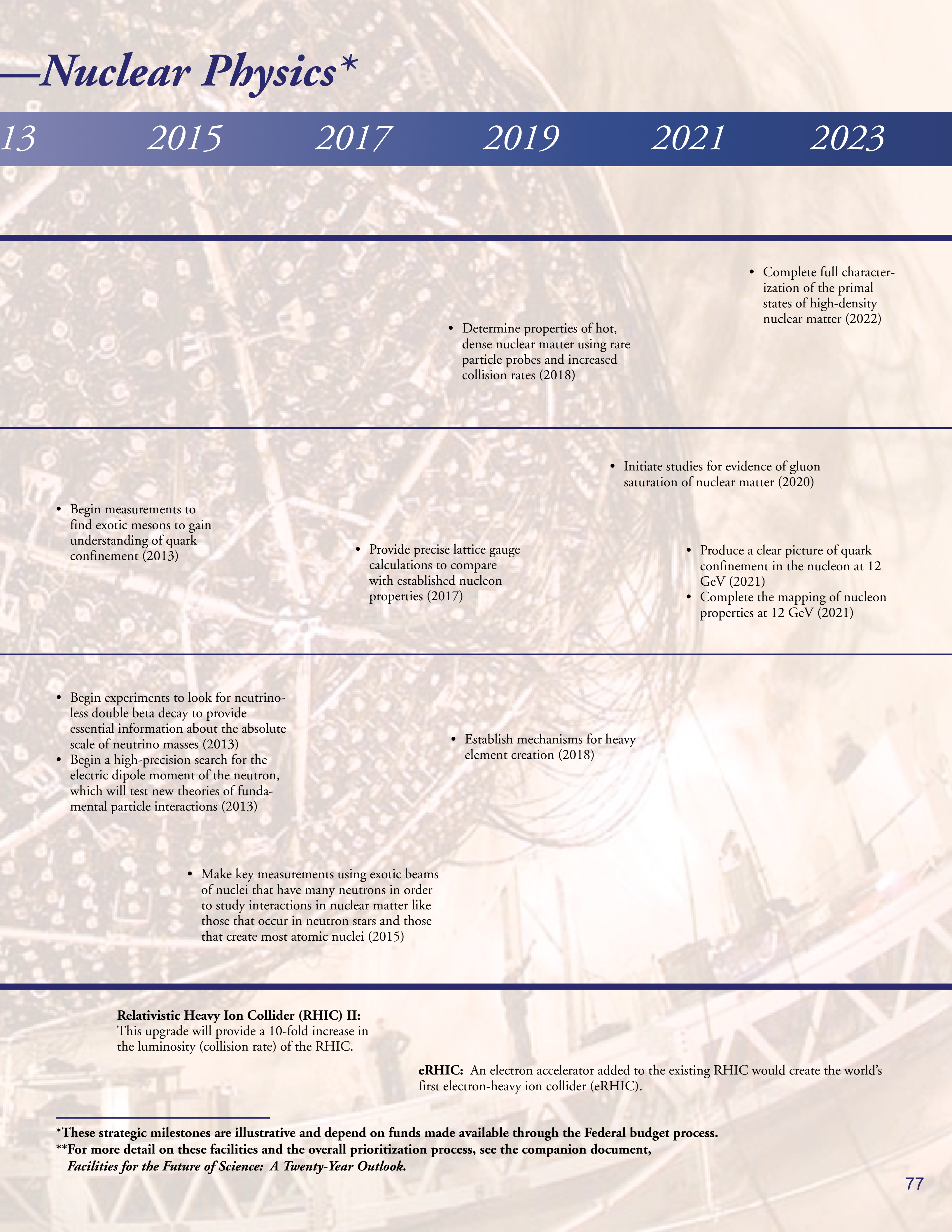
- Establish an electron neutrino mass (2011)

Future Facilities**

Rare Isotope Accelerator (RIA): The RIA will be the world's most powerful research facility dedicated to producing and exploring new rare isotopes that are not found naturally on Earth.

Continuous Electron Beam Accelerator Facility (CEBAF) Upgrade: The upgrade to the CEBAF at Thomas Jefferson National Accelerator Laboratory is a cost-effective way to double the energy of the existing beam.

Double Beta Decay Underground Detector: The underground double beta decay detector will enable measurements of neutrino masses and determination of whether the neutrino and its anti-particle are identical.



—Nuclear Physics*

13 2015 2017 2019 2021 2023

- Determine properties of hot, dense nuclear matter using rare particle probes and increased collision rates (2018)
- Complete full characterization of the primal states of high-density nuclear matter (2022)

- Begin measurements to find exotic mesons to gain understanding of quark confinement (2013)
- Provide precise lattice gauge calculations to compare with established nucleon properties (2017)
- Initiate studies for evidence of gluon saturation of nuclear matter (2020)
- Produce a clear picture of quark confinement in the nucleon at 12 GeV (2021)
- Complete the mapping of nucleon properties at 12 GeV (2021)

- Begin experiments to look for neutrinoless double beta decay to provide essential information about the absolute scale of neutrino masses (2013)
- Begin a high-precision search for the electric dipole moment of the neutron, which will test new theories of fundamental particle interactions (2013)
- Make key measurements using exotic beams of nuclei that have many neutrons in order to study interactions in nuclear matter like those that occur in neutron stars and those that create most atomic nuclei (2015)
- Establish mechanisms for heavy element creation (2018)

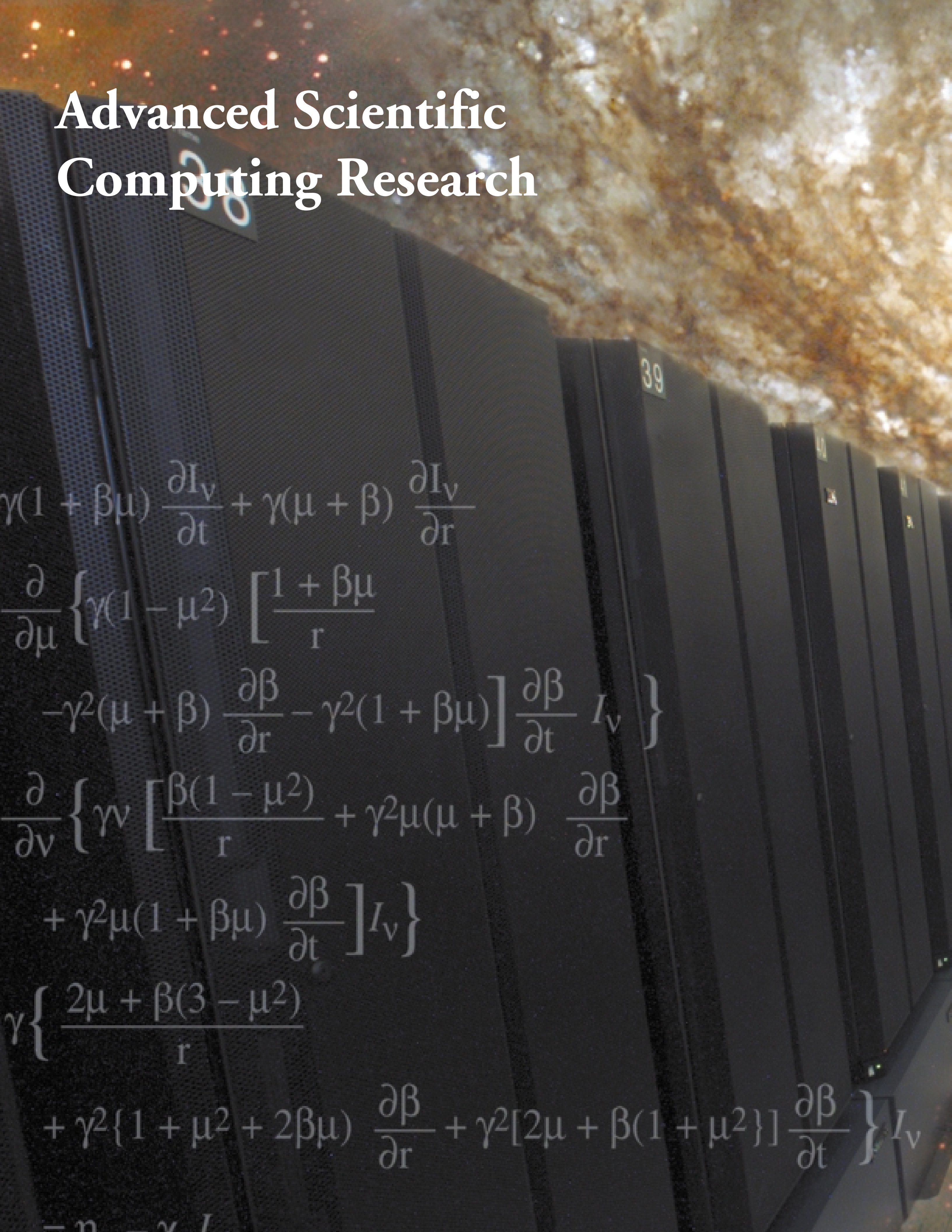
Relativistic Heavy Ion Collider (RHIC) II: This upgrade will provide a 10-fold increase in the luminosity (collision rate) of the RHIC.

eRHIC: An electron accelerator added to the existing RHIC would create the world's first electron-heavy ion collider (eRHIC).

***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.***

Advanced Scientific Computing Research



$$\gamma(1 + \beta\mu)\,\frac{\partial I_\nu}{\partial t} + \gamma(\mu + \beta)\,\frac{\partial I_\nu}{\partial r}$$

$$\frac{\partial}{\partial\mu}\Big\{\gamma(1 - \mu^2)\,\Big[\frac{1 + \beta\mu}{r}$$

$$-\gamma^2(\mu + \beta)\,\frac{\partial\beta}{\partial r} - \gamma^2(1 + \beta\mu)\Big]\,\frac{\partial\beta}{\partial t}\,I_\nu\Big\}$$

$$\frac{\partial}{\partial\nu}\Big\{\gamma\nu\,\Big[\frac{\beta(1 - \mu^2)}{r} + \gamma^2\mu(\mu + \beta)\,\frac{\partial\beta}{\partial r}$$

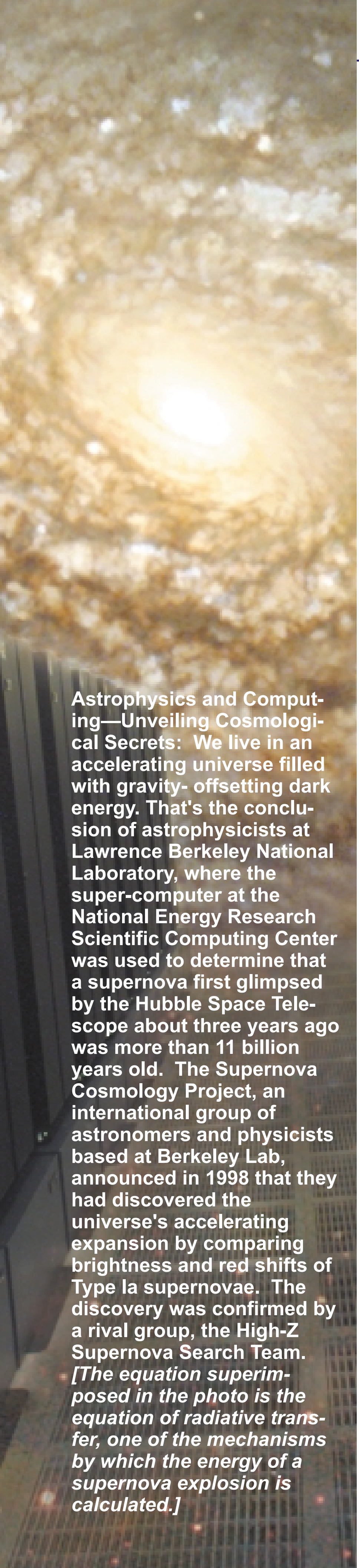
$$+\gamma^2\mu(1 + \beta\mu)\,\frac{\partial\beta}{\partial t}\Big]I_\nu\Big\}$$

$$\gamma\Big\{\frac{2\mu + \beta(3 - \mu^2)}{r}$$

$$+\gamma^2\{1 + \mu^2 + 2\beta\mu)\,\frac{\partial\beta}{\partial r} + \gamma^2[2\mu + \beta(1 + \mu^2\}]\,\frac{\partial\beta}{\partial t}\Big\}I_\nu$$

6

Deliver Computing for the Frontiers of Science



Astrophysics and Computing—Unveiling Cosmological Secrets: We live in an accelerating universe filled with gravity- offsetting dark energy. That's the conclusion of astrophysicists at Lawrence Berkeley National Laboratory, where the super-computer at the National Energy Research Scientific Computing Center was used to determine that a supernova first glimpsed by the Hubble Space Telescope about three years ago was more than 11 billion years old. The Supernova Cosmology Project, an international group of astronomers and physicists based at Berkeley Lab, announced in 1998 that they had discovered the universe's accelerating expansion by comparing brightness and red shifts of Type Ia supernovae. The discovery was confirmed by a rival group, the High-Z Supernova Search Team. *[The equation superimposed in the photo is the equation of radiative transfer, one of the mechanisms by which the energy of a supernova explosion is calculated.]*

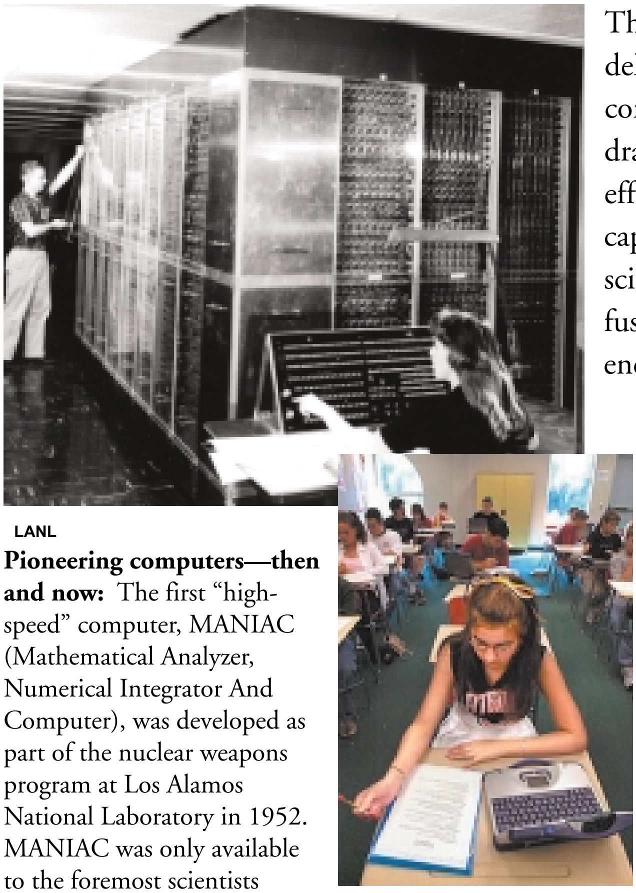
LBNL

Deliver forefront computational and networking capabilities to scientists nationwide that enable them to extend the frontiers of science, answering critical questions that range from the function of living cells to the power of fusion energy.

Computer-based simulation enables us to predict the behavior of complex systems that are beyond the reach of our most powerful experimental probes or our most sophisticated theories. Computational modeling has greatly advanced our understanding of fundamental processes of Nature, such as fluid flow and turbulence or molecular structure and reactivity. Through modeling and simulation, we will be able to explore the interior of stars and learn how protein machines work inside living cells. We can design novel catalysts and high-efficiency engines. Computational science is increasingly central to progress at the frontiers of almost every scientific discipline and to our most challenging feats of engineering.

The science of the future demands that we advance beyond our current computational abilities. Accordingly, we must address the following challenges:

- What new mathematics are required to effectively model systems such as the Earth's climate or the behavior of living cells that involve processes taking place on vastly different time and/or length scales?
- Which computational architectures and platforms will deliver the most benefit for the science of today and the science of the future?
- What advances in computer science and algorithms are needed to increase the efficiency with which supercomputers solve problems for the Office of Science?
- What operating systems, data management, analysis, model development, and other tools are required to make effective use of future-generation supercomputers?
- Is it possible to overcome the geographical distances that often hinder science by making all scientific resources readily available to scientists, regardless of whether they are at a university, national laboratory, or industrial setting?



LANL

Pioneering computers—then and now: The first "high-speed" computer, MANIAC (Mathematical Analyzer, Numerical Integrator And Computer), was developed as part of the nuclear weapons program at Los Alamos National Laboratory in 1952. MANIAC was only available to the foremost scientists around the country to help solve the critical scientific problems of that era. It occupied a large room and was the first computer programmed to play chess, possessing enough memory to store up to 5000 words. It is hardly a comparison to the laptops of today, each with gigabytes of memory and available now to children in grade schools. Many technologies from Office of Science programs have contributed to the present generation of computers, and the Office of Science operates the premier supercomputer available for civilian research and development within DOE at NERSC.

The Office of Science will deliver models, tools, and computing platforms to dramatically increase the effective computational capability available for scientific discovery in fusion, nanoscience, high-energy and nuclear physics, climate and environmental science, and biology. We will develop new mathematics and computational methods for modeling complex systems; work with the scientific community and vendors to develop computing architectures tailored to simulation and modeling; develop improved networking resources; and support interdisciplinary teams of scientists, mathematicians, and computer scientists to build sophisticated computational models that fully exploit these capabilities. Our role complements and builds on the National Nuclear Security Administration's Accelerated Strategic Computing Initiative, delivering forefront modeling capabilities for stockpile stewardship, the basic computer science and mathematics research programs conducted by the National Science Foundation, and mission-focused programs of other agencies.

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 three future facilities to realize our Advanced Scientific Computing Research vision and to meet the science challenges described in the following pages. All three of the facilities are near-term priorities: the **UltraScale Scientific Computing Capability (USSCC)**, the **Energy Sciences Network (ESnet) Upgrade**, and the **National Energy Research Scientific Computing Center (NERSC) Upgrade**. The USSCC, located at multiple sites, will increase by a factor of 100 the computing capability available to support open (as opposed to classified) scientific research—reducing from years to days the time required to simulate complex systems, such as the chemistry of a combustion engine, or

Our History of Discovery…Select Examples

1970s
Established the first national unclassified computer center, the Controlled Thermonuclear Research Center, the forerunner to today's National Energy Research Scientific Computing Center.

1980s
Built ESnet to link research facilities and supercomputers to users and the emerging Internet.

1991
Pioneered the transition to massively parallel supercomputing, enabling 1000 or more processors to work together.

1970 *1980* *1990*

1970s
Determined the emergence of chaotic behavior in systems thought to be stable.

1990s
Installed the first supercomputer available to the civilian research community that broke the peak performance barrier of 1 teraflop computing speed.

weather and climate—and providing much finer resolution. The ESnet upgrade will enhance the network services available to support Office of Science researchers and laboratories and maintain their access to all major DOE research facilities and computing resources, as well as fast interconnections to more than 100 other networks. The NERSC upgrade will ensure that DOE's premier scientific computing facility for unclassified research continues to provide high-performance computing resources to support the requirements of scientific discovery. All three facilities are included in our Advanced Scientific Computing Research Strategic Timeline at the end of this chapter and in the facilities chart in Chapter 7 (page 93), and they are discussed in detail in the *Twenty-Year Outlook*.

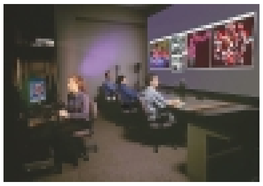
Our Strategies

6.1 Advance scientific discovery through research in the computer science and applied mathematics required to enable prediction and understanding of complex systems.

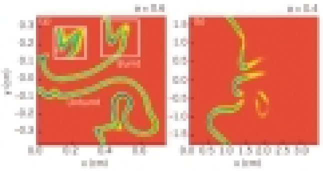
New computational methods are needed to make possible the simulation of the most complex physical and biological systems and to gain efficiency on multiprocessor terascale computers. Effective application of supercomputers requires sophisticated, scalable, operating systems; large-scale data management tools; and other computer science tools. We will support individual investigators and teams to develop new methods and tools, and encourage their transition to advanced computational science applications.

Our strategy includes the following emphases:

- Develop new and improved mathematical methods for addressing the challenges of multi-scale problems.
- Create methods and capabilities to address large-scale data management.
- Develop and apply middleware tools that enable researchers to focus on science while obtaining effective computational performance.



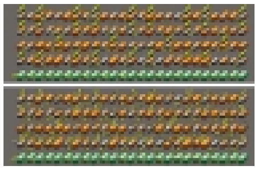
1992
Launched the first Internet videoconference.



1998
Simplified the development of scientific simulations in complex geometrics such as diesel engines.

1998
Wrote the first application code that surpassed one teraflop.

2000



1995
Developed a "spin dynamics" computational method to accurately model magnetic materials.

1998
Announced the discovery from the Supernova Cosmology Project that the universe is expanding.

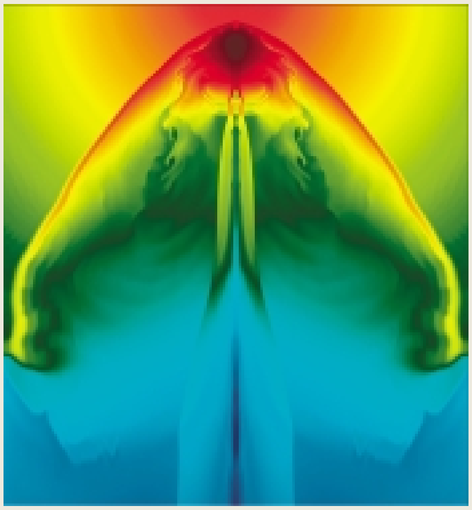
2001
Launched Scientific Discovery through Advanced Computing (SciDAC), a program that accelerates advances in computing and information technologies as tools for scientific discovery.

Scientific Discovery Through Advanced Computing (SciDAC)

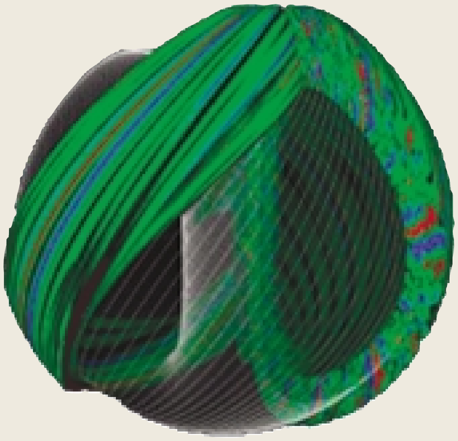
SciDAC is a research program with the goal to achieve breakthrough scientific advances through computer simulation. SciDAC has established a new model for collaboration among the scientific disciplines, computer scientists, and mathematicians. The SciDAC program is creating a new generation of scientific simulation codes and developing collaboratory software to enable geographically separated scientists to use scientific instruments and computers remotely, enabling distant colleagues to share data and function together as a team.

Current projects involve collaborations among 13 DOE laboratories and more than 50 colleges and universities in a broad spectrum of projects such as:

- Climate simulation and prediction
- Quantum chemistry and fluid dynamics
- Plasma systems to advance fusion energy science
- High energy and nuclear physics
- Software infrastructure
- Applied Mathematics Integrated Software Infrastructure Centers
- Computer Science Integrated Software Infrastructure Centers
- National collaboratory, middleware, and network research.



Model of a Supernova Blast



Plasma Microturbulence Simulation

6.2 Extend the frontiers of scientific simulation through a new generation of computational models that fully exploit the power of advanced computers and collaboratory software that makes scientific resources available to scientists anywhere, anytime.

Scientific discovery in many areas requires computational models that incorporate more complete and realistic descriptions of the phenomena being modeled than are possible today.

Our strategy includes the following emphases:

- Create, in partnerships across the Office of Science, new generations of models for fusion science, biology, nanoscience, physics, chemistry, climate, and related fields that provide high-fidelity descriptions of the underlying science.
- Incorporate the new models into scientific simulation software that achieves substantially greater performance from terascale supercomputers than we can achieve today.
- Build on the successes of the SciDAC program.

6.3 Bring dramatic advances to scientific computing challenges by supporting the development, evaluation, and application of supercomputing architectures tailored to science.

Major improvements in scientific simulation and analysis can be obtained through advances in the design of supercomputer architectures. Most of today's supercomputers were designed for commercial applications. However, computational science places stringent requirements on supercomputer designs that are often quite different from what arise in commercial applications. To meet the need for effective computing performance in the 100-teraflop range and beyond, we will support the evaluation, installation, and application of new very high-end computing architectures for computational science.

Our strategy includes the following emphases:

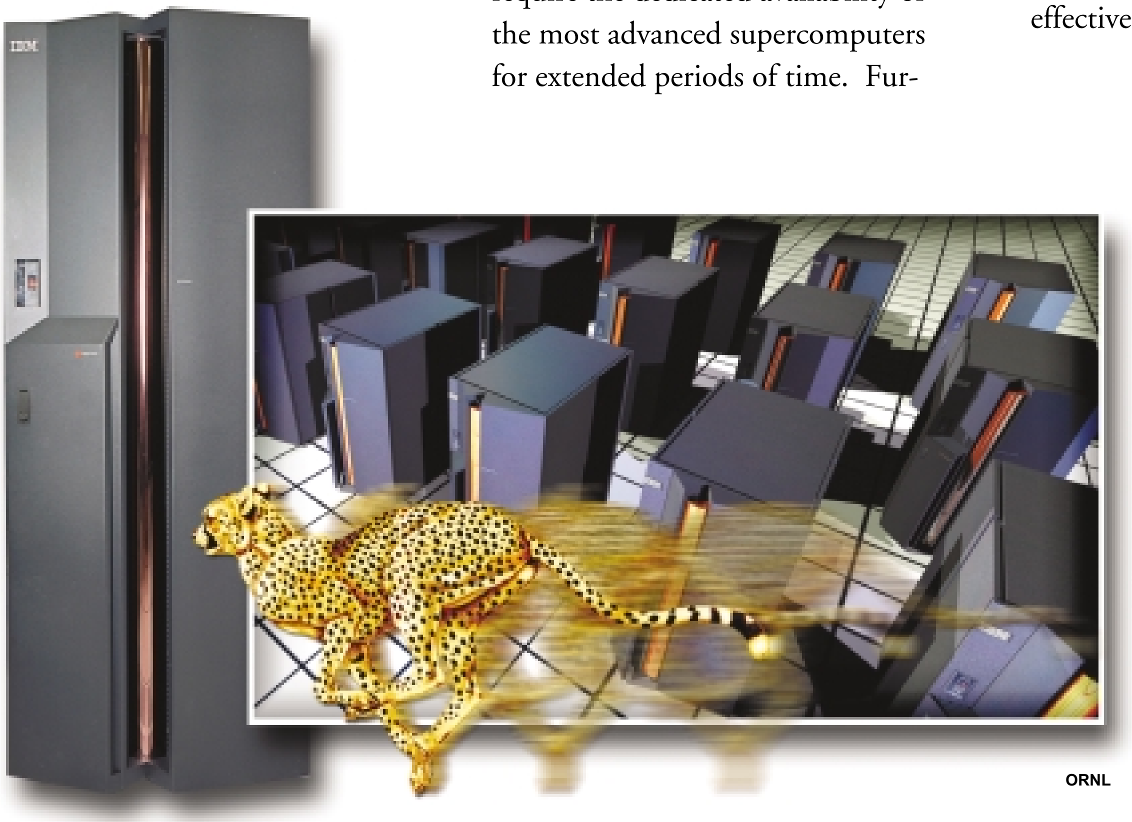
- Develop partnerships with U.S. industry in the near term to adapt current and next-generation products to more fully meet the needs of visionary computational science.
- Develop partnerships with the Department of Defense, the Defense Advanced Research Projects Agency (DARPA), and other Federal agencies to evaluate long-term architecture developments at the scale needed for Office of Science computation.
- Advance the focused research and development of systems software for radical increases in performance, reliability, manageability, and ease of use.

6.4 Provide computing resources at the petascale and beyond, network infrastructure, and tools to enable computational science and scientific collaboration.

Work at the forefront of science can require the dedicated availability of the most advanced supercomputers for extended periods of time. Furthermore, it is likely that at least a few different supercomputer designs will offer significant advantages for different classes of problems.

Our strategy includes the following emphases:

- Provide sustained, high-bandwidth access to the highest possible performance computers for the most demanding applications at the scientific frontiers.
- Upgrade the network and data management infrastructure supporting these resources to enable computational scientists to manage the extraordinarily large volumes of data often generated by large-scale scientific computing and modern experiment.
- Create supporting resources, grid nodes, and tools that enable teams of scientists to collaborate effectively at a distance.



ORNL

Computing test beds: Advanced Computing Research test beds evaluate new computing hardware and software, such as Oak Ridge National Laboratory's IBM Power4 Cheetah (pictured left) and Cray Xl, and Argonne National Laboratory's IBM/Intel/ Cluster.

"It is unworthy of excellent men to lose hours like slaves in the labor of calculation which could be relegated to anyone else if machines were used."

—Gottfried Wilhelm von
Leibnitz (1646-1716),
German philosopher
and mathematician

Our Timeline and Indicators of Success

Our commitment to the future and to the realization of **Goal 6: Deliver Computing for the Frontiers of Science** is not only reflected in our strategies, but also in our Key Indicators of Success, below, and our Strategic Timeline for Advanced Scientific Computing Research (ASCR), at the end of this chapter.

The ASCR 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 6. 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 toward developing the mathematics, algorithms, and software that enable effective scientifically critical models of complex systems, including highly nonlinear or uncertain phenomena, or processes that interact on vastly different scales or contain both discrete and continuous elements.
- Progress toward developing, through the Genomics: GTL partnership with the Biological and Environmental Research program, the computational science capability to model a complete microbe and a simple microbial community.

Strategic Timeline for Advanced Scientific Computing Research

Strategic Timeline—Advanced

2003 2005 2007 20

The Science

Computer Science and Applied Mathematics Research

- Complete ASCR roadmap that defines national approach to the challenges of mathematics for complex systems (2003)
- Deliver operating systems for scientific computers that incorporate fault tolerance (2005)
- Deliver algorithms that scale to tens of thousands of processors for key mathematical libraries (2007)

Extending Science through Computation and Collaboration

- Simulate gyrokinetic transport of fusion plasma without detailed electron dynamics (2004)
- Enable secure, remote operation of fusion facilities (2004)
- Complete computational model of gene regulation (2005)
- Calculate enhanced optical properties at the nanoscale (2007)
- Simulate the catalyst action in automobile exhaust (2007)
- Perform full three-dimensional supernova simulation (2008)
- Simulate soot formation in diesel engines (2008)
- Enable real-time collaborative remote teams at the Spallation Neutron Source (2008)

Supercomputing Architectures for Science

- Complete evaluation of Cray X1 (2003)
- Complete evaluation of first computer with more than 50,000 processors (2005)
- Initiate evaluation of systems from DARPA High Productivity Computing Systems program (2007)

Computational and Network Infrastructure and Tools

- Deliver computing facilities for open science with a 50-fold increase in capability (2005)
- Complete expansion of ESnet to deliver core bandwidth of 10 gigabytes per second (2005)
- Deliver computing facilities for open science with 100-fold increase in capability relative to 2004 (2007)
- Increase ESnet core capability by 400% (2008)

Future Facilities**

UltraScale Scientific Computing Capability (USSCC): The USSCC, located at multiple sites, will increase by a factor of 100 the computing capability available to support open (as opposed to classified) scientific research—reducing from years to days the time required to simulate complex systems.

***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.***

Scientific Computing Research*

09 2011 2013 2015

- Complete programming model that enables scientists to use 100,000 processors (2009)
- Deliver mathematics of complex systems that enables accurate linkage of multiple time and length scales (2011)
- Deliver mathematics of complex systems that enables simulations of microbes (2013)
- Revolutionize computing in U.S. industry through research results from applied mathematics and computer science (2015)

- Achieve seamless integration of astrophysics simulation and data (2009)
- Perform climate simulations that incorporate biological carbon sequestration (2011)
- Deliver virtual catalogue that enables access to all climate data worldwide (2012)
- Complete simulation of tokamak disruptions that enable design of active control system to avoid disruptions (2013)
- Enable computational design of microbe for energy production (2014)
- Compete first integrated burning plasma simulation (2014)
- Deliver hundreds of petabytes per year of data to scientists, routinely (2015)

- Complete tests of computer systems that lead to the first system with sustained application performance over 10 petaflops (2011)

- Achieve computational capability for open science that reaches one petaflop (2012)
- Expand ESnet core capability to exceed 100 gigabytes per second (2013)

Energy Sciences Network (ESnet) Upgrade: The ESnet upgrade will enhance the network services available to support Office of Science researchers and laboratories and maintain their access to all major DOE research facilities and computing resources.

National Energy Research Scientific Computing Center (NERSC) Upgrade: This upgrade will ensure that NERSC continues to provide high-performance computing resources to support the requirements of scientific discovery.