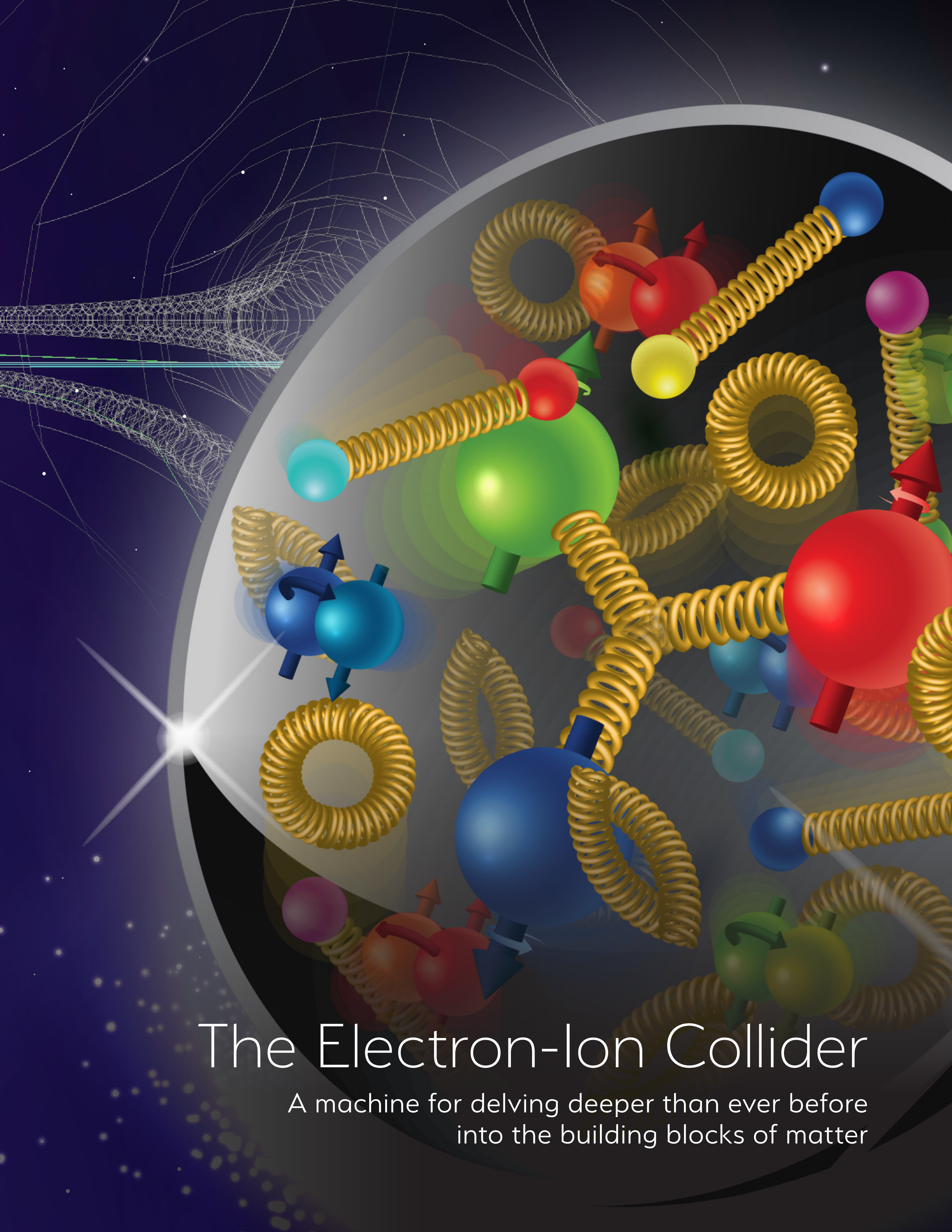
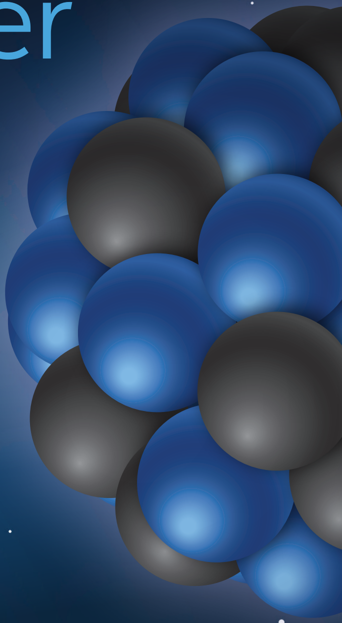


The Electron-Ion Collider

A machine for delving deeper than ever before into the building blocks of matter

The Electron-Ion Collider

A discovery machine for unlocking the secrets of the "glue" that binds the building blocks of visible matter in the universe.

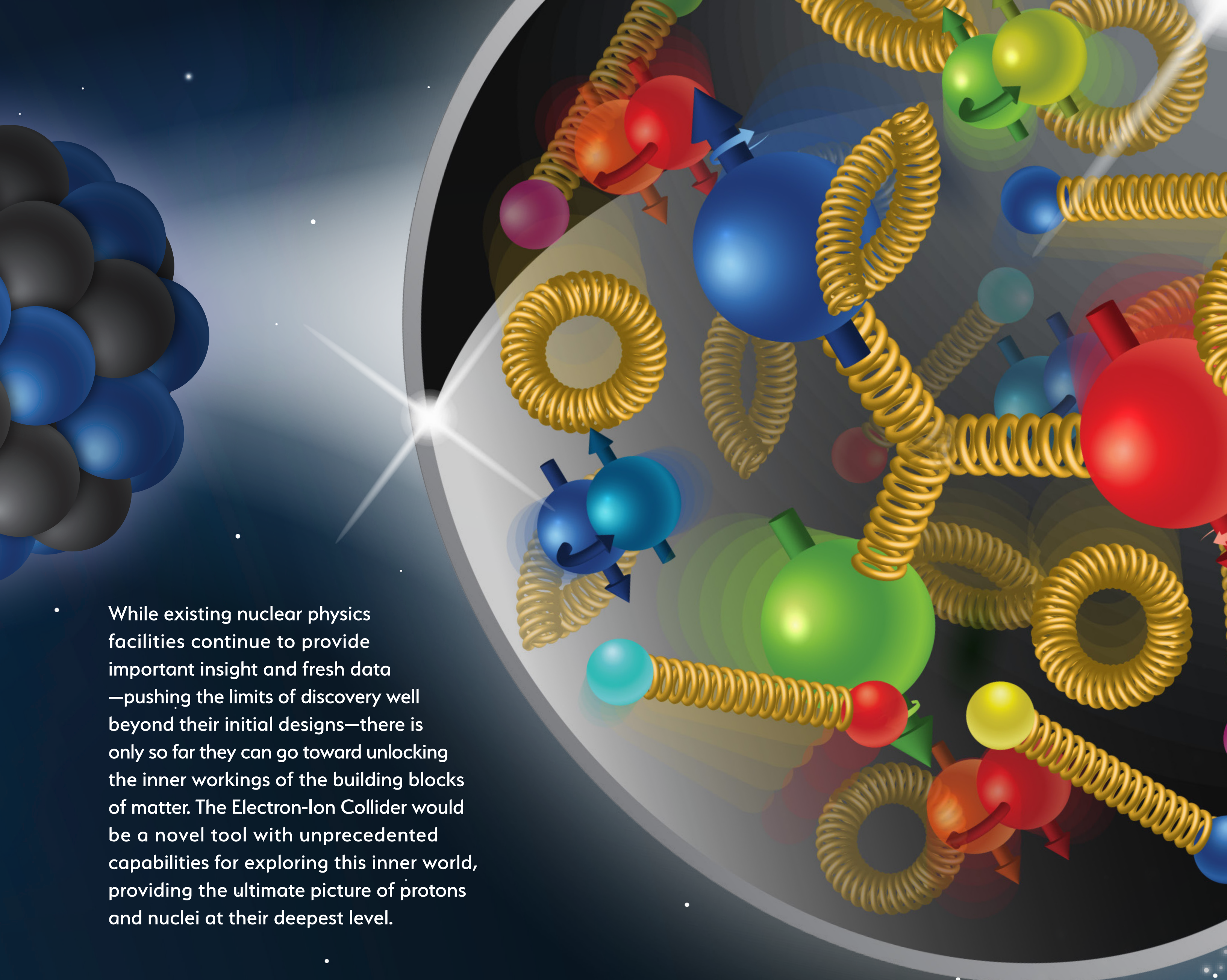


The proton may seem like a simple object, but it's not. Inside, there's a teeming microcosm of quarks and glue-like gluons whose ethereal interactions help establish its essential properties. Along with neutrons, protons form the nuclei of atoms, which make up the bulk of the mass of everything we see in the universe today, from stars to planets to people. Although the fundamental constituents of protons are known to be quarks and gluons, we know little about how these tiniest building blocks are arranged within the proton.

To probe the intricacies of the proton's inner microcosm, and how this internal structure relates to proton properties and the large-scale structure of the universe, nuclear physicists hope to build an Electron-Ion Collider (EIC) —a machine that would open a new window through which we can study and understand the matter within us and its role in the universe around us.

Building Upon Discovery

Experiments in nuclear physics provide an unparalleled opportunity for physicists to "go back in time" to study matter as it existed in the very early universe—before the first protons, neutrons, or atoms ever formed. So far, these experiments have given scientists a vague glimpse of the inner structure of the proton, as well as hints of other intriguing states of matter and brand new questions to explore. One key question is how massless gluons —particles that generate the glue-like force field that binds the building blocks of matter—could account for more than 90 percent of the mass of visible matter in the universe.



While existing nuclear physics facilities continue to provide important insight and fresh data—pushing the limits of discovery well beyond their initial designs—there is only so far they can go toward unlocking the inner workings of the building blocks of matter. The Electron-Ion Collider would be a novel tool with unprecedented capabilities for exploring this inner world, providing the ultimate picture of protons and nuclei at their deepest level.

The U.S. Nuclear Science Advisory Committee recommends building an Electron-Ion Collider as the highest-priority new facility for the field.

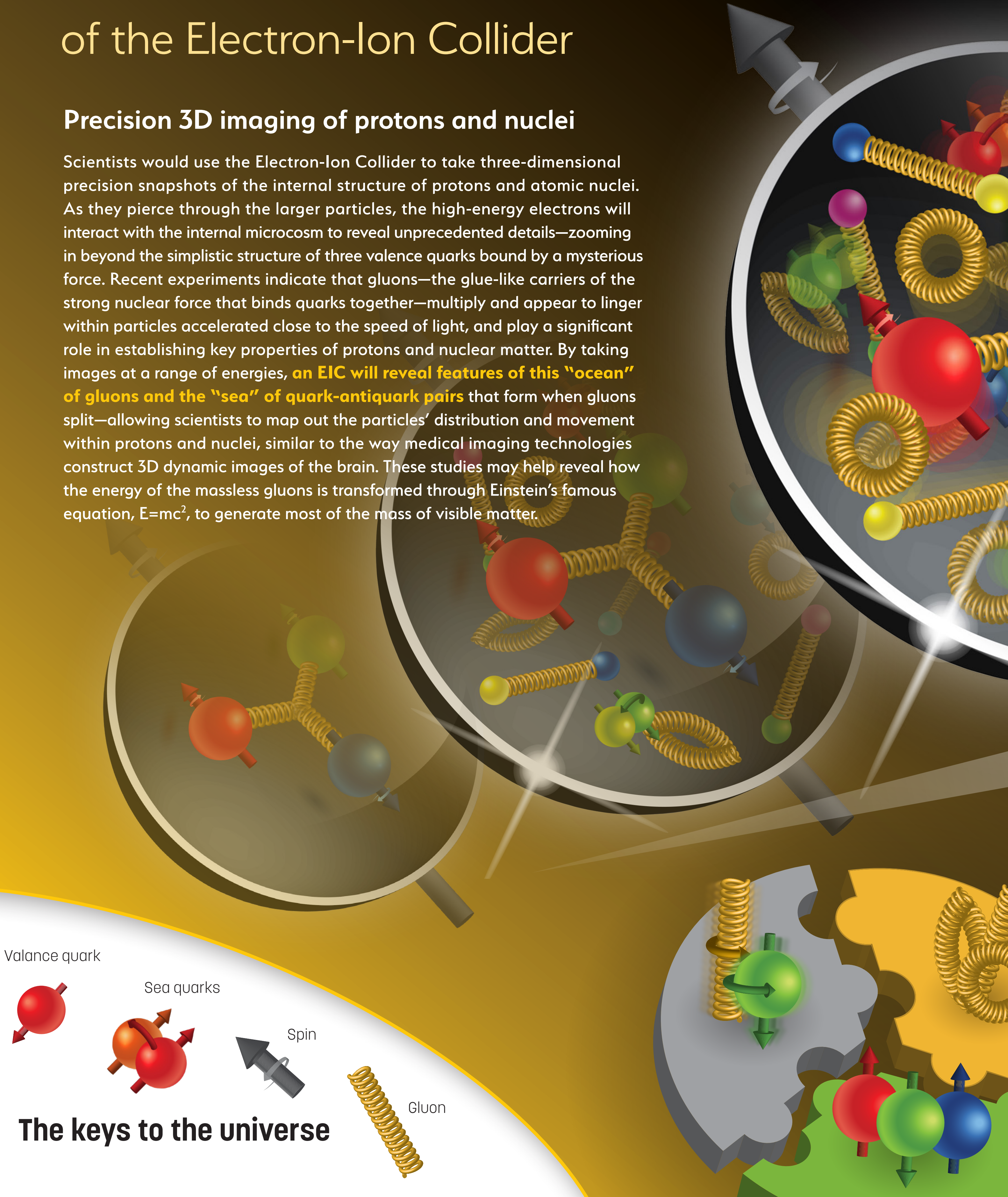
The Electron-Ion Collider would steer a high-intensity beam of high-energy electrons into head-on collisions with protons or larger atomic nuclei. The intensity and energy of the electron beam would produce rapid-fire interactions allowing detectors to capture "freeze-frame" snapshots of the inner structure of the protons and nuclear matter with unprecedented detail. These collisions would reveal fine details of the "sea" of quarks and "ocean" of gluons that make up the larger particles, and help physicists unravel how their dynamic interactions generate the energy, motion, mass, and spin of the building blocks of nearly all the visible matter in the universe. The Electron-Ion Collider would greatly advance our understanding of how matter is constructed from these elementary building blocks.

Scientific Goals

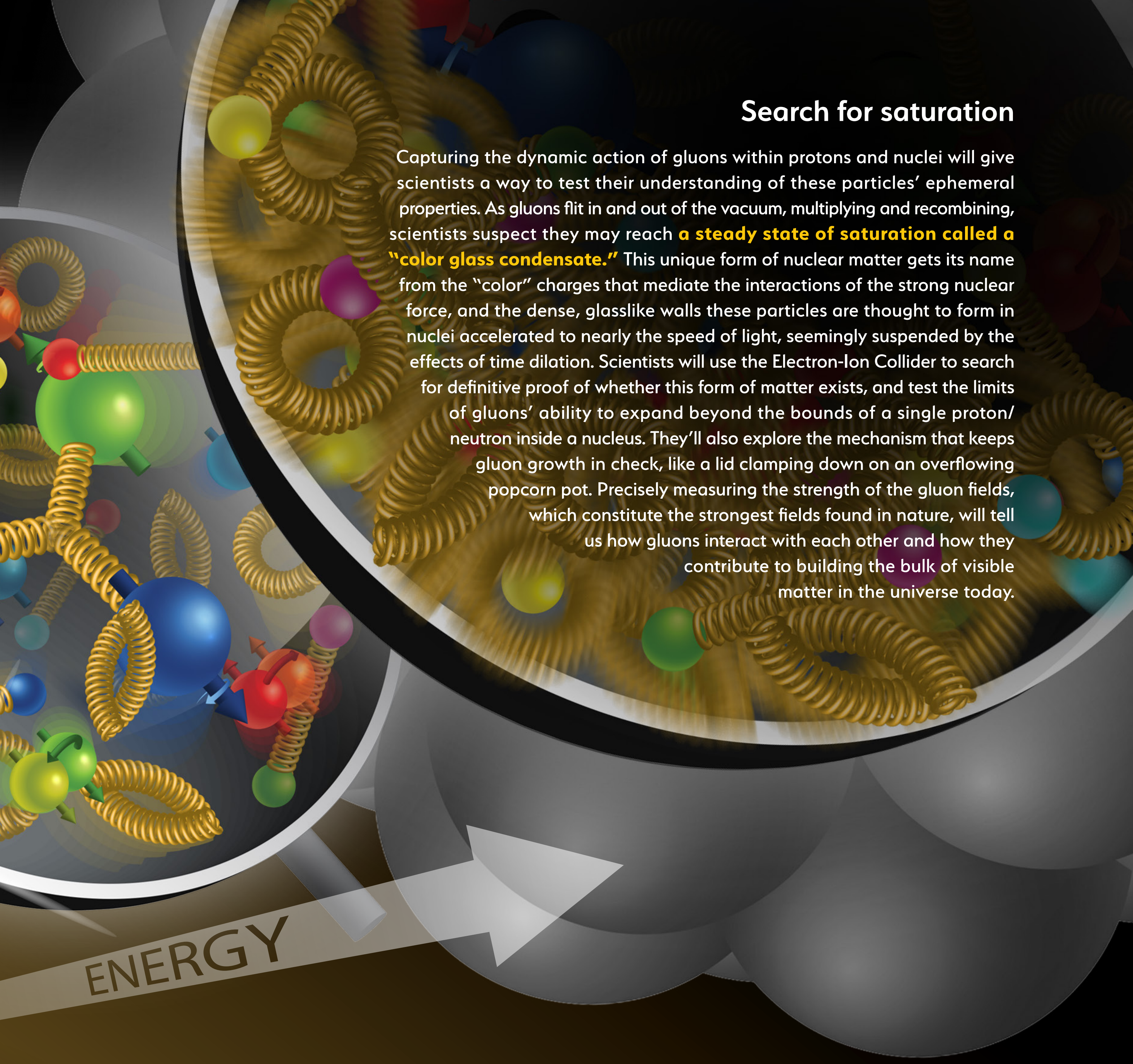
of the Electron-Ion Collider

Precision 3D imaging of protons and nuclei

Scientists would use the Electron-Ion Collider to take three-dimensional precision snapshots of the internal structure of protons and atomic nuclei. As they pierce through the larger particles, the high-energy electrons will interact with the internal microcosm to reveal unprecedented details—zooming in beyond the simplistic structure of three valence quarks bound by a mysterious force. Recent experiments indicate that gluons—the glue-like carriers of the strong nuclear force that binds quarks together—multiply and appear to linger within particles accelerated close to the speed of light, and play a significant role in establishing key properties of protons and nuclear matter. By taking images at a range of energies, **an EIC will reveal features of this "ocean" of gluons and the "sea" of quark-antiquark pairs** that form when gluons split—allowing scientists to map out the particles' distribution and movement within protons and nuclei, similar to the way medical imaging technologies construct 3D dynamic images of the brain. These studies may help reveal how the energy of the massless gluons is transformed through Einstein's famous equation, $E=mc^2$, to generate most of the mass of visible matter.



The keys to the universe



Search for saturation

Capturing the dynamic action of gluons within protons and nuclei will give scientists a way to test their understanding of these particles' ephemeral properties. As gluons flit in and out of the vacuum, multiplying and recombining, scientists suspect they may reach **a steady state of saturation called a "color glass condensate."** This unique form of nuclear matter gets its name from the "color" charges that mediate the interactions of the strong nuclear force, and the dense, glasslike walls these particles are thought to form in nuclei accelerated to nearly the speed of light, seemingly suspended by the effects of time dilation. Scientists will use the Electron-Ion Collider to search for definitive proof of whether this form of matter exists, and test the limits of gluons' ability to expand beyond the bounds of a single proton/neutron inside a nucleus. They'll also explore the mechanism that keeps gluon growth in check, like a lid clamping down on an overflowing popcorn pot. Precisely measuring the strength of the gluon fields, which constitute the strongest fields found in nature, will tell us how gluons interact with each other and how they contribute to building the bulk of visible matter in the universe today.

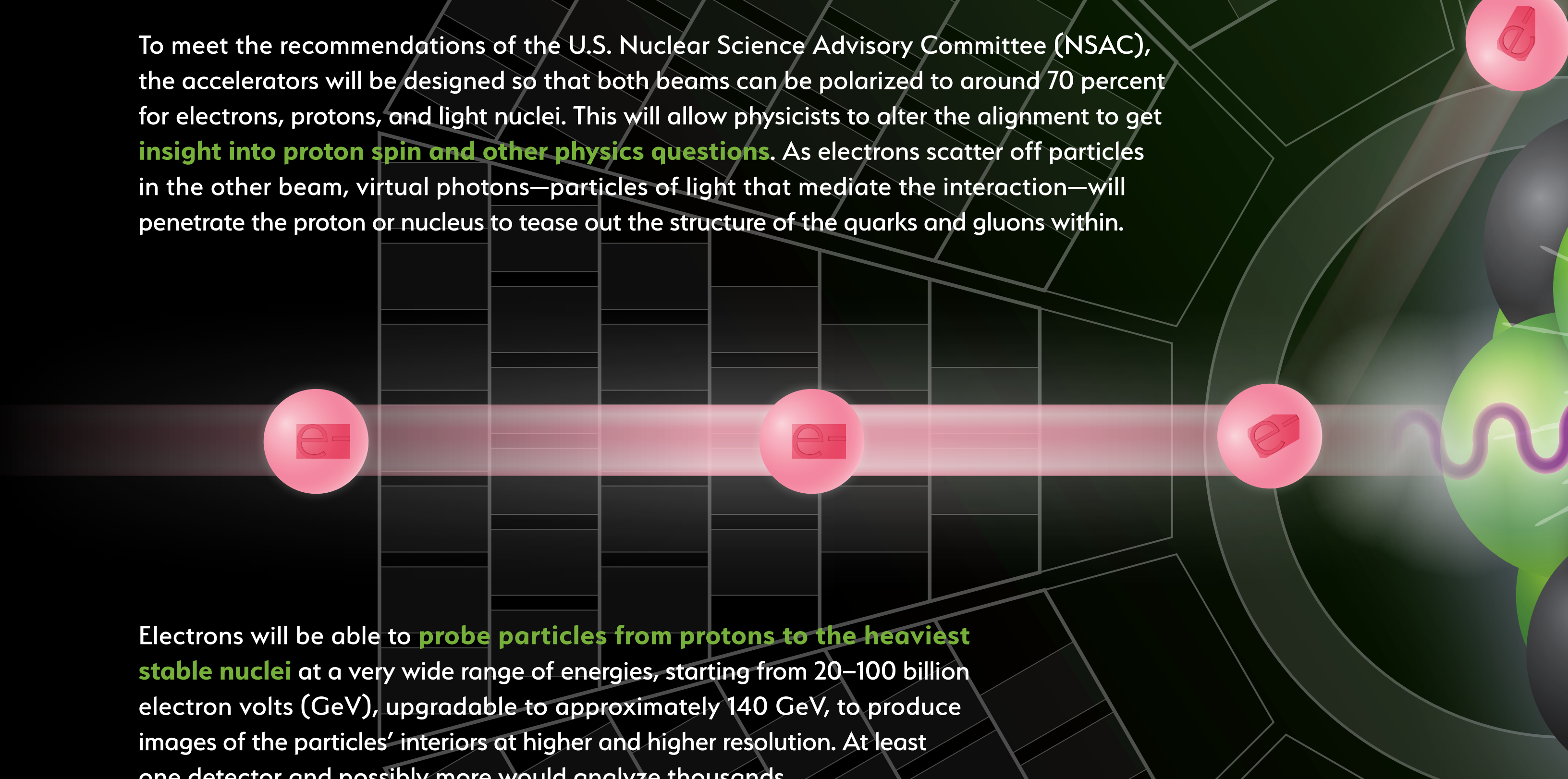
Solving the proton spin puzzle

The Electron-Ion Collider would be the **world's first polarized electron-proton collider** where both the electron and proton beams have their spins aligned in a controllable way. This polarization makes it possible to make **precision measurements** of how a proton's constituent quarks and gluons and their interactions contribute to the proton's **intrinsic angular momentum, or spin**. Spin influences the proton's optical, electrical, and magnetic characteristics and makes technologies such as MRI scanning work, but its origin has eluded physicists ever since experiments in the 1980s revealed that quarks can account for only about a third of the total spin. More recent experiments show that gluons make a significant contribution, perhaps even more than the quarks. An Electron-Ion Collider would produce definitive measurements of the gluons' contributions, including how their movements within the proton microcosm affect its overall spin structure—thus providing the final pieces needed to solve this longstanding puzzle.

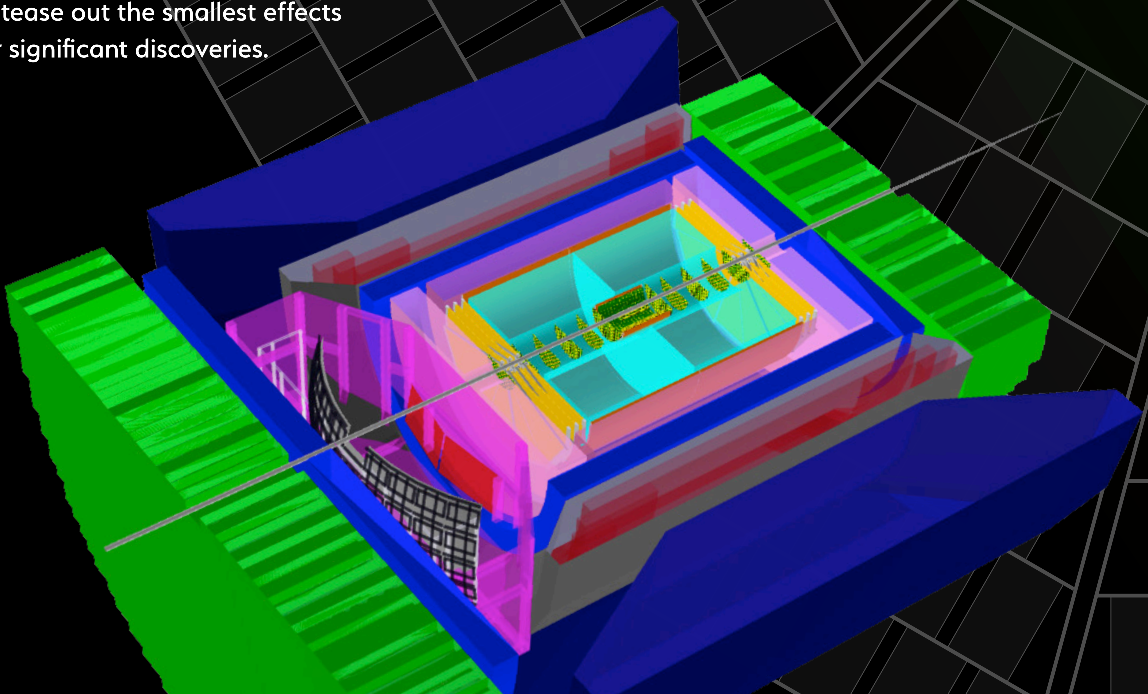
Inside an EIC Collision

The Electron-Ion Collider (EIC) would consist of two intersecting accelerators, one producing an intense beam of electrons, the other a beam of either protons or heavier atomic nuclei, which are then steered into head-on collisions.

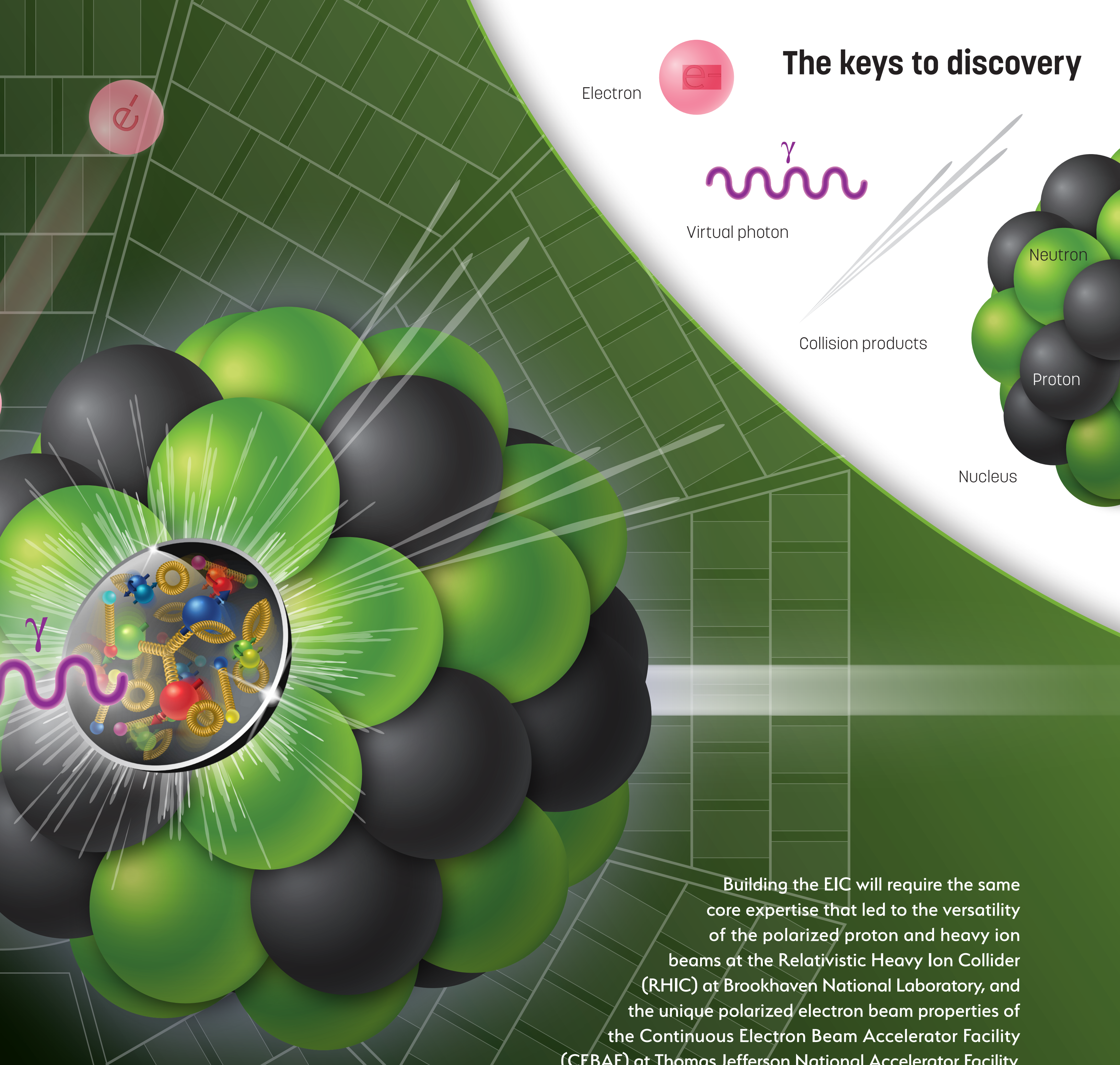
To meet the recommendations of the U.S. Nuclear Science Advisory Committee (NSAC), the accelerators will be designed so that both beams can be polarized to around 70 percent for electrons, protons, and light nuclei. This will allow physicists to alter the alignment to get **insight into proton spin and other physics questions**. As electrons scatter off particles in the other beam, virtual photons—particles of light that mediate the interaction—will penetrate the proton or nucleus to tease out the structure of the quarks and gluons within.



Electrons will be able to **probe particles from protons to the heaviest stable nuclei** at a very wide range of energies, starting from 20–100 billion electron volts (GeV), upgradable to approximately 140 GeV, to produce images of the particles' interiors at higher and higher resolution. At least one detector and possibly more would analyze thousands of particle collisions per second, amassing the data required to tease out the smallest effects required for significant discoveries.



The keys to discovery



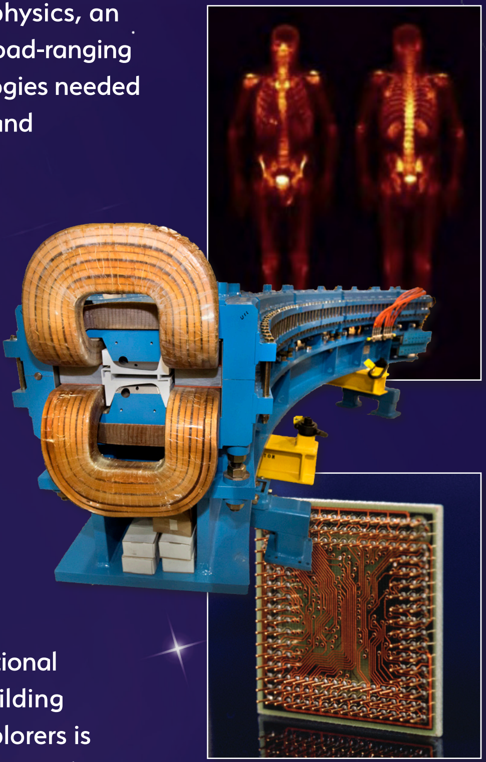
Building the EIC will require the same core expertise that led to the versatility of the polarized proton and heavy ion beams at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, and the unique polarized electron beam properties of the Continuous Electron Beam Accelerator Facility (CEBAF) at Thomas Jefferson National Accelerator Facility. These two Department of Energy laboratories have been **collaborating on initial studies** and developing designs that make use of key existing infrastructure and capitalize on investments in science and technology. Each design approach would require the development of innovative accelerator and detector technologies to answer the questions described in this brochure.

Building the EIC will **maintain and continue to expand U.S. leadership in the fields of nuclear physics and accelerator science** while also stimulating strong international collaboration. Since the publication of the NSAC recommendations, the community of EIC scientists has been growing rapidly—already more than 800 strong, from more than 175 institutions in 30 countries on 6 continents. This energized international community is working to tackle the scientific and technical challenges of building **the world's most powerful microscope for studying matter.**

National Academy of Sciences Assessment of U.S.-Based Electron-Ion Collider Science

In 2018, after reviewing the science case for a future U.S.-based EIC, a National Academy of Sciences (NAS) committee concluded that an EIC is timely and that the science it will achieve is unique and world leading and will ensure global U.S. leadership in nuclear science, accelerator science, and the technology of colliders. The NAS report emphasized that the science questions regarding the building blocks of matter are fundamental and compelling; that an EIC is essential to answering these questions; that the answers will have implications for particle physics and astrophysics and possibly other fields; and that innovations required to construct an EIC will benefit all accelerator-based sciences.

Benefits Beyond Physics



Beyond sparking scientific discoveries in a new frontier of fundamental physics, an Electron-Ion Collider will trigger **technological breakthroughs** that have broad-ranging impact on human health and national challenges. Research on the technologies needed to make this machine a reality is already pushing the evolution of magnets and other particle accelerator components. Some of these advances could lead to **energy-efficient accelerators**, thereby dramatically shrinking the size and operating costs of accelerators used across science and industry —for example, to make and test computer chips; to deliver energetic particle beams to zap cancer cells; to study and design improved **sustainable energy technologies** such as solar cells, batteries, and catalysts; and to develop new kinds of drugs and other medical treatments. New methods of particle detection developed for an EIC could also lead to **advances in medical imaging and national security.**

In truth, it's nearly impossible to predict what will come from the knowledge gained from an EIC. History shows that applications springing from a deeper understanding of matter and fundamental forces—things like GPS, microelectronics, and radiological techniques for diagnosing and treating disease—often emerge many years after the foundational physics discoveries that make them possible. But one thing is certain: Building the experiments that inspire and train the next generation of scientific explorers is essential for maintaining **U.S. leadership in nuclear science**—and for developing the **high-tech workforce** needed to address some of our nation's deepest challenges.

Hundreds of students will help to build and conduct research at an EIC. Some will go on to explore other new questions in physics, but many will apply their expertise in a range of careers that **fuel the economy**, provide for security, and pave the way to a healthier, brighter future for all. In building an Electron-Ion Collider, today's U.S. nuclear physics community hopes to **lay the foundation for that future.**

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