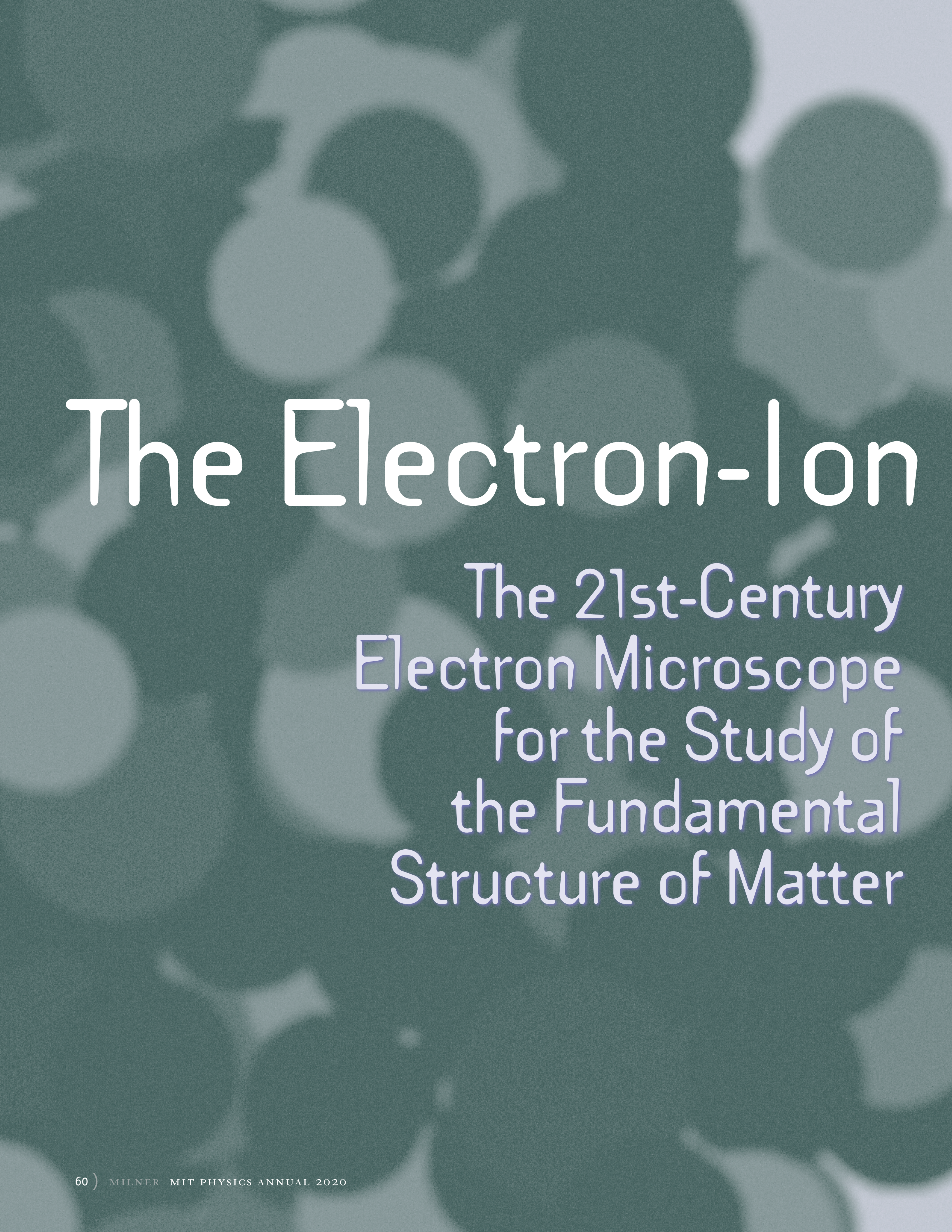


# The Electron-Ion

## The 21st-Century Electron Microscope for the Study of the Fundamental Structure of Matter

### by Richard G. Milner

# Collider

## The Fundamental Structure of Matter

Fundamental, curiosity-driven science is funded by developed societies in large part because it is one of the best investments in the future. For example, the study of the fundamental structure of matter over about two centuries underpins modern human civilization. There is a continual cycle of discovery, understanding and application leading to further discovery. The timescales can be long. For example, Maxwell's equations developed in the mid-nineteenth century to describe simple electrical and magnetic laboratory experiments of that time are the basis for twenty-first century communications. Fundamental experiments by nuclear physicists in the mid-twentieth century to understand spin gave rise to the common medical diagnostic tool, magnetic resonance imaging (MRI). Quantum mechanics, developed about a century ago to describe atomic systems, now is viewed as having great potential for realizing more effective twenty-first century computers.

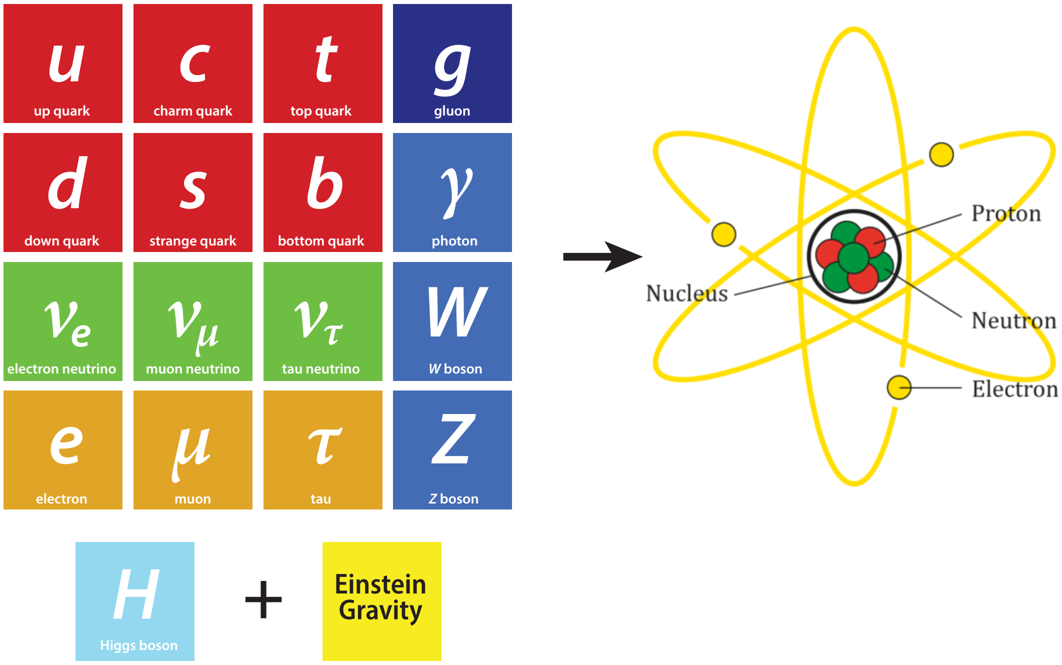


FIGURE 1

*Left: **Schematic illustration** [1] of the fundamental structure of the Standard Model showing the fermions (quarks and leptons), exchange bosons, Higgs boson and Einstein gravity. Right: **The quarks and gluons** form the protons and neutrons, the building blocks of atomic nuclei, which bind the orbiting electrons to form atoms.*

THE STANDARD MODEL (SM), whose fundamental constituents are shown schematically in *Figure 1*, represents an enormous intellectual human achievement. At least eighteen Nobel prizes in Physics have been awarded since 1950 to the physicists who made the key experimental discoveries and critical theoretical insights, several of whom were or are members of the MIT physics department.

However, the SM is framed in terms of particles, most of which are undetectable in the laboratory or are very short-lived. The electron and photon stand apart in *Figure 1* as being stable and straightforwardly accessible in the laboratory and, consequently and not surprisingly, the quantum theory of electrons and photons, Quantum Electrodynamics (QED), is the best understood aspect of the SM.

The fundamental quarks and gluons are not accessible in the laboratory but are confined in protons and neutrons, the building blocks of nuclei. The charged quarks can be accessed directly by high-energy electron scattering and studied in the framework of QED.

The study of the fundamental structure of matter has long relied on electron-proton scattering to determine the existence of point-like quark constituents of the nucleons, the momentum distribution of nucleons in the nucleus, and the most precise information on systems bound by the strong (or nuclear) force. Thus, the discovery of quarks by the Nobel prize winning MIT-SLAC experiment in 1967 provided a cornerstone of the theory of the strong force, Quantum Chromodynamics (QCD). QCD describes the proton (the nucleus of the hydrogen atom), as a highly relativistic system of quarks and gluons interacting via a color force. Basic properties of the proton, like its mass (explains most of what is measured when you stand on the bathroom scale) and spin (the property manipulated in an MRI scan) arise in QCD from these complicated interactions in ways we do not yet understand. MIT physicist and Nobel laureate Frank Wilczek is one of the fathers of QCD.

Nuclear physicists have developed a powerful theory of nuclei as a system of protons and neutrons using a parametrization of the interaction between these constituents that are readily detectable in the laboratory. This theory is used to understand the formation of stars and atomic elements in the universe as well as important societal applications like nuclear energy and medicine. If quarks and gluons are the fundamental particles, can the theory of nuclei be derived from QCD? Can the origin of the mass and spin of the proton be understood in terms of the quarks and gluons of QCD? Can quarks and gluons exhibit different behavior when bound in the nucleus rather than the proton?

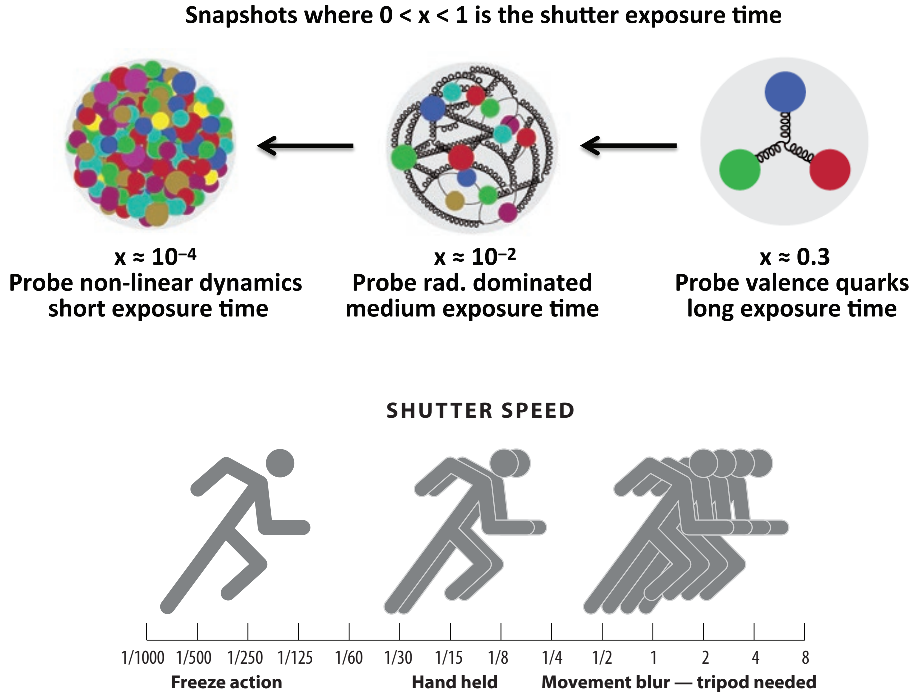
Over about two decades, the QCD community in the U.S. has carefully considered the next generation accelerator facility to study the fundamental structure of matter and has developed a compelling scientific case for a high-luminosity, polarized electron-ion collider (EIC). Most recently, it is summarized in the 2015 white paper, *Electron-Ion Collider: The Next QCD Frontier* [2] and has been favorably reviewed in 2018 by a committee appointed by the U.S. National Academy of Sciences (NAS) [3]. The EIC is the 21st-century instrument for a research field that was born in the U.S. at the MIT-Bates Linear Accelerator Center in the late 1960s.

## Visualizing the proton

The collision at high energy of an electron and proton directly probes the quark substructure of the proton when interpreted in a boosted reference frame [4]. In this boosted frame, snapshots of the quarks can be taken with different spatial resolutions (1/Q) and shutter exposure times ($x$). Both $Q^2$ and $x$ are defined independently of the reference frame, have rigorous interpretations in QCD, and can be precisely varied experimentally to probe different aspects of the proton substructure. *Figure 2* shows schematically (in analogy to a camera) that at low $x$ very rapid fluctuations of the proton's substructure can be recorded, while at high $x$ the time-average is dominant. The $Q^2$ dependence allows determination of the gluon distributions using the equations of QCD. A collaboration of physicists, film producers and artists has been funded by the MIT Center for Art, Science and Technology to develop an animation of the quark and gluon structure of the proton, which can be viewed at *arts.mit.edu/artists/richard-milner-visualizing-the-proton/#about-the-project*.

FIGURE 2

***Visualizing proton structure**: the analogy of x as the shutter exposure time.*



The electron-ion collider accelerator offers important advantages: the electron beam allows access to a large range of $Q^2$ and $x$; the final-state particles are distributed over a larger angular range, which makes their detection much easier than for a fixed-target experiment at high energy; beams of ions from the proton to uranium can be accelerated so that QCD can be studied across the full range of available nuclei; and beams of polarized electrons, protons and light ions can be used so that the spin-dependence of fundamental process can be measured. Attaining a high-luminosity collision rate is essential for precision measurements.

An important and new aspect of high-energy QCD studies is the realization that transverse imaging of the quarks and gluons is possible. Essentially all experiments in the half-century since quarks were discovered have been of the *longitudinal* distributions, *i.e.*, along the incident beam direction. Nuclear physicists have figured out that by measuring processes where the incident electron loses a large fraction of its energy to a specific final-state particle and the target stays intact, the distributions in position and momentum *transverse* to the beam can be measured. This new approach, known as *parton tomography*, is being pursued in a systematic way at long exposure time ($0.1 < x < 1$) at Jefferson Laboratory after their recent energy upgrade. A variant of tomography would study transverse motion rather than transverse position. Tomography will be pursued at EIC over a much larger range of spatial resolutions and shutter exposure times. Scanning through these pictures, starting from the valence quark regime, will enable the determination of where and how gluons and sea quarks appear and whether the gluon distribution has a compact core smaller than the electric charge radius of the proton, or whether the gluon distribution is extended.

## Scientific opportunities with EIC

An EIC is needed to address the picture of nucleons and nuclei as complex interacting many-body systems, and in particular to address three immediate and profound questions about neutrons and protons and how they are assembled to form the nuclei of atoms.

**How does the mass of the nucleon arise?** *i.e.*, How do the constituents of the nucleon, the quarks, the virtual quark-antiquark pairs and the gluons, and importantly their interactions, lead to a mass some 100 times larger than the sum of the three constituent quarks alone?

Most of the mass in the visible universe is due to the protons and neutrons of nuclei. These protons and neutrons are bound systems of very light quarks so that their mass is generated dynamically through interactions in QCD, *i.e.*, via Einstein's famous equation $E=Mc^2$. Physicists are used to the mass of a bound system—a nucleus made of neutrons and protons, an atom made of a nucleus and electrons or even two black holes bound together by gravity—having a mass less than the sum of its parts. The difference is the binding energy of the system. In a nucleon, the opposite is true: half of the mass exists in the gluons that hold it together. How do gluons provide this mass?

An EIC will address this gap in the understanding of fundamental aspects of the nucleon in several ways. First, an EIC will map the gluon distribution in the proton, both in space and in momentum, with unprecedented precision, using the new technique of parton tomography. These images can be used to analyze the coupling between spin and orbital angular momentum. An EIC would not only determine the distribution of gluons but also measure the distribution of gluonic energy density and pressure in the proton. These measurements would directly inform our understanding of the origin of mass and constrain models of the gluon field inside the nucleon. Two key features of an EIC enable measurements of gluons. The first is large kinematic coverage, which provides multiple independent avenues for accessing gluons. The second is large luminosity, which is important for identifying specific final states in high-energy electron scattering. It is this information that can be used to obtain tomographic images.

**How does the spin of the nucleon arise?** Spin, or internal angular momentum, is one of the basic properties of a neutron or proton, central both to understanding atoms and their practical applications. While nucleons are made of three quarks, each with spin-½, the spins of these quarks constitute only a small fraction of the nucleon's spin, the rest seemingly carried by the gluon spins, the sea quarks, and the orbital motion of the quarks and gluons.

The spin of a nucleon is an important property; through the electric charges of quarks, spin allows protons and neutrons to behave as tiny magnets. The magnetic axis is aligned with the spin axis, and external radio frequency fields can drive resonant spin transitions. This is the basis of MRI imaging and many other applications. It is remarkable that scientists do not know in detail the origin of the proton (or neutron) spin.

The proton has spin-½, and in a simple quark picture the total spin arises from three valence quarks of spin-½ that combine to form a total spin-½. While this naive picture qualitatively describes the observed magnetic moment of the proton, it fails quantitatively. In particular, experiments at SLAC, CERN and DESY have shown that the sum of all quark spins in the nucleon accounts for only about one-third of the total spin of the proton. The remainder of the proton spin must reside in orbital angular momentum or gluon spin.

An EIC can comprehensively explore these contributions. The orbital angular momentum of quarks and gluons can be extracted using the transverse position information contained in the tomographic measurements. Measurements of the gluon-spin contribution to the spin of the proton are based on the idea that the gluon can transfer its polarization to a quark-antiquark pair, which can be probed using polarized electrons.

**What are the emergent properties of dense systems of gluons?** The color force mediated by gluons is fundamentally different from the electromagnetic force that binds atoms and molecules. In particular, the force between quarks strengthens as the objects get farther apart, and quarks are permanently confined in neutrons and protons. Two questions concerning the gluons arise when nucleons are combined into nuclei: How is the gluon field modified in a nucleus to accommodate the binding of nucleons? And does a novel regime of nuclear physics emerge in the high-energy limit, a regime in which the complicated structure of the nucleus is radically simplified, leading to a state in which the whole nucleus becomes a dense gluon system?

Nuclear physics exhibits one remarkable limit where simplicity emerges. Despite the extraordinary complexity of QCD—the strength and presence of interactions among all quarks and gluons—at ordinary densities and low temperature, nuclei can be accurately modeled as collections of colorless composite particles (nucleons), interacting through long-range forces understood as arising from the exchange of mesons. An EIC would seek to explore a second regime where great simplicity may emerge, despite the inherent complexity of QCD: in this regime, quarks are predicted to behave as a nearly static source of a gluon field that reaches a limiting density, producing *dense gluonic matter*. At an EIC, this regime would manifest itself in terms of reactions on nuclei that cannot be understood in terms of approximately independent nucleons. Because the color force is so profoundly different from the electromagnetic force, there are also big differences and deep mysteries to be understood, including how quark distributions are modified in nuclei, how the gluons are distributed, and how gluons bind nucleons into nuclei.

Physicists understand well why atoms retain their individual identities in molecules, but not why nucleons retain their identities within nuclei. In fact, nuclear matter can have simpler states where nucleons do not retain their individual identities, as in the quark matter seen in ultra-relativistic heavy ion collisions, and inferred in massive neutron stars. In addition, nucleons and nuclei differ from atoms and molecules because they contain so many gluons, whose implications are still not well understood.

This abundance of gluons provides the opportunity to address fundamental questions about nucleons and nuclei. The number of gluons grows significantly in the small $x$, high-energy limit. This means that gluons must overlap in the plane transverse to the electron-ion collision. The most interesting case is when this limit can be achieved at high resolution (high $Q^2$), so that the number of gluons that can be packed into the transverse area of a proton or nucleus is large. An EIC of sufficiently large energy would be able to reach this limit. Under such conditions, a quantum state of *cold dense gluonic matter* may exist. Such a state is possibly analogous to Bose-Einstein condensates of clouds of cold atoms created in atomic physics laboratories.

The EIC will be able to reach unprecedented gluon densities by using the concentrated gluon fields of large nuclei. Relativistic length contraction [4] implies that the number of gluons per transverse area is proportional to the radius of the nucleus, which is itself proportional to the one-third power of the nuclear mass number A. Although an EIC would operate at lower energies than HERA (which collided beams of electrons and protons), an EIC would achieve higher gluon densities because it can accelerate ions with high atomic weight.

## The EIC accelerator

The EIC is a challenging accelerator to build, requiring well beyond state-of-the-art in electron and ion beam capabilities. However, the U.S. nuclear physics community uniquely possesses the required accelerator physics expertise at Brookhaven National Laboratory (BNL) and Thomas Jefferson National Accelerator Facility (TJNAF, also known as JLab). Further, the scientific programs at the existing Relativistic Heavy Ion Collider at BNL and Continuous Electron Beam Facility at JLab are expected to be largely completed in about a decade. Thus, the EIC represents a clear opportunity for U.S. science both to maintain leadership at the QCD frontier as well as to regain leadership in collider accelerator technology.

Building an EIC capable of fully exploring the physics described above is by no means an easy task. *Figure 3* shows how the scientific areas map onto the required collider luminosity and center-of-mass energy. The machine must collide electrons with protons and other atomic nuclei (ions) over a range of energies. There must be enough collisions for the experiment to gather adequate data to elucidate or settle the known physics questions, and other questions that may emerge, in a reasonable time. A collider's ability to squeeze many particles of two beams into a tiny volume where they collide defines its luminosity. The luminosity ultimately required of an EIC is comparable to those of the highest performing colliders built to date, such as the Large Hadron Collider (LHC) at CERN and the B-meson factories at SLAC and KEK. Furthermore, given the crucial role of spin, both beams must be polarized. To achieve these goals, a host of techniques in accelerator physics and technology must be brought to bear. Only a few are mentioned here. State-of-the-art superconducting radio frequency (SRF) cavities will accelerate high-intensity beams efficiently. Further specialized radio frequency (RF) cavities will rotate the beams as they collide to optimize their overlap. Elaborate interaction region designs must squeeze two very different beams simultaneously into the tiny collision volume using advanced superconducting magnet designs. The hadron beams must be compressed in volume by sophisticated new beam cooling techniques that involve subtle interaction with yet other electron beams. Polarized beams require polarized particle sources, special magnets, and a further level of mastery of beam physics to preserve the polarization through the acceleration process to the collisions. The required specifications of the EIC accelerator are summarized as follows:

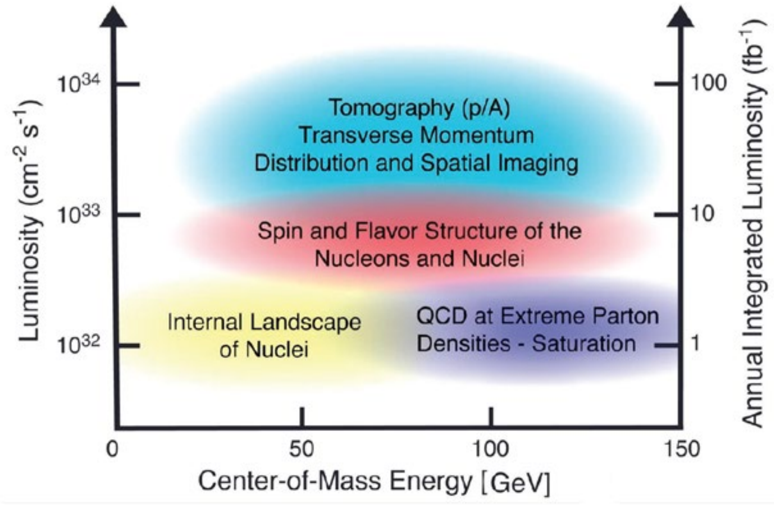


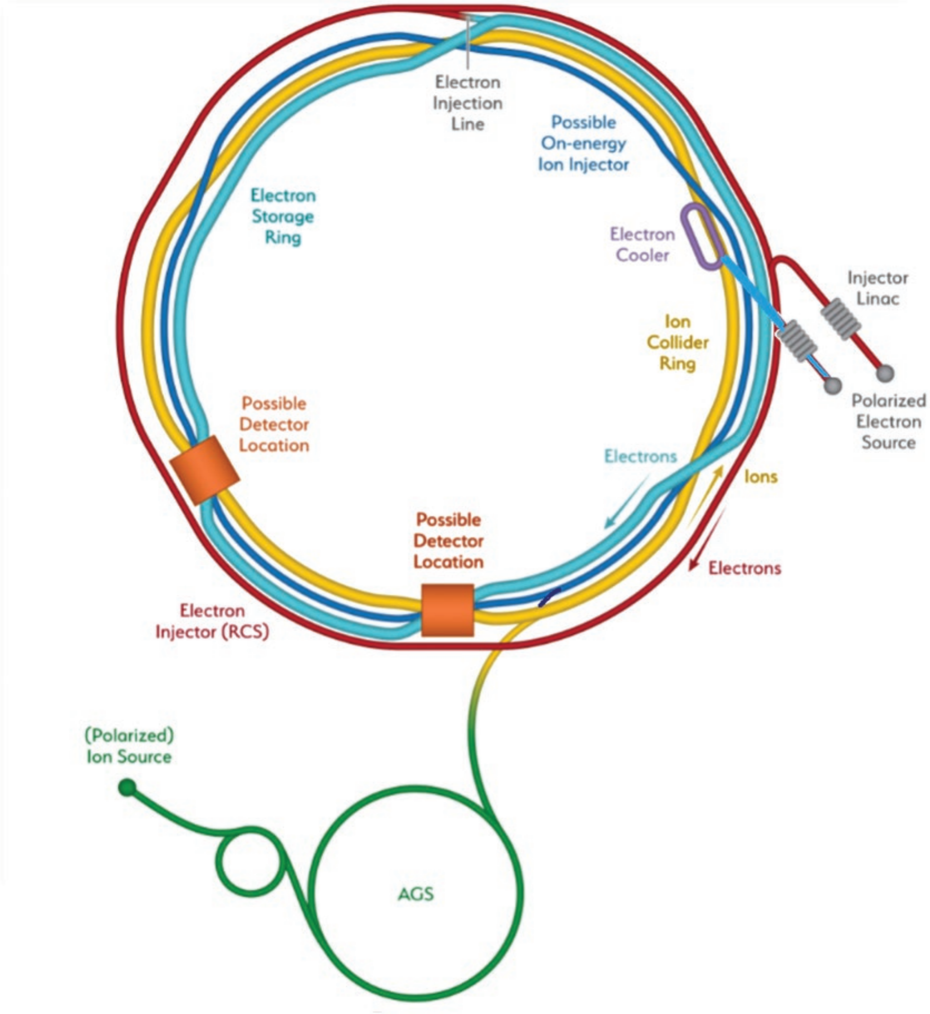
FIGURE 3

***The EIC luminosity*** *vs. center-of-mass energy with the different scientific areas highlighted.*

- **Highly polarized (~70%) electron and nucleon beams**
- **Ion beams from deuterons to the heaviest nuclei (uranium or lead)**
- **Variable center of mass energies from 20 – 100 GeV, upgradable to140 GeV**
- **High collision luminosity $10^{33} – 10^{34}$ cm$^{-2}$ s$^{-1}$**
- **Possibility to have more than one interaction region**

FIGURE 4

***Schematic layout** of the planned EIC accelerator based on the existing RHIC complex at Brookhaven National Laboratory.*



Two conceptual EIC designs, both ring-ring configurations, have been developed: JLEIC using the existing CEBAF electron accelerator at JLab as an injector and eRHIC using the existing RHIC ion accelerator at BNL. In 2019, the U.S. Department of Energy carried out a detailed consideration of both designs. In January 2020, the EIC project was formally launched and it was announced that the BNL design, shown schematically in *Figure 4*, was selected as the design to be constructed. At present, it is anticipated that the EIC will begin operation in the early 2030s.

More than fifteen MIT physics faculty members lead research groups that study QCD in the Laboratory for Nuclear Science (LNS). This work is principally funded by the U.S. Department of Energy. MIT-LNS physicists have played a leadership role over two decades in the realization of the EIC. It is anticipated that the study of QCD at EIC will continue to be a significant focus of MIT-LNS well into the twenty-first century.

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PROFESSOR OF PHYSICS RICHARD G. MILNER *was born and raised in Mayfield, Cork, Ireland. He holds a BSc (Hons.) in Experimental Physics and an MSc in Theoretical Physics from University College Cork, Ireland, and a PhD in physics from Caltech. After graduation, he continued as a postdoctoral researcher at Caltech before taking up a faculty position at MIT in 1988. At MIT, he has served as director of the Bates Linear Accelerator Center from 1998 to 2006 and director of MIT's Laboratory for Nuclear Science from 2006 to 2015.*

*Milner's research focuses on understanding nucleon and nuclear structure using the lepton probe, frequently using spin observables. He has proposed and led experiments at SLAC, IUCF, MIT, DESY, and Jefferson Lab. His current research is focused on the CLAS12 experiment at Jefferson Lab and development of a polarized He-3 ion source for RHIC at BNL. He has been an advocate for a U.S.-based Electron-Ion Collider for two decades.*

*He has served on numerous international advisory committees, was chair of the Division of Nuclear Physics of the American Physical Society (APS) in 2007, and served as chair of the International Spin Physics Committee from 2014 to 2017. Milner is a fellow of the APS, recipient of an award from the Alexander von Humboldt Foundation, Germany, and was conferred with a degree of D.Sc. (honoris causa) by the National University of Ireland in 2010. In 2020, he was awarded the APS's Tom W. Bonner Prize in Nuclear Physics for pioneering work developing and using polarized internal targets in storage rings and for leadership in the study of the structure of the nucleon in a wide range of electronuclear experiments.*