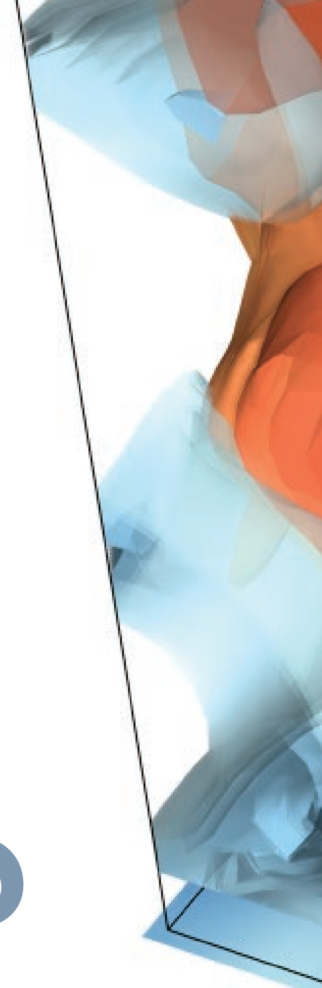
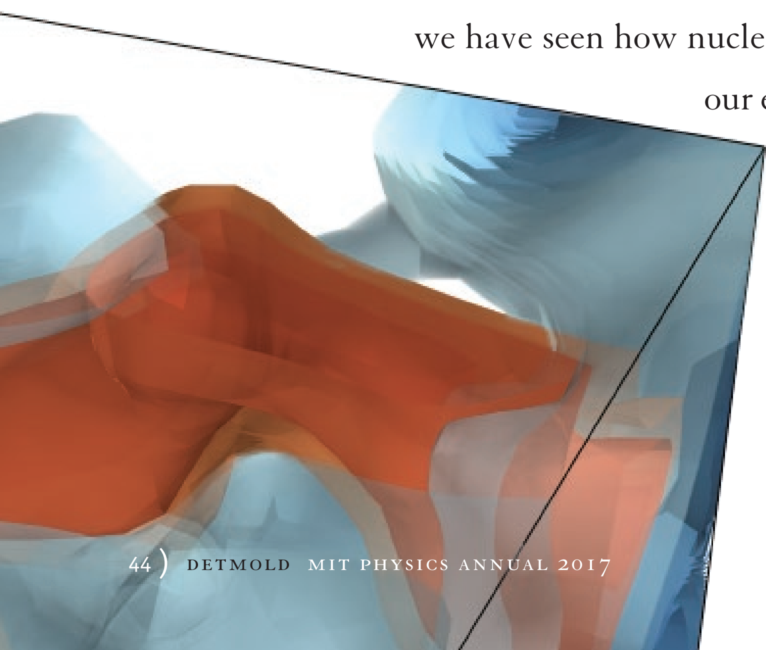
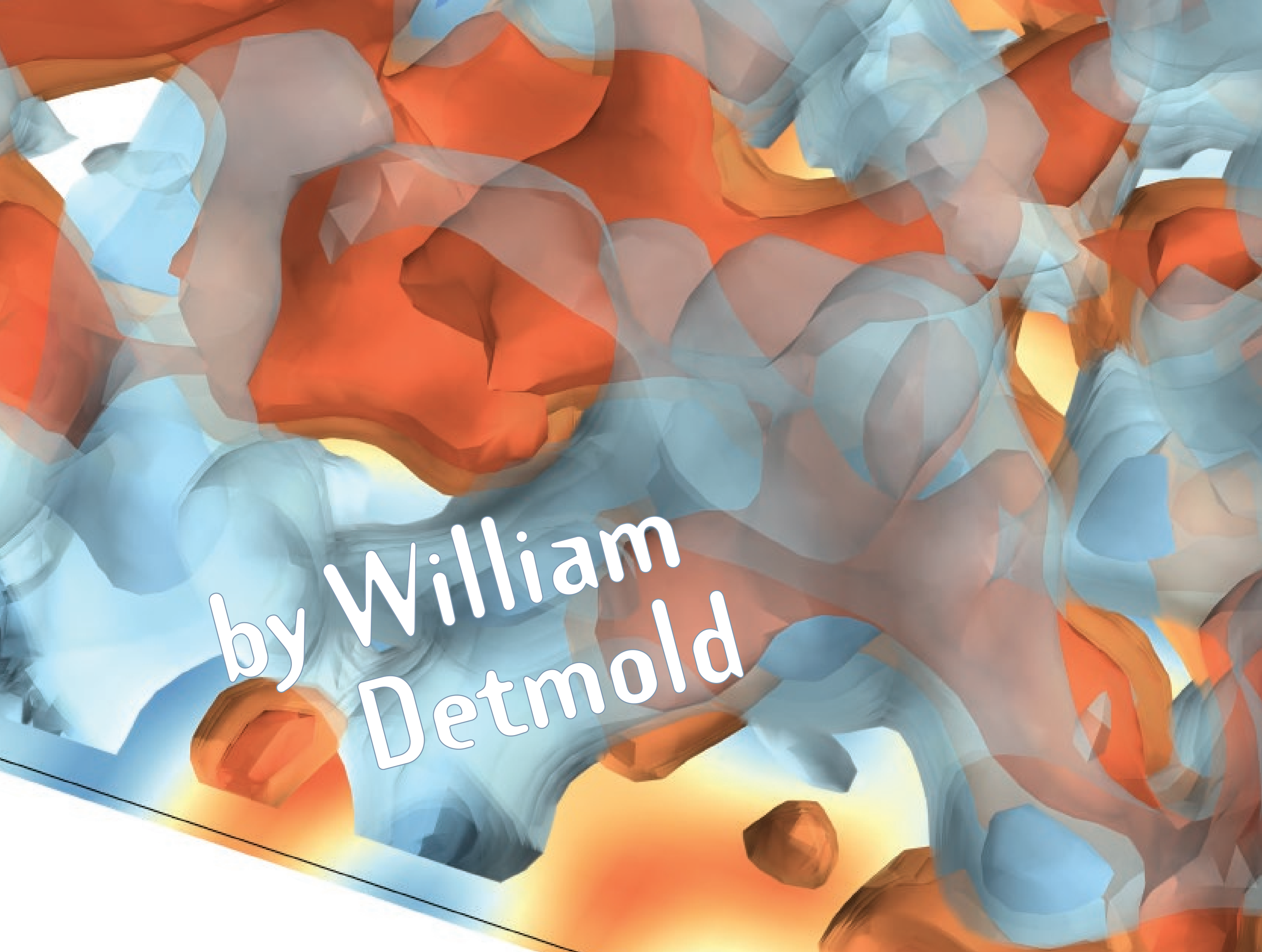
The secret life of quarks



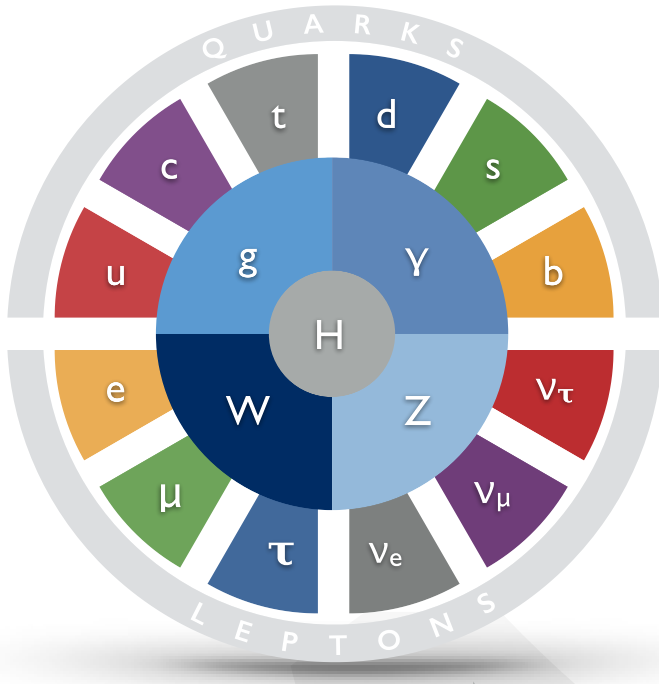
Since the brilliant insights and pioneering experiments of Geiger, Marsden and Rutherford first revealed that atoms contain nuclei [1], nuclear physics has developed into an astoundingly rich and diverse field. We have probed the complexities of protons and nuclei in our laboratories; we have seen how nuclear processes writ large in the cosmos are key to our existence; and we have found a myriad of ways to harness the nuclear realm for energy, medical and security applications. Nevertheless, many open questions still remain in nuclear physics—the mysterious and hidden world that is the domain of quarks and gluons.





by William Detmold

The modern picture of an atom includes multiple layers of structure: atoms are composed of nuclei and electrons; nuclei are composed of protons and neutrons; and protons and neutrons are themselves composed of quarks—matter particles—that are held together by force-carrying particles called gluons. And it is the primary goal of the Large Hadron Collider (LHC) in Geneva, Switzerland, to investigate the tantalizing possibility that an even deeper structure exists. Despite this understanding, we are only just beginning to be able to predict the properties and interactions of nuclei from the underlying physics of quarks and gluons, as these fundamental constituents are never seen directly in experiments but always remain confined inside composite particles (hadrons), such as the proton. Recent progress in supercomputing and algorithm development has changed this, and we are rapidly approaching the point where precision calculations of the simplest nuclear processes will be possible. With exascale computers capable of 10^{18} floating point operations per second available in the near future, we will achieve a new understanding of the structure and complexity of hadrons and nuclei, and new paths to test fundamental aspects of nature using nuclei will open up.



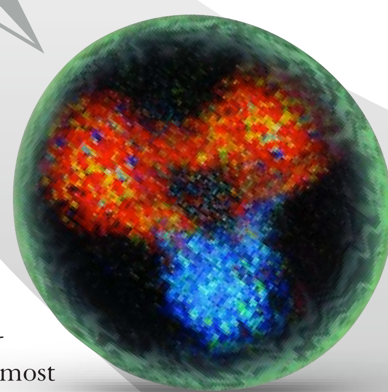


FIGURE 1

The Standard Model *(top left) forms the basis for our understanding of the universe. From it emerge the complex structures of the proton, nuclei, supernovae and everything in between. [Images courtesy of Thomas Jefferson National Accelerator Facility and Anthony Mezzacappa, University of Tennessee]*

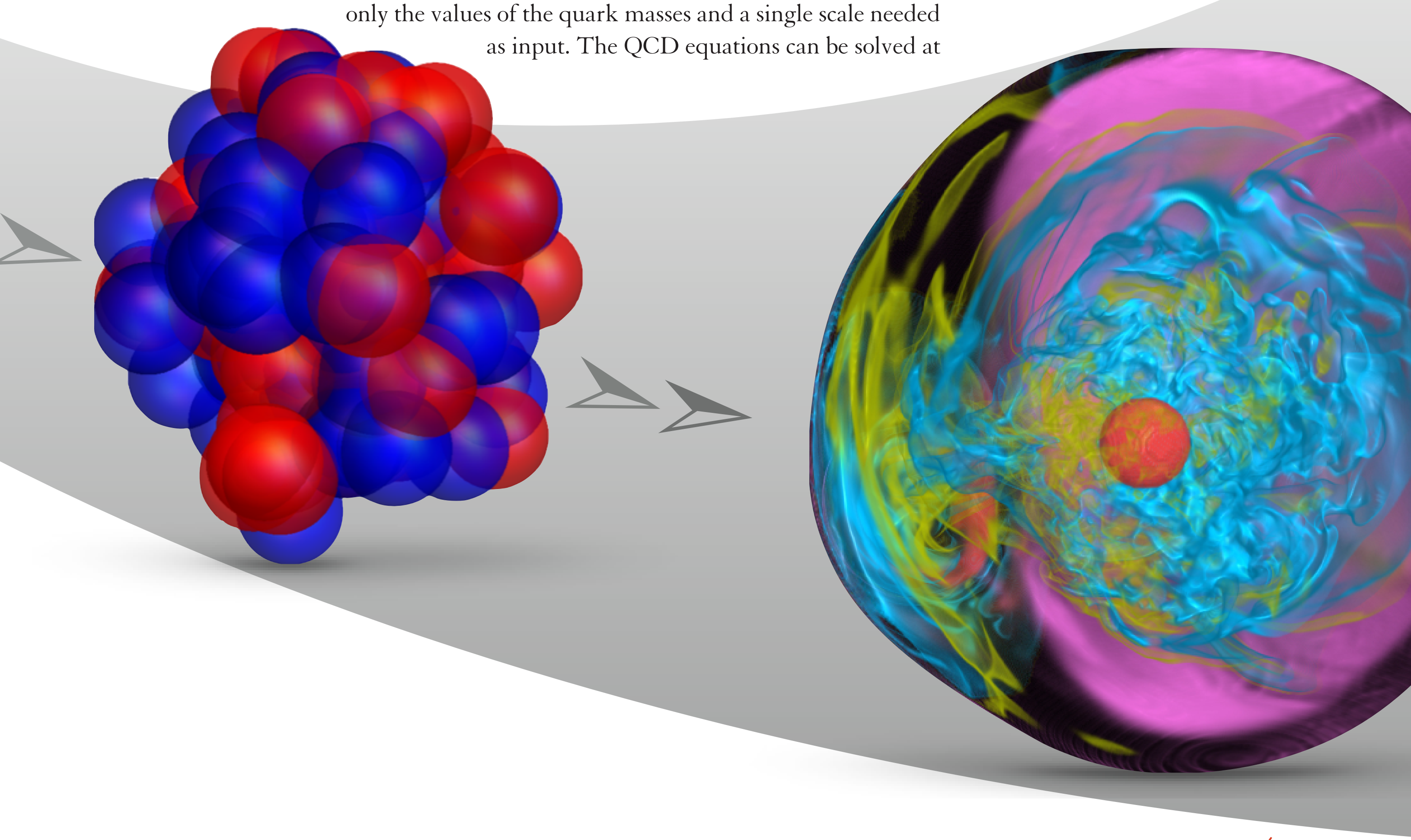
The modern understanding of nuclei is encoded in the Standard Model (SM) of particle physics *(see Figure 1)*, the coupled set of quantum field theories that describe the strong, electromagnetic and weak interactions between quarks and leptons (the electron and its heavier cousins). For nuclear physics, the strong interactions between quarks and gluons are the most important part of the Standard Model. These interactions are described by the theory of Quantum Chromodynamics (QCD), developed in the 1970s by Frank Wilczek, David Gross and David Politzer [2]. From the complex interactions of QCD, the intricate bound-state structure of hadrons such as the proton, neutron (collectively, nucleons) and pion emerges. The quest to understand this emergence and the resulting structure of the nucleon is a major driver of experimental nuclear physics at colliders and accelerators around the world. Only recently are we reaching the point where this structure can be calculated reliably.

Like protons and neutrons, the multitude of nuclear isotopes that have been discovered and produced over the last century are fundamentally comprised of quarks and gluons. Nuclei are, however, described very effectively using nucleon degrees of freedom interacting through effective nuclear forces. This approach is the cornerstone of the phenomenological modelling of nuclei and nuclear processes that has been enormously successful over the last 70 years. Quantitatively understanding the QCD origins of these nuclear forces, and the way in which nuclei interact through the electromagnetic and weak interactions, is vital in order to provide a solid foundation for this vast phenomenology. It will also help resolve open puzzles in our description of nuclei and empower searches for physics beyond the SM.

Nuclear interactions, in addition to gravity, are of defining importance on astrophysical scales where they drive stellar burning, cause cataclysmic events such as supernovae, and determine the properties of the neutron stars that are sometimes left in the aftermath. These processes are central to the history of the universe and to our existence, as they are the origin of essentially all nuclei heavier than lithium. Over many years of astronomical observation, terrestrial experiments and sophisticated nuclear theory, we have developed a basic understanding of the life cycles of stars, but here, too, many questions remain. In stellar environments, it is only feasible to consider the bulk properties of nuclear matter, such as pressure, temperature and density, rather than attempting to describe stars as collections of individual nucleons or nuclei. Quantitatively describing the emergence of these coarse-grained properties from nuclear forces, and understanding the incredibly complex, multi-scale dynamics that determine their evolution, are major goals of the field and there is a significant need for theoretical input on hadronic interactions that are difficult to constrain in terrestrial experiments.

The emergence of hadrons

QCD is an elegant theory which is encapsulated in relatively simple equations, with only the values of the quark masses and a single scale needed as input. The QCD equations can be solved at



the high energies relevant at particle colliders, as a defining property of QCD is that the quarks and gluons become asymptotically free particles that are almost non-interacting in this limit. However, at low energies relevant for understanding the internal structure of the proton or the interactions that bind protons and neutrons together to form nuclei, these equations are notoriously difficult to solve as the interaction between the quarks and gluons becomes increasingly strong, and can no longer be treated as a small perturbation. For this reason, direct comparison of QCD predictions with experiment has historically only been possible at high energies where the strong interactions become weak, and electron scattering experiments pioneered by Friedman, Kendall and Taylor [3] have revealed the quark and gluon substructure of hadrons. In the last decade, this situation has changed dramatically and we now have experimental confirmation of QCD at the low energies relevant for hadronic and nuclear physics.

With years of research developments and advances in computing, the numerical approach named LATTICE QCD (see sidebar, opposite) has matured to a level where many properties of hadrons, such as their masses, can be computed precisely from QCD with fully quantified uncertainties. A comparison of lattice QCD calculations of many hadron masses with experiment is shown in *Figure 2* and provides

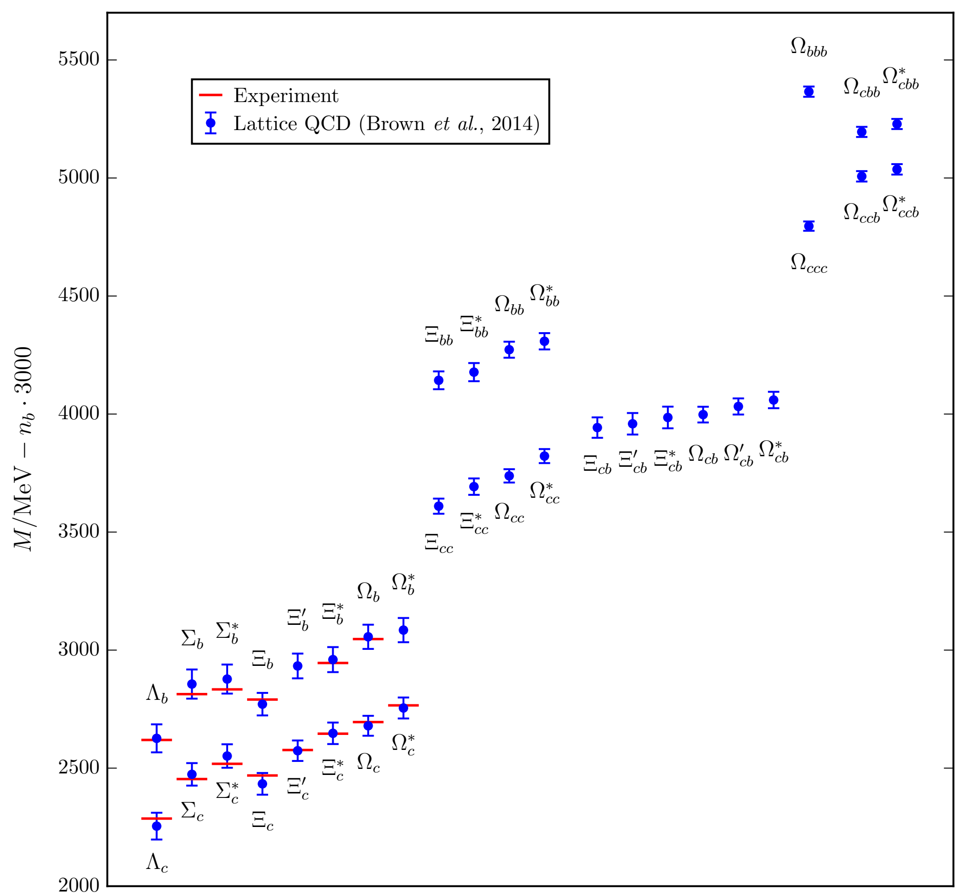


FIGURE 2

Comparison of lattice QCD calculations *(blue data points) of masses of many hadrons containing charm and bottom quarks (heavy types of quarks produced in colliders) with experiment (red lines). The masses are scaled down by 3000 n_b, where n_b is the number of bottom quarks involved. Masses of many of the hadrons containing two or three heavy quarks are predictions awaiting future experiments. [4]*

Lattice Quantum Chromodynamics

Lattice QCD (LQCD), pioneered in 1974 by Nobel laureate Kenneth Wilson [5], provides a rigorous numerical approach to QCD calculations in the low-energy, strong-coupling regime. The approach is directly related to Richard Feynman's path integral formulation describing the quantum mechanics of a single particle as the sum over all possible paths that it could take. In LQCD, this formulation is implemented on a discretized version of the theory defined on a space-time grid (a four-dimensional hypercubic lattice), amenable to numerical calculations.

The quarks and gluons are represented on the vertices and edges of the grid, and calculations are performed using probabilistic Monte Carlo methods in which representative configurations (the analogues of Feynman's paths) of the quark and gluon degrees of freedom are generated with a distribution prescribed by QCD. Physical observables are then extracted from correlations in these samplings.

An important feature of LQCD is that the statistical uncertainties from the Monte Carlo sampling and the systematic uncertainties from the finite volume and discretization can be fully quantified. These uncertainties can be systematically reduced to any prescribed level of accuracy, yielding first-principles QCD determinations of observables limited only by computational resources.

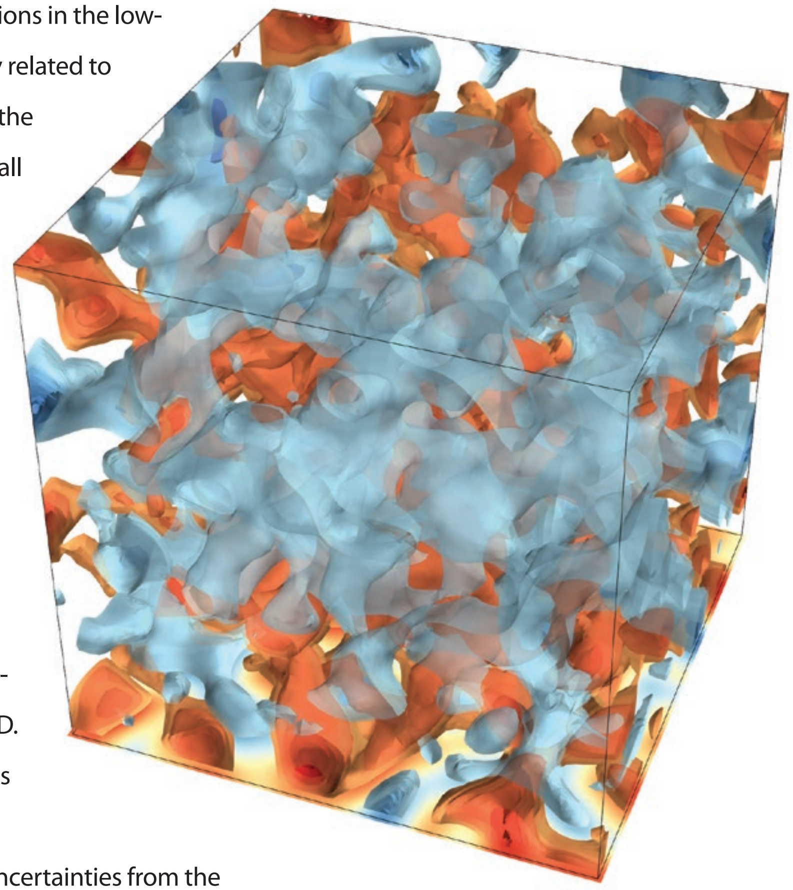


FIGURE 3
LQCD gluon field configuration.
[Courtesy Daniel Trewartha, Thomas Jefferson National Accelerator Facility.]

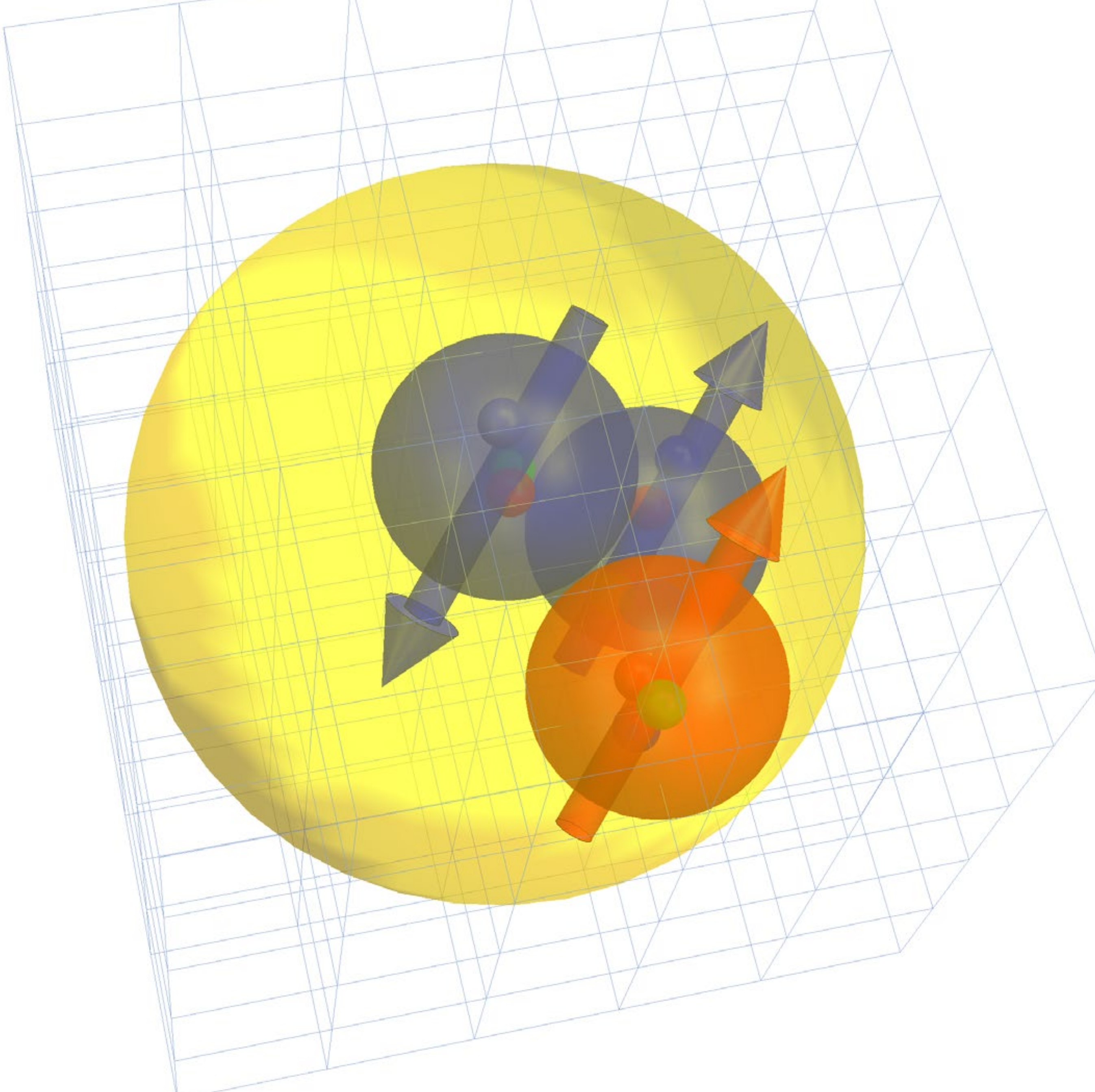
confirmation that QCD describes the strong interactions in the low-energy regime. Furthermore, it makes predictions for masses of new particles not yet seen in experiment. Lattice QCD calculations are already crucial to particle physics as the determinations of most Standard Model parameters depend on this technique, and many searches for new physics rely heavily on lattice QCD results to set Standard Model benchmarks. The last few years and the coming decade present a golden opportunity for further improvements in high performance computing techniques to extend these successes to the realm of nuclear physics.

In the coming years, lattice QCD will provide even more precise determinations of quantities related to the distribution of charges, currents and spin within the proton, namely the electromagnetic and weak form factors and transverse momentum dependent parton distributions (TMDs). From the form factors, it is possible to extract the charge radius of the proton, an elementary property for which different experimental approaches yield numerical values that are in significant disagreement. This may be due to unaccounted systematics in the experiments or their analysis, or may be a sign of physics beyond the Standard Model; a precise QCD calculation may help to resolve this intriguing discrepancy. TMDs similarly hold the promise of unveiling a complete spatial picture of the proton and will help answer the seemingly simple question of how the intrinsic spin of the proton arises from the spins and orbital angular momenta of its constituent quarks and gluons—a question that has puzzled the community since the 1980s. Moreover, quantitative numerical calculations of the gluon distributions in both protons and nuclei will provide predictions and QCD benchmarks for the first measurements of these quantities at a planned electron-ion collider (EIC). The EIC is a high priority of the entire nuclear physics community and will likely be the next big-science machine built in the U.S.

Onward to nuclei

An immense wealth of experimental data on the structure and properties of nuclei has been amassed over the last decades. The chart of nuclides contains some 2,000 isotopes about which something (and in many cases, much) is known. A prime goal for nuclear theorists is to explain these data and, within the same formalism, make predictions for situations that have not been or cannot be probed experimentally. Such predictions motivate new experiments and provide guidance about physics in inaccessible environments such as the interiors of neutron stars and nuclear reactors.

Increased supercomputing power and major algorithmic advances over the last five years have led to the first crude calculations of the binding energies and simple properties of light nuclei (atomic number $A<5$) using lattice QCD. Most recently, a series of calculations have shown that the electromagnetic and weak interactions of these nuclei can be studied, and first calculations of the proton-proton fusion process that begins the reaction chain that powers the sun have recently been performed. Over the next several years, exascale computing will allow these calculations to be repeated at high precision. Beyond revealing properties of light nuclei, this will enable a refinement of the nuclear forces used in nuclear structure calculations of



larger nuclei and astrophysical environments. Importantly, three-nucleon interactions, which are very difficult to access experimentally but essential for a precise understanding of the properties of nuclei, can be constrained from lattice QCD calculations. Through collaborations with nuclear structure theorists, such few-body calculations will provide the tools to more reliably predict the properties of larger nuclei, as needed for a host of current and future experiments involving nuclear targets. A prime example is the Deep Underground Neutrino Experiment (DUNE), designed to further our understanding of neutrino oscillations and potentially reveal violation of CP-symmetry in the neutrino sector. (This symmetry demands that the laws of physics should be the same if a particle is interchanged with its antiparticle while all positions are interchanged, as if reflected in a mirror.) This facility is a top priority for U.S. particle physics, planned to be operational in

FIGURE 4

As verified by LQCD calculations, the magnetic moment of the triton *is dominated by that of the proton as the neutrons pair to spin zero.*

the late 2020s. To calibrate the DUNE experiment, which will employ an argon target, neutrino interactions with nuclei must be determined quantitatively to a far greater precision than they are currently known. While challenging, recent advances indicate that a calculation of the relevant scattering cross-sections based on numerical calculations of the Standard Model will be possible on the timescale of the experiment.

The cosmic frontier

The scope of nuclear physics expanded greatly when Sir Arthur Eddington (1920), Hans Bethe (1939) and their contemporaries realized that nuclear processes power stars. While compelling models of stellar nucleosynthesis and Big Bang nucleosynthesis (BBN), through which the elements are formed, now exist, there are still many unanswered puzzles. For example, there is less lithium in the universe than predicted and the exact sites of heavy element production are as yet uncertain. In concert with astronomers and astrophysicists, nuclear physicists are working to resolve these issues through better understanding of the nuclear reaction pathways relevant to BBN and of the nuclear physics of stellar life cycles, including their violent ends in supernova explosions. The most important inputs from nuclear physics in these studies are the reaction networks and the nuclear equation of state (NEOS) that govern the relationship between the energy, pressure and density of nuclear matter. Focusing on the NEOS relevant for neutron stars, this relation is uncertain as we do not know the multi-neutron interactions and potentially other hadronic interactions that become relevant at the high densities that occur inside neutron stars. One possibility is that new degrees of freedom such as hyperons (hadrons containing strange quarks) or quark matter become relevant at the extreme densities produced in the core of supernovas. With very little ability to probe these scenarios in terrestrial experiments, a quantitative understanding of their effects on the NEOS must be built from QCD, with the results fed into nuclear many-body calculations, to explain and predict astrophysical observations. Recent work has revealed the potential importance of hyperons in neutron stars, even in light of observations of two-solar-mass supernova remnants that were thought to favor a NEOS less susceptible to such new degrees of freedom. Excitingly, neutron star–neutron star or neutron star–black hole mergers may soon be observed at Advanced LIGO and would provide a wealth of complementary information.

The exascale future

Nuclear physics is entering an exciting new era in which the phenomenological approaches to understanding nuclear dynamics that have seen such success over the last decades are directly related to the Standard Model. Advances in supercomputers, and the algorithms to utilize them, will allow the numerical first-principles calculations of QCD in nuclei that have been achieved over the last five years to be extended in scope and in precision, giving us further insight into the strange quantum world of quarks and gluons.

references

[1] For a student-friendly summary, see Wikipedia's "Geiger-Marsden experiment" essay at en.wikipedia.org/wiki/Geiger-Marsden_experiment.

[2] The Nobel Prize in Physics 2004: nobelprize.org/nobel_prizes/physics/laureates/2004/.

[3] The Nobel Prize in Physics 1990: nobelprize.org/nobel_prizes/physics/laureates/1990/.

[4] Zachary S. Brown, William Detmold, Stefan Meinel, and Kostas Orginos, "Charmed bottom baryon spectroscopy from lattice QCD," *Phys. Rev. D* **90**, 094507, 2014.

[5] The Nobel Prize in Physics 1982: nobelprize.org/nobel_prizes/physics/laureates/1982/.

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william detmold *is an associate professor of physics at MIT whose research interests are in strong-interaction dynamics in theoretical particle and nuclear physics. Detmold uses analytic methods and supercomputers to solve the complex equations of quantum chromodynamics (QCD) that describe the strong interaction and seeks to understand the emergence of hadrons and nuclei from the underlying Standard Model of particle physics. He aims to determine the properties and interactions of these systems from first principles in order to confront experiment and to make predictions for regimes, such as in the interior of neutron stars, where experiments are not possible.*

Detmold obtained his PhD from the University of Adelaide, Australia, and joined the MIT physics faculty as an assistant professor in 2012. Prior to that he was on the physics faculty at the College of William & Mary and at the University of Washington. He is the recipient of the U.S. Department of Energy's Outstanding Junior Investigator and Early Career Awards. In 2016, Detmold was named a Fellow of the American Physical Society.