The National Academies of
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BOARD ON PHYSICS AND ASTRONOMY (BPA)

An Assessment of U.S.-Based Electron-Ion Collider Science

A study under the auspices of the U.S. National Academies of Sciences, Engineering, and Medicine

Gordon Baym and Ani Aprahamian, Co-Chairs

The study is supported by funding from the DOE Office of Science.

(Further information can be found at: https://www.nap.edu/25171)

The National Academies of Science, Engineering and Medicine

The National Academies produce reports that shape policies, inform public opinion, and advance the pursuit of science, engineering, and medicine.

The present report is carried out under the leadership of the Board on Physics and Astronomy (James Lancaster, Director).
The BPA seeks to inform the government and the public about what is needed to continue the advancement of physics and astronomy and why doing so is important.

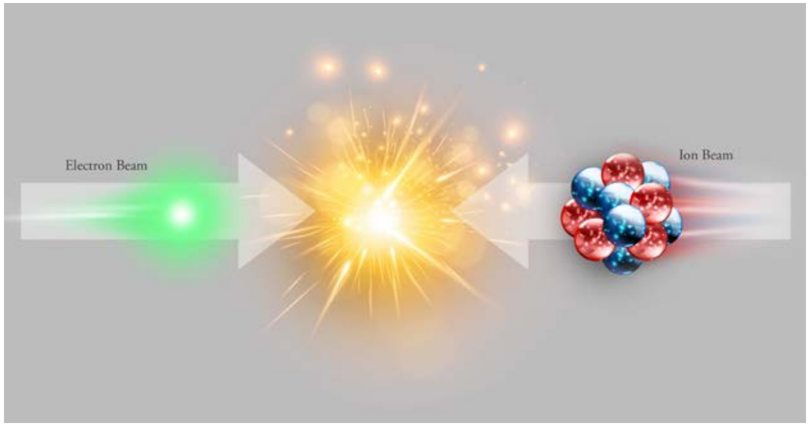
Committee on Assessment of U.S.-Based Electron-Ion Collider Science

The National Academies of Sciences, Engineering, and Medicine was asked by the U.S. Department of Energy to assess the scientific justification for building an Electron-Ion Collider (EIC) facility. The unanimous conclusion of the Committee is that an EIC, as envisioned in this report, would be…

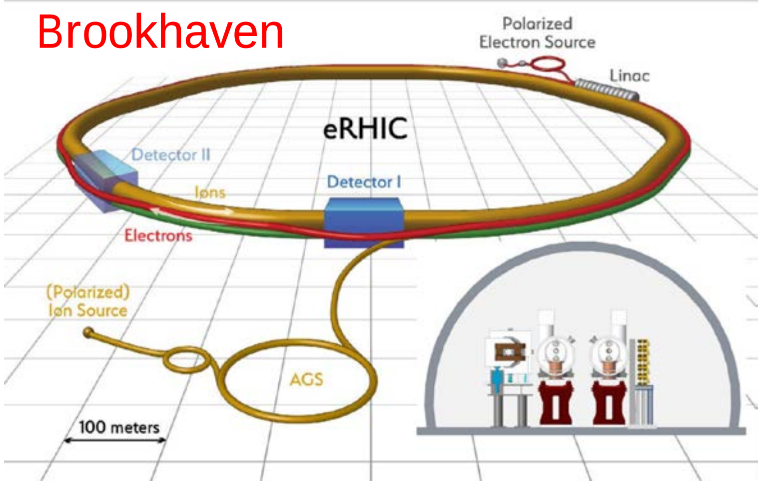
… a unique facility in the world that would answer science questions that are compelling, fundamental, and timely, and help maintain U.S. scientific leadership in nuclear physics.

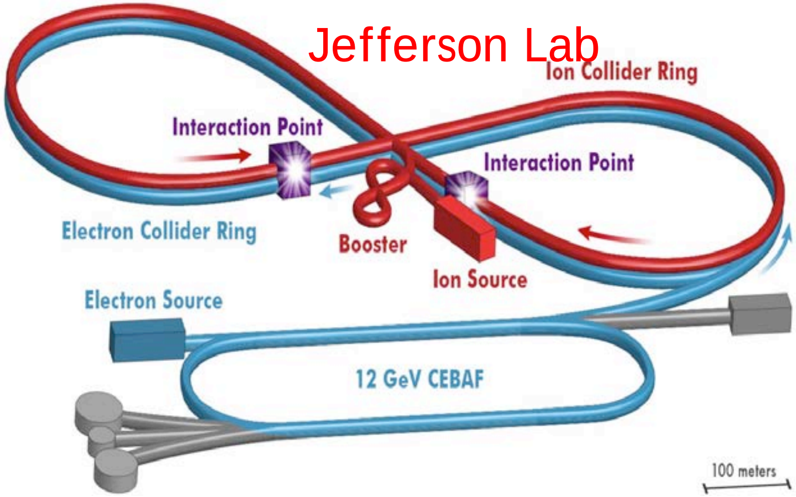
What is an Electron-Ion Collider?

An advanced accelerator that collides beams of electrons with beams of protons or heavier ions (atomic nuclei).
Electron-ion center of mass energy ~20-100 GeV, upgradable to ~140 GeV.
High luminosity and polarization!



1) highly polarized electrons, E ~ 4 GeV to possibly 20 GeV
2) highly polarized protons, E ~ 30 GeV to some 300 GeV, and heavier ions





Two possible configurations: Brookhaven Nat'l Lab and Jefferson Lab

Committee Statement of Task -- from DOE to the BPA

The committee will assess the scientific justification for a U.S. domestic electron ion collider facility, taking into account current international plans and existing domestic facility infrastructure. In preparing its report, the committee will address the role that such a facility could play in the future of nuclear physics, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics.

In particular, the committee will address the following questions:

- What is the merit and significance of the science that could be addressed by an electron ion collider facility and what is its importance in the overall context of research in nuclear physics and the physical sciences in general?
- What are the capabilities of other facilities, existing and planned, domestic and abroad, to address the science opportunities afforded by an electron-ion collider?
- What unique scientific role could be played by a domestic electron ion collider facility that is complementary to existing and planned facilities at home and elsewhere?
- What are the benefits to U.S. leadership in nuclear physics if a domestic electron ion collider were constructed?
- What are the benefits to other fields of science and to society of establishing such a facility in the United States?

Committee Membership

Gordon Baym, Co-Chair (Illinois): theoretical many-particle physics
Ani Aprahamian, Co-Chair (Notre Dame): nuclear experiment

Christine Aidala (Michigan):	heavy ion experiment
Richard Milner (MIT):	high energy electron experiment
Ernst Sichtermann (LBNL):	heavy ion experiment
Zein-Eddine Meziani (Temple):	high energy electron experiment
Thomas Schaefer (NC State U):	theoretical nuclear physics
Michael Turner (Chicago):	theoretical astronomy, cosmology
Wick Haxton (UC Berkeley):	theoretical nuclear physics
Kawtar Hafidi (Argonne):	high energy electron experiment
Peter Braun-Munzinger (GSI):	heavy ion experiment
Larry McLerran (Washington):	theoretical nuclear physics
Haiyan Gao (Duke):	high energy electron experiment
John Jowett (CERN):	accelerator physics
Lia Merminga (Fermilab):	accelerator physics

Report Process & Meeting Schedule

Four meetings in 2017, plus three conference calls for entire committee, and many smaller conference calls among working groups

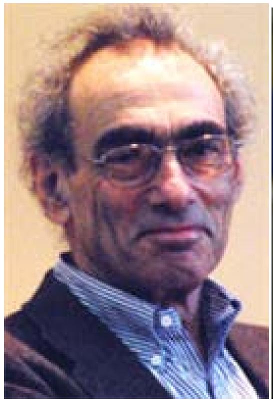
First meeting   Feb. 1-2 Washington
Funding agencies, House Science and Technology Committee, NSAC, EIC collider physics, European perspective, RHIC plans

Second meeting   April 19-20 Irvine
JLab plans, EIC User Group, EIC in China, CERN, gluon and deep inelastic scattering physics

Third meeting   Sept. 11-12 Woods Hole
EIC accelerator technology, EIC computing, gluon saturation

Fourth and final meeting: Nov. 27-28 Washington

Committee members talking today

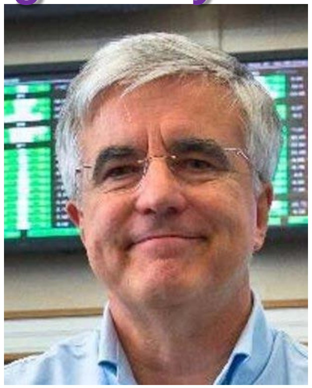


Gordon Baym

Ani Aprahamian

Richard Milner

Ernst Sichtermann



John Jowett

Thomas Schaefer

Committee at the Academies, Washington D.C.

Bottom Line

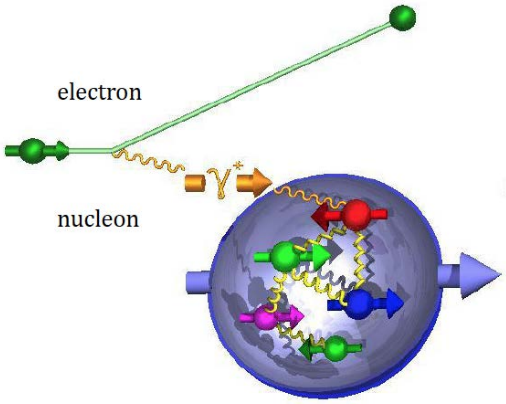
The committee unanimously finds that the science that can be addressed by an EIC is compelling, fundamental, and timely.

The unanimous conclusion of the Committee is that an EIC, as envisioned in this report, would be a unique facility in the world that would boost the U.S. STEM workforce and help maintain U.S. scientific leadership in nuclear physics.

The project is strongly supported by the nuclear physics community.

The technological benefits of meeting the accelerator challenges are enormous, both for basic science and for applied areas that use accelerators, including material science and medicine.

Outline of the Report



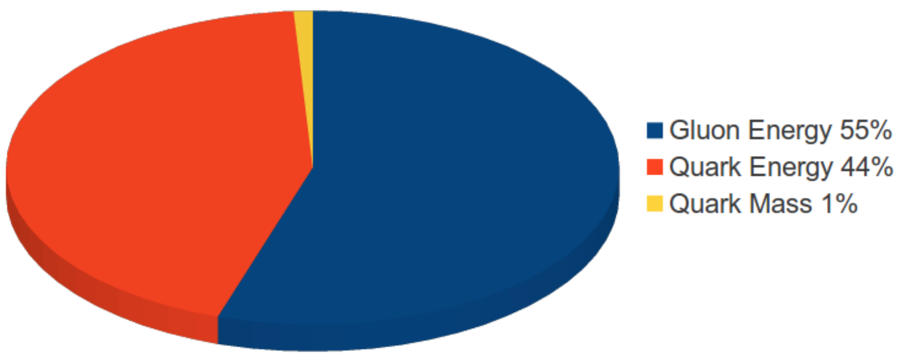
Front Matter
Preface
Summary

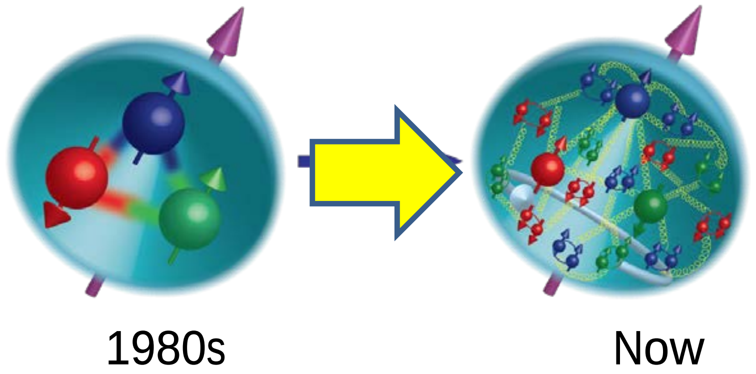
- Ch 1: Introduction (overview)
- Ch 2: The scientific case for an electron-ion collider (and how an EIC would do the science)
- Ch 3: The role of an EIC within the context of nuclear physics in the U.S. and internationally
- Ch 4: Accelerator science, technology, and detectors needed for a U.S.-based EIC
- Ch. 5: Comparison of a U.S.-based EIC to current and future facilities
- Ch. 6: Impact of an EIC on other fields
- Ch 7: Conclusion and findings

Appendixes: Statement of Task; Bios; Acronyms

Ch. 2: Basic science to be explored

How does a nucleon acquire mass? -- almost 100 times greater than the sum of its valence quark masses. Cannot be understood via Higgs mechanism

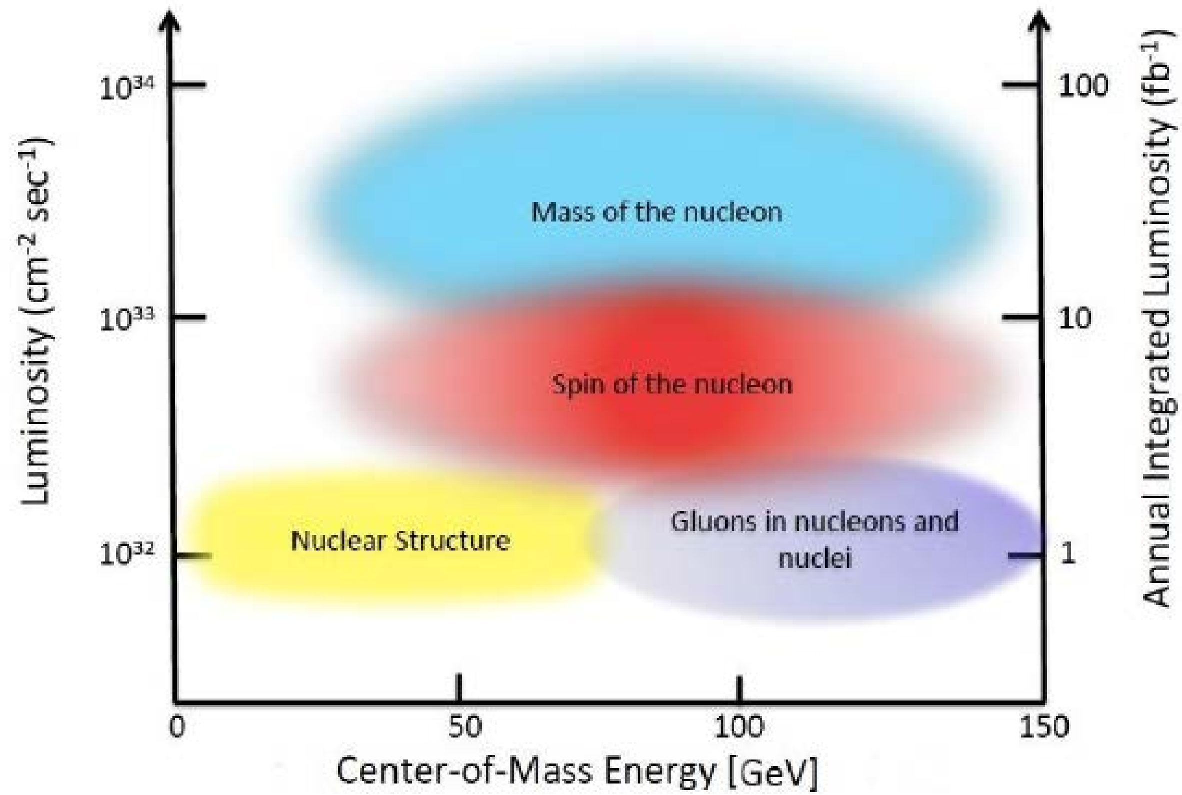


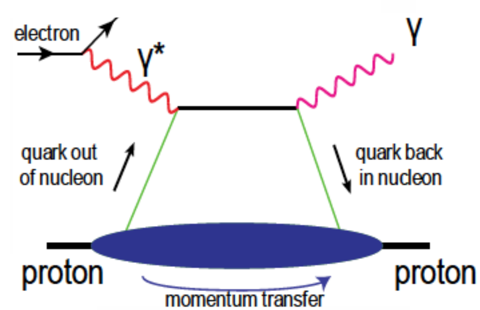


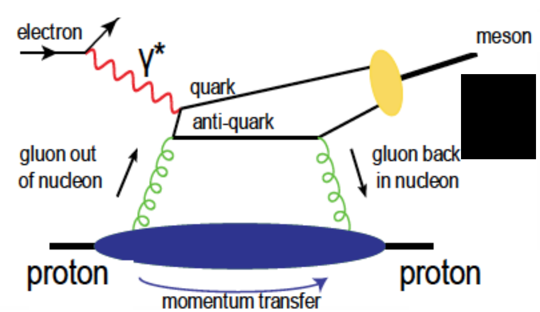
How does the spin (internal angular momentum) of the nucleon arise from its elementary quark and gluon constituents? Proton spin is the basis of MRI imaging.

What are the emergent properties of dense systems of gluons? How are they distributed in both position and momentum in nucleons and nuclei, and how are they correlated among themselves and with the quarks and antiquarks present? *What are their quantum states?* Are there new forms of matter made of dense gluons?

Basic experiments in c.m. energy - luminosity landscape



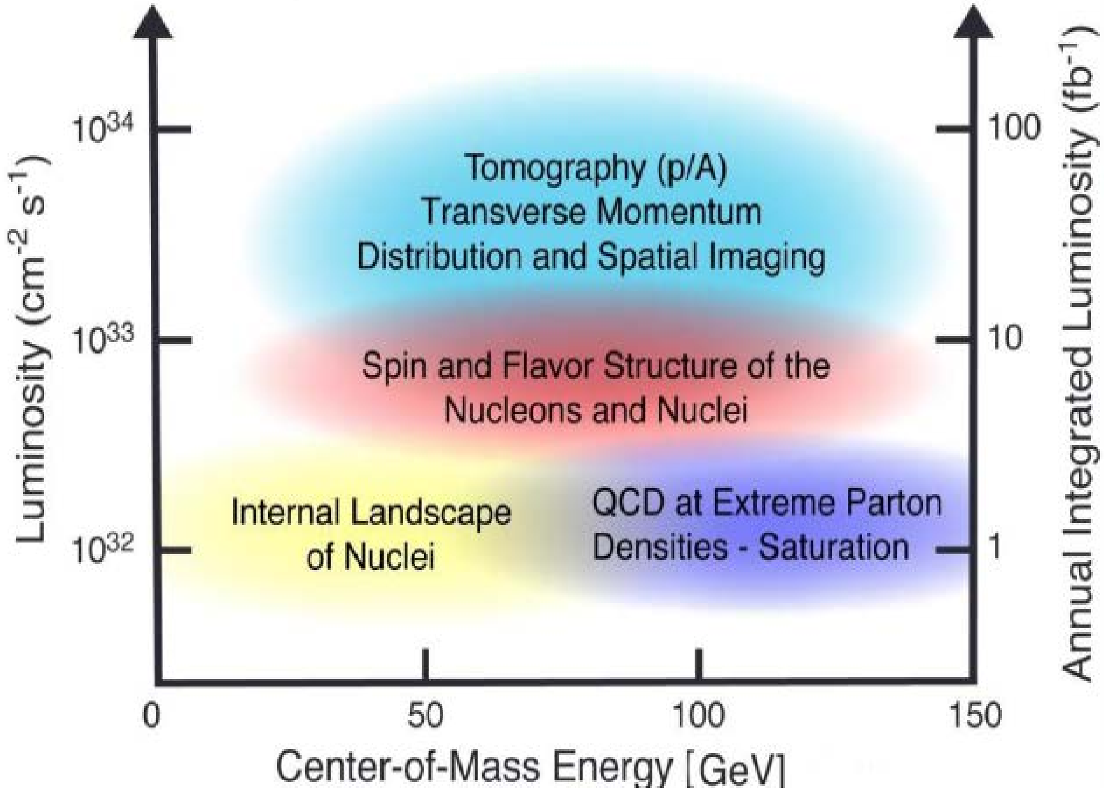


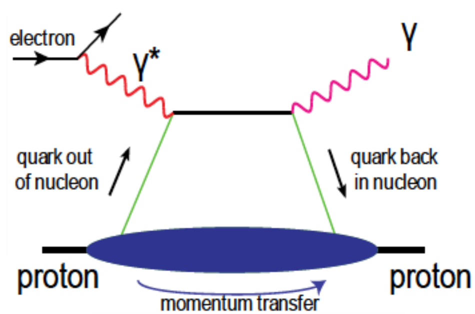


Deeply virtual Compton scattering

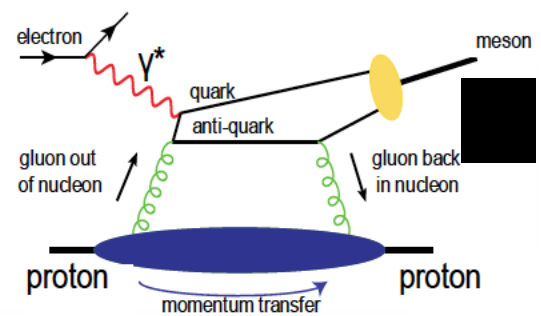
Deeply virtual meson production

Basic experiments in c.m. energy - luminosity landscape





Deeply virtual Compton scattering



Deeply virtual meson production

Ch. 3: The role of an EIC within the context of nuclear physics in the U.S. and internationally

"Nuclear physics today is a diverse field, encompassing research that spans dimensions from a tiny fraction of the volume of the individual particles (neutrons and protons) in the atomic nucleus to the enormous scales of astrophysical objects in the cosmos."

FRIB in construction at MSU will keep us at a leadership position in the world in understanding the behavior of hadrons inside the atomic nucleus

Inside hadrons, the interactions of gluons and quarks address the fundamental questions on the origin of mass, spin, and saturation. Quantum Chromodynamics (QCD) physics

U.S. Nuclear Science Context for an **Electron-Ion Collider**

U.S. Leadership in Nuclear Science

Ch. 4: Accelerator science, technology, and detectors needed for a U.S.-based EIC

(Choice of design/site for am EIC was not in our statement of task)

Major challenges in accelerator design:

- o High energy, spin-polarized beams colliding with high luminosity

BNL eRHIC and JLab JLEIC Conceptual Designs

- o build on existing accelerators in different ways
- o both require extensive R&D to fully address the science

Enabling Accelerator Technologies

- o Interaction region design, magnet technology
- o Strong hadron beam cooling (innovative concepts)
- o Energy Recovery Linacs
- o Crab Cavity operation in hadron ring
- o Polarized e,p and ^{3}He Sources, preservation in accelerators
- o Simulations of beams in novel EIC operating modes

Detector Technologies

Ch. 5: Comparison of a U.S.-based EIC to current and future facilities

HERA at DESY… A (former) collider of electrons with protons

CEBAF at JLab….Electron accelerator to 12 GeV

Compass experiment at CERN…muons and protons in collisions

RHIC…Heavy Ion and polarized proton collider

LHC at CERN…Large Hadron Collider: protons and heavy ions

Other Future Electron-Hadron Collider Proposals
- LHeC
- FCC-he …Future Circular Collider
- China: possible low energy EIC at HIAF
  (High Intensity Heavy-Ion Accelerator Facility)

Opportunities for future collaborations!!

Ch. 6: Impact of an EIC on other fields

EIC will sustain a healthy U.S. accelerator science enterprise
- Maintain leadership in collider accelerator technology
- Enable new technology essential for future particle accelerators
- EIC R&D targeted at developing cutting-edge capabilities

Workforce
- Nuclear physicists essential to U.S. security, health & economic vitality
- About one half of U.S. PhDs in nuclear physics are in QCD

Advanced scientific computing
- Maintaining a competitive high performance computing capability is essential to U.S. scientific leadership
- Lattice QCD uses the worlds most advanced computers to provide *ab initio* QCD calculations essential to interpret EIC data

Connections to:
- Condensed matter and atomic-molecular physics
- High-energy physics
- Astrophysics

Findings

The science

Finding 1: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

•*How does the mass of the nucleon arise?*
•*How does the spin of the nucleon arise?*
•*What are the emergent properties of dense systems of gluons?*

Accelerator

Finding 2: These three high-priority science questions can be answered by an EIC with highly polarized beams of electrons and ions, with sufficiently high luminosity and sufficient, and variable, center-of-mass energy.

Findings

Finding 3: An EIC would be a unique facility in the world, and would maintain U.S. leadership in nuclear physics.

Finding 4: An EIC would maintain U.S. leadership in the accelerator science and technology of colliders, and help to maintain scientific leadership more broadly.

Finding 5: Taking advantage of existing accelerator infrastructure and accelerator expertise would make development of an EIC cost effective and would potentially reduce risk.

Finding 6: The current accelerator R&D program supported by the Department of Energy is crucial to addressing outstanding design challenges.

Findings

Finding 7: To realize fully the scientific opportunities an EIC would enable, a theory program will be required to predict and interpret the experimental results within the context of QCD, and further, to glean the fundamental insights into QCD that an EIC can reveal.

Finding 8: The U.S. nuclear science community has been thorough and thoughtful in its planning for the future, taking into account both science priorities and budgetary realities. Its 2015 Long Range Plan identifies the construction of a high luminosity polarized Electron Ion Collider (EIC) as the highest priority for new facility construction following the completion of the Facility for Rare Isotope Beams (FRIB) at Michigan State University.

Finding 9: The broader impacts of building an EIC in the U.S. are significant in related fields of science, including in particular the accelerator science and technology of colliders and workforce development.

Bottom Line (again)

The committee unanimously finds that the science that can be addressed by an EIC is compelling, fundamental, and timely.

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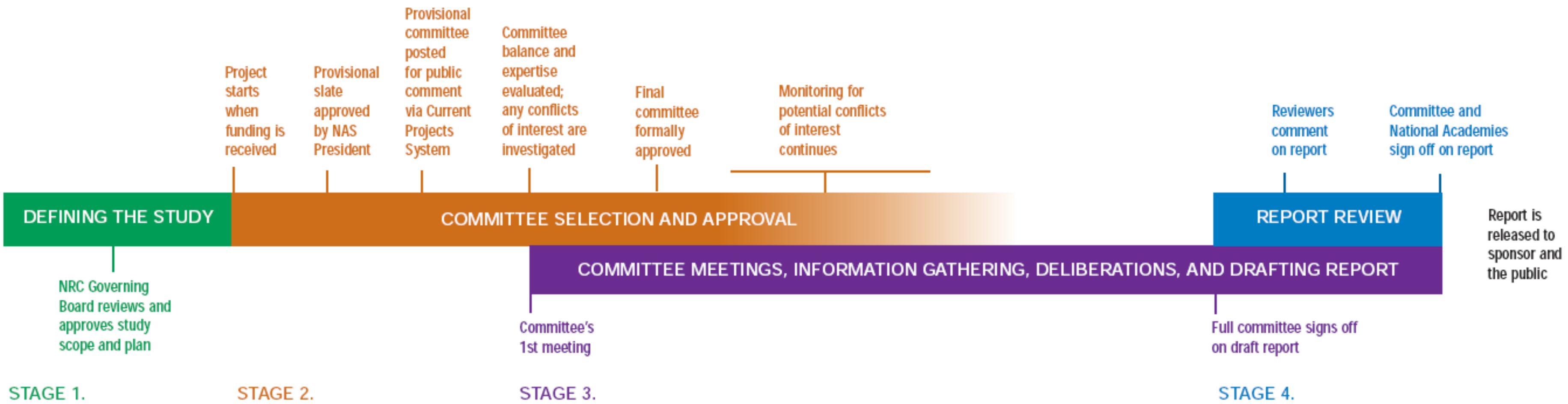
QUESTIONS and ANSWERS

Extra slides

The Report Process



Stages:
1) Defining the study.
2) Committee selection and approval
3) Committee meetings, gather information and write the report
4) Report review via Report Review Committee ~30 members
5) Release of report to public (TODAY)