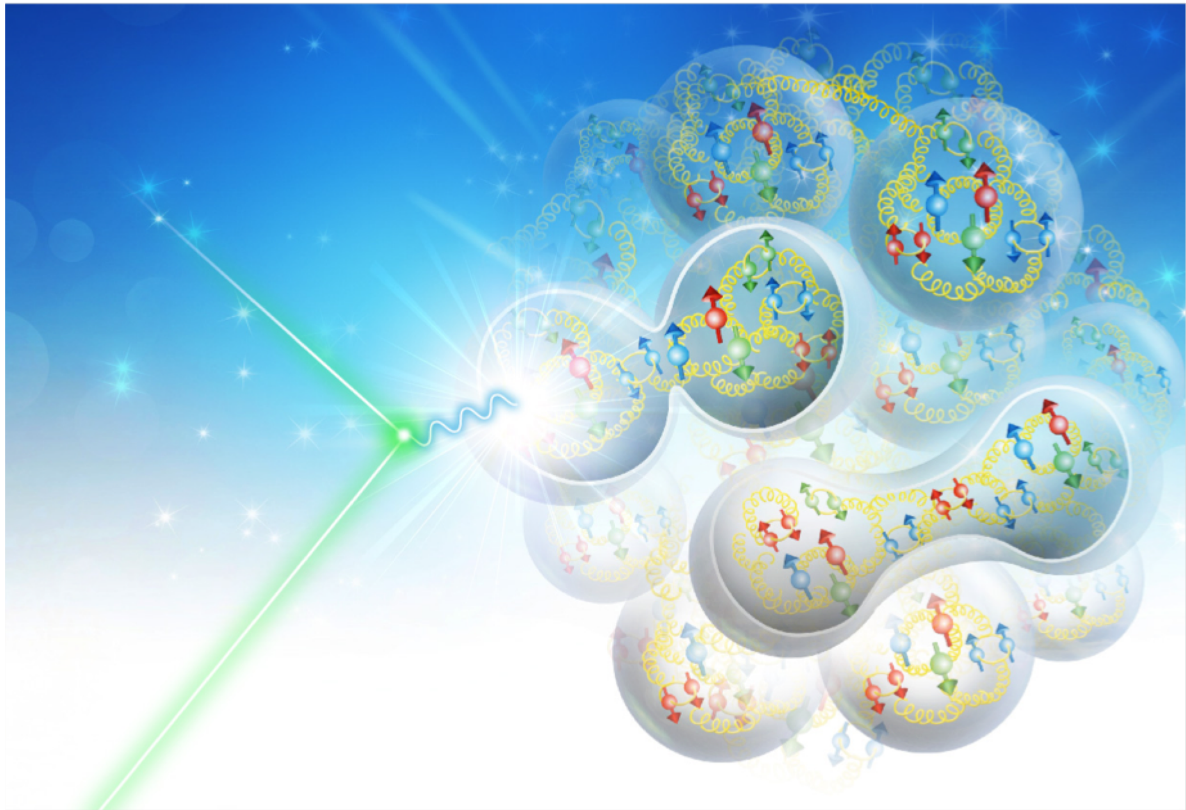
# Lectures 2a and 2b on Electron-Ion Collider

**Lecture 2a (Slides 2 – 18)**

EIC: Benefits to U.S. Leadership in Nuclear Physics

**Lecture 2b (Slides 19 – 40)**

EIC: Benefits to other fields of science and to society



Markus Diefenthaler (EIC$^2$, Jefferson Lab)

EIC Center at Jefferson Lab

Jefferson Lab
Exploring the Nature of Matter

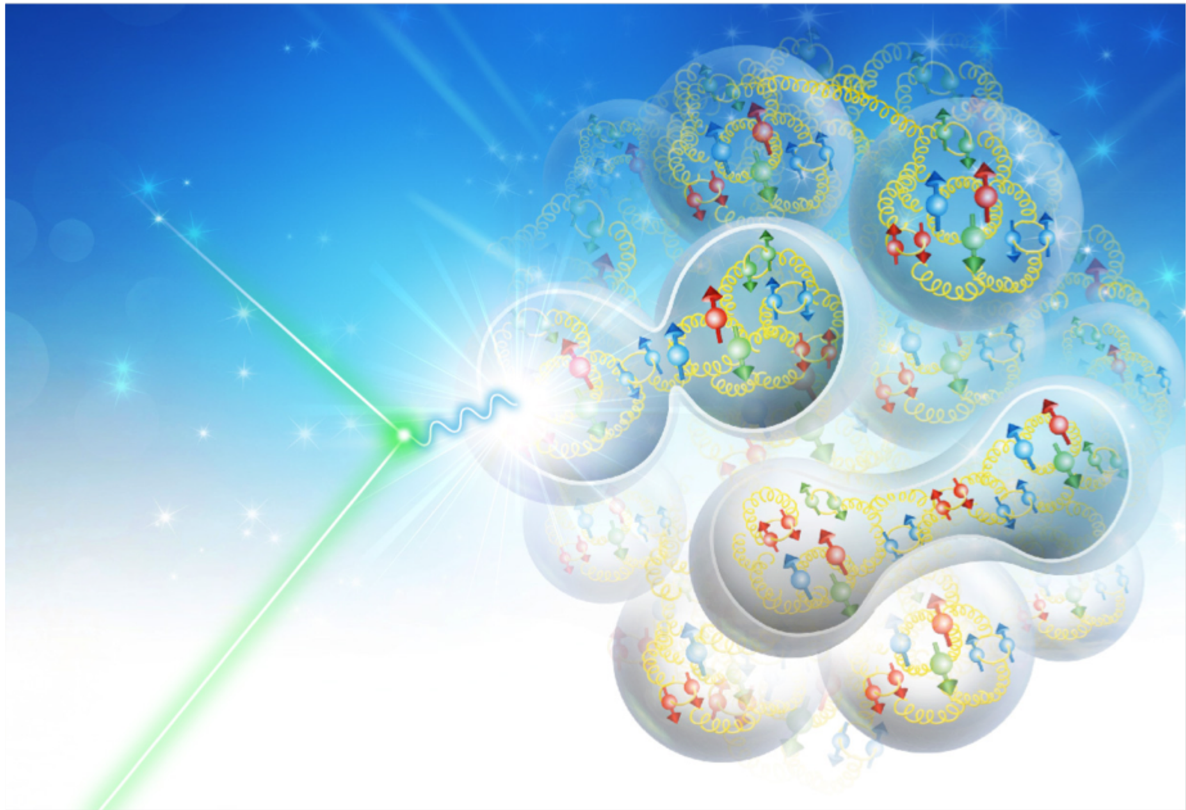
## Part 1

# EIC: Benefits to U.S. Leadership in Nuclear Physics

# EIC: Benefits to U.S. Leadership in Nuclear Physics

## Following up on questions on EIC overview on June 5

Slides from EIC User Group preparation for "An Assessment of U.S.-Based Electron-Ion Collider Science" by National Academies of Sciences, Engineering, and Medicine

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# What Are the Benefits to US Leadership?

At every stage of implementation, the EIC will benefit US leadership:

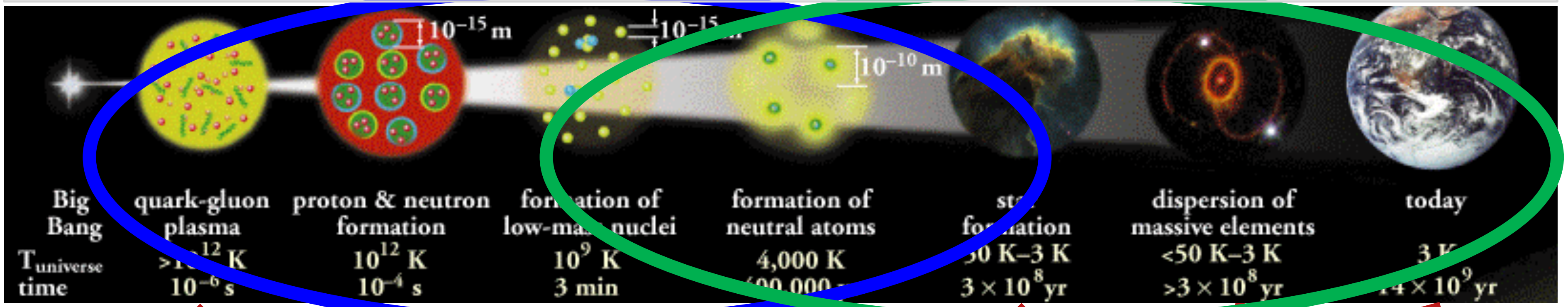
1. Developing and building the accelerator infrastructure will contribute to **leadership in accelerator technology**.
2. Constructing the detectors to realize the EIC science will contribute to **leadership in detector technology**.
3. Developing the scope of the science program will contribute to **leadership in QCD theory**.
4. Bringing the expertise of an international users' group to the US will contribute to **leadership and visibility as a hub of the nuclear physics community**.
5. Delivering on the science program of an EIC will lead to **landmark discoveries in nuclear physics**.

Following completion of FRIB, construction of an EIC will **reinforce the U.S. role as a global leader in Nuclear Physics**.

# Future US Leadership in Nuclear Science: EIC & FRIB

+ applications of technology

An EIC is required to investigate, with precision, the dynamics of gluons & sea quarks and their role in structure and interactions in visible matter



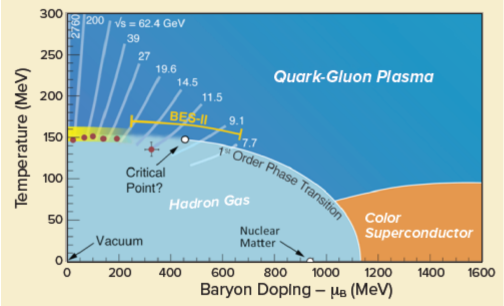

phases of nuclear matter

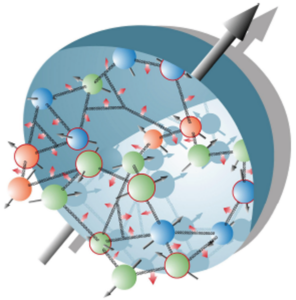
mass, spin, 3D structure

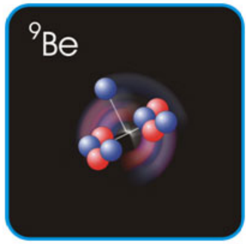
nuclear binding

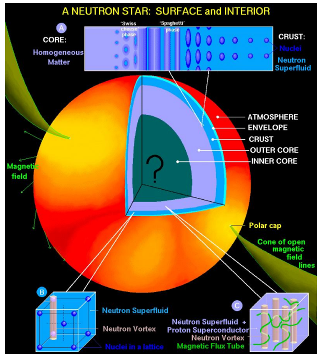
neutron and compact stars

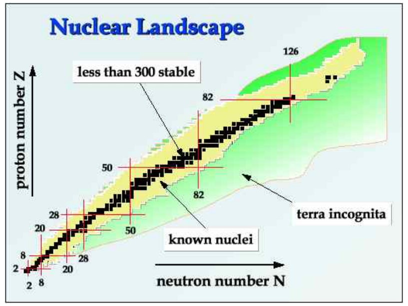
origin of heavy elements, structure






**Nuclear Science goal** "a roadmap of matter that will help unlock the secrets of how the universe is put together"

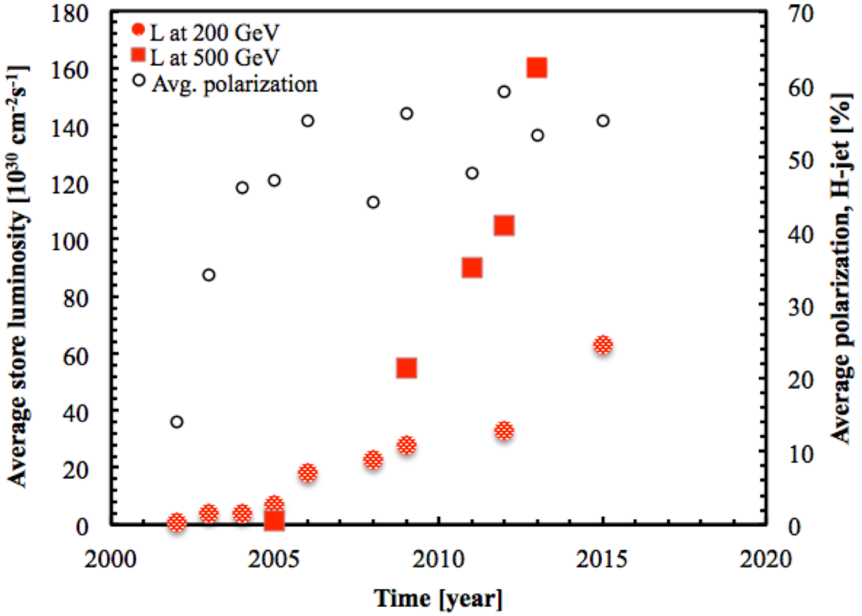
A multitude of emergent phenomena

$$L_{QCD} = \bar{q}(i\gamma^\mu\partial_\mu - m)q - g(\bar{q}\gamma^\mu T_a q)A^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

# RHIC: Delivering on Accelerator Leadership

***Spin-polarized proton and relativistic heavy ion beams, and versatility***

World's only spin-polarized proton beam collisions – with continuous increases in luminosity and polarization




World's greatest flexibility in ion beams and world's highest heavy ion luminosity

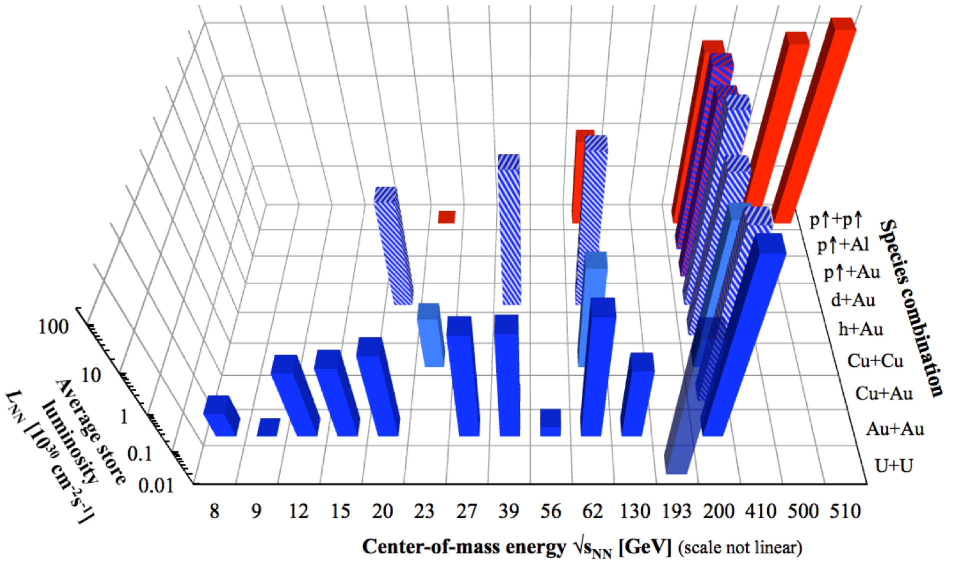


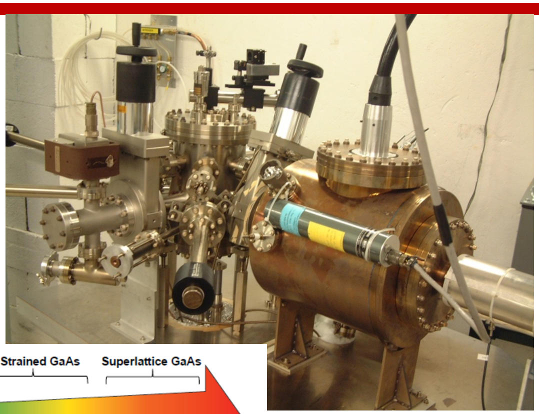

Figure-Of-Merit for EIC Spin Physics

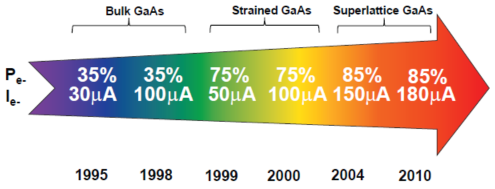
$$= \text{Luminosity} \times (\text{Ion Polarization})^2 \times (\text{Electron Polarization})^2$$

# CEBAF: Delivering on Accelerator Leadership

***Spin-polarized electron beams***

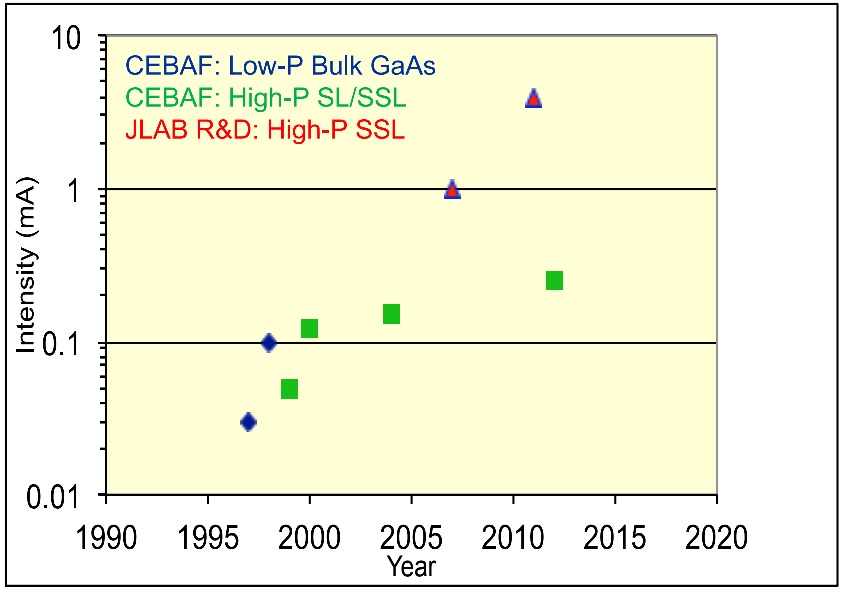
- US Nuclear Physics spin program has driven need for improved polarized electron beams
- DOE SBIR program fueled **High-Polarization** and **High-QE** photocathode development
- Improved high voltage dc photoguns are the enabling technology for **sustained high current** spin polarized electron beams





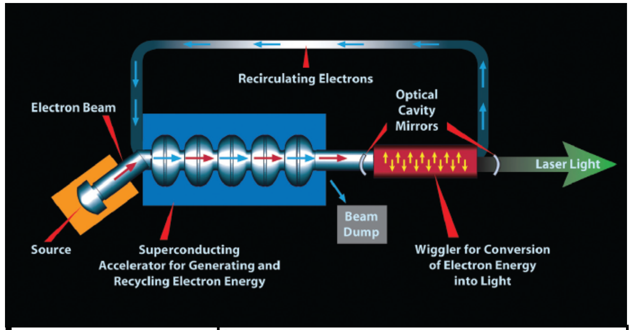

| Year | Photocathode Development | QE (%) | P (%) | FOM |
|---|---|---|---|---|
| 1995 | Bulk GaAs | 5.0 | 35 | 0.6 |
| 1999 | Strained Layer GaAs/GaAsP | 0.2 | 75 | 0.1 |
| 2004 | Superlattice GaAs/GaAsP | 1.2 | 89 | 1.0 |
| 2016 | DBR Superlattice GaAs/GaAsP | 6.4 | 84 | 4.5 |

DOE SBIR



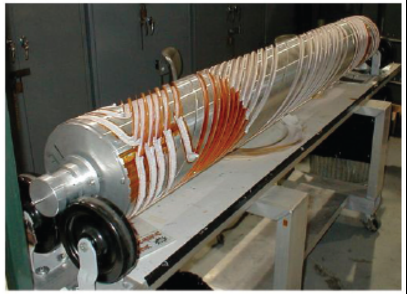
# EIC: Enabling US Accelerator Leadership

**Realization of US EIC will push the accelerator science and technologies related to luminosity & polarization to their limit, keeping US on the cutting edge.**

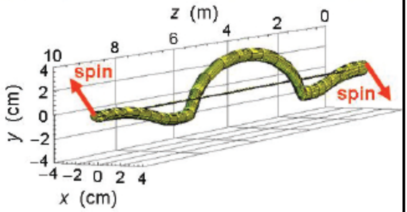



### Colliding Beams
- Colliding Beam Dynamics and Technology
- High-Gradient Crab Cavities
- Computational Accelerator Techniques

### Luminosity
- Electron Cooling
- High-Current Energy Recovery Linear Accelerator



### Polarization
- Intense Polarized Electron and Ion-Beam Sources
- Efficient Spin Manipulation in Polarized Beams




### Accelerator
- Superconducting and/or Super-ferric Magnet Technology
- Advanced Accelerator Design and Modeling

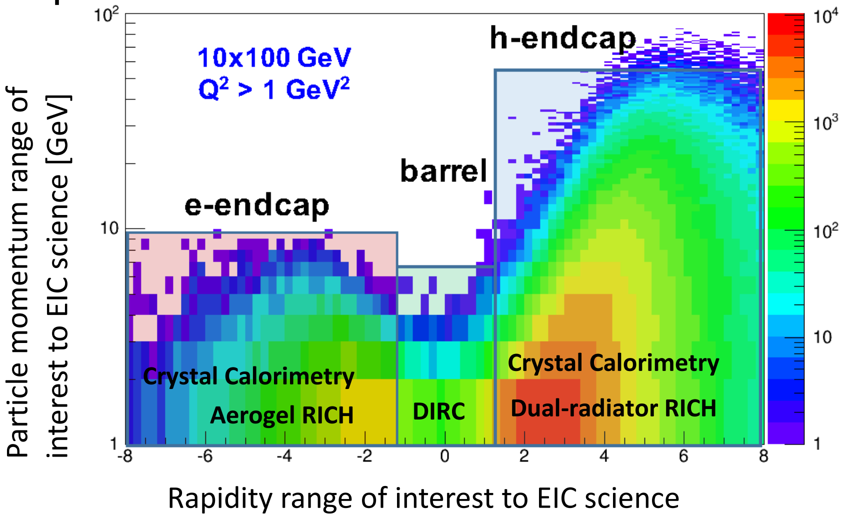
"... on average accelerator science contributed to a Nobel Prize for Physics every 2.9 years."
[E. Haussecker and A. Chao, Phys. Perspect. 13 (2011) 146–160]

# EIC: Enabling US Leadership in Detector Technology

- **EIC Science** imposes unique requirements - **particles** associated with the struck parton ***must* have their species identified** and measured to access nucleon/nuclear structure at its inner quark flavor and gluon 3D and spin description

- **EIC Detectors** push current technologies in both momentum range and energy/position resolution capabilities towards the required **excellent particle identification**

- **EIC Detector Technology** addresses the need for high-tech materials, a major area of connection for nuclear physics with impact on other fields of science and society
  - Contributes to US independence from foreign produced materials
  - Methodologies and manufacturing technologies for emerging markets in medical industry and homeland security




**Particle Identification is critical**

- ➢ Requires hermetic coverage over an unprecedented range in momentum
- ➢ High resolution calorimetry requires high-tech crystal-based technologies
- ➢ Requires specialized new technologies for PID detectors

- **Opportunities** for US small businesses (SBIR/STTR)

# Nobel Prizes of Physics and EIC Science

- Hideki Yukawa, 1949 "for his prediction of the existence of mesons on the basis of theoretical work on nuclear forces"

  **But the quark-gluon origin of the nuclear binding force remains an unknown**

- Robert Hofstadter, 1961 "for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"

  **But the 3D quark-gluon structure of nucleons remains an unknown**

- Jerome Friedman, Henry Kendall, Richard Taylor,1990 "for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"

  **But the role of gluons in protons and bound neutrons remains unknown**

- David Gross, David Politzer, Frank Wilczek, 2004 "for the discovery of asymptotic freedom in the theory of the strong interaction"

  **But the confinement aspect of the theory remains unknown**

- Yoichiro Nambu, 2008 "for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

  **But how dynamical chiral symmetry breaking shapes the mass and structure of quark-gluon systems remains unknown**

*Blue reflects US based affiliation*

# A Record of Publications to Underpin EIC Science

| **Topic** | | |
|---|---|---|
| **Author (US-based author indicated in blue)** | **Publication** | **Citations** |
| Spin of the Proton and Polarized Parton Distributions | | |
| Bob Jaffe, Aneesh Manohar (MIT-LNS)<br>M. Gluck, Ewald Reya (Dortmund), Marco Stratmann (Regensburg),<br>Werner Vogelsang (RIKEN-BNL) | *Nucl. Phys. B337 (1990) 509*<br>*Phys. Rev. D63 (2001)094005* | 732<br>572 |
| 3D Spatial Imaging – Theoretical Framework Independently developed by | | |
| Xiangdong Ji (U Maryland)<br>Dieter Mueller (Bochum) *et al.*<br>Anatoly Radyushkin (Old Dominion U & JLab) | *Phys. Rev. Lett. 78 (1997) 610*<br>*Fortschr. Phys. 42 (1994) 101*<br>*Phys. Lett. B380 (1996) 417*<br>*Phys. Rev. D56 (1997) 5524* | 1516<br>1028<br>604<br>998 |
| Relation of Transverse Momentum and Single Spin Production Asymmetries | | |
| Dennis Sivers (ANL)<br>Stan Brodsky (SLAC), Dae Sung Hwang (SLAC & Sejong U),<br>Ivan Schmidt (Valparaiso)<br>John Collins (Penn State) | *Phys. Rev. D41 (1990) 83*<br>*Phys. Lett. B530 (2002) 99*<br><br>*Phys. Lett. B536 (2002) 43* | 977<br>706<br><br>757 |
| Factorization in QCD | | |
| John Collins, Mark Strikman (Penn State), Leonid Frankfurt (Tel Aviv)<br>Christian Bauer, Dan Pirjol, Iain Stewart (UC San Diego) | *Phys. Rev. D56 (1997) 2982*<br>*Phys. Rev. D65 (2002)054022* | 800<br>918 |
| Gluon Recombination and Shadowing | | |
| Alfred Mueller, Jianwei Qiu (Columbia U)<br>Ian Balitsky (MIT) | *Nucl. Phys. B268 (1986) 427*<br>*Nucl. Phys. B463 (1996) 99* | 1273<br>1332 |
| Gluon Saturation – Theoretical Framework developed by | | |
| Larry McLerran, Raju Venugopalan (Minnesota U)<br><br>Yuri Kovchegov (Minnesota U) | *Phys. Rev. D49 (1994) 2233*<br>*Phys. Rev. D49 (1994) 3352*<br>*Phys. Rev. D60 (1999)034008* | 1655<br>1211<br>1174 |

Note: >5000 citations are rare (Maldacena, Weinberg, CTEQ2002)
A. Einstein, on General Relativity, Annalen Phys. 49 (1916) 573 citations (443 after 2000)

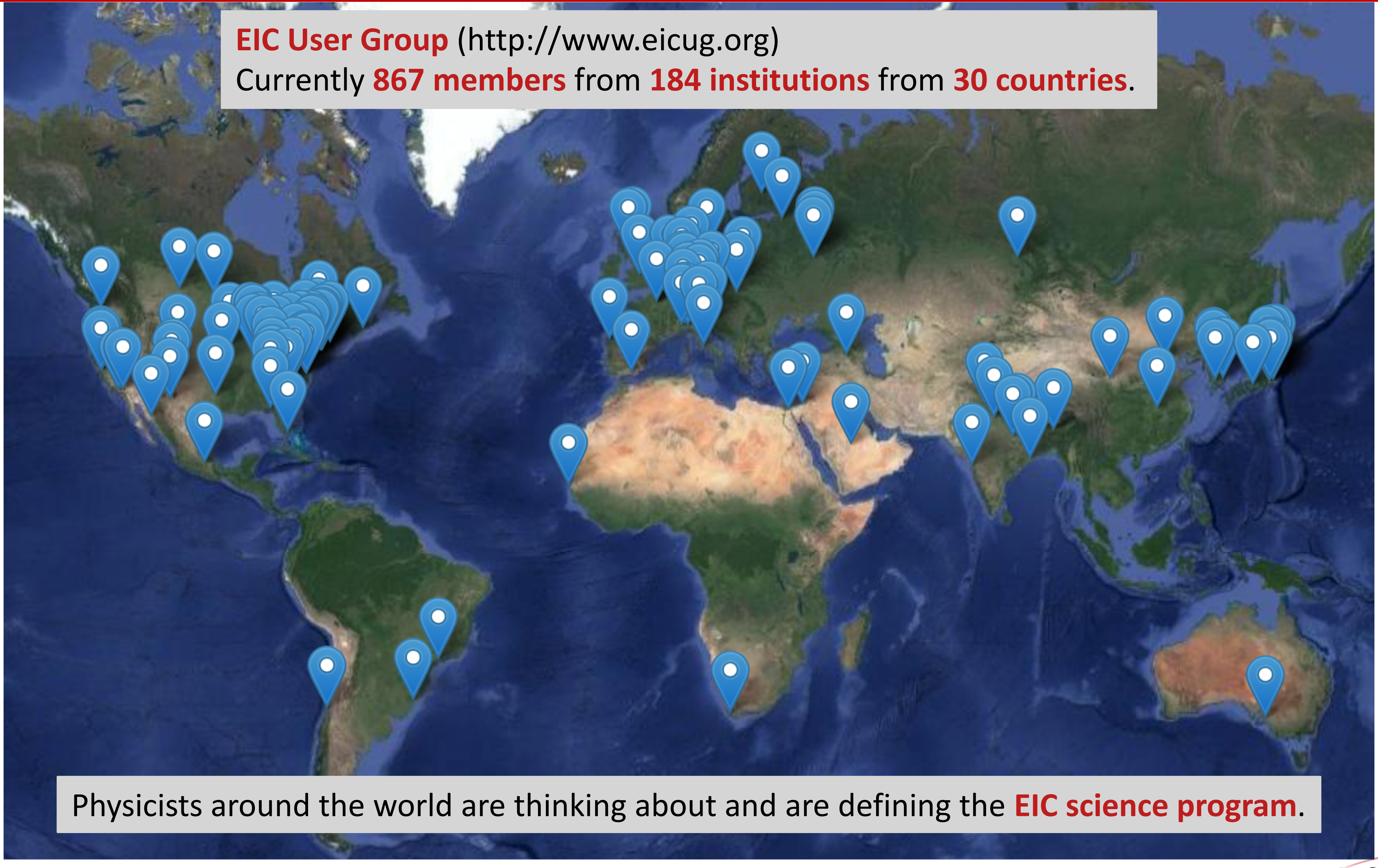
# EIC: Enabling Leadership in QCD Theory

Designing the science program of a US EIC will drive novel calculations and advancements in QCD theory. The EIC is precisely targeted to address the outstanding fundamental questions at the forefront of QCD research:

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties emerge from quarks, gluons and their interactions?
- How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions? What happens to the gluon density in nuclei? Does it saturate?
- How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons, and how do the quark-gluon interactions create nuclear binding?

A **track record of high-impact publications and Nobel Prizes** in EIC-related physics **proves the community can deliver** on leadership in QCD theory.

# Worldwide interest in EIC



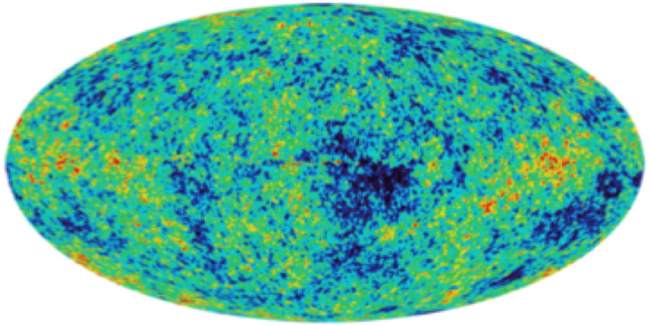
**EIC User Group** (http://www.eicug.org)

Currently **867 members** from **184 institutions** from **30 countries**.

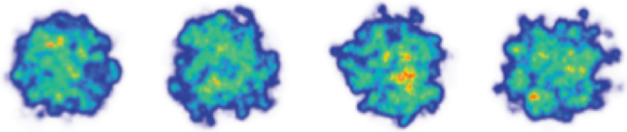
Physicists around the world are thinking about and are defining the **EIC science program**.

# EIC: Enabling US Leadership for Hot QCD

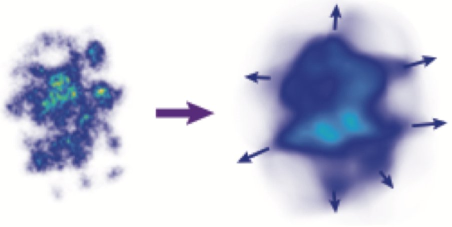
**Fluctuations contain tremendous amount of information**



**in the Big Bang…**

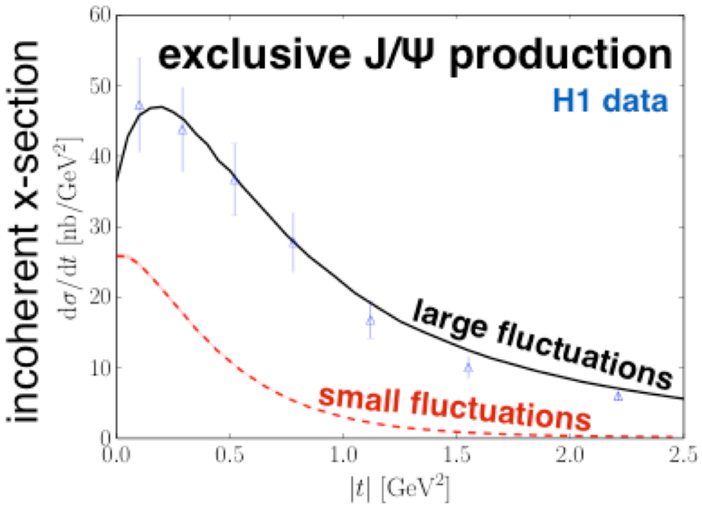


**… and the ‘little bangs’**



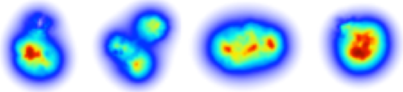
**All model predictions for collective flow in heavy ion collisions depend on the initial state and its fluctuations**

**Critical need for independent constraint of fluctuating initial states**




J/Ψ transverse momentum squared

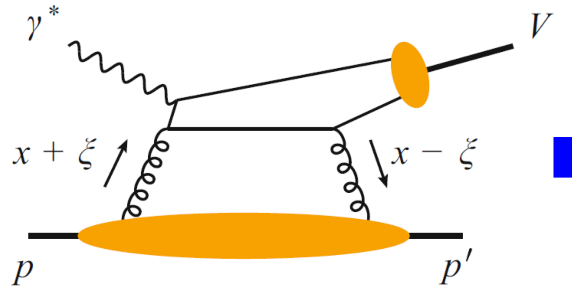
**Proton shape fluctuations constrained in e+p provide input to p+A collisions**

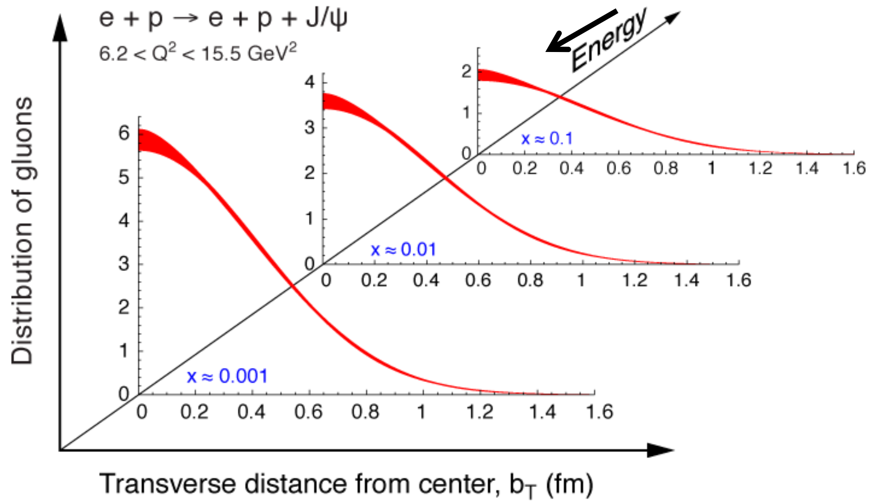


**EIC will provide higher precision, all *A*, large range in *x* and $Q^2$, and determine angular dependence of fluctuations**

# EIC: Enabling US Leadershio in Cold QCD

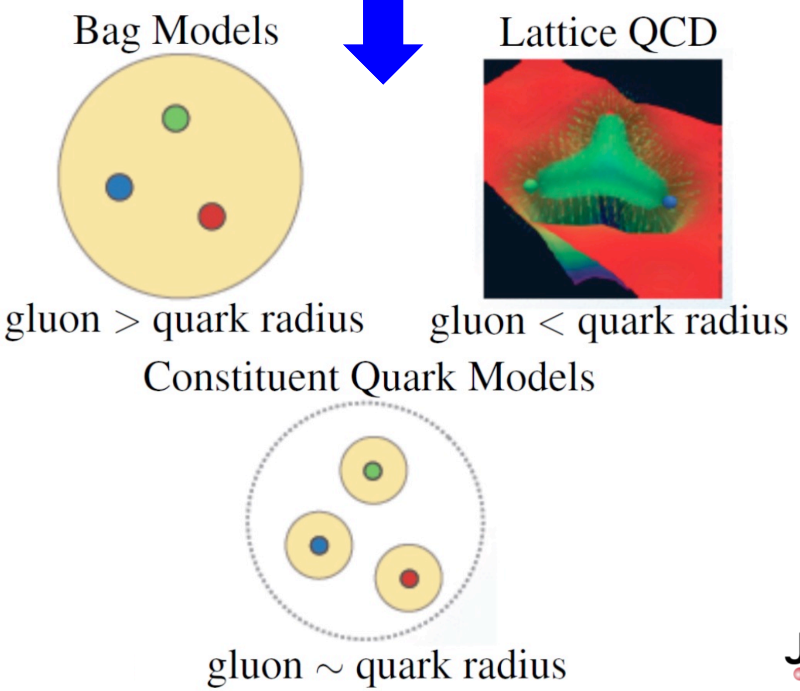
*Unique EIC tool: (near-) exclusive processes at high energies!*




- The EIC can give unique images of the quark-gluon landscape of pions, kaons, nucleons and nuclei
- An EIC will:
  - Unravel the origin of most of the mass in the visible universe
  - Expose the role of Dynamical Chiral Symmetry Breaking and Confinement in creating the hadronic final states and the properties of nuclear matter
  - Identify the hidden role of glue in the force between nucleons

Insight *e.g.* confinement



# Community Benefits to the US of Leadership

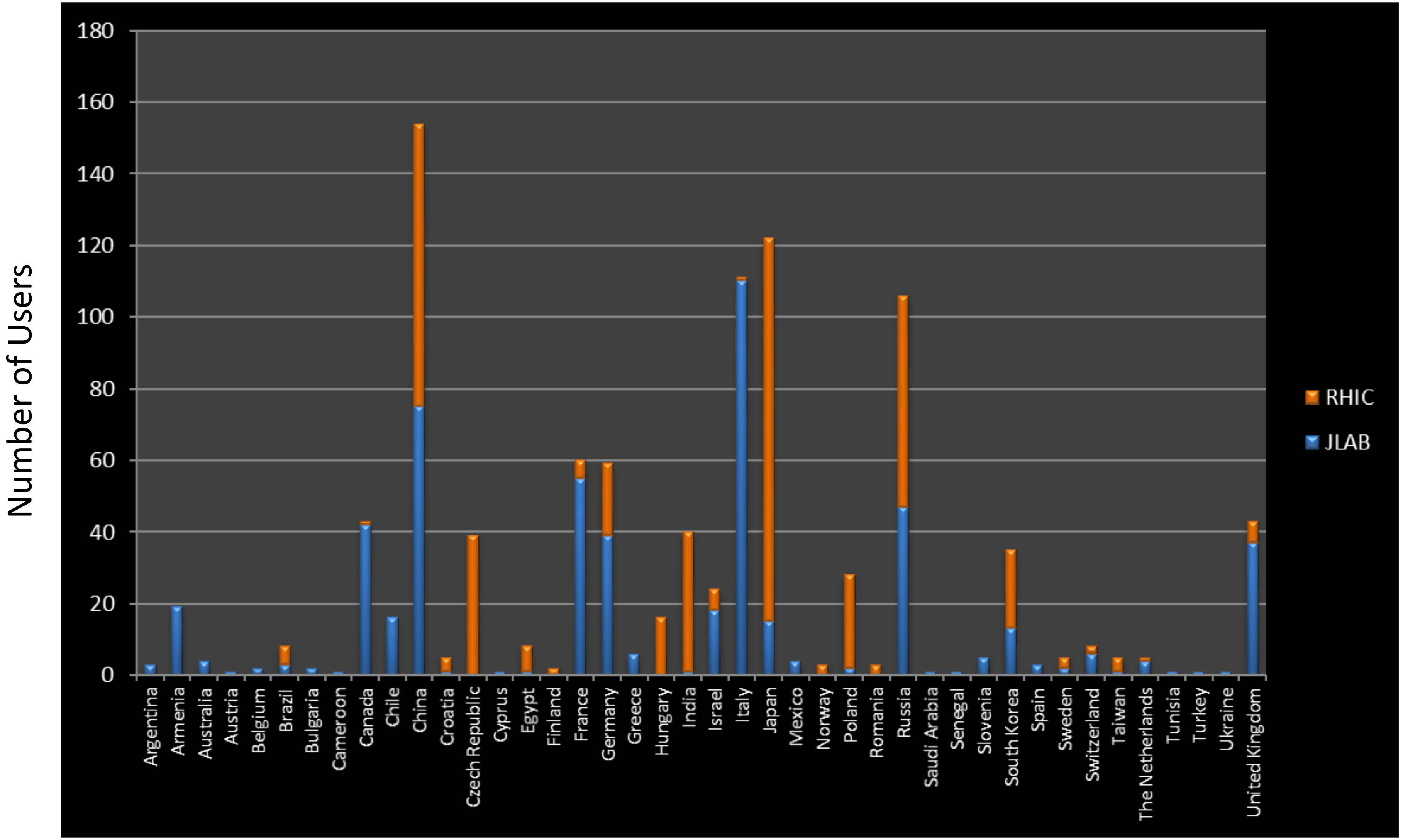
- Competitiveness in the global market – attracting, educating and retaining the most talented ensuring the US maintains a highly trained work force meeting societal needs.
  - RHIC + JLab together attract well over 2600 users, of which ~40% are international
  - RHIC + JLab together delivered 461 PhDs over the 2008-2014 period, of which ~150 are PhDs of foreign users
  - RHIC + JLab together produce ~50% of the US nuclear science Ph.D. degrees

- Scientific Productivity and Technical Innovation
  - RHIC + JLab together: 360 articles in Phys. Rev. Letters (up to 04/2015)
  - RHIC + JLab together: ~100 patents

- Ambassadorship for the US.
  - RHIC + JLab together: >1000 users from international institutions
  - RHIC + JLab together: Key hardware contributions from foreign countries

- Accelerator applications beyond EIC – medical industry, materials and life science, photon science, …

# Internationa; Character of RHIC and JLAB





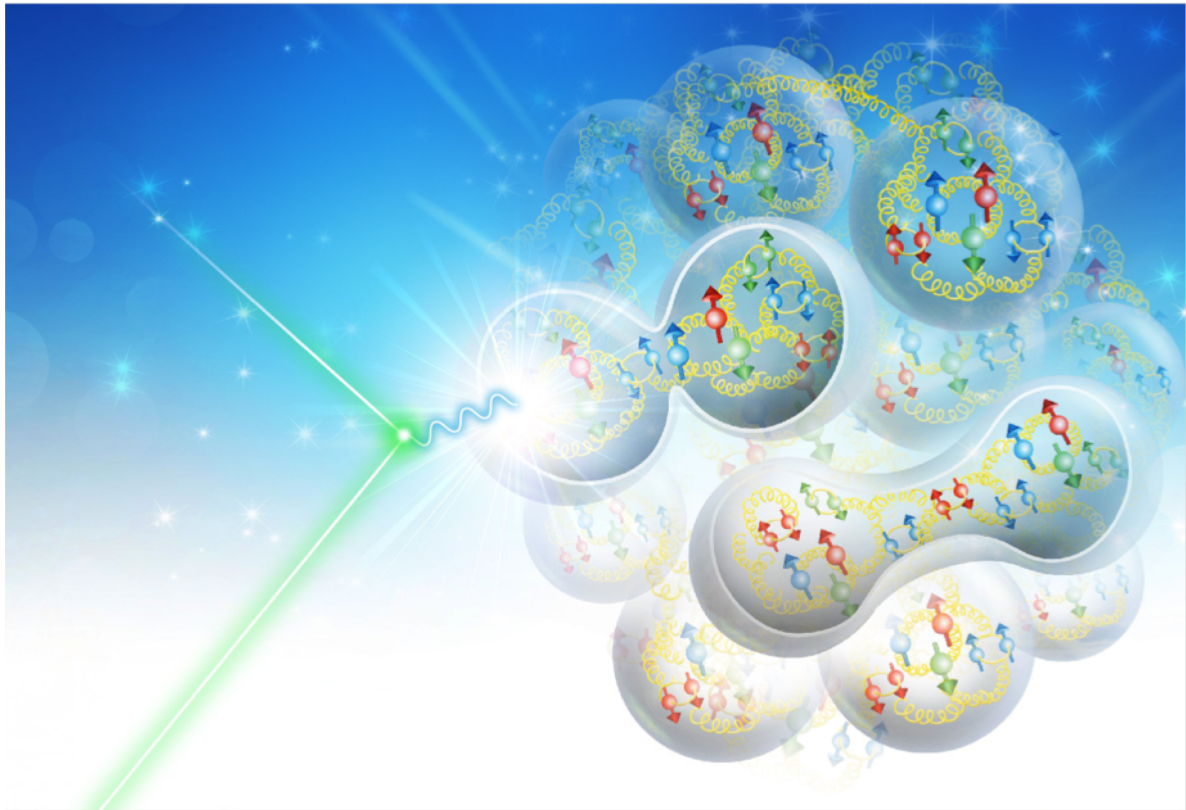

Jefferson Lab

Markus Diefenthaler

mdiefent@jlab.org

# Conclusion

- The EIC will give the US the leadership in exploring and expanding our knowledge of QCD, the fundamental force that governs all visible matter. It represents the most powerful tool to investigate novel regions with its high luminosity and energy, wide range of beam species and polarization and provides the means for new discoveries.
- Within the US, the EIC and FRIB together will bridge our understanding of nuclei from quarks & gluons to the cosmos.
- There exists world wide interest in collaborating on the EIC, which will result in an influx of knowledge and a highly trained workforce in the US.
- The realization of the EIC, a frontier accelerator facility, will build on and expand upon US intellectual and technical leadership, with benefits to many DOE/OSC projects and society.



# Part 2

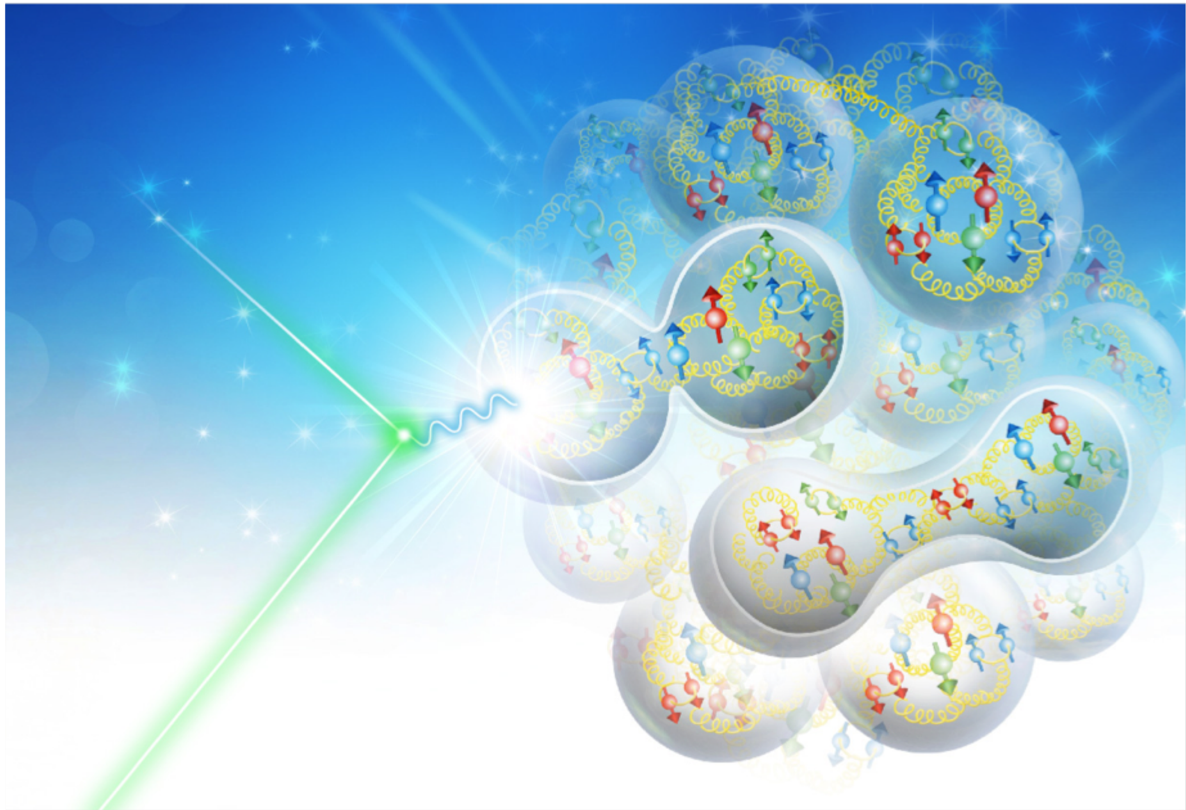
# EIC: Benefits to other fields of science and to society

# EIC: Benefits to other fields of science and to society

## Following up on questions on EIC overview on June 5

Slides from EIC User Group preparation for "An Assessment of U.S.-Based Electron-Ion Collider Science" by National Academies of Sciences, Engineering, and Medicine

Markus Diefenthaler (EIC$^2$, Jefferson Lab)



EIC$^2$
EIC Center at Jefferson Lab

Jefferson Lab
Exploring the Nature of Matter

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# What are the benefits to other fields of science and society?

- Education and training
  - Individuals going on to other sectors benefitting society
  - Relevance for Medical Science
  - Ambassadorship of Nuclear Scientists
- Technology – accelerator, detector, data science and data management
  - Benefits to society outside of academic research
  - Benefits to other fields of academic research
- Science
  - How scientific advances driven by an EIC will benefit other fields
- Economic impact
  - Economic output and jobs

# Education and training

Johan Gonzalez
PhD 2006, UCLA
Based on work at RHIC

Defense & Space Professional
Raytheon Company
Works on algorithm development and analysis of radar sensor data for military applications. His work has led to three patents and two more in the U.S. Patent Office pending approval.

Michel Beaumier
PhD 2016, UC Riverside
Based on work at RHIC

Machine Learning Engineer
Mercedes Benz R&D North America
Works on machine learning for in-car artificial intelligence interfaces in vehicles, to help build industry leading technology into high performance automobiles.

Naohito Saito
PhD 1995, Kyoto U
RIKEN-BNL Research Center Fellow

Director, J-PARC Center
Japan Proton Accelerator Research Complex
Worked many years in the spin program at RHIC, and further in defining the spin physics program at J-PARC and fundamental physics experiments with muons.

Kathy McCormick
PhD 1999, ODU
Based on work at JLab

Radiation Detector Subject Matter Expert
US Customs and Border Protection (CBP)
Work on the radiation detection program, including various security applications, at the headquarters level. Also represents CBP in meetings with other government agencies and at the White House.

# Education and training

Derek Van Westrum
PhD 1998, Colorado
Based on work at JLab

Director of Production Services

MicrogLaCosta

Works on terrestrial gravity measurements, used both for geodesy and for practical applications like mineral locations and elevation measurements, correcting for general relativity effects on earth.

Alicia Uzzle
PhD 2002, Hampton
Based on work at JLab

Manager, Academics

The Apprentice School

Works at the Apprentice School, the U.S.'s preeminent apprenticeship program offering four-, five-, and eight-year apprenticeships in nineteen shipbuilding disciplines and eight advanced programs of study.

Adam Kocoloski
PhD 2010, MIT
Based on work at RHIC

CTO, Cloud Data Services & IBM Fellow

IBM

Works at IBM. Founded Cloudant with fellow MIT students Alan Hoffman and Mike Miller and in 2009, as a database-as-a-service for developers to build apps. Now working on IBM's data and analytics platform in the cloud, using open source technologies and development practices.

Stephanie Bailey
PhD 2007, W&M
Based on work at JLab

Physics Lecturer

University of California Santa Cruz

Works on development of population-based computer simulation models to inform decision making in human rights violations and health policy, covering a range of health outcomes and diseases, including breast cancer, child welfare, obesity, HIV, and sex trafficking.

# Education and training

Vahagn Nazaryan
PhD 2004, W&M
Based on work at JLab on theory and experiment

Executive Director
Hampton University Proton Therapy Institute
Responsible for all clinical and operational aspects of the institute, including physics, dosimetry, therapy, nursing, clinic operations, HUPTI technology service and maintenance, and research at HUPTI.

Ben Clasie
PhD 2006, MIT
Based on work at JLab

Assistant Technical Director, PTC
Massachusetts General Hospital
Works on intensity-modulated proton therapy and pencil beam scanning in the department of radiation oncology at the Francis H. Burr Proton Therapy Center.

Steve Avery
PhD 2002, Hampton
Based on work at JLab

Assistant Professor of Radiation Oncology
Hospital of the University of Pennsylvania Works on small animal radiation research and on quality assurance and safety in proton therapy treatment delivery. Also works as adjunct professor at the Physics Department, and on D&I of under-represented groups in physics.

Anuj Purwar
PhD 2004, SBU
Based on work at RHIC as student and postdoc.

Senior Staff Scientist
Varian Medical Systems
Works on compact linear accelerators and gaseous ionizing radiation detectors to improve steering and focusing of cancer-killing beams and ensure optimized doses of radiation can be delivered precisely to tumors, as well as the design of radiation shielding.

# Ambassadorship of Nuclear Scientists within the US

Ernie Moniz, Ph.D. 1972, Stanford U

Previous United States Secretary of Energy.
Served before as Associate Director for Science in the Office of Science and Technology Policy and as Under Secretary of Energy.
At  MIT, faculty since 1973 and served as head of the Department of Physics, as director of the Bates Linear Accelerator Center, as the Director of the Energy Initiative, and as the Director of the Laboratory for Energy and the Environment.

Mark Harvey, Ph.D. 2001, Hampton U, Postdoc at BNL

Director and primary instructor of the health physics program at Texas Southern University.
Work related to secondary neutron exposure in proton radiotherapy, and simulation to model both the therapeutic absorbed dose and the secondary at the Proton Therapy Center. Appointed to the Texas Radiation Advisory Board with a term set to expire April 16, 2021.

James Maxwell, Ph.D. 2011, UVa, Postdoc at MIT

Presently staff scientist with the Polarized Target Group at JLab.
Works on polarized and high-power cryogenic target systems, and polarized 3He ion sources. While postdoc at MIT, acted as technical advisor for the recent 2015 remake of the Ghostbusters movie.

# Benefits to Society of Accelerator Technology

*There are many societal applications of accelerators, see some examples in: [http://www.symmetrymagazine.org/article/march-2013/how-particle-physics-improves-your-life](http://www.symmetrymagazine.org/article/march-2013/how-particle-physics-improves-your-life)*

**Shrink wrap**
If you buy a Butterball turkey, you have particle accelerators to thank for its freshness. For decades now the food industry has used particle accelerators to produce the sturdy, heat-shrinkable film that Butterball turkeys—as well as fruits and vegetables, baked goods, board games and DVDs—come wrapped in.

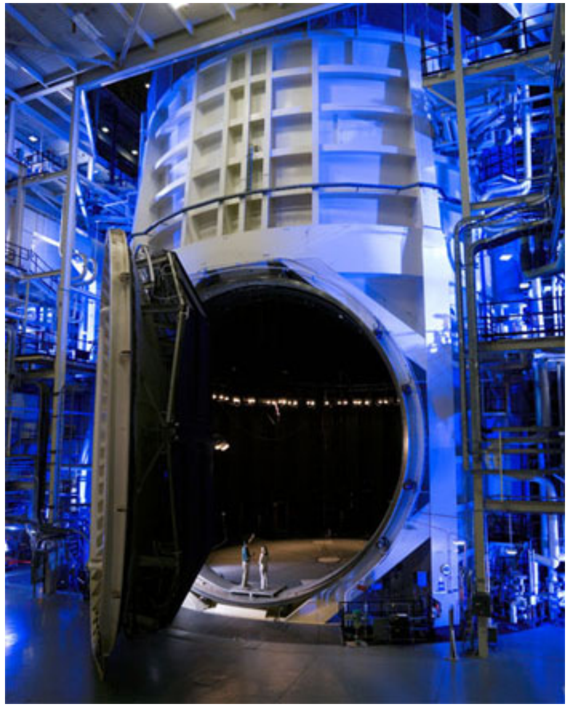

**Furniture finish**
For a quarter of a century, companies around the world used beams of electrons from particle accelerators to make scratch- and stain-resistant furniture. The surfaces of these treated desks, shelves and tables look like wood but are nearly impossible to scuff.


**Cargo scanning**
More than 2 billion tons of cargo pass through ports and waterways annually in the United States. Many ports are now turning to high-energy X-rays generated by particle accelerators to identify contraband and keep ports safe. These X-rays penetrate deeper and give screeners more detail about the nature of the cargo.

**Intense light for research**
Circular particle accelerators bend the paths of speeding electrons, causing the electrons to emit light. This light is a powerful research tool with many applications. Dedicated synchrotron accelerators known as light sources allow scientists to control the intensity and wavelength of light for research that's led to better batteries, greener energy, new high-performance materials, more effective drug treatments and a deeper understanding of nature.

**A US-based Electron-Ion Collider will enable to maintain stewardship of accelerator science.**

# Benefits to the US of Leadership in Large Facilities



NASA Johnson Space Center's Space Environment Simulation Lab Chamber A. Photo: NASA.

Cryogenics expertise relevant to NASA and also to other Office of Science projects such as the FRIB cryo plant.

- As it stood, NASA's Chamber A's cryogenics systems were **not capable of meeting the basic requirements of the tests for the James Webb Space Telescope**.
- Jefferson Lab's cryogenics group helped NASA scientists design and commission a cryogenics plant to cool the telescope's components to *temperatures its instruments will experience in space*, to within 30 degrees Fahrenheit of absolute zero.
  - The cryogenic refrigeration system **tripled the capacity** of the former existing refrigeration system.
  - The new nitrogen system cut the **liquid nitrogen consumption in half** – from 48,000 to just 24,000 gallons each day.
  - Due to the Floating Pressure - Ganni Cycle, invented at Jefferson Lab, the helium refrigerator system now automatically matches to the load and **maintains peak efficiency down to one-third of its maximum capacity**.

# EIC Accelerator Technology Will Inspire New Ideas

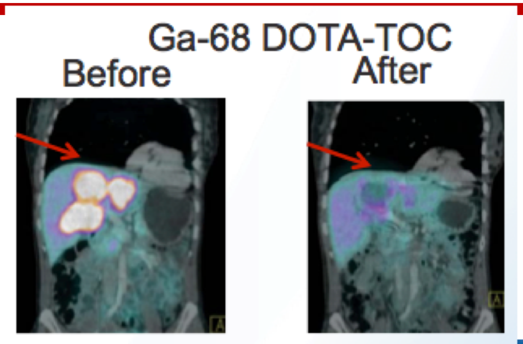
**Beams in an EIC accelerator complex are usable in multiple applications – this will inspire new ideas**

**Ion Beams**

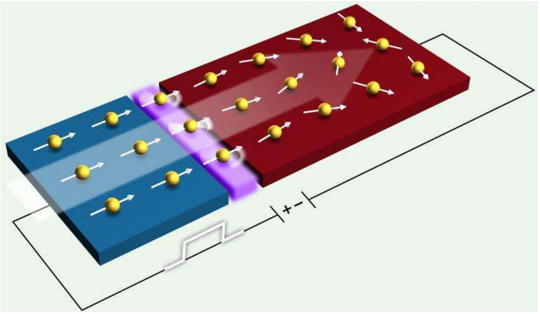
- High-intensity proton/H⁻ beams for medical isotope production
- Flexible ion beams for material and life science experiments, like in the NASA Space Radiation Laboratory

**Electron beams**

- Medical isotope production through photonuclear reactions
- High intensity high brightness electron beams for new types of light sources
- Intense polarized beams as a diagnostic tool in the testing of materials and new designs for spintronic devices.
- DC high-voltage photo-guns to enable ultrafast table-top molecular imaging




Response of multiple liver lesions after intra-arterial therapy with 14 GBq $^{213}$Bi DOTA-TOC



# Benefits to Other Fields – Nuclear Medicine

- In the late 1950's, Brookhaven scientists developed a generator system for producing **Tc-99m** and suggested its use for medical imaging. **This revolutionized the practice of nuclear medicine**; Tc-99m is the work horse and still now used in over 80% of all nuclear medicine imaging procedures worldwide (>60 million/year).

DATE: December 4, 1958

TO: Addressees Below

BNL Patent Office
SUBJECT: P-701 and P-702 - PREPARATION OF CARRIER-FREE MOLYBDENUM AND OF TECHNETIUM FROM FISSION PRODUCTS

The New York Patent Group has carefully studied the information available relative to the above-identified item. The AEC does not at present desire to prepare a patent application on this item for the following reason:

"The method of producing carrier-free molybdenum-99 from fission products is disclosed in U. S. Patent Application S.N. 732,108, Green, Powell, Samos& Tucker (BNL Pat No. 58-17). It is noted that molybdenum-99 may be separated from its radioactive daughter, technetium-99, by absorption of a solution of molybdenum-99 on alumina and subsequent elution of its daughter with .1 nitric acid. ***While this method is probably novel, it appears that the product will probably be used mostly for experimental purposes in the laboratory. On this basis, no further patent action is believed warranted."***

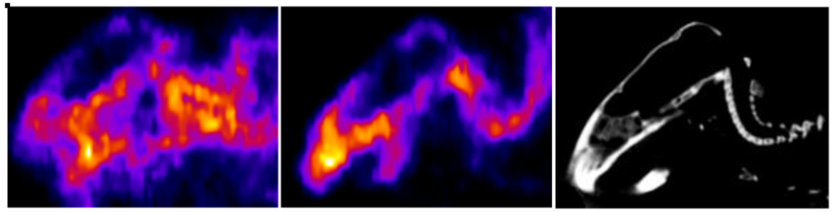
- In 1976, scientists at Brookhaven developed the method for producing **F-18 FDG** (fluoro-deoxy glucose). Collaboration with the University of Pennsylvania and the NIH led to a combined expertise in chemistry, neuroscience and instrumentation to develop F-18 FDG for brain imaging, that revolutionized the study of the human brain. Also, in 1980, BNL scientists first reported high FDG uptake in tumors, **leading to the use of FDG/PET** for managing the cancer patient.

# Benefits to Other Fields of Detector Technology: Medical Imaging

*(example from ongoing programs)*

**Problem**: Methods based upon anesthesia inhibit/complicate brain based studies.
**Solution**: an imaging methodology in awake humans to study neurological based diseases such as:

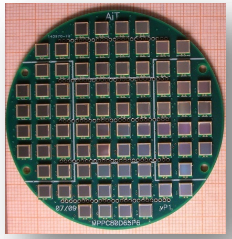
- Addiction research
- Neuro-degeneration:
  - Alzheimer's Disease
  - Parkinson's Disease
- Brain inflammation (e.g. HIV, MS)
- Stem cell trafficking

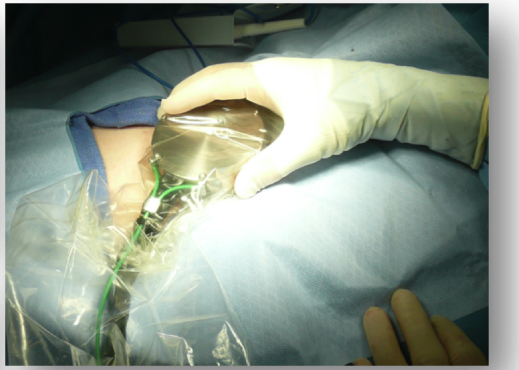


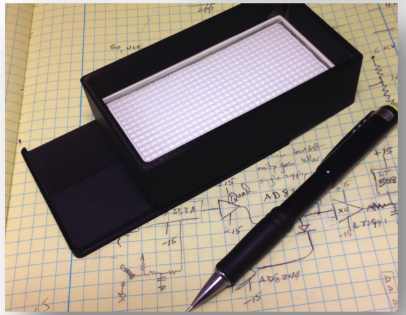
*awake moving mouse without motion correction* | *awake moving mouse with motion correction* | *x-ray CT Scan*

**Problem:** Surgeons use non-imaging hand-held probe in a "Geiger Counter" mode (audio) to guide surgery.
**Solution**: Hand-held wireless gamma camera to provide imaging information to assist cancer surgery:

- Silicon PMs provide precise imaging at low voltages
- Wire-free and wireless gives flexible motion, no tethering





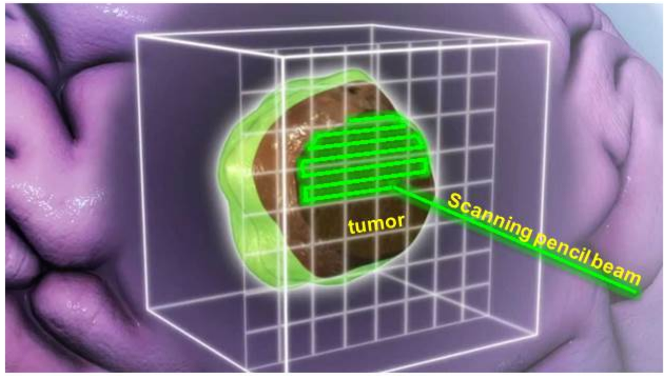


*Above: SiPM disk to provide camera during clinical tests. Left: new wireless handheld gamma camera.*

# Benefits to Other Fields of Nuclear Technology: Radiation Therapy

**Problem:** Deliver lethal doses to a tumor while minimizing or eliminating normal tissue injury for often close-by critical organs.
**Solution:** Proton (beam) radiation therapy centers - an alliance of applied nuclear science and medicine – with a 17% annual growth in such centers.

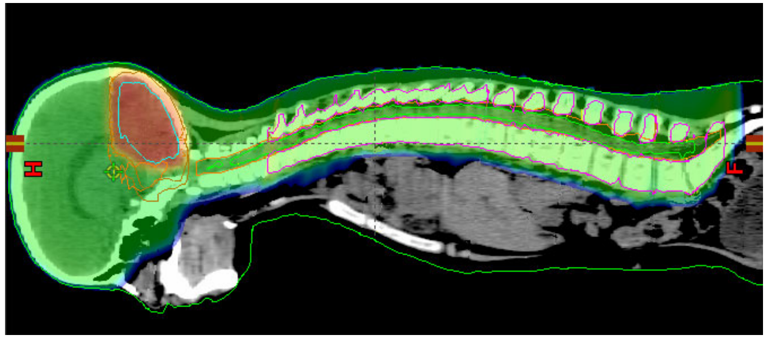
Nuclear scientists have been <u>key</u> to the concept, design, construction and operation of these centers, and continue to improve precision of dose delivery and measurement, facilitating accurate treatment plans to minimize radiation damage to nearby biological functions.




*An example of the technique of pencil beam scanning where a narrow beam is rapidly scanned laterally to conform accurately to a tumor of arbitrary but precise shape.*

**Proton Radiation Therapy Future:**

- Cost and footprint reduction
- Available in community hospitals
- On-board imaging to verify range and dose delivered
- Proton Computed Tomography
- Neutron hard electronics
- Pencil beam scanning advanced to real-time tumor tracking
- On-board wireless motion tracking

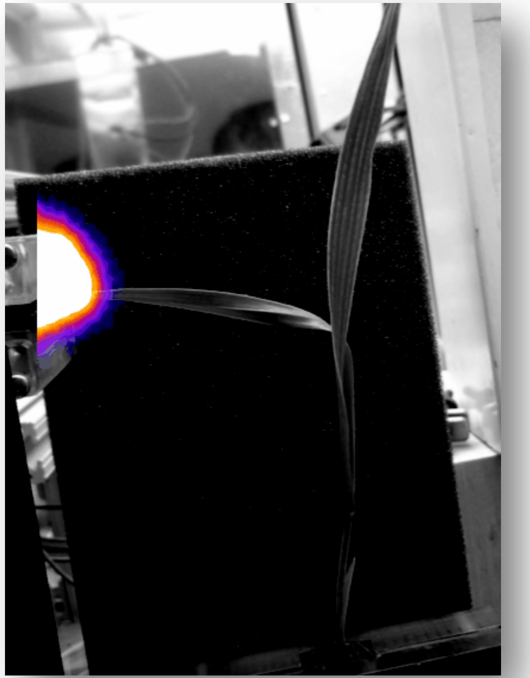


*An example of a pediatric medulloblastoma proton treatment plan depicting the characteristic lack of dose to critical organs on the distal side of the delivery as well as precision beam shaping along the spine.*

# Benefits to Other Fields of Detector Technology: Biological Imaging

*(example from ongoing programs)*

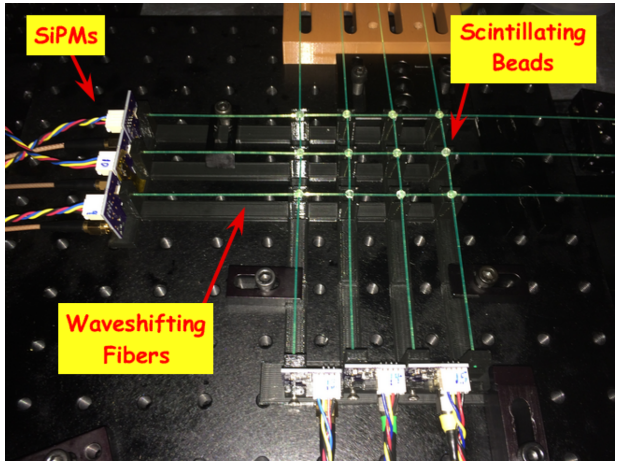
**Problem:** limiting factors of enhanced plant productivity in increased $CO_2$ environment not understood.
**Solution**: Specialized plant PET for *in vivo* carbon-11 imaging to facilitate photosynthesis studies.



*Overlay movie of carbon translocation in barley plant, 5 min x 12 frames = 1 hour*

A good understanding of the biochemical processes in soil is critical for maintaining the health of the planet and feeding the organisms that live on it.

**Problem:** Soil is opaque so how does one visualize the fungal network / root interaction on molecular level?
**Solution**: Radioisotope based methods for high sensitivity imaging/detection of plant-fungal interactions in the rhizosphere.




*Lattice of waveshifting fibers with scintillating beads – to insert in soil around plant roots*

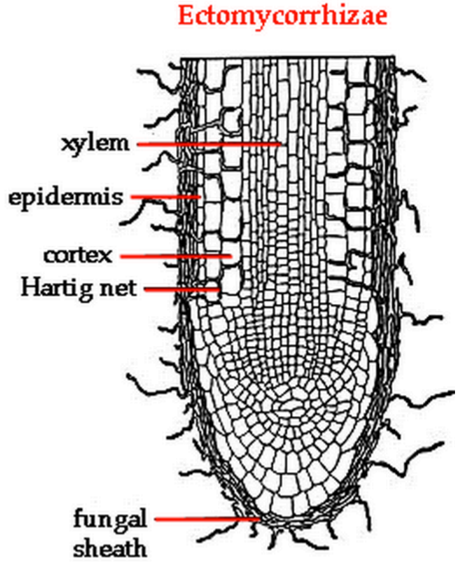
# Benefits to Other Fields of Detector Technology: Biological Imaging

## Solve Global Challenge of Sustainable Food, Fuel and Fiber Production

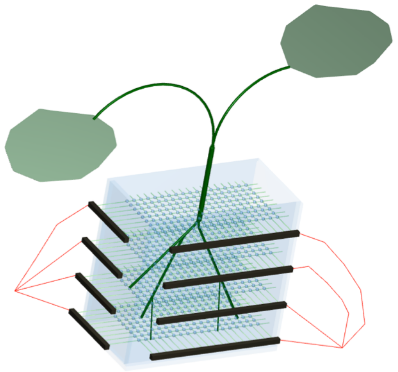
Mounting needs towards more productively grown:

- food
- feed
- fiber

**on less optimal (and often infertile) lands**




The interaction of microbes such as fungi in the soil near plant roots (the rhizosphere) is proving to be extremely important in plant wellbeing. It is not enough to just dump nutrients in the soil. We are just coming to understand the importance of microbes. Symbiotic root associated fungi form a physical network that actually links soils and plants. This is relevant to carbon and nutrient cycling in terrestrial ecosystems.



Radioisotopes used as biomarkers can allow scientists to study this interaction nondestructively in natural soils

→ Direct nuclear physics techniques to address the global challenge of sustainable nutritious food, fuel and fiber production.



Jefferson Lab

# Benefits to Large Scale Computing

- Novel computer architectures first realized by Lattice QCD theorists in the 2000-2005 period by a collaboration of Columbia, IBM and RBRC have allowed U.S. computer manufacturers to gain world leadership in capability computing.
- The knowledge in the use of field programmable gate arrays and graphics cards for the low-cost solution of extremely CPU-intensive, repetitive computations was first implemented in the Jefferson Lab Lattice QCD calculations. This is now applied on leadership GPU systems such as DOE Titan (ORNL) and NSF Blue Waters (NCSA - University of Illinois).
- The effort to boost the computing capabilities will continue with the Exascale Computing Project and will enable an era of high-precision Lattice QCD calculations.

Past efforts in lattice QCD in collaboration with industry have driven development of new computing paradigms that benefit large scale computation. These capabilities underpin many important scientific challenges, *e.g*. studying climate and heat transport over the Earth.

The EIC will be the facility in the era of high precision QCD and a prime US-based facility in the era of Exascale Computing. This will affect the interplay of experiment, simulations, and theory profoundly and result in a new computing paradigm that can be applied to other fields of science and industry.

# Economic Impact of a US-based EIC

According to 2010 and 2012 economic studies of Jefferson Lab and RHIC, resp., *(each escalated to FY17$)*:

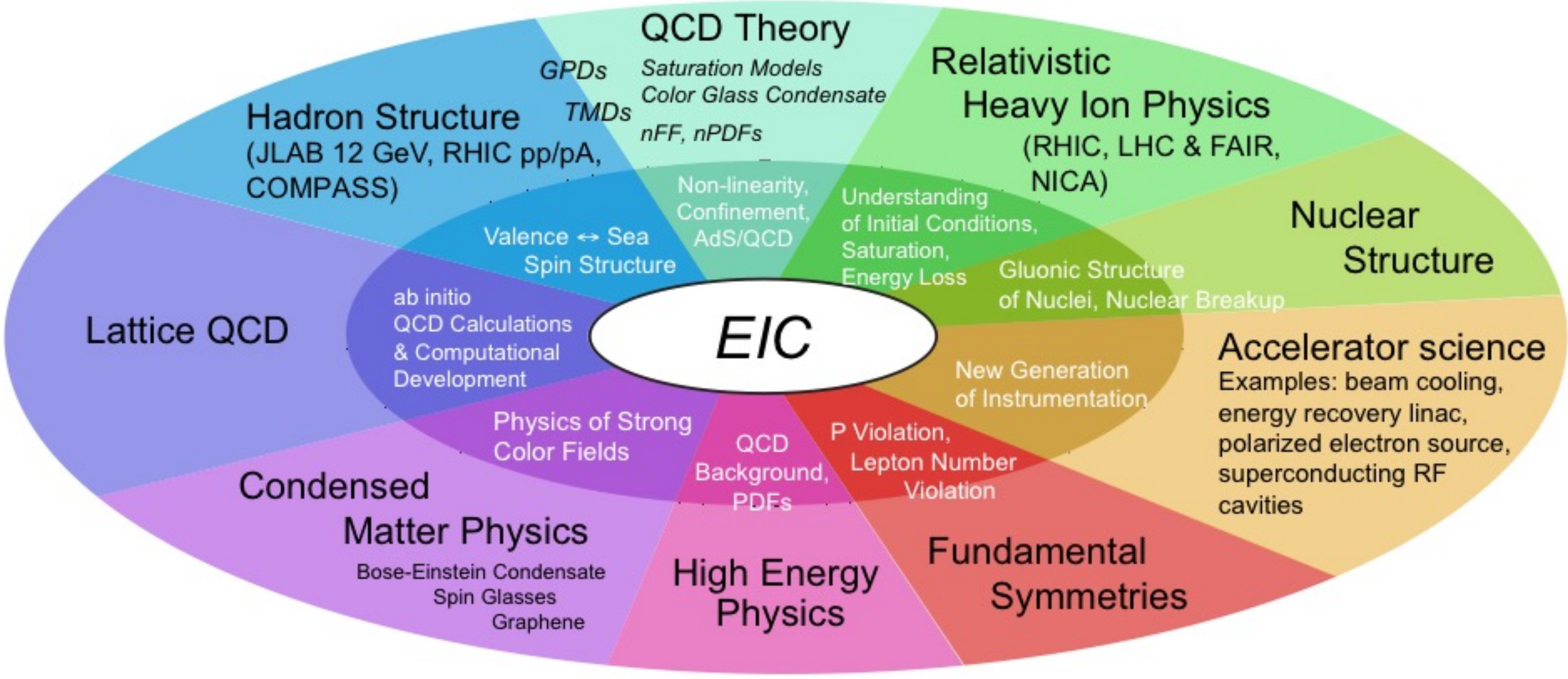
- For the **nation**, each generates approximately **$230 million** annually in economic output generated by the labs and visiting researchers.
- For the **nation**, each supports approximately **1,500** full-time equivalent **jobs** annually.
- For RHIC, the impact of RHIC-related spending was concentrated (~95%) on Long Island, for Jefferson Lab the impact was more spread, ~35% on Hampton Roads.
- The economic impact and related jobs represent the potential loss of gross output and employment that would be felt by the country if the labs suddenly were to vanish.
- Extrapolated to an EIC construction phase, the US investment is expected to **more than double** in economic output generated.

Sources: http://www.jsallc.org/news/EconImpact2011.pdf, and https://www.bnl.gov/rhic/docs/EconomicImpact_RHIC_2012_Final.pdf

# Connections of EIC Science to Other Fields

The **study of QCD at an EIC** – both in theory and in experiment – has **revealed connections to other fields in science** including condensed matter physics, cosmology / gravitation and particle astro-physics.

Illustration of connections:




Synergy of theory and experiment are crucial!



Jefferson Lab

# Connections of EIC Science to Other Fields

**Examples** emphasizing the connection to the **non-linear nature of QCD**:

**(1) Condensed Matter Physics:**

The dynamics of strongly coupled cold atom gases and non-Abelian gauge fields show strikingly common features. Cold atom physicists are actively engaged in engineering cold atom simulators of gauge field dynamics.

Strong connections have emerged between studies of strongly correlated condensed matter systems and QCD, in particular relating to topological effects arising from the chiral anomaly.

**(2) Cosmology / Gravitation:**

Gravitational waves powerfully illustrate the non-linear nature of gravity. Explorations of the stringy dynamics of hadrons led to the string theory of Gravity. A weakly coupled regime of 10-d Gravity, in turn, is conjectured to be dual to strongly coupled 4-d QCD-like theories. Further profound connections may emerge from deeper investigation of the QCD landscape.

# Connections of EIC Science to Other Fields

**(3) QED:**

Strong field QED explores the breakdown of the QED vacuum and its nonlinear optical response resulting in electron-positron pair creation. Reaching this regime is a major goal in developing powerful lasers.

**(4) Particle-Astro-Physics:**

The flux of high-energy extraterrestrial particles such as the study of prompt neutrino flux by the IceCube Collaboration at the South Pole involves interactions of partons inside athmospheric nuclei at very low-x values approaching the region where non-linear effects might become relevant similar to the study of very forward particle production by the TOTEM experiment at the LHC.

# Benefits to National Security

## Securing US Borders

- Nuclear physics provides solutions to prevent illicit transport of radiological materials:
  - Neutron detectors.
  - Small-scale accelerators and radioactive sources coupled to detector systems.
- Collaboration of academic institutions and e.g. Passport Systems Inc. on the commercial development of cargo inspection devices.
- Early cooperation between EIC R&D program and nuclear-security company such as Silverside Detectors Inc. on micro-pattern gas detectors (GEMs).

## Assuring the integrity of US nuclear arsenal

- Important contributions from nuclear physicists to Stockpile Stewardship programs.
- Development of highly qualified workforce necessary to enable NNSA and DHS nuclear activities.

Markus Diefenthaler

mdiefent@jlab.org

# Conclusion

- **EIC will help to maintain international leadership in accelerator science and technology of colliders**:
  - **HEP** End of Tevatron and no plans to construct a new collider
  - **NP** accelerator-collider expertise in the US
  - future accelerators with high energy and high luminosity will benefit significantly from EIC R&D
- **EIC will impact on other research areas** particle physics, astrophysics, theoretical and computational modeling as well as atomic and condensed matter physics.
- **With the exciting physics frontier program enabled by an EIC, nuclear science will continue to attract outstanding graduate students**, more than half of whom will go on to science, technology, engineering, and mathematics jobs in industry and DOE National Nuclear Security Administration and Office of Science laboratories.