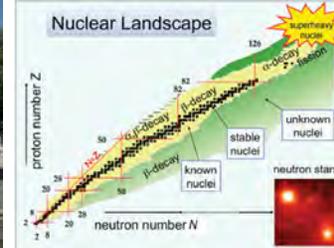
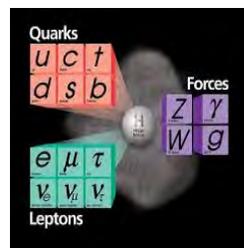
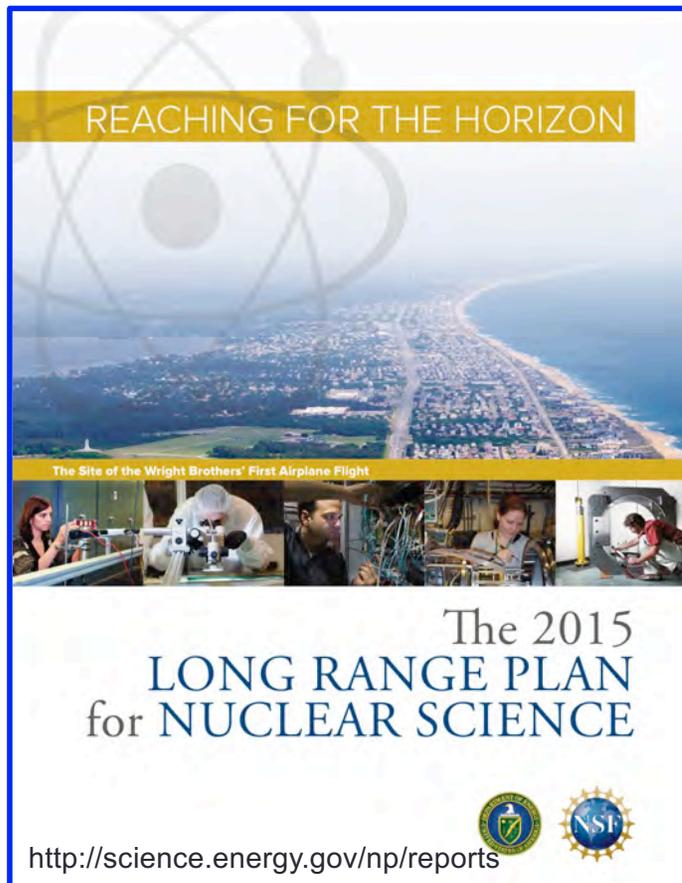


# Electron Ion Collider: The next QCD frontier

Why the EIC? → “Gluon Imaging”  
 To understand the role of gluons in binding quarks & gluons into Nucleons  
 and Nuclei





**RECOMMENDATION:**

*We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.*

**Initiatives:**

Theory

Detector & Accelerator R&D

Detector R&D money ~1.3M/yr since 2011  
Significant increase anticipated soonr

**Since FY 2017**

EIC Accelerator R&D already assigned \$7m/yr



# The Electron Ion Collider

## For e-N collisions at the EIC:

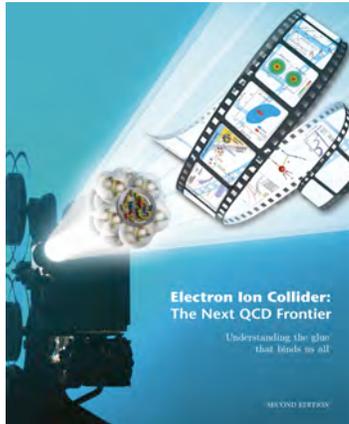
- ✓ Polarized beams: e, p, d/<sup>3</sup>He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity  $L_{ep} \sim 10^{33-34} \text{ cm}^{-2}\text{sec}^{-1}$   
100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

## For e-A collisions at the EIC:

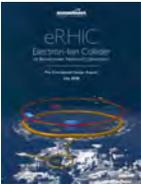
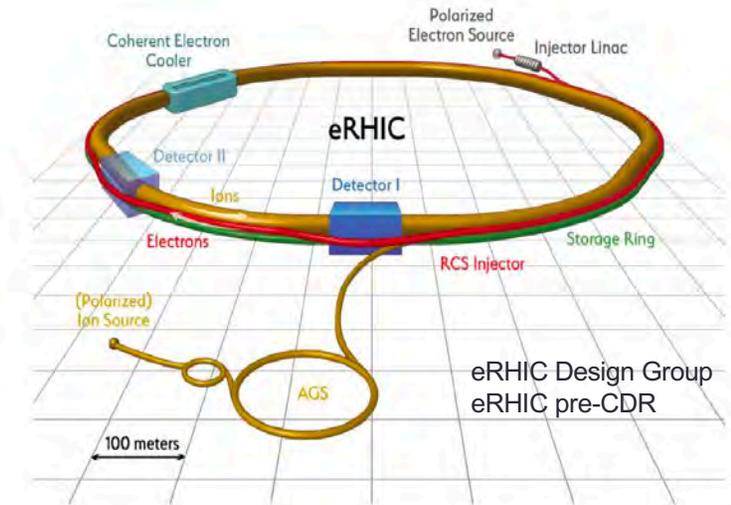
- ✓ Wide range in nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

**World's first**  
**Polarized electron-proton/light ion**  
**and electron-Nucleus collider**

Both designs use DOE's significant investments in infrastructure

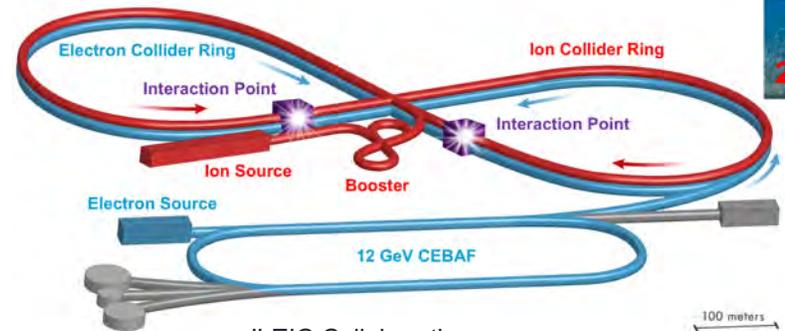


1212.1701.v3  
 A. Accardi et al  
 Eur. Phys. J. A, 52 9(2016)



2018

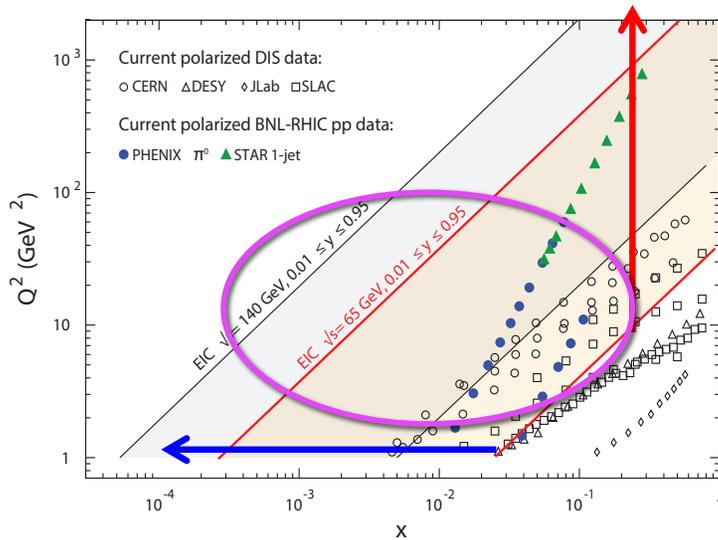
eRHIC Design Group  
 eRHIC pre-CDR



2018

JLEIC Collaboration  
 JLEIC Pre-CDR about to be finalized

# EIC: Kinematic reach & properties

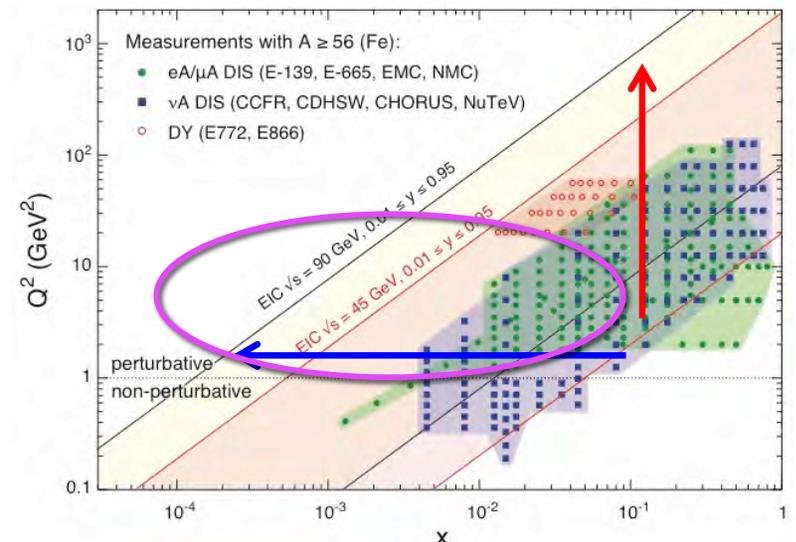


## For e-N collisions at the EIC:

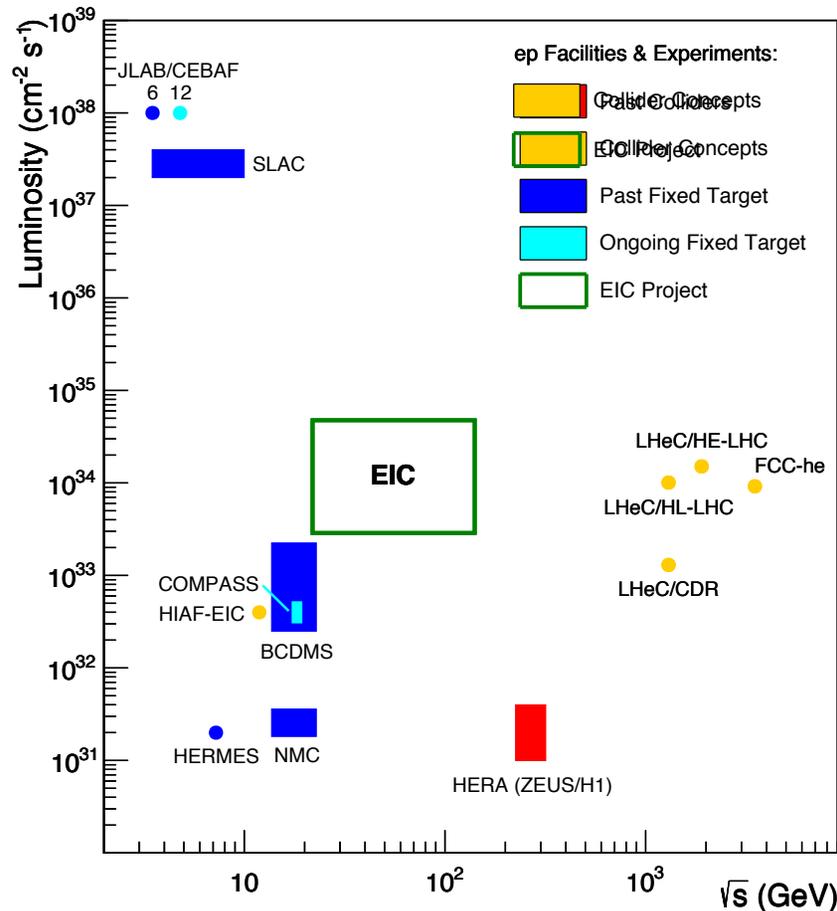
- ✓ Polarized beams: e, p, d/<sup>3</sup>He
- ✓ Variable center of mass energy
- ✓ Wide Q<sup>2</sup> range → evolution
- ✓ Wide x range → spanning valence to low-x physics

## For e-A collisions at the EIC:

- ✓ Wide range in nuclei
- ✓ Lum. per nucleon same as e-p
- ✓ Variable center of mass energy
  - ✓ Wide x range (evolution)
- ✓ Wide x region (reach high gluon densities)



# Uniqueness of EIC among all DIS Facilities



All DIS facilities in the world.

However, if we ask for:

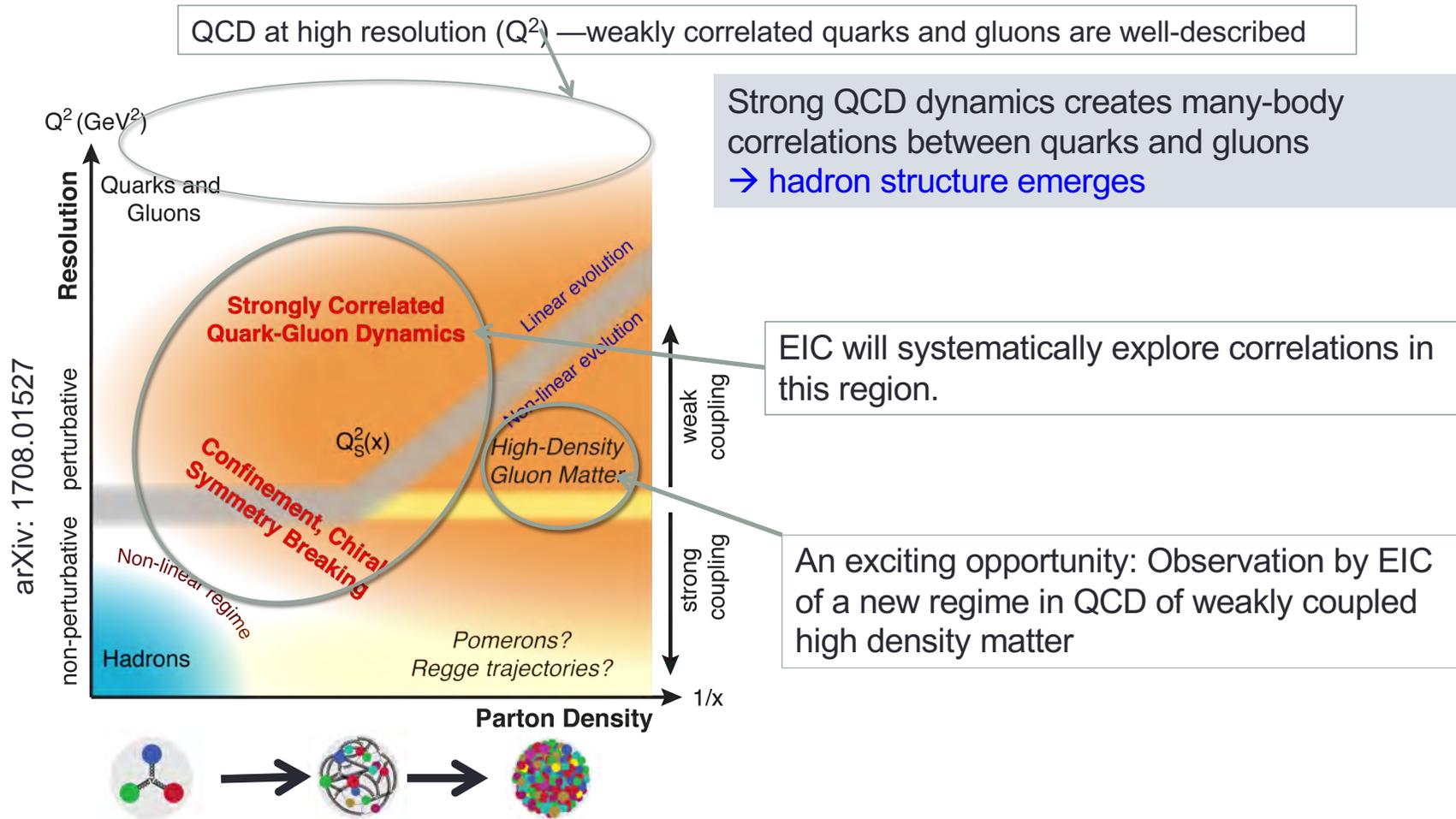
- high luminosity & wide reach in  $\sqrt{s}$
- polarized lepton & hadron beams
- nuclear beams

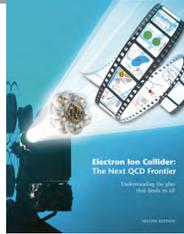
**EIC stands out as  
unique facility ...**

# QCD at the EIC

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# QCD Landscape to be explored by EIC

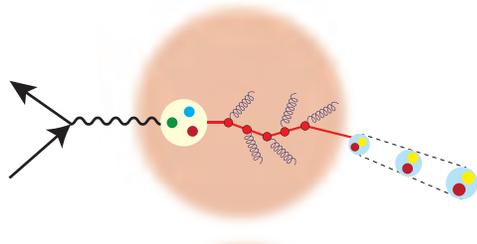
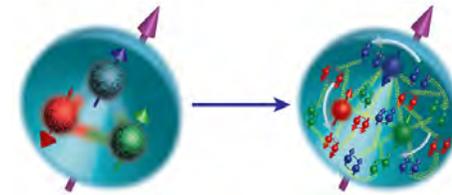




A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

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 them and their interactions?



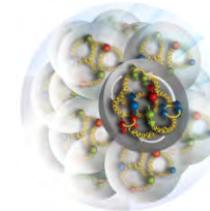
How do color-charged quarks and gluons, and colorless jets, **interact with a nuclear medium**?

How do the **confined hadronic states emerge** from these quarks and gluons?

How do the quark-gluon **interactions create nuclear binding**?

How does a **dense nuclear environment affect** the quarks and gluons, their correlations, and their interactions?

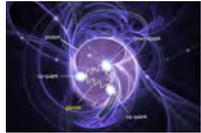
What happens to the **gluon density in nuclei**? Does it **saturate at high energy**, giving rise to a **gluonic matter with universal properties** in all nuclei, even the proton?



?

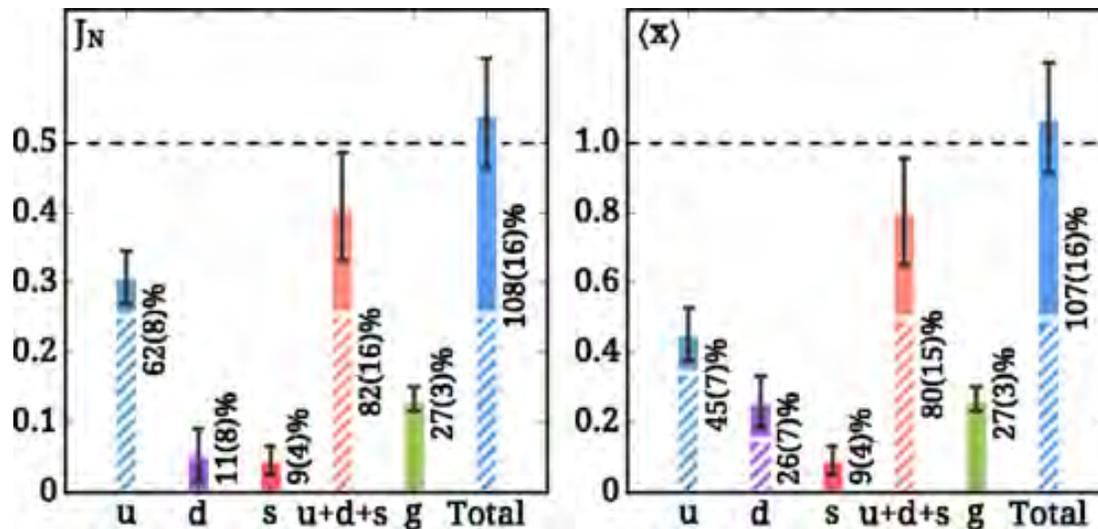
## Recent progress in Lattice QCD

- Accessing Gluon Distribution in Large Momentum Effective Theory, Jian-Hui Zhang et al., PRL 122, 142001, April 2019
- First Direct lattice-QCD calculation of the x-dependence of the pion PDF, J-W.Chen et al, arXiv 1804.01483
- Parton Distribution functions and one loop matching, <https://doi.org/10.1142/S2010194516600533> , X. Ji et al.
- And many such papers .... **For the first time PDFs are attempted to being calculated on the lattice! → Precision lattice calculations need precision experimental measurements!**



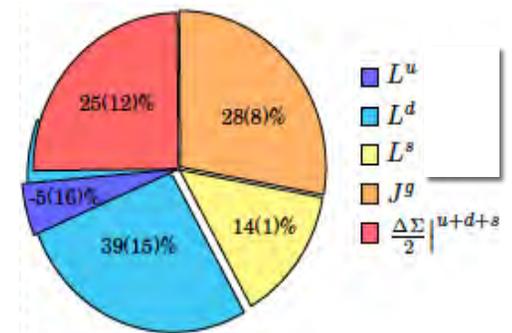
# Solving the nucleon spin puzzle on the lattice

C. Alexandrou et al. PRL 119, 142002 (2017)

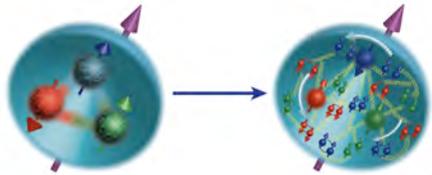


(Left panel) Nucleon spin decomposition. (Right panel) Nucleon momentum decomposition. All quantities are given in the  $\overline{MS}$  scheme at 2 GeV. The striped segments show valence quark contributions (connected), and the solid segments the sea quark and gluon contributions (disconnected).

## Spin and Lattice: Recent Activities



- **Gluon's spin contribution on Lattice:  $S_G = 0.5(0.1)$ :** Yi-Bo Yang et al. PRL 118, 102001 (2017)
- **$J_q$  calculated on Lattice QCD:**  $\chi$ QCD Collaboration, PRD91, 014505, 2015

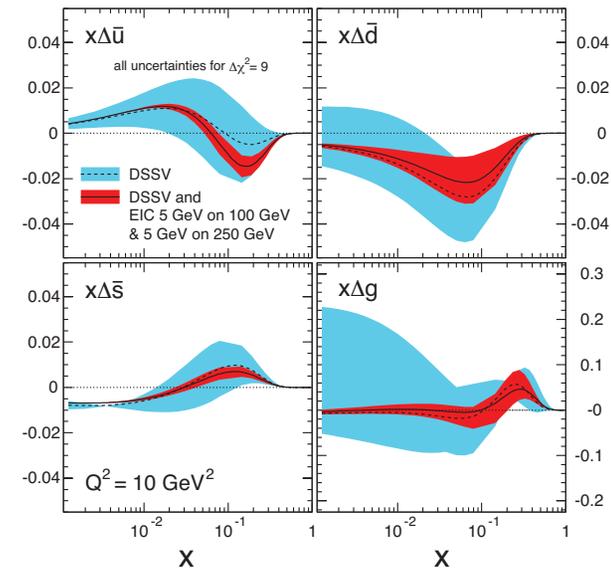
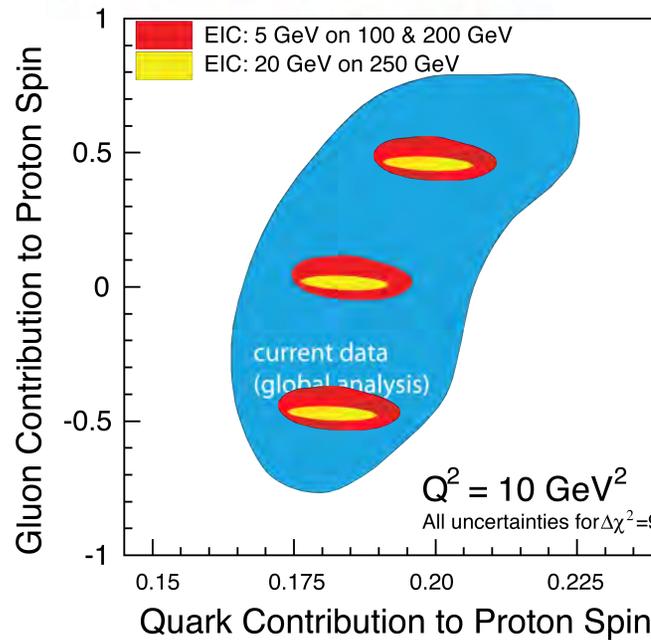
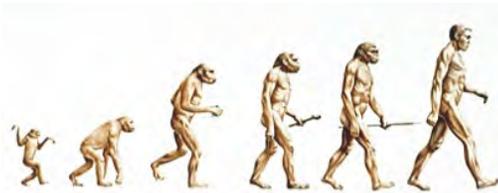


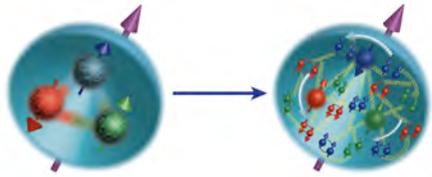
# Understanding of Nucleon Spin

$$\frac{1}{2} = \left[ \frac{1}{2} \Delta\Sigma + L_Q \right] + [\Delta g + L_G]$$

$\Delta\Sigma/2$  = Quark contribution to Proton Spin  
 $L_Q$  = Quark Orbital Ang. Mom  
 $\Delta g$  = Gluon contribution to Proton Spin  
 $L_G$  = Gluon Orbital Ang. Mom

Precision in  $\Delta\Sigma$  and  $\Delta g \rightarrow$  A clear idea Of the magnitude of  $L_Q+L_G$



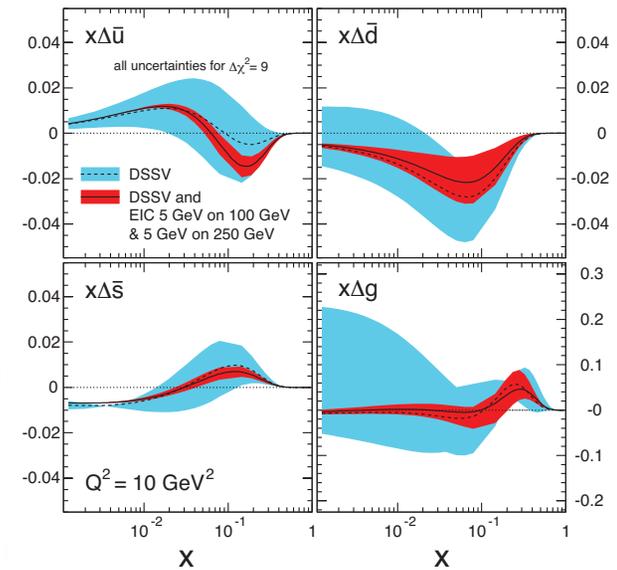
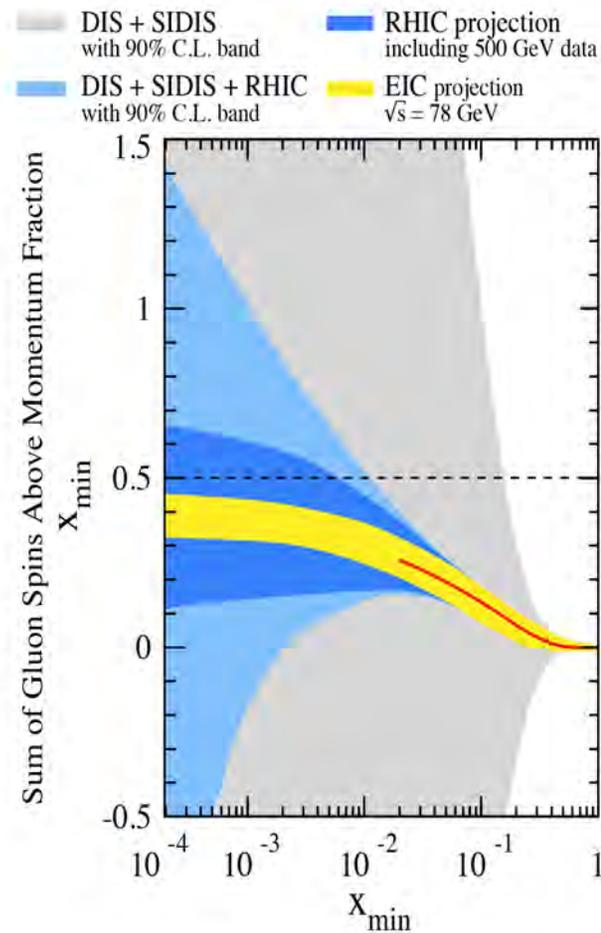


# Understanding of Nucleon Spin

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 $\Delta g$  = Gluon contribution to Proton Spin  
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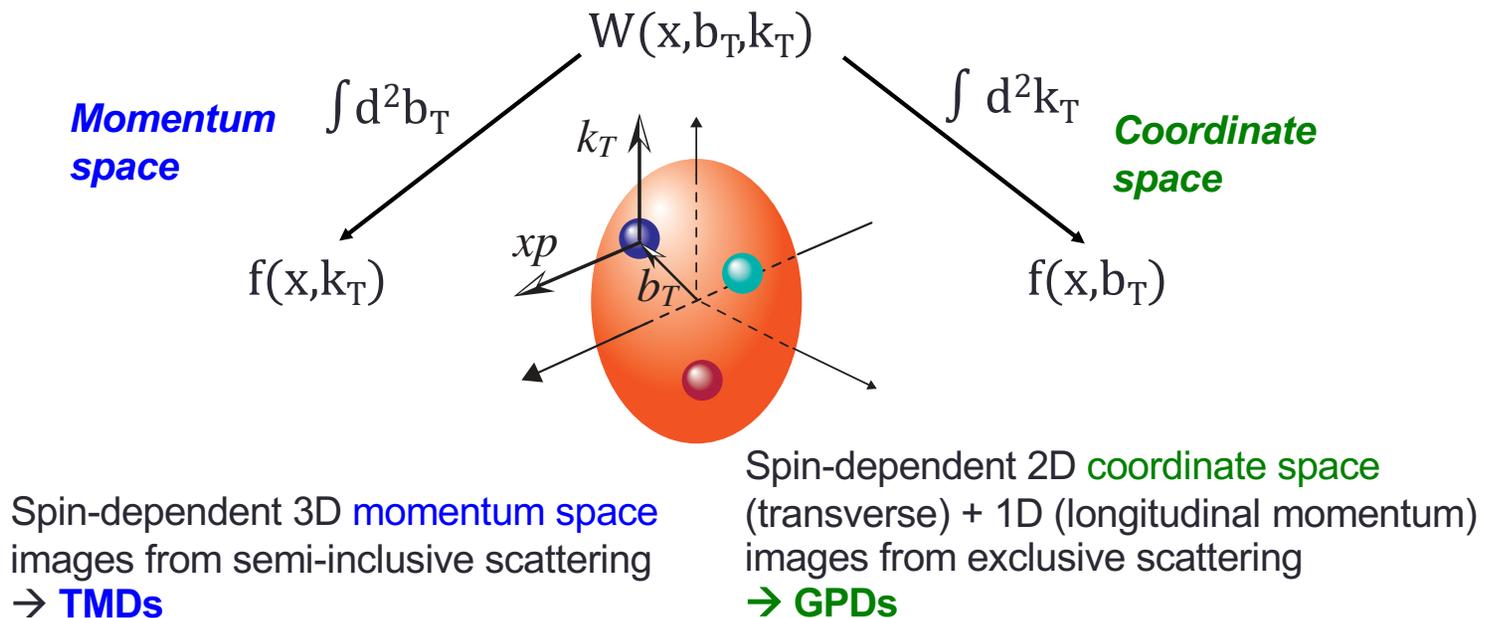
Precision in  $\Delta\Sigma$  and  $\Delta g \rightarrow$  A clear idea Of the magnitude of  $L_Q+L_G$



# 3-Dimensional Imaging Quarks and Gluons

## Wigner functions $W(x, b_T, k_T)$

offer unprecedented insight into confinement and chiral symmetry breaking.

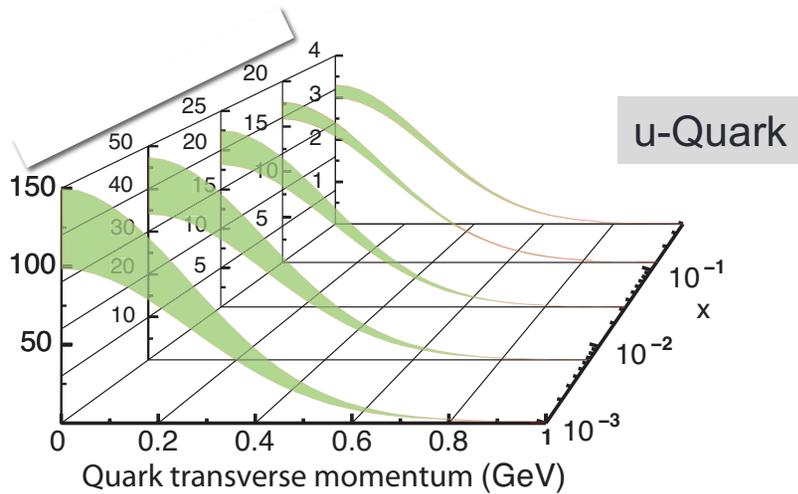


Position and momentum → Orbital motion of quarks and gluons

# 2+1 D partonic image of the proton with the EIC

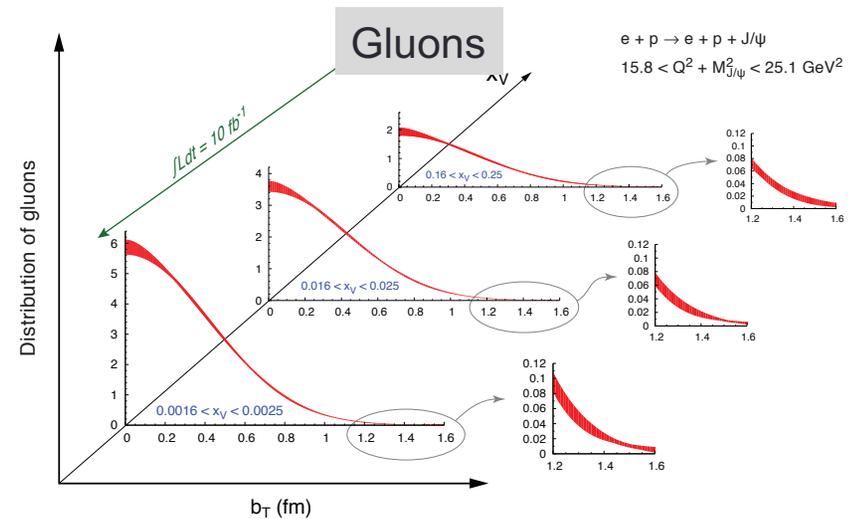
Spin-dependent 3D **momentum space** images from semi-inclusive scattering

## Transverse Momentum Distributions



Spin-dependent 2D **coordinate space** (transverse) + 1D (longitudinal momentum) images from exclusive scattering

## Transverse Position Distributions

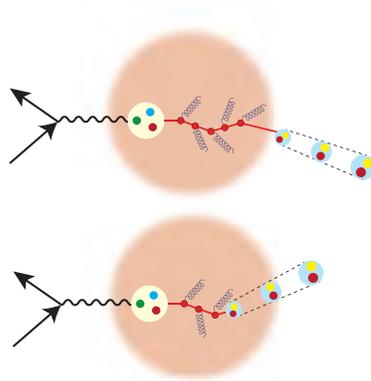


# Emergence of Hadrons from Partons

## Nucleus as a Femtometer sized filter

Unprecedented  $\nu$ , the virtual photon energy range @ EIC : precision & control

$$\nu = \frac{Q^2}{2mx}$$

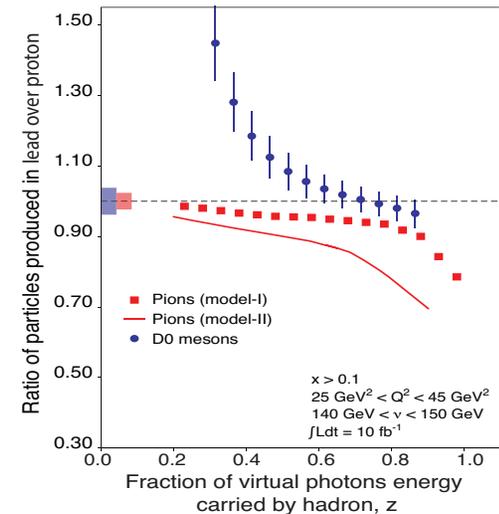


Control of  $\nu$  by selecting kinematics;  
Also under control the nuclear size.

(colored) Quark passing through cold QCD matter emerges as color-neutral hadron → Clues to color-confinement?

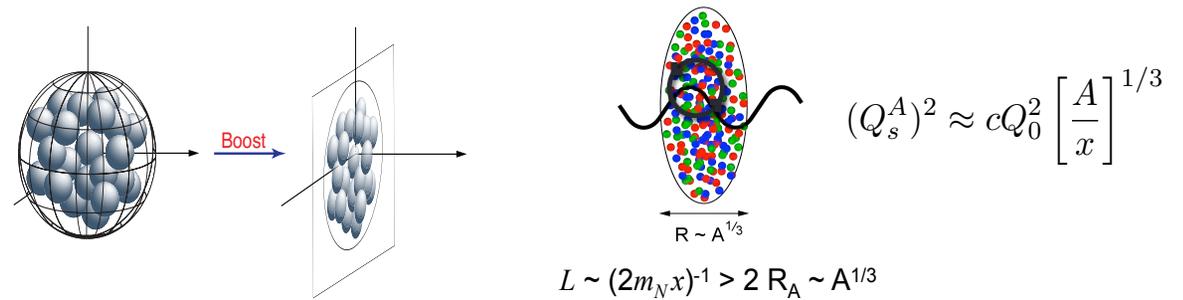
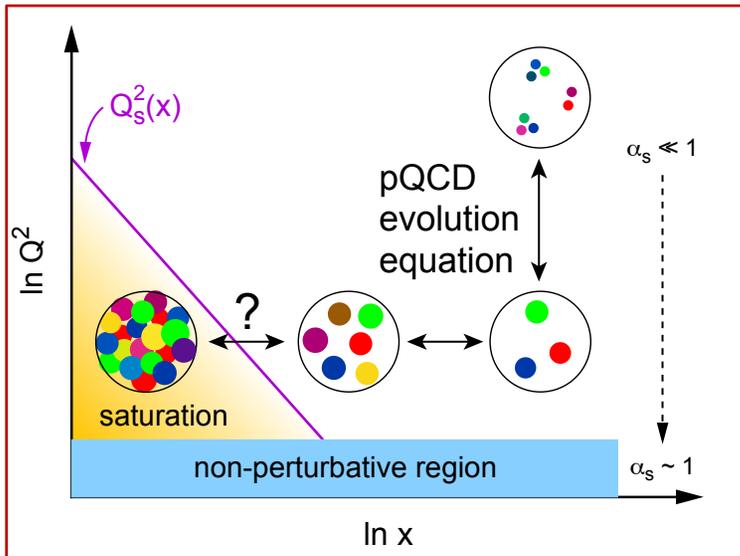
**Need the collider energy of EIC and its control on parton kinematics**

Energy loss by light vs. heavy quarks:

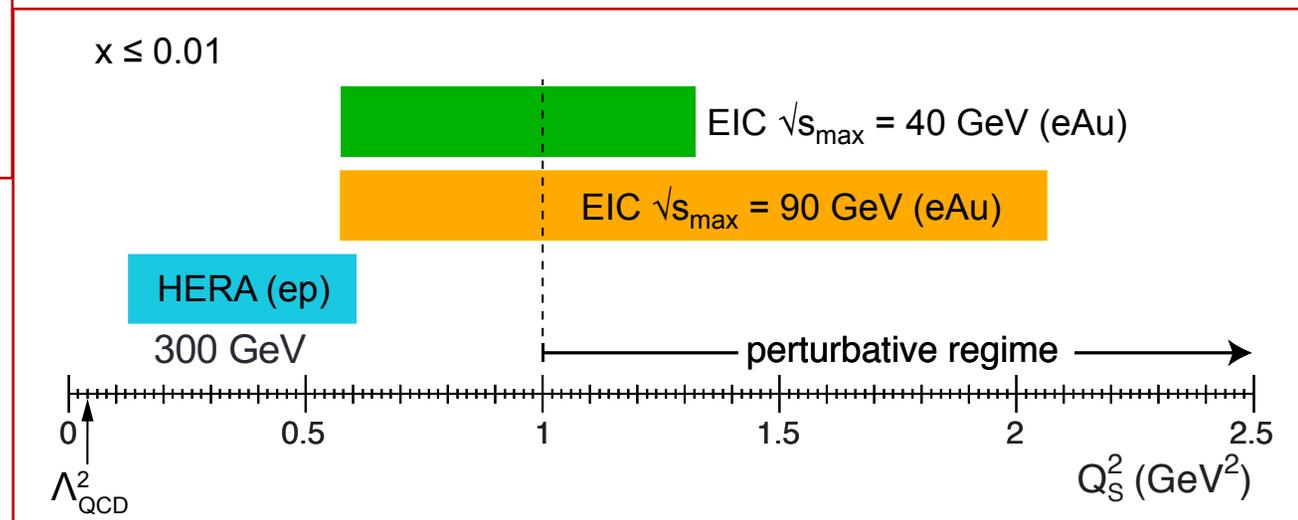


Identify  $\pi$  vs.  $D^0$  (**charm**) mesons in e-A collisions:  
Understand energy loss of light vs. heavy quarks  
traversing the cold nuclear matter:  
Connect to energy loss in Hot QCD

# Advantage of the nucleus over proton



Accessible range of saturation scale  $Q_s^2$  at the EIC with e+A collisions.  
arXiv:1708.01527



# Detector integration with the Interaction Region

## Lessons learned from HERA

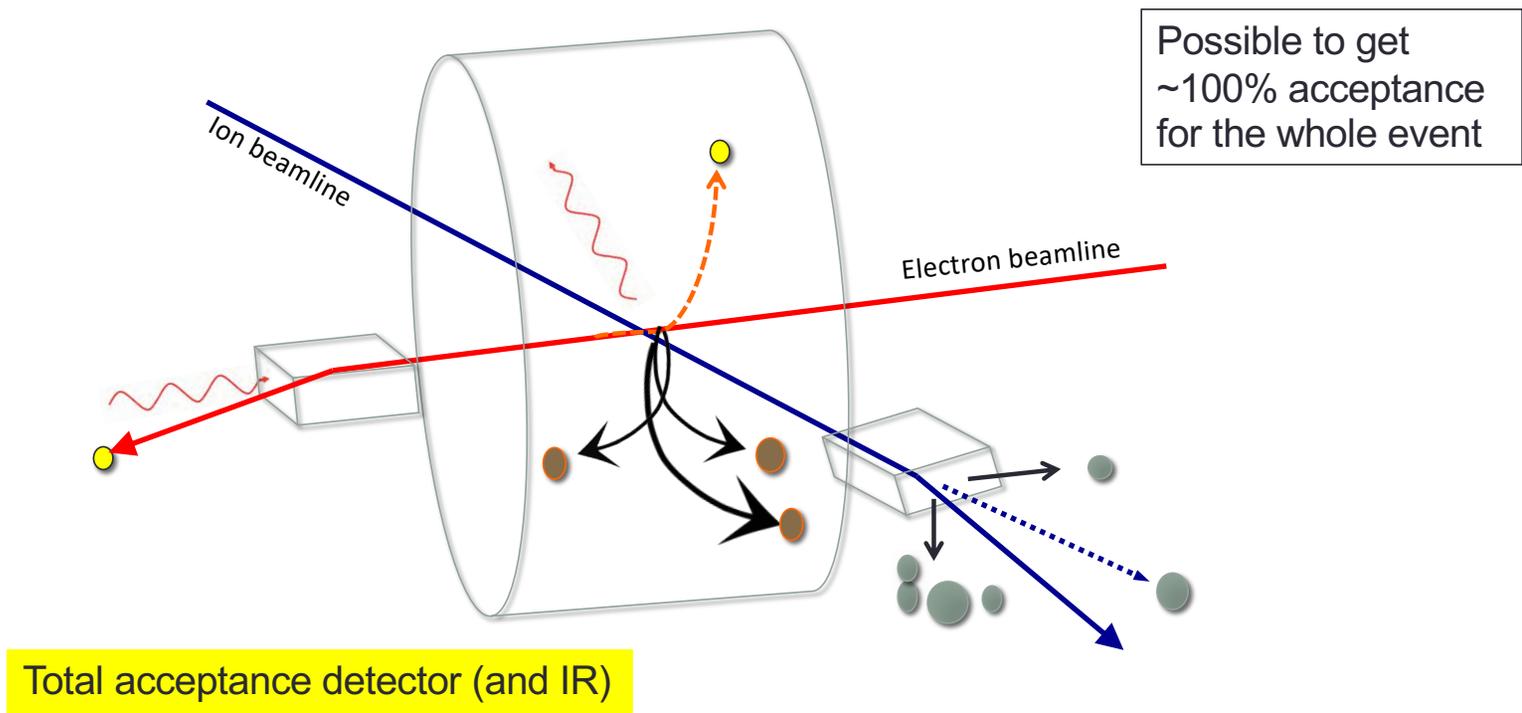
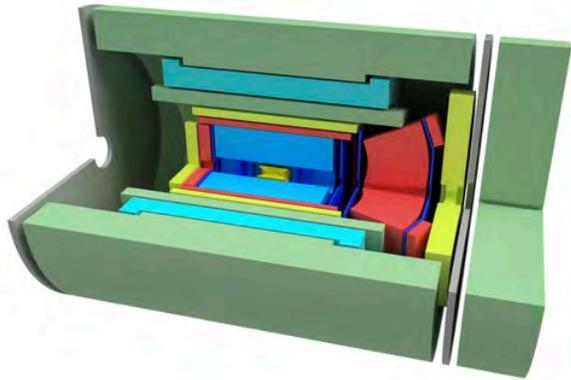


Figure Courtesy: Rik Yoshida

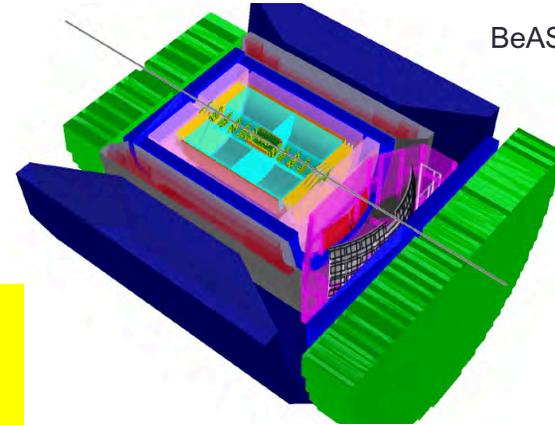
# EIC Detector Concepts, others expected to emerge

EIC Day 1 detector, with BaBar Solenoid

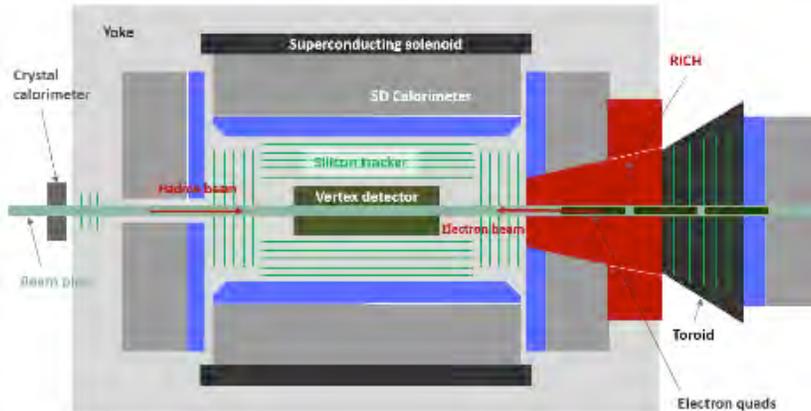


Ample opportunity and need for additional contributors and collaborators

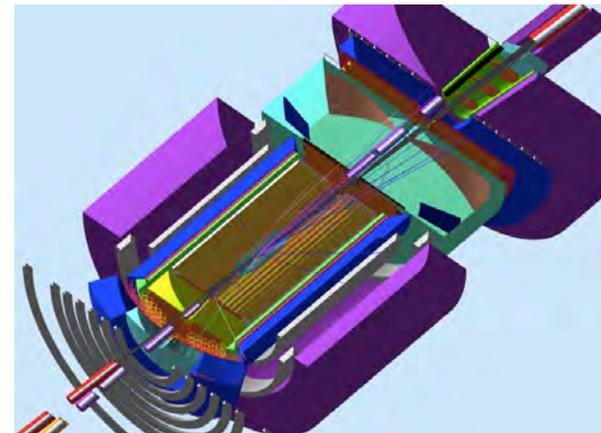
BeAST at BNL



TOPSIDE: Time Optimized PID Silicon Detector for EIC



JLEIC Detector Concept, with CLEO Solenoid

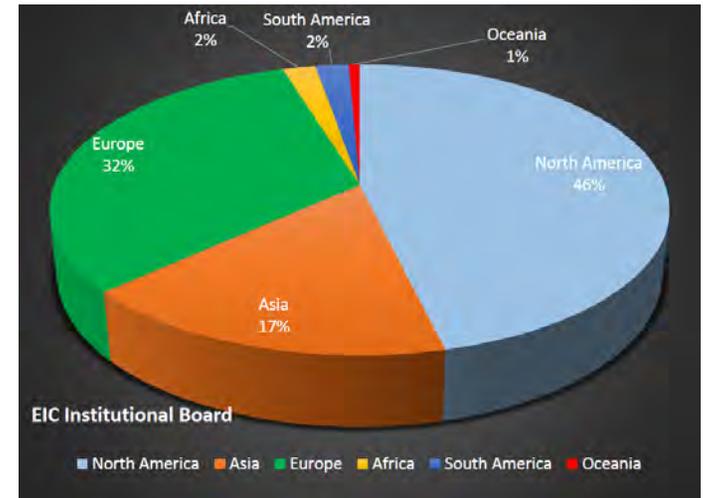


# The EIC Users Group: [EICUG.ORG](http://EICUG.ORG)

Formally established in 2016  
 864 Ph.D. Members from 30 countries, 184 institutions



**New:**  
[Center for Frontiers in Nuclear Science](#) (at Stony Brook/BNL)  
[EIC<sup>2</sup>](#) at Jefferson Laboratory



## EICUG Structures in place and active.

- EIC UG Steering Committee (w/ **European Representative**)
- EIC UG Institutional Board
- EIC UG Speaker's Committee (w/**European Rep.**)

## Task forces on:

- Beam polarimetry
- Luminosity measurement
- Background studies
- IR Design

Annual meetings: Stony Brook (2014), Berkeley (2015), ANL (2016), **Trieste (2017)**, CAU (2018), **Paris (2019)**

# The National Academy Review of the EIC

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2017-2018

## Statement of Task from the Office of Science (DOE/NSF) to the National Academy of Science, Engineering & Medicine (NAS)

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.

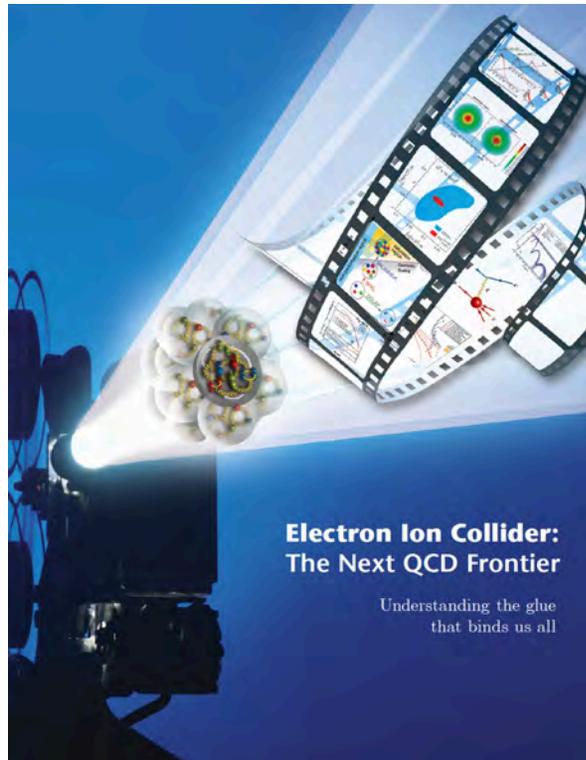
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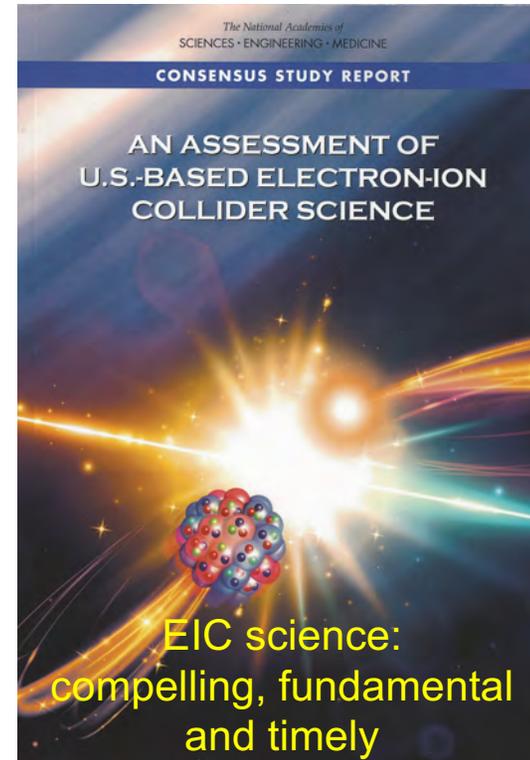
In particular, the committee will address the following questions:

- ❖ 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?

# EIC Science Endorsed Unanimously by the NAS



Developed by US QCD community over two decades



Developed by NAS with broad science perspective

A consensus report  
July 26, 2018

# National Academy's Findings

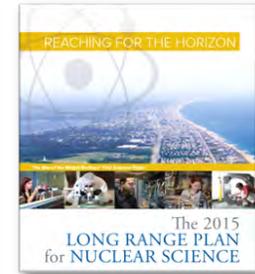
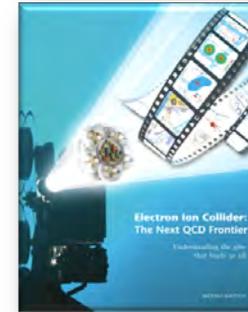
- **Finding 1:** An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:
  - How does the **mass** of the nucleon arise?
  - How does the **spin** of the nucleon arise?
  - What are the **emergent properties** of dense systems of gluons?
- **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**.
- **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**.

## National Academy's Findings

- **Finding 6:** The current **accelerator R&D program** supported by DOE is crucial to addressing outstanding design challenges.
- **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 furthermore, 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 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 United States are significant in **related fields of science**, including in particular the **accelerator science and technology of colliders** and workforce development.

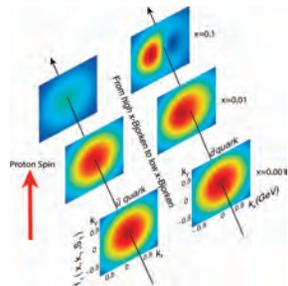
In order to definitively answer the compelling scientific questions elaborated in Chapter 2, including the origin of the mass and spin of the nucleon and probing the role of gluons in nuclei, a new accelerator facility is required, an electron-ion collider (EIC) with unprecedented capabilities beyond previous electron scattering programs. An EIC must enable the following:

- Extensive center-of-mass energy range, from ~20-~100 GeV, upgradable to ~140 GeV, to map the transition in nuclear properties from a dilute gas of quarks and gluons to saturated gluonic matter.
- Ion beams from deuterons to the heaviest stable nuclei.
- Luminosity on the order of 100 to 1,000 times higher than the earlier electron-proton collider Hadron-Electron Ring Accelerator (HERA) at Deutsches Elektronen-Synchrotron (DESY), to allow unprecedented three-dimensional (3D) imaging of the gluon and sea quark distributions in nucleons and nuclei.
- Spin-polarized (~70 percent at a minimum) electron and proton/light-ion beams to explore the correlations of gluon and sea quark distributions with the overall nucleon spin. Polarized colliding beams have been achieved before only at HERA (with electrons and positrons only) and Relativistic Heavy Ion Collider (RHIC; with protons only).

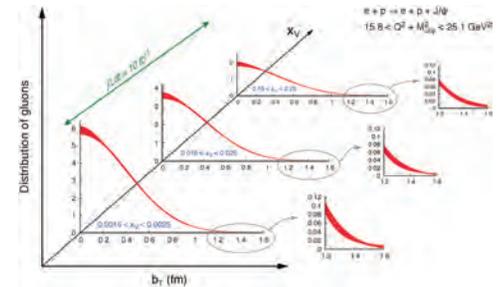
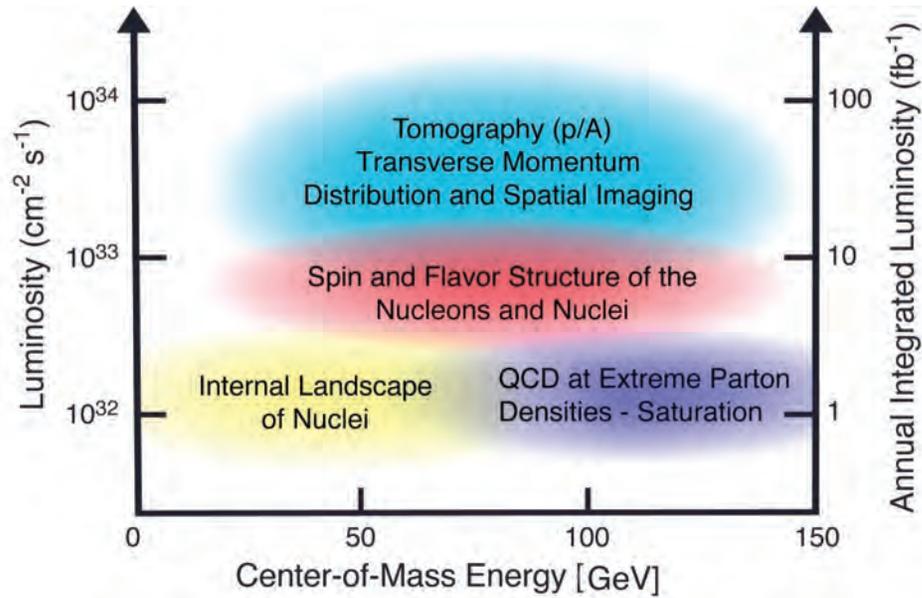
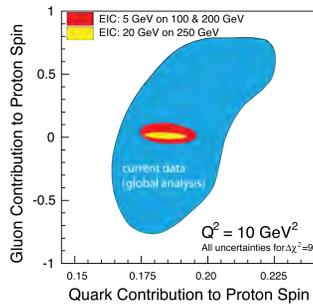


**NAS Study endorses machine parameters suggested by the 2012 White Paper and 2015 NSAC Long Range Plan**

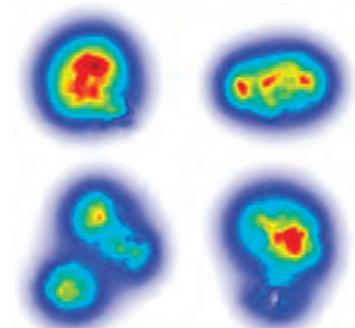
# EIC science and required luminosity



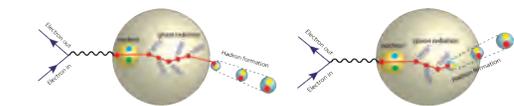
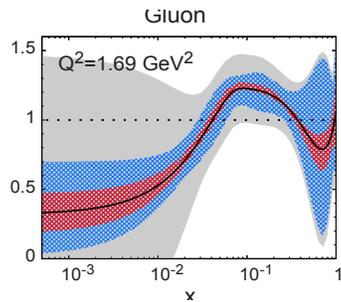
2+1D imaging of quarks and gluons, dynamics, and emergence of spin & mass



Gluon imaging in nucleons

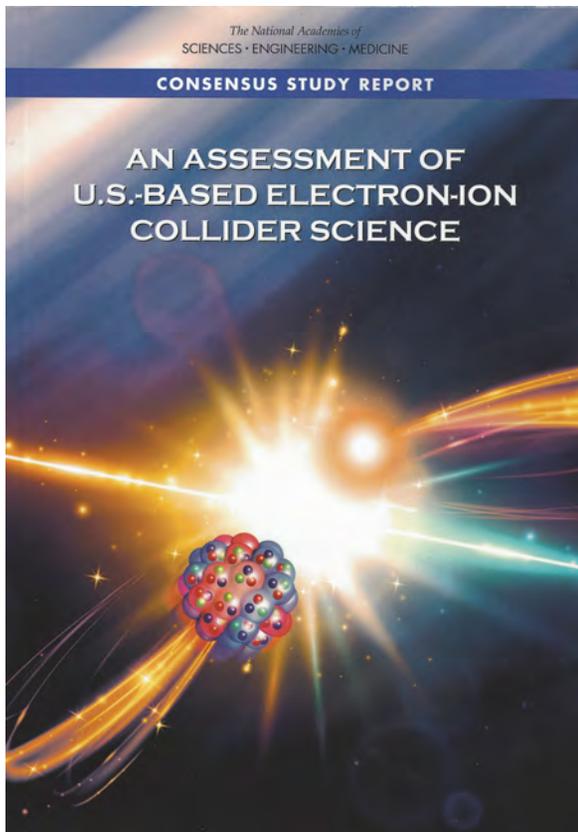


Gluons at high energy in nuclei: (Gluon imaging in nuclei)



Color propagation, neutralization in nuclei & hadronization



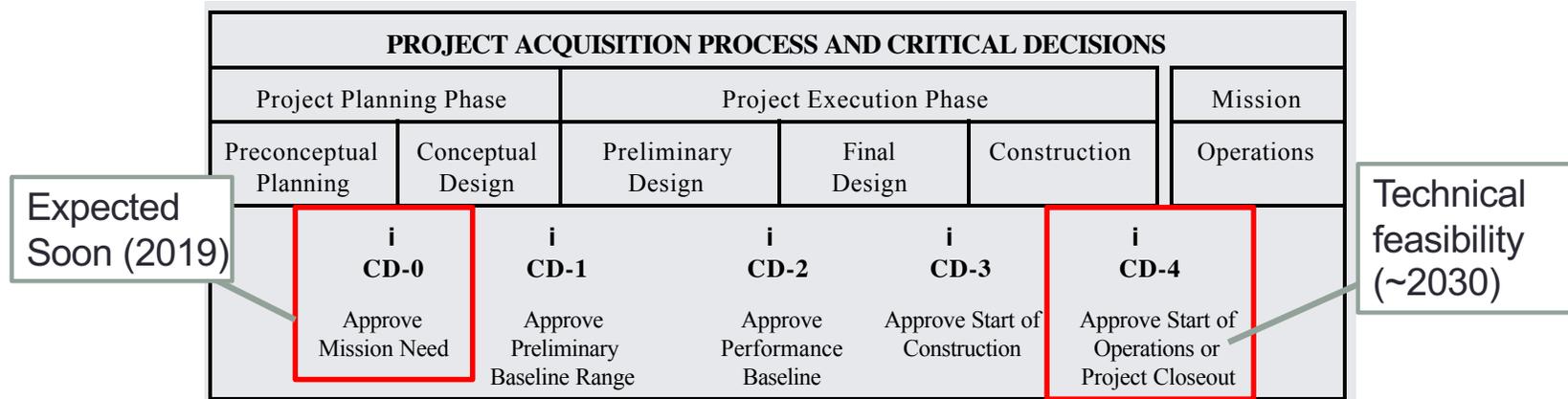


## Consensus Study Report on the US based Electron Ion Collider

### Summary:

The science questions that an EIC will answer are *central* to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today. In addition, the development of an EIC would *advance accelerator science and technology* in nuclear science; it would as well *benefit other fields of accelerator based science and society*, from medicine through materials science to elementary particle physics

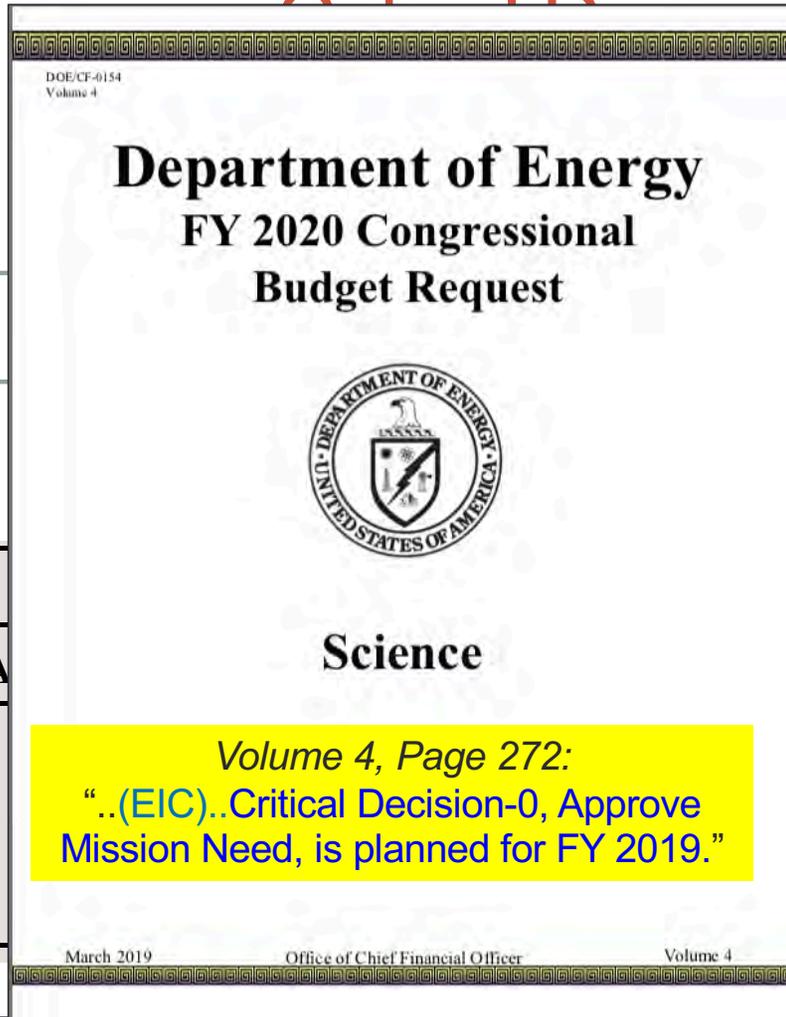
# Critical Decision Process DOE



CD-0	CD-1	CD-2	CD-3	CD-4
<b>Actions Authorized by Critical Decision Approval</b>				
<ul style="list-style-type: none"> <li>Proceed with conceptual design using program funds</li> <li>Request PED funding</li> </ul>	<ul style="list-style-type: none"> <li>Allow expenditure of PED funds for design</li> </ul>	<ul style="list-style-type: none"> <li>Establish baseline budget for construction</li> <li>Continue design</li> <li>Request construction funding</li> </ul>	<ul style="list-style-type: none"> <li>Approve expenditure of funds for construction</li> </ul>	<ul style="list-style-type: none"> <li>Allow start of operations or project closeout</li> </ul>

PED: Project Engineering & Design

# Decision Process DOE



DECISIONS AND CRITICAL DECISIONS		
Project Execution Phase		Mission
Final Design	Construction	Operations
D-2	i CD-3	i CD-4
Approve performance baseline	Approve Start of Construction	Approve Start of Operations or Project Closeout

Technical feasibility (~2030)

D-2	CD-3	CD-4
Initial		
baseline budget mission signature construction	<ul style="list-style-type: none"> <li>Approve expenditure of funds for construction</li> </ul>	<ul style="list-style-type: none"> <li>Allow start of operations or project closeout</li> </ul>

# EIC support, outreach and other news

## European High Energy Physics Strategic Planning:

- CERN management very well informed about the US EIC status, very supportive, suggested strong involvement and input on EIC in the European High Energy Strategy Planning activity (ongoing now)
- EICUG presenting a science paper (led by its European contingent), and an accelerator design paper led by BNL and Jlab together
- EIC at the Plenary session of ECFA meeting November 2018

Recent success in funding of EIC as part of the Hadron studies (Strong2020) in [European Nuclear Physics \\$Eu 12M \(Saclay, INFN and others\) over 3 years](#)

A Consortium of [5 California Universities and 3 national labs](#) supported by UC Chancellor's office for EIC in addition to contributions from the **States of New York and Virginia.**

## Summary:

- Science of EIC: Gluons that bind us all... understanding their role in QCD
- EIC precision measurements  $\leftrightarrow$  Lattice QCD : essential interplay  $\rightarrow$  deeper understanding of QCD
- The US EIC project has significant momentum on all fronts right now:
  - National Academy's positive evaluation  $\rightarrow$  Science compelling, fundamental and timely
  - EIC Users Group is energized, active and enthusiast: organized
    - EICUG led working groups on polarimetry, luminosity measurement, IR design evolving
  - Funding agencies taking note of the momentum: not just in the US but also internationally
- The science of EIC, technical designs (eRHIC and JLEIC) moving forward
  - Pre-CDRs prepared by BNL (eRHIC) and Jlab (under preparation) : machine & IR designs
  - CFNS, EIC<sup>2</sup> Centers established in the US to help EIC Users
- CD0 for the EIC project very near.... Exciting times ahead....

Thank you.

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