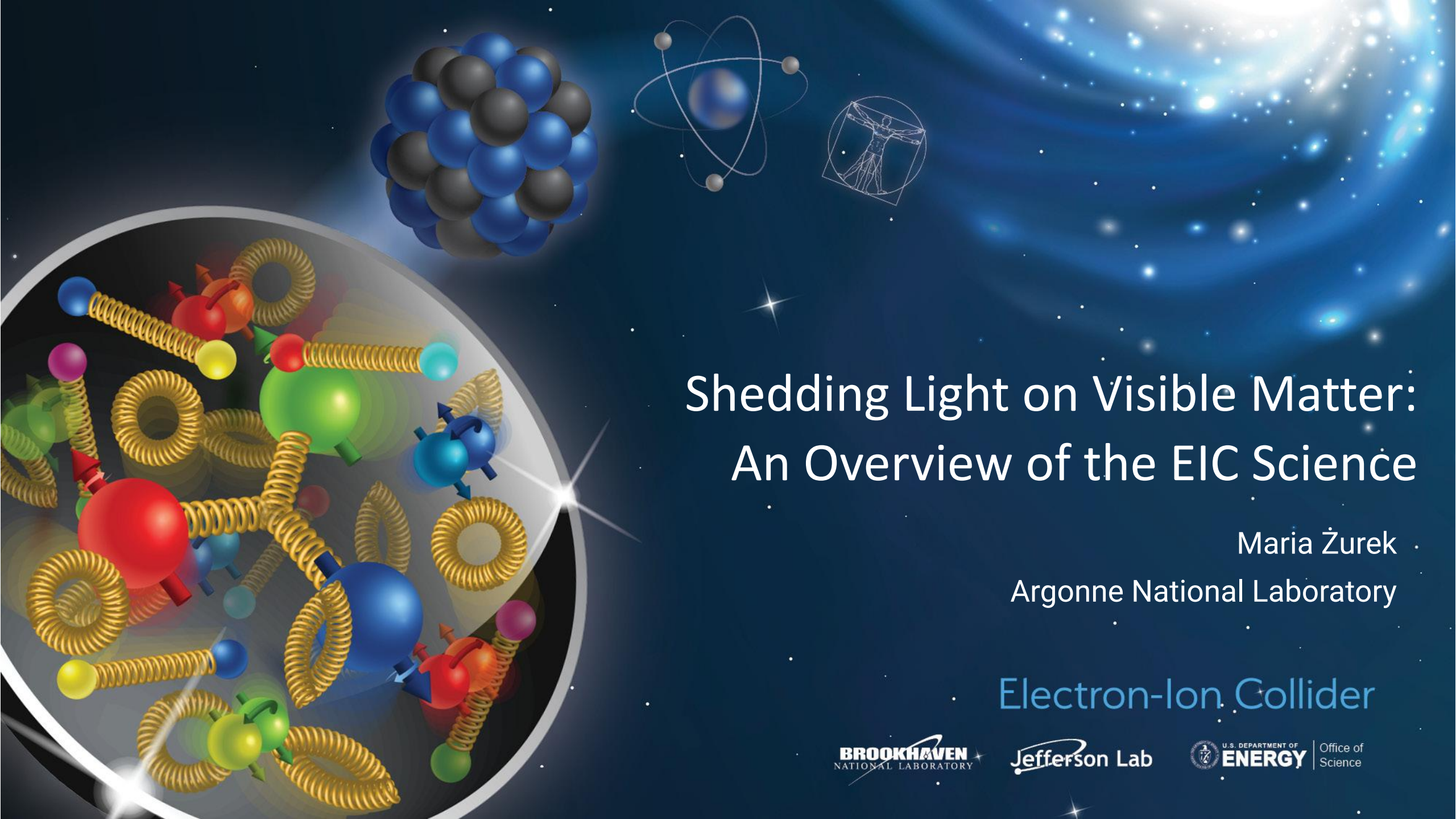


Shedding Light on Visible Matter: An Overview of the EIC Science

Maria Żurek

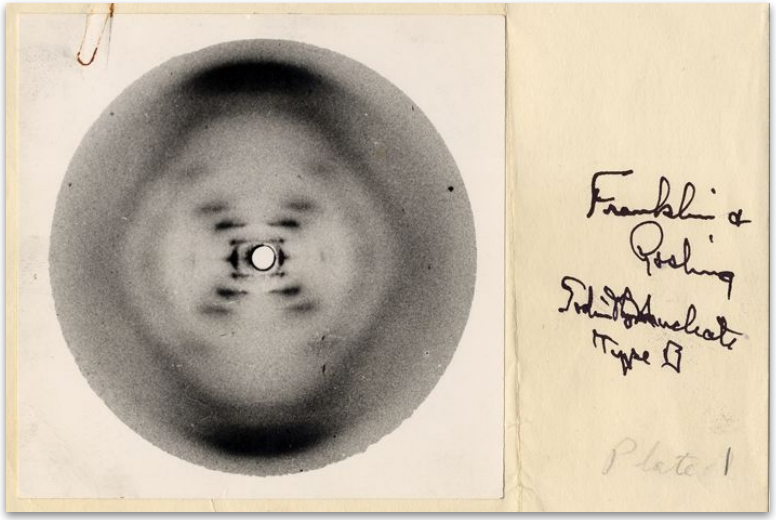
Argonne National Laboratory

Electron-Ion Collider

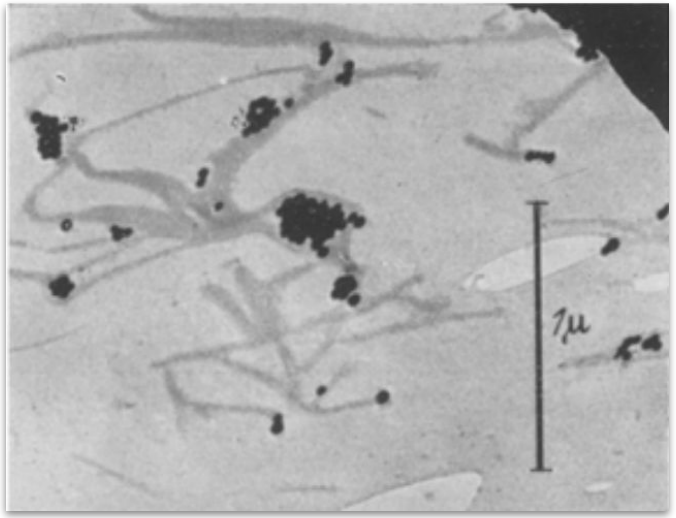
BROOKHAVEN NATIONAL LABORATORY

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science



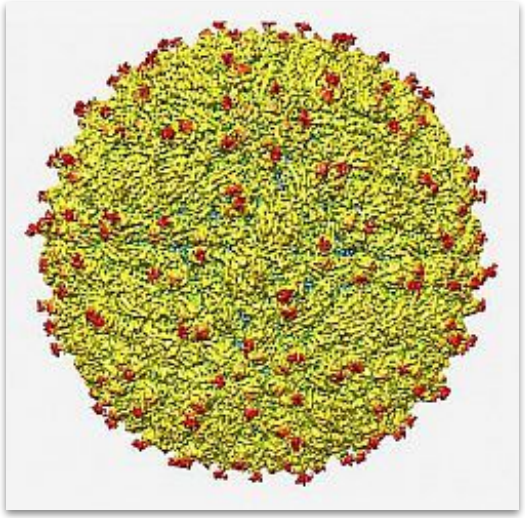
Rosalind Franklin's "Photo 51" (1952) – DNA Double Helix



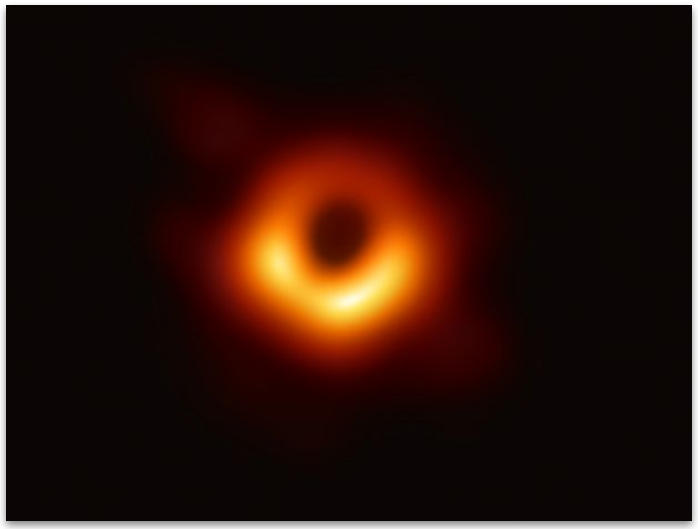
First Electron Microscope Image of a Virus (1939)

High-resolution Ribosome Structure (2000)

Hubble Deep Field Picture (1995)



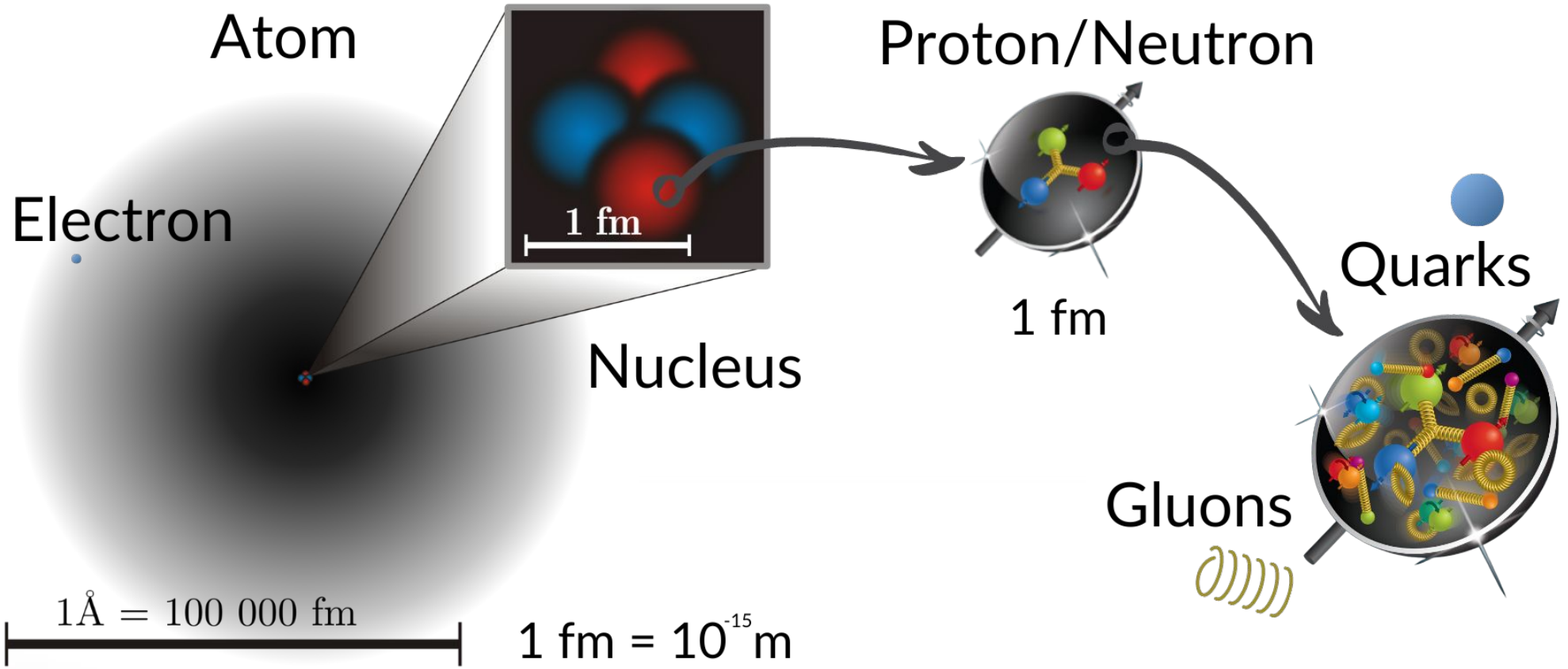
Cryo-EM Image of Zika Virus (2016)



First Image of a Black Hole (2019)

Pictures: See Bibliography on Slide 22

Exploring the Structure of Visible Matter: Nuclear Femtoscopy



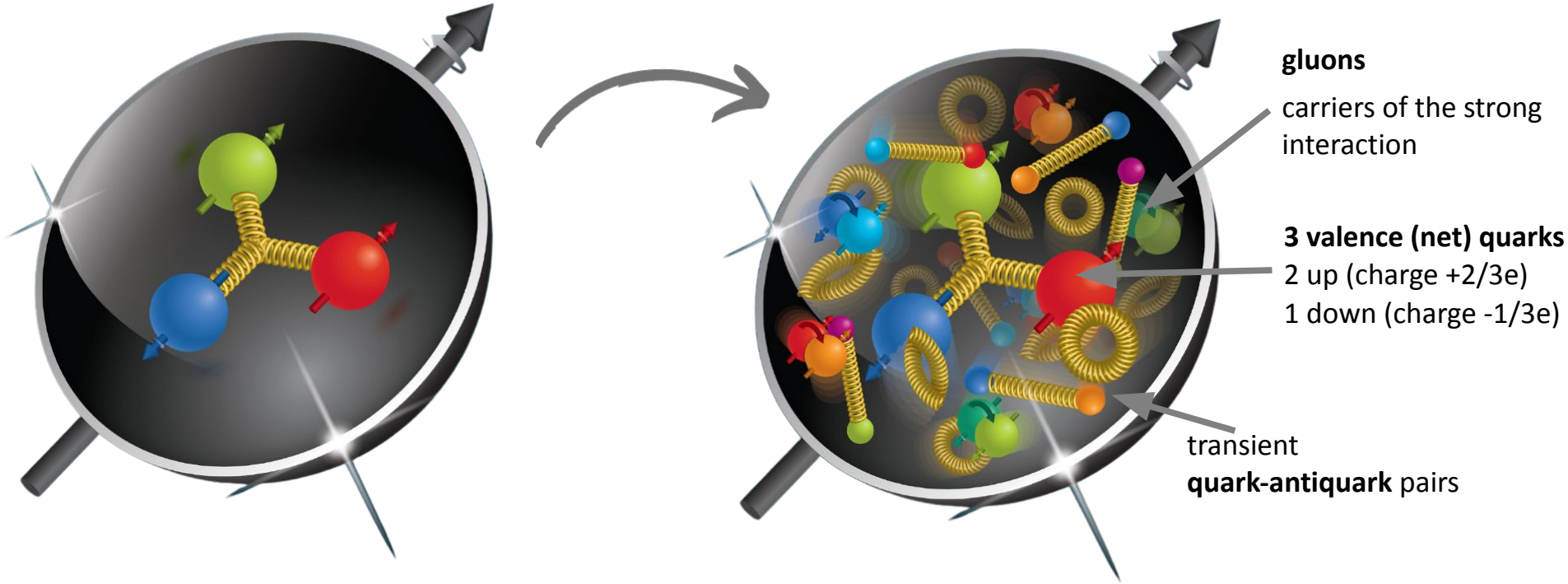
How does visible matter and its properties emerge from the smallest elementary constituents?

EIC: *Understanding the Glue that Binds Us All*

Electron-Ion Collider

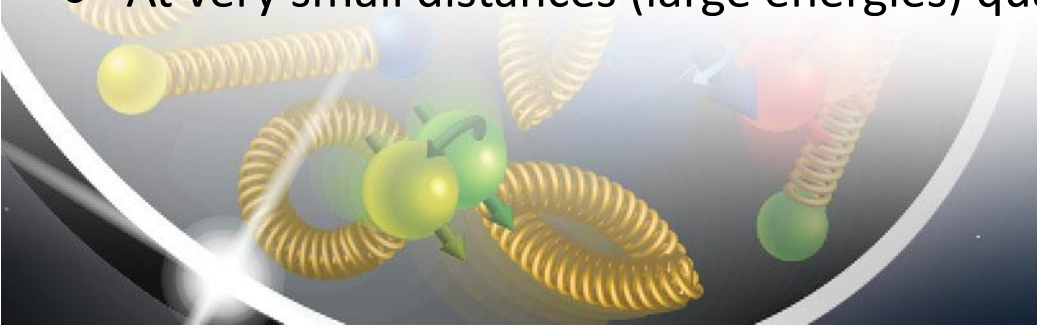
Pictures: adapted from Brookhaven National Laboratory, Wikimedia Commons

The Evolving Understanding of the Structure of the Nucleon



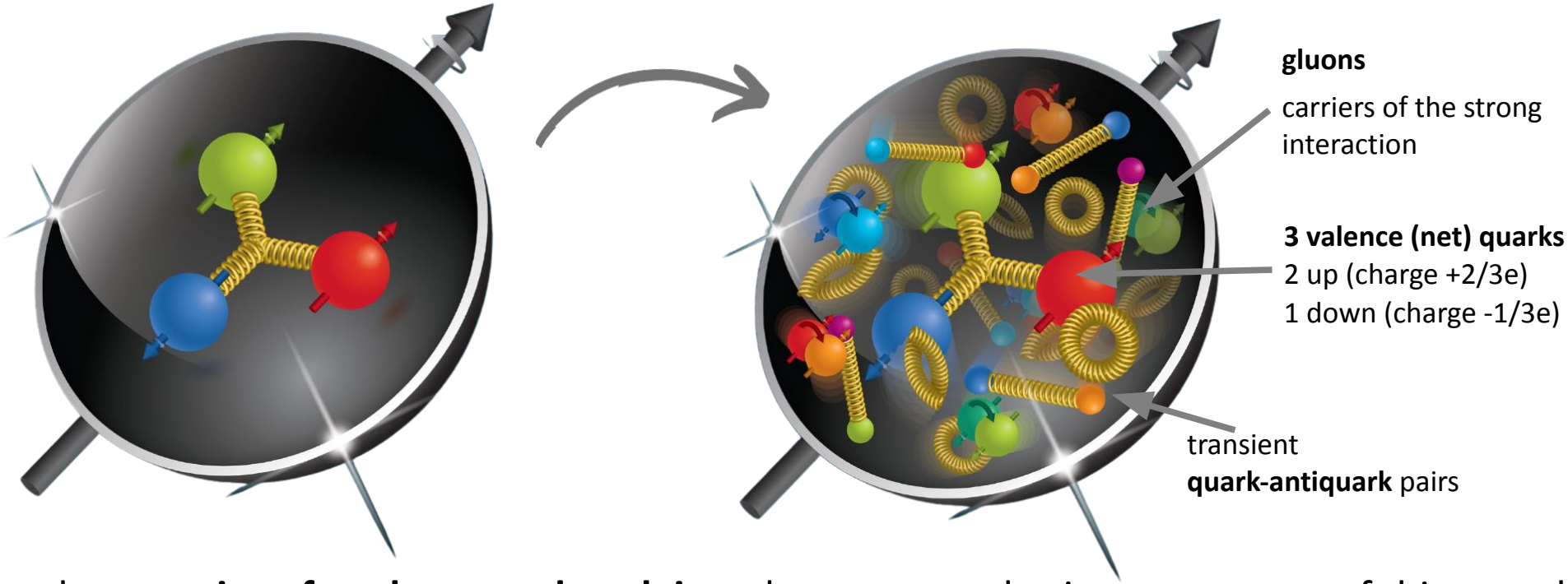
The theory that describes interactions between quarks and gluons (partons): **Quantum Chromodynamics**

- The *color* force gets stronger at large distances → quarks and gluons can not be found in isolation
- At very small distances (large energies) quarks barely interact and are nearly free



Pictures: adapted from Brookhaven National Laboratory

The Evolving Understanding of the Structure of the Nucleon



The observed **properties of nucleons and nuclei**, such as mass and spin, **emerge** out of this complex system of interacting quarks and gluons

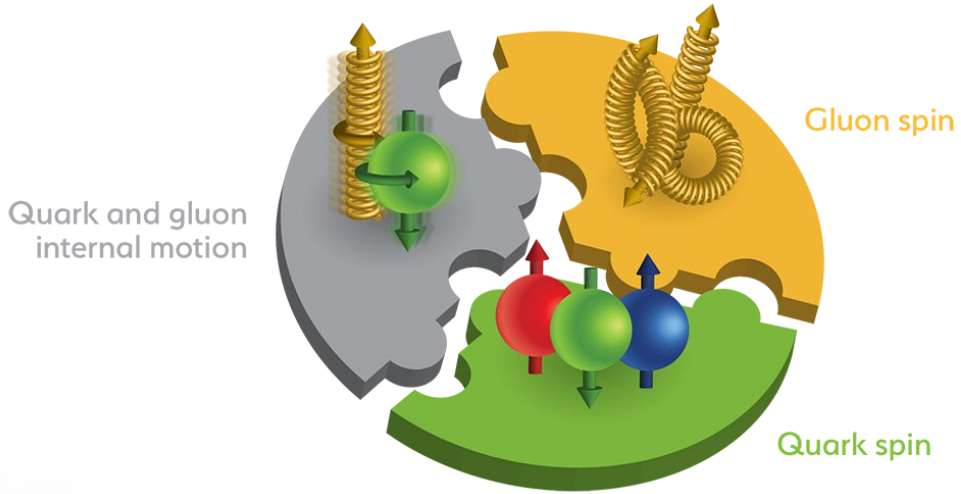
The EIC aims to reveal the internal structure of the proton and nuclei, comparable to our understanding of the electronic structure of atoms that drives modern technologies

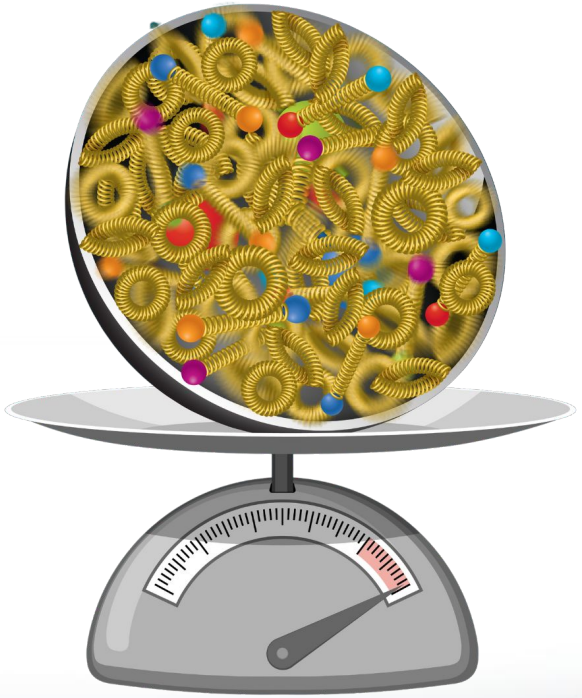
Pictures: adapted from Brookhaven National Laboratory

Peering into the Heart of Matter

The Physics Quest of the EIC

- How do the nucleon properties like mass and spin emerge from their partonic structure?
- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?



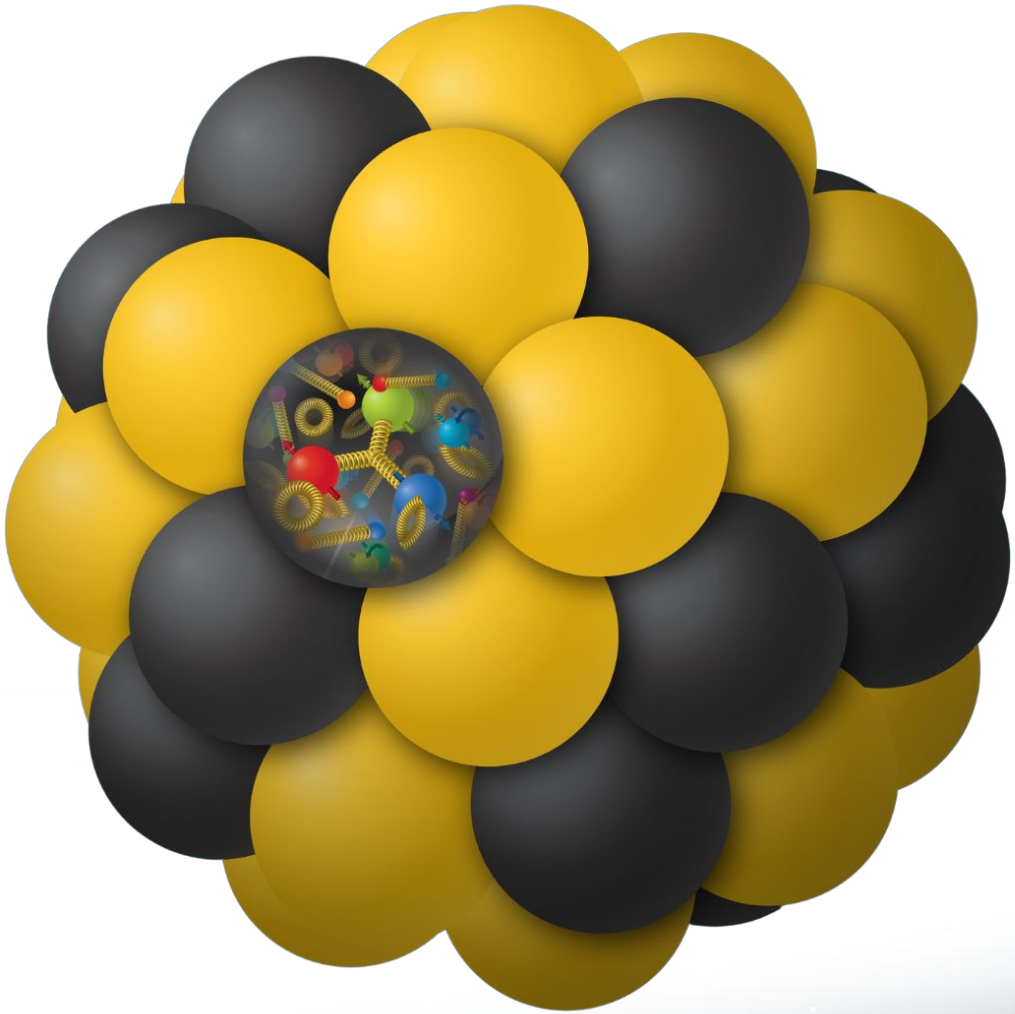


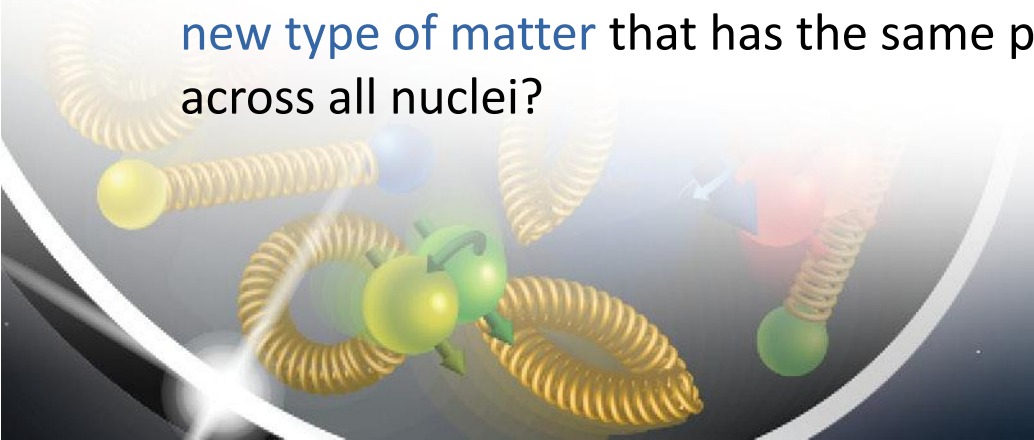
Pictures: adapted from Brookhaven National Laboratory

Peering into the Heart of Matter

The Physics Quest of the EIC

- What impact does a high-density nuclear environment have on the interactions, correlations, and behaviors of quarks and gluons?
- What is the mechanism through which quark-gluon interactions give rise to interactions between protons and neutrons that bind nucleus together?
- Is there a limit to how densely gluons can be packed inside nuclei at high energies (so called saturation point)? And if so, could this lead to a new type of matter that has the same properties across all nuclei?





Pictures: adapted from Brookhaven National Laboratory

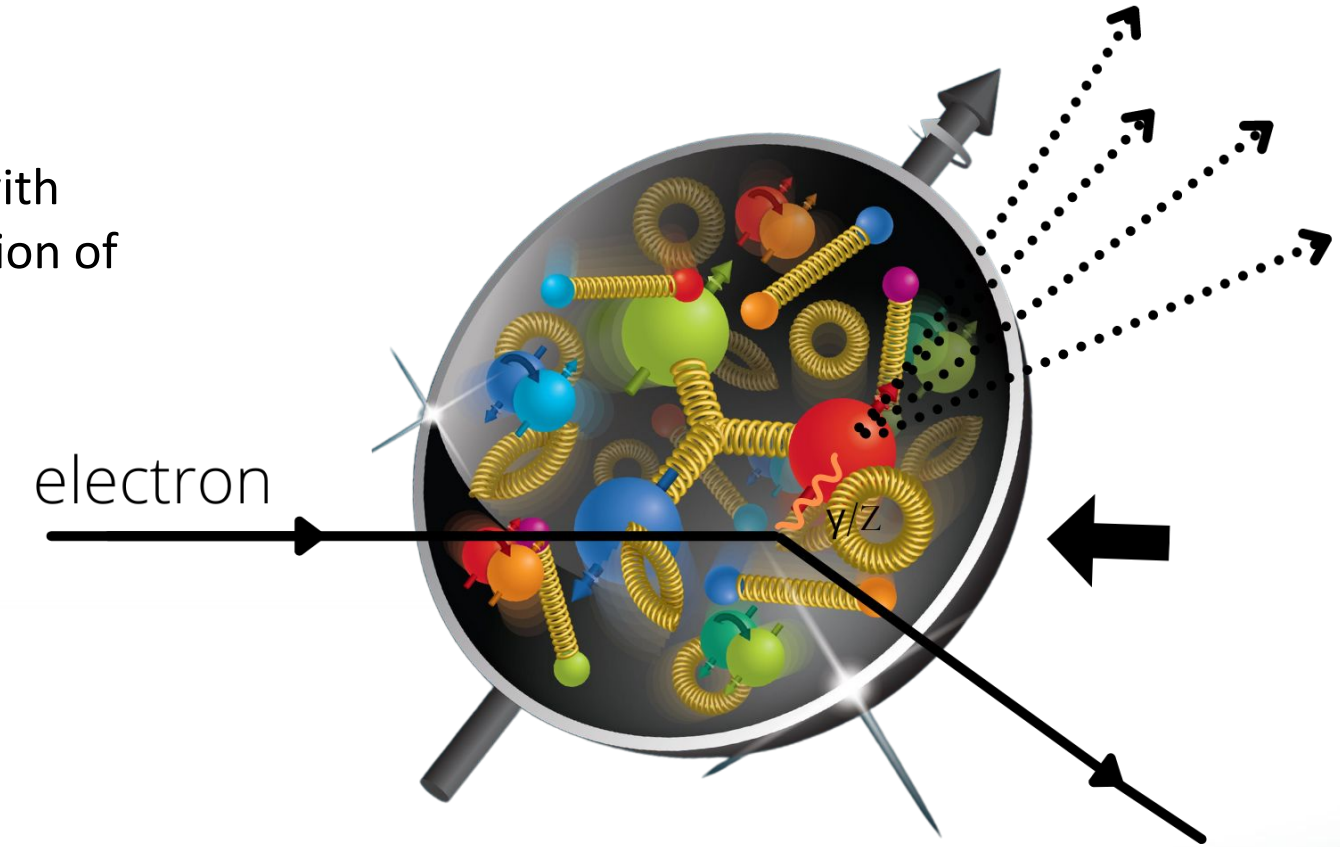
How will the EIC Study the Structure of Visible Matter

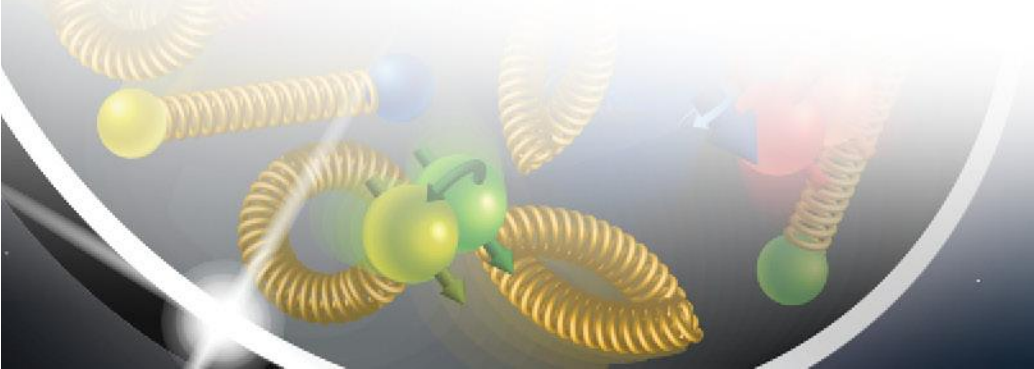
Deep Inelastic Scattering

- **Golden process to probe nucleons and nuclei** with electron beams providing the unmatched precision of electromagnetic interactions

$$Q^2 = s \cdot x \cdot y$$

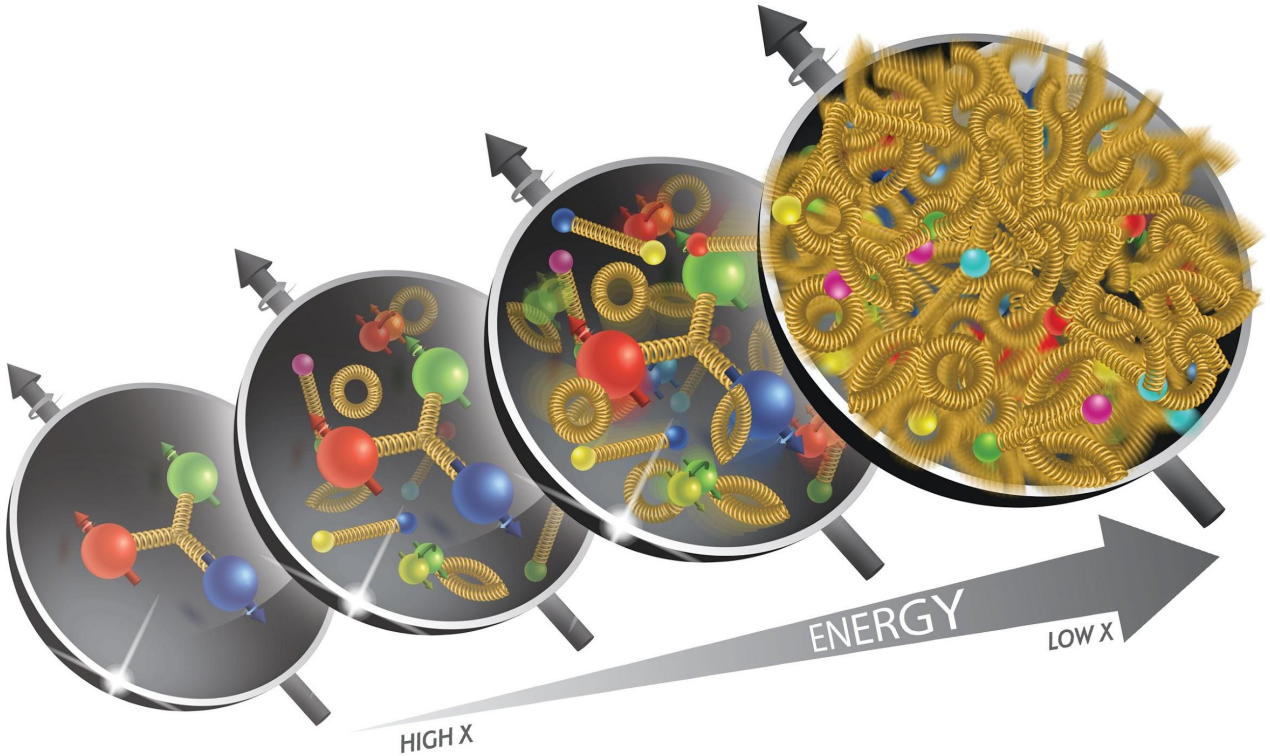
Q^2 – resolution power (virtuality of the photon)
s – center-of-mass energy squared
x – the fraction of the nucleon's momentum that the struck quark caries
y – inelasticity





Pictures: adapted from Brookhaven National Laboratory

How will the EIC Study the Structure of Visible Matter



Center-of-mass energy $\sqrt{s}$: 20 – 140 GeV

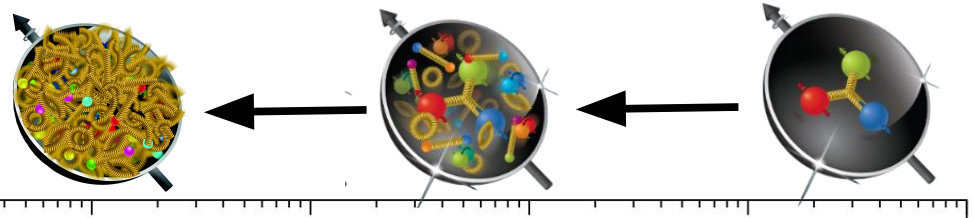
Explore QCD landscape over large range of resolution (Q^2) and quark/gluon density (1/x)

EIC needed as microscope to explore the region from where a proton is (mostly) an up-up-down quark system to the gluon dominated region

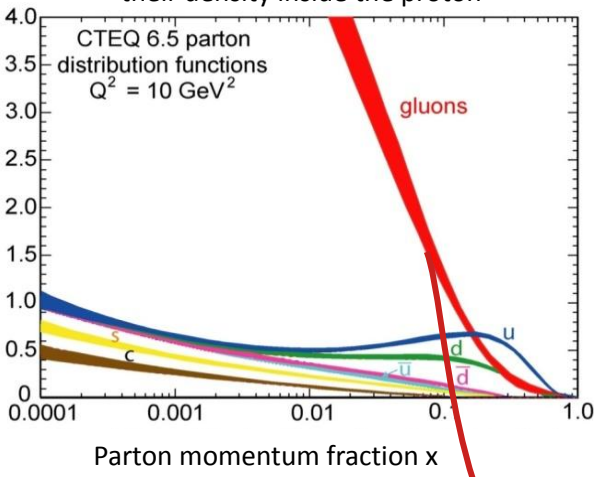
Pictures: adapted from Brookhaven National Laboratory

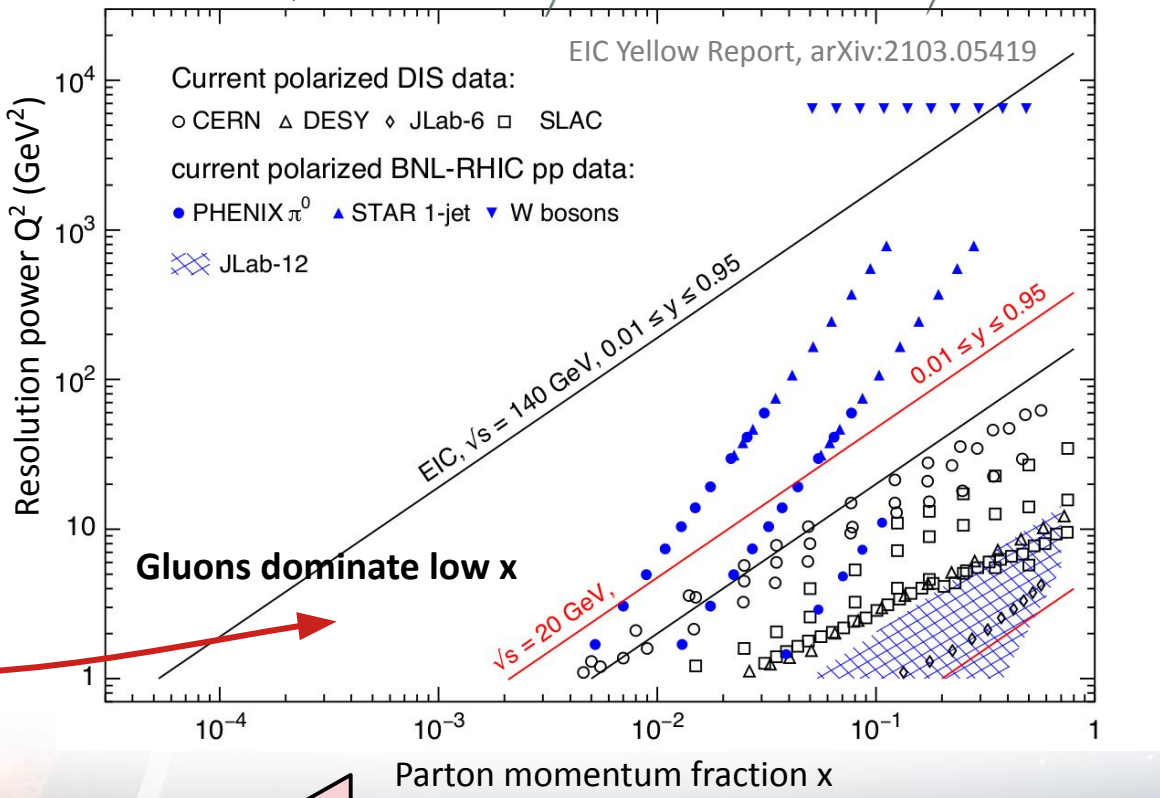
Probing Uncharted Territory

Unprecedented Access to Nucleon and Nucleus Structure



Quarks and gluons momentum fraction times their density inside the proton





Larger center of mass energy

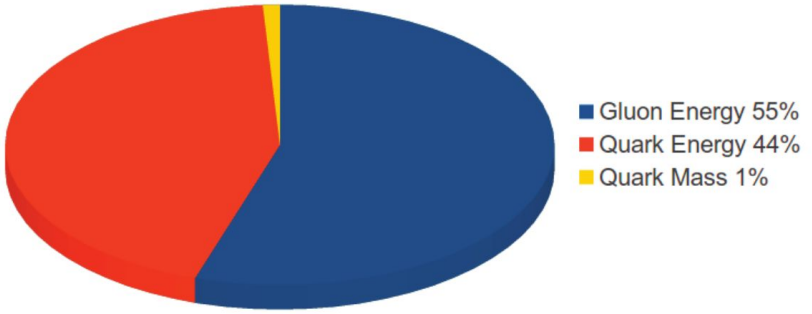
Larger center of mass energy and luminosity

Electron-Ion Collider

Pictures: adapted from Brookhaven National Laboratory

How do Nucleons Acquire Mass?

Contributions to the total mass of the nucleon



Gluons have no mass and **quarks are nearly massless**, but nucleons and nuclei are heavy, making up most of the visible mass of the universe

Visible world mostly made out of light quarks: **masses emerge form quark-gluon interactions**

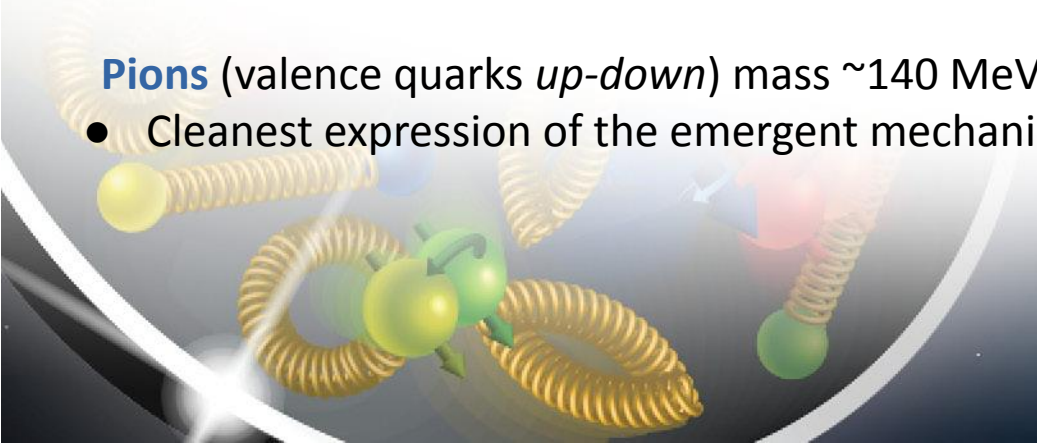
Proton (valence quarks *up-up-down*) - mass ~940 MeV

- The mass is dominated by the energy of the highly relativistic gluonic fields
- EIC will allow determination of an important term contributing to the proton mass, the so-called "QCD trace anomaly" → accessible in exclusive reactions

What about the mass of light mesons (quark-antiquark bound states)?

Pions (valence quarks *up-down*) mass ~140 MeV

- Cleanest expression of the emergent mechanism: Empty or full of gluons?

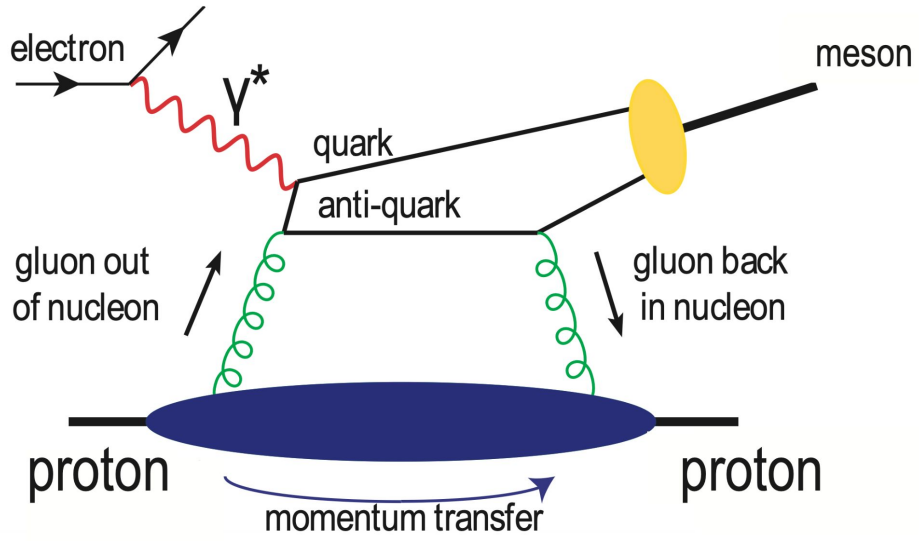


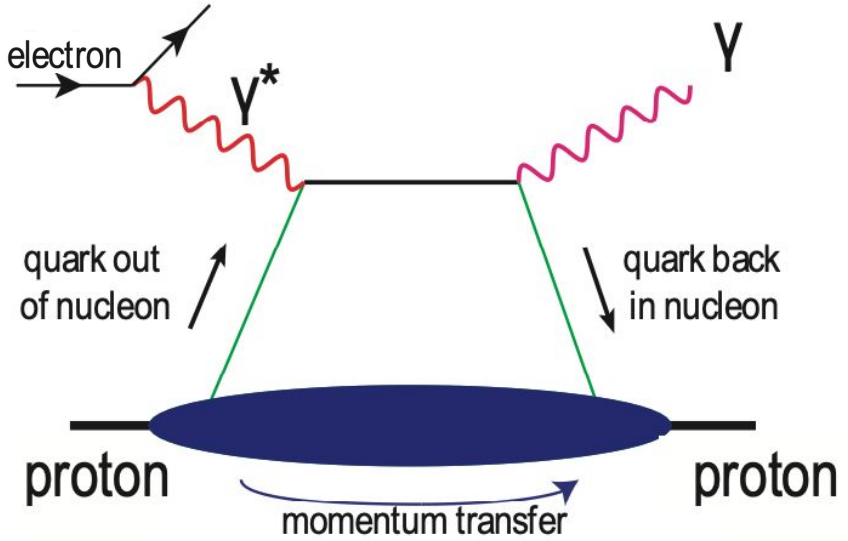
Electron-Ion Collider

Pictures: adapted from Brookhaven National Laboratory (bottom), EIC NAS Assessment (top)

Tomographic Image of Quarks and Gluons within Matter

Spatial imaging of Quarks and Gluons via exclusive reactions where the nucleon is left intact in the final state





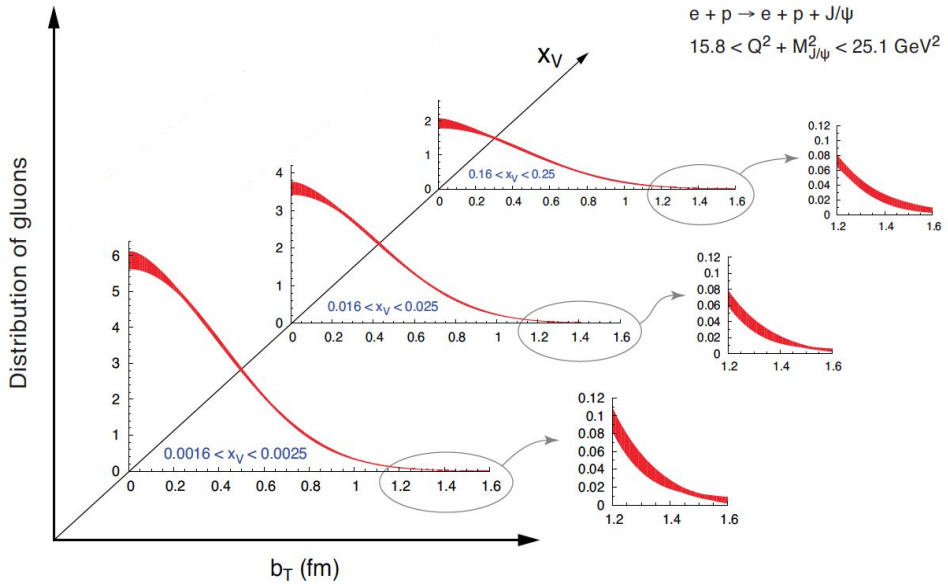
Deeply Virtual Meson production: quark-antiquark bound state is produced

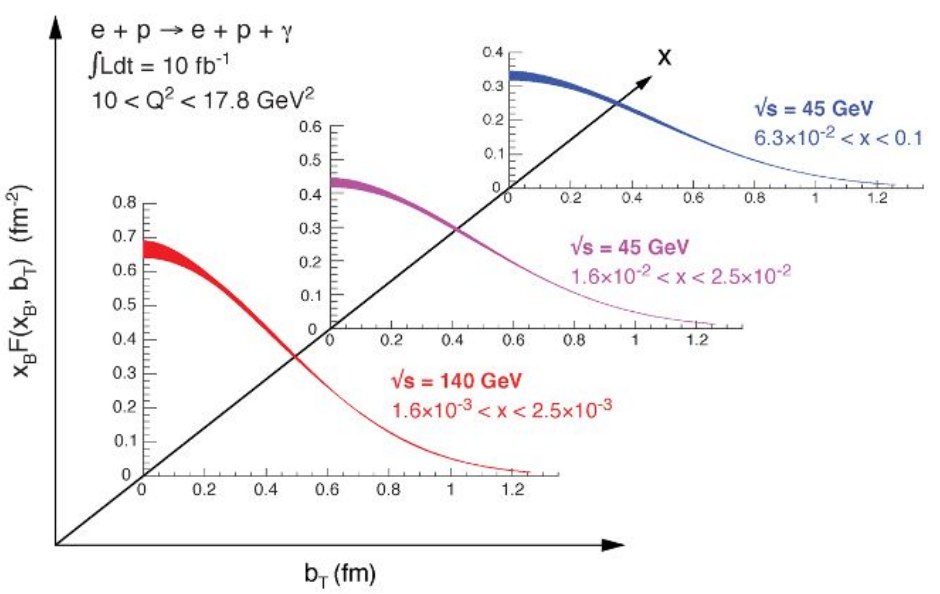
Deeply Virtual Photon scattering: real photon is produced

Pictures: adapted from EIC NAS Assessment

Tomographic Image of Quarks and Gluons within Matter

Spatial imaging of Quarks and Gluons via exclusive reactions where the nucleon is left intact in the final state





Deeply Virtual J/Ψ production: quark-antiquark bound state is produced

Deeply Virtual Photon scattering: real photon is produced

EIC will take first ever tomographic images of ocean of gluons within matter!

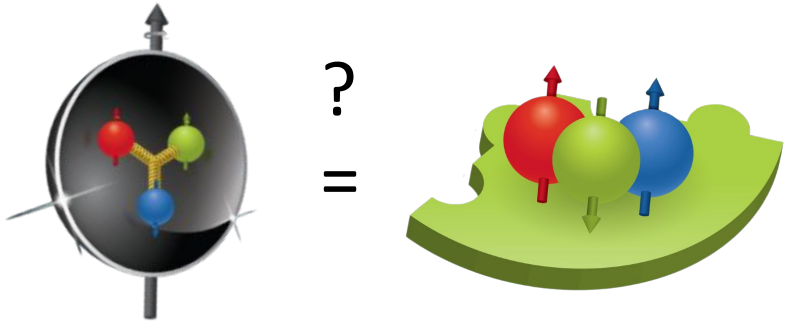
Electron-Ion Collider

Pictures: EIC NAS Assessment (left) and arXiv:1108.1713 (right)

Unraveling the Mystery of the Origin of the Nucleon Spin

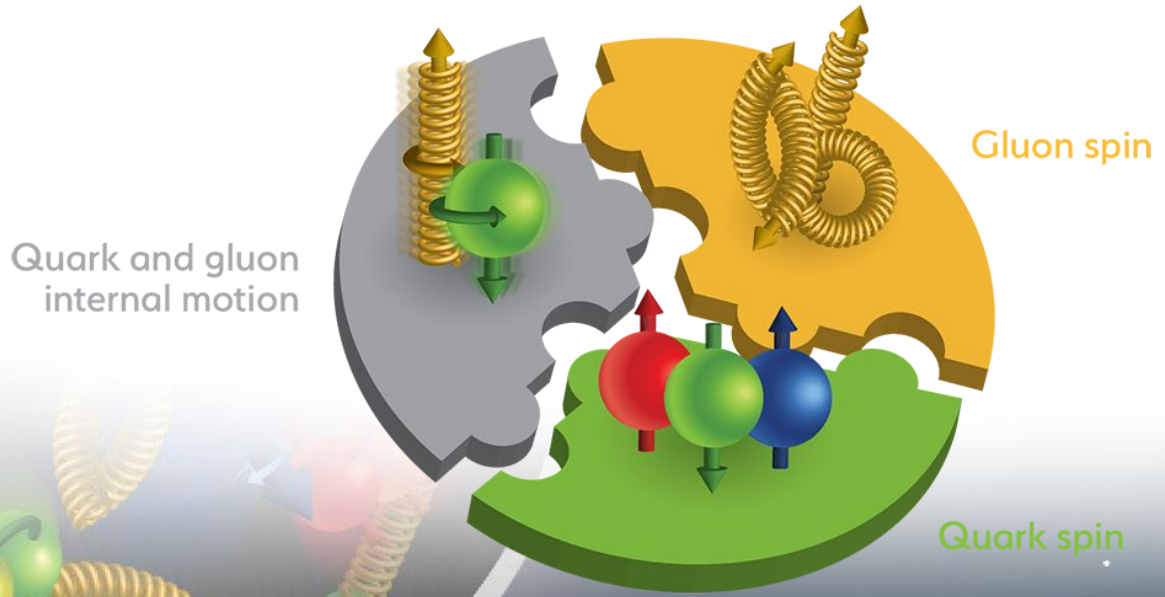
Spin – one of the fundamental properties of particles

How does the **nucleon spin originate** from its **quark, anti-quark,** and **gluon** constituents and their dynamics?



Proton Spin Puzzle
EMC Experiment (1987)

- Proton spin doesn't originate only from its 3 valence-quark spins
- After decades of experiments: quark spins contribute ~30% to the proton spin



Electron-Ion Collider

Pictures: adapted from Brookhaven National Laboratory

Unraveling the Mystery of the Origin of the Nucleon Spin

$$\Delta\Sigma/2 + \Delta G + \ell_q + \ell_g = \hbar/2$$

Quark spins

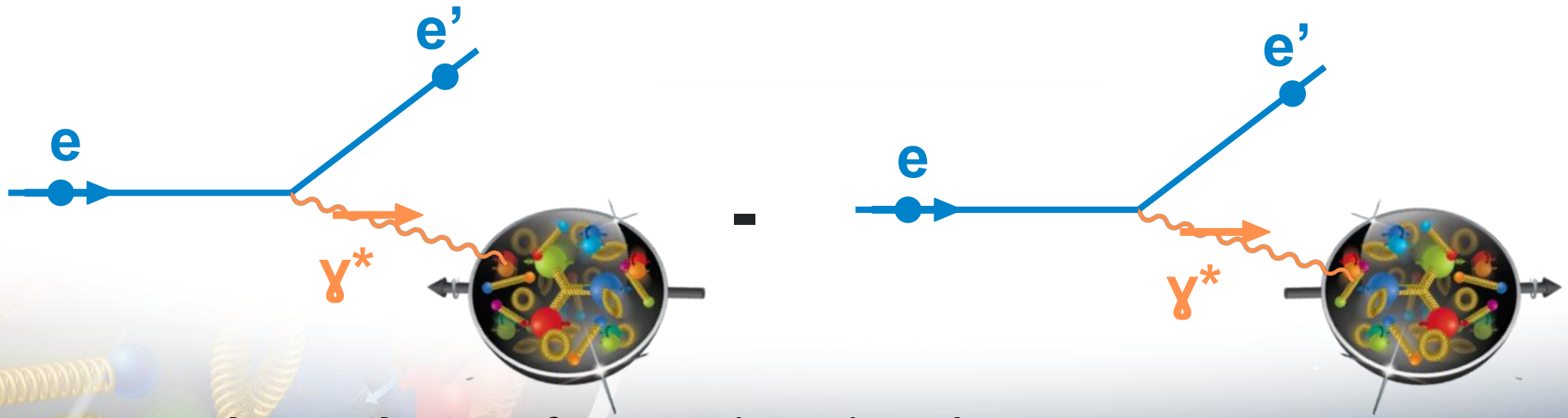
Gluon spins

Quark orbital angular momentum

Gluon orbital angular momentum

Access to gluon spin with the measurement of the so-called g_1 structure function

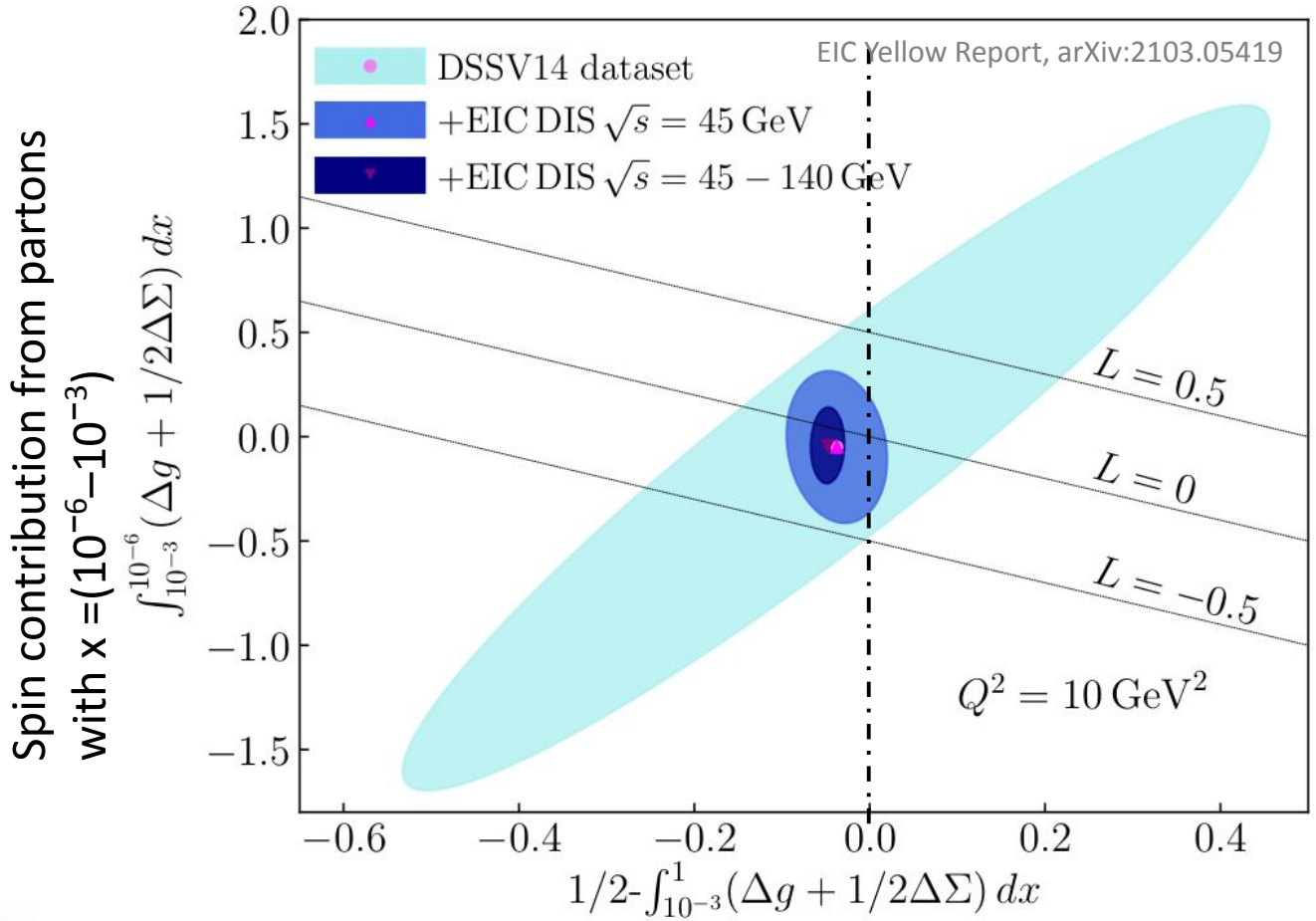
- Difference of cross-sections with **different longitudinal spin orientation** of e and proton



Access to quark contribution of OAM – through exclusive processes

Pictures: adapted from Brookhaven National Laboratory

Unraveling the Mystery of the Origin of the Nucleon Spin



Room left for potential OAM contributions to the proton spin from partons with x > 0.001

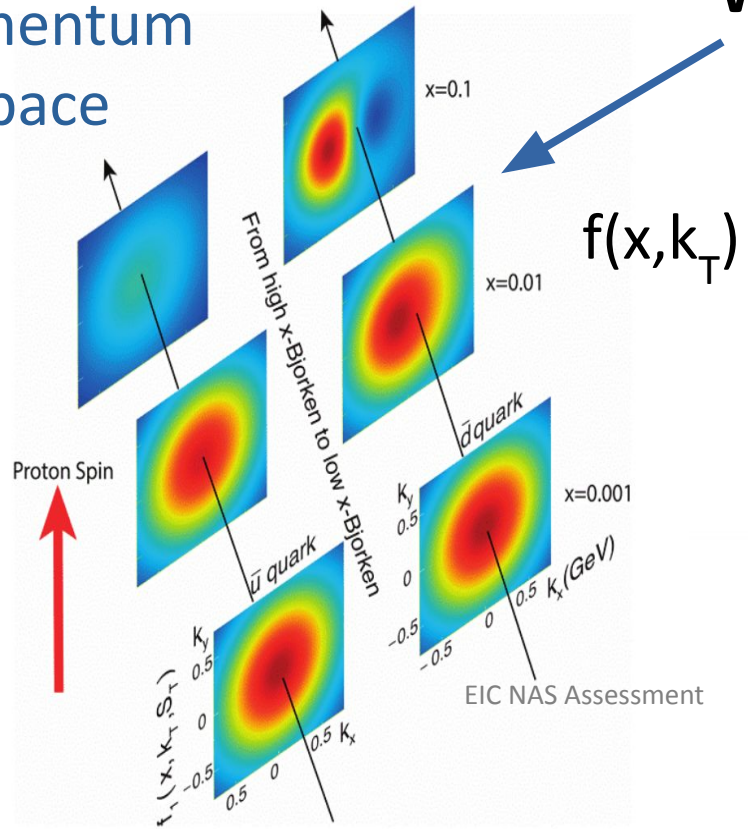
Spatial and Momentum Structure of Nucleons and Nuclei in 3D

Wigner functions

$W(x,b_T,k_T)$

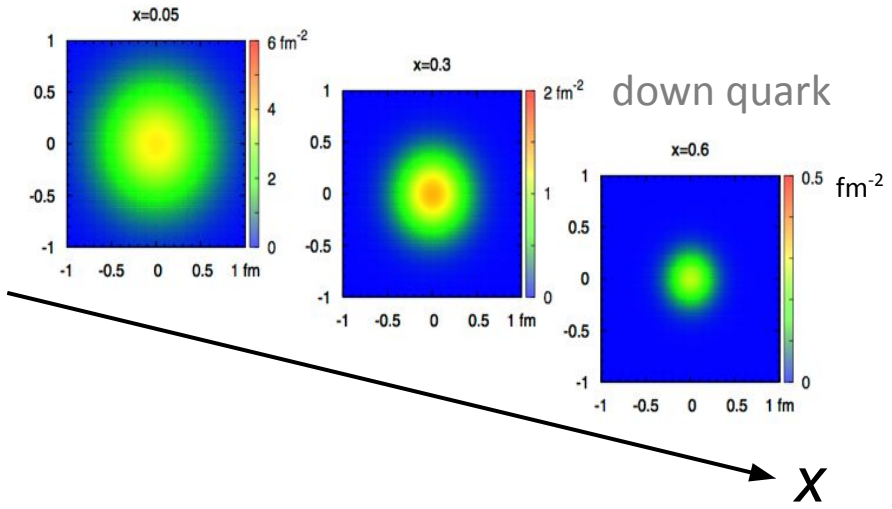
Momentum space

$f(x,k_T)$



Coordinate space

$f(x,b_T)$



→ **Access to e.g., spin-orbit correlations**

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

k_T - transverse momentum

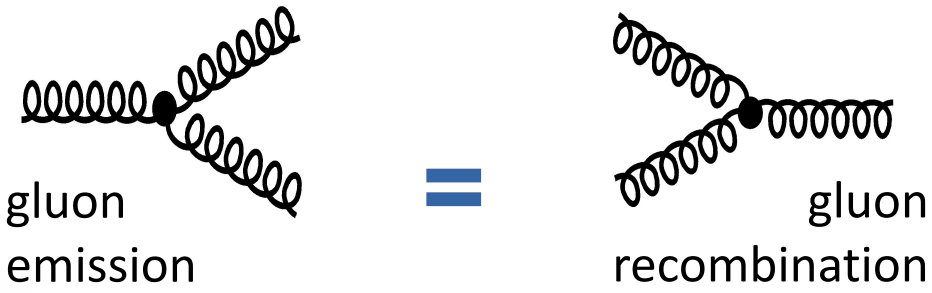
Spin-dependent 2+1D coordinate space images from exclusive scattering

b_T - transverse spatial position

Can the EIC Give Us Access to New State of Gluonic Matter?

What happens to the **gluon density in nuclei**?

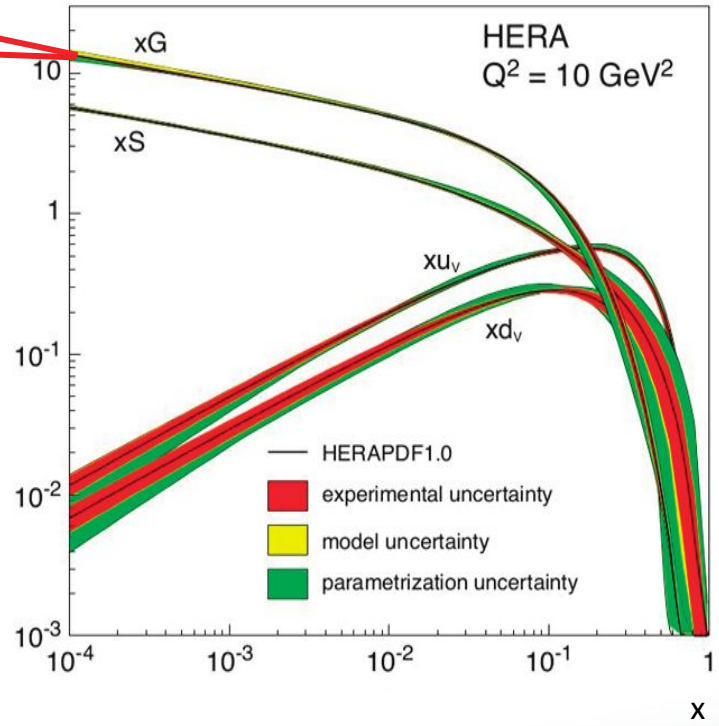
- Number of gluons **grows in the low-x limit**
- At some point the **density becomes so large** that gluons lose their individual identity and are **strongly overlapping**



At saturation scale Q_S

???

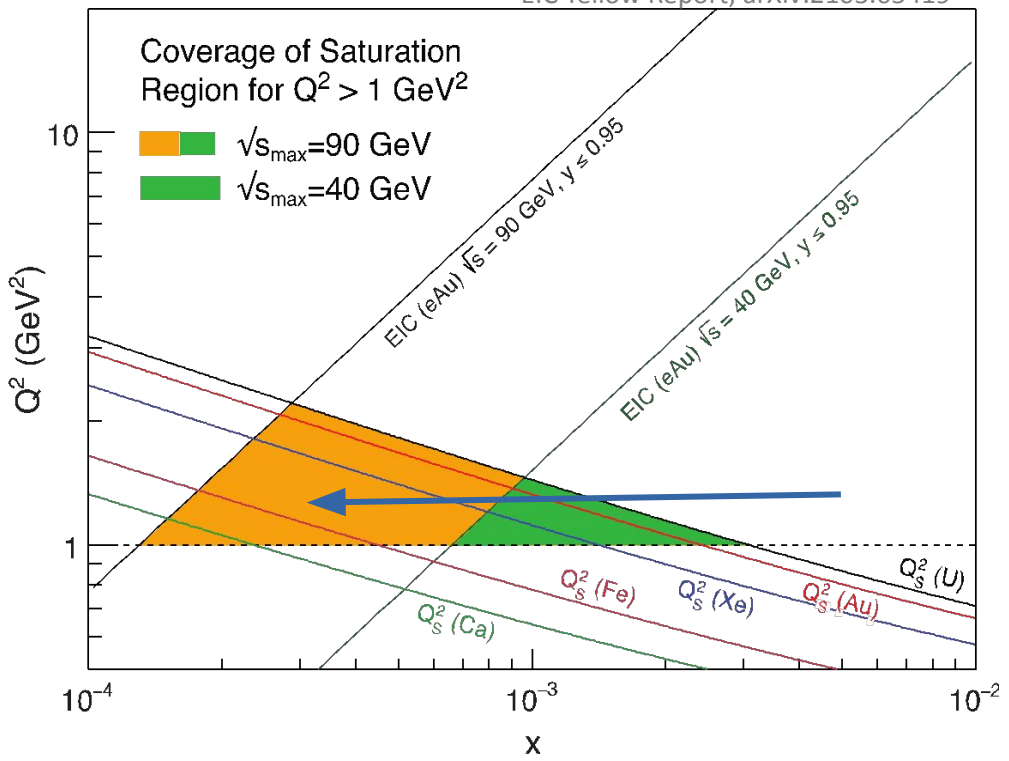
EIC NAS Assessment



Can the EIC Give Us Access to New State of Gluonic Matter?

- EIC provides a unique opportunity to have very high gluon densities
  electron – heavy nuclei (e.g., Pb) collisions
- Combined with an unambiguous observables, e.g., di-hadrons (jets) in ep and eA
- **EIC will allow to unambiguously map the transition from a non-saturated to saturated regime**

EIC Yellow Report, arXiv:2103.05419



Q_S – resolution scale at which the number density so large that gluons are no longer independent

$$Q_s^2 \propto \left(\frac{A}{x}\right)^{1/3}$$

Increases with mass number of a nucleus A

Decreased with momentum fraction x

Summary

EIC science program will profoundly impact our understanding of the most fundamental inner structure of the matter that builds us all

Our current knowledge about the structure of matter is a **mysterious dark room** even after decades of studies

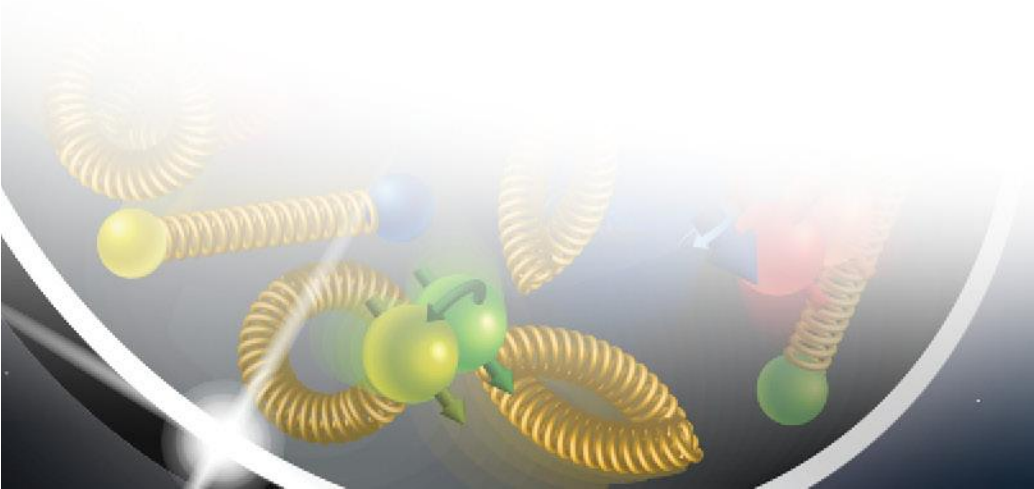
- We can see shadows and shapes with some important bright spots with existing tools
- With the EIC, we can turn on the light and reveal the hidden details inside

Access to EIC Physics through

- Large kinematic coverage
- Polarized electron and hadron beams and unpolarized nuclear beams with high luminosities
- Detector setup fulfilling specific requirements of the polarized e-p/A collider

Pictures: adapted from Brookhaven National Laboratory

Backup



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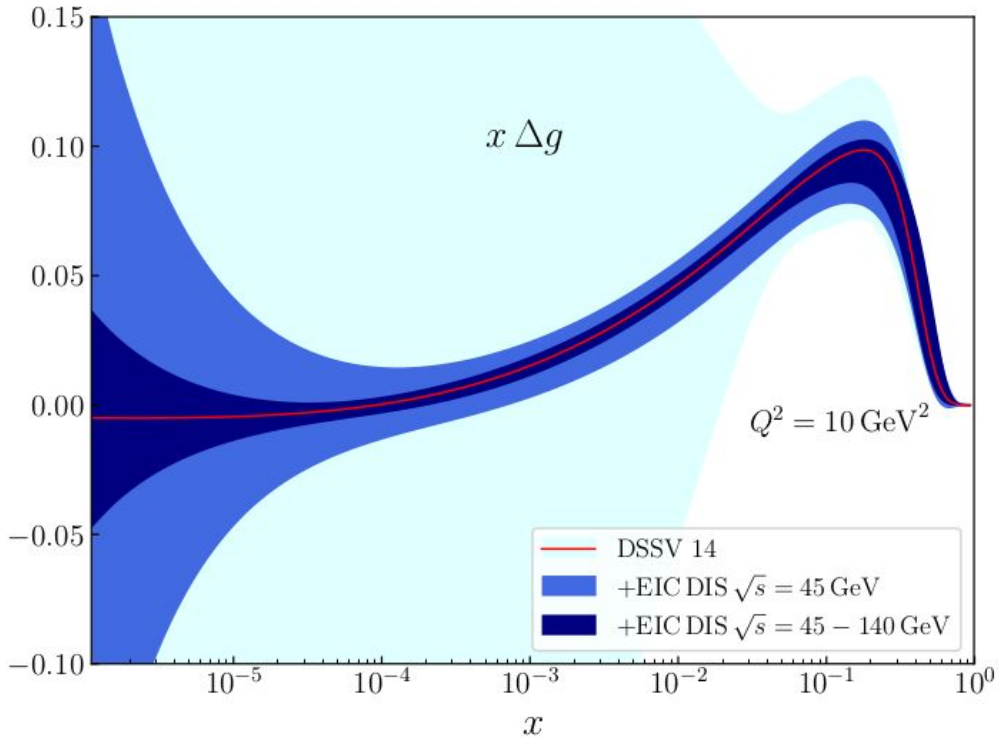
Pictures on Slide 2

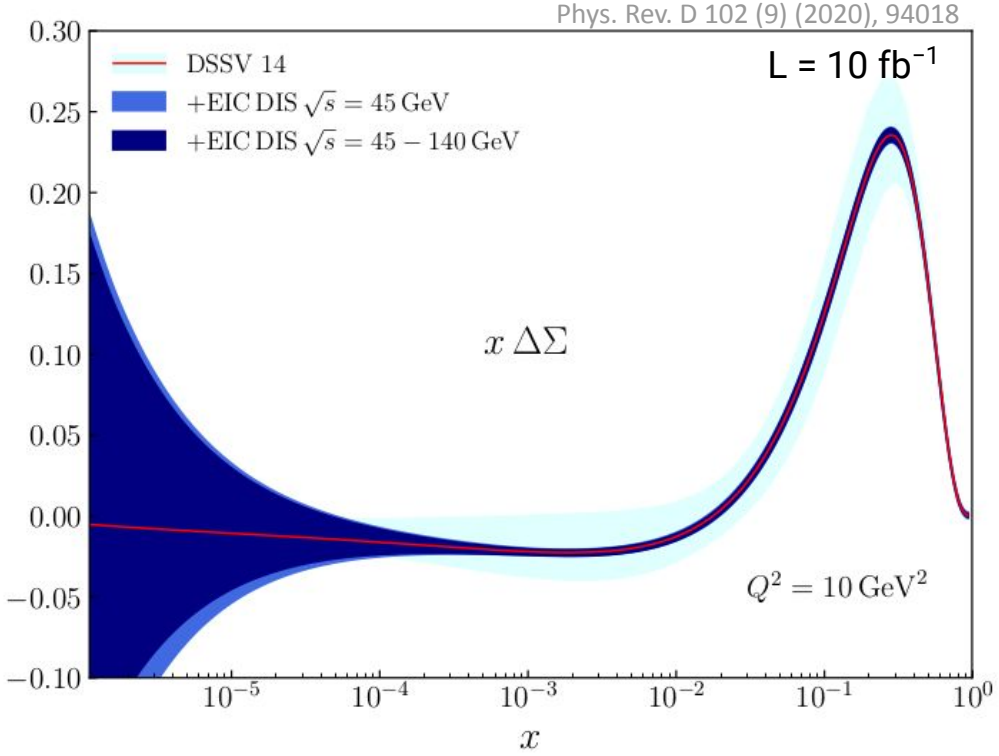
1. **Rosalind Franklin's "Photo 51"**
   - **Citation**: IUCr Newsletter. Rosalind Franklin (1920–1958). Volume 28, Number 2. Available at: IUCr
2. **First Electron Microscope Image of a Virus**
   - **Citation**: Bawden, F. C., & Pirie, N. W. (1939). The visualisation of viruses using electron microscopy. Naturwissenschaften, 27, 292–299. DOI: 10.1007/BF01489805
3. **High-Resolution Ribosome Structure**
   - **Citation**: Ramakrishnan, V., Steitz, T. A., & Yonath, A. (2009). Nobel Prize in Chemistry for studies on the structure and function of the ribosome. Available at: LMB
4. **Hubble Deep Field**
   - **Citation**: NASA, Robert Williams, and the Hubble Deep Field Team (STScI). Hubble Deep Field. Available at: NASA
5. **Cryo-EM Image of Zika Virus**
   - **Citation**: Zhu, Y. et al. (2016). Cryo-EM analysis of the Zika virus. Science, 352(6284), 467–470. DOI: 10.1126/science.aaf5316
6. **First Image of a Black Hole**
   - **Citation**: The Event Horizon Telescope Collaboration et al. (2019). First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole. The Astrophysical Journal Letters, 875, L1. DOI: 10.3847/2041-8213/ab0ec7

Unraveling the Mystery of the Origin of the Nucleon Spin

Projected impact of the EIC pseudodata on the gluon and sea-quark spin contribution to the proton spin

Phys. Rev. D 102 (9) (2020), 94018

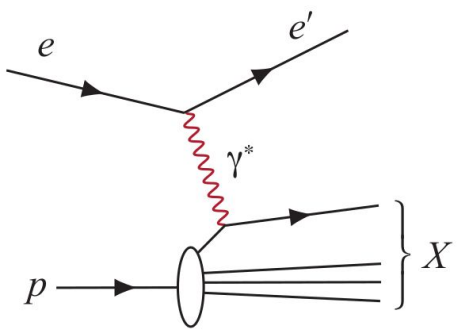




Current world data: Helicity distributions known for **x > ~0.01** with good precision

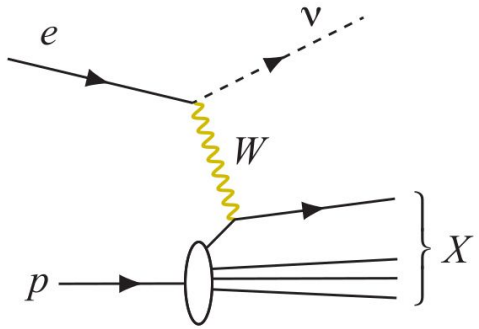
Experimental Processes to Access EIC Physics

DIS event kinematics - scattered electron or final state particles



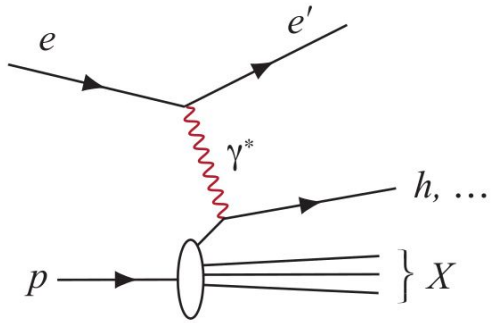
Neutral Current DIS

- Detection of scattered electron with high precision - event kinematics



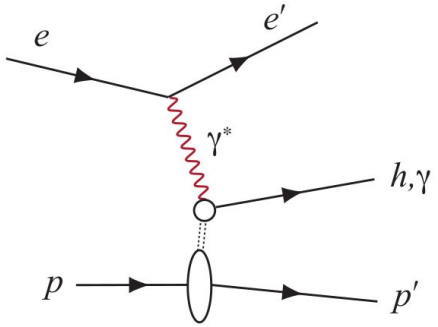
Charged Current DIS

- Event kinematics from the final state particles



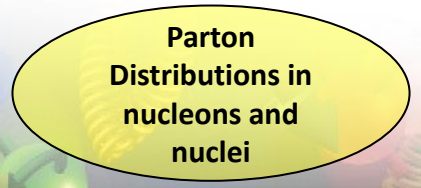
Semi-Inclusive DIS

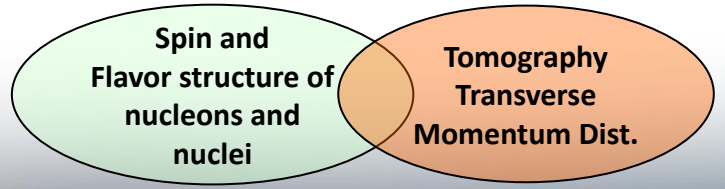
- Precise detection of scattered electron in coincidence with at least 1 hadron

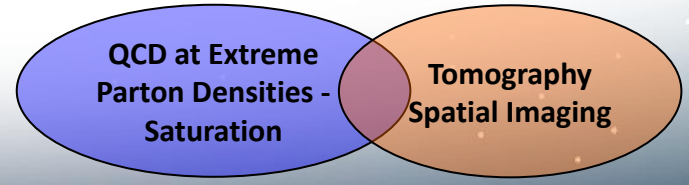


Deep Exclusive Processes

- Detection of all particles in event







Experimental Processes to Access EIC Physics