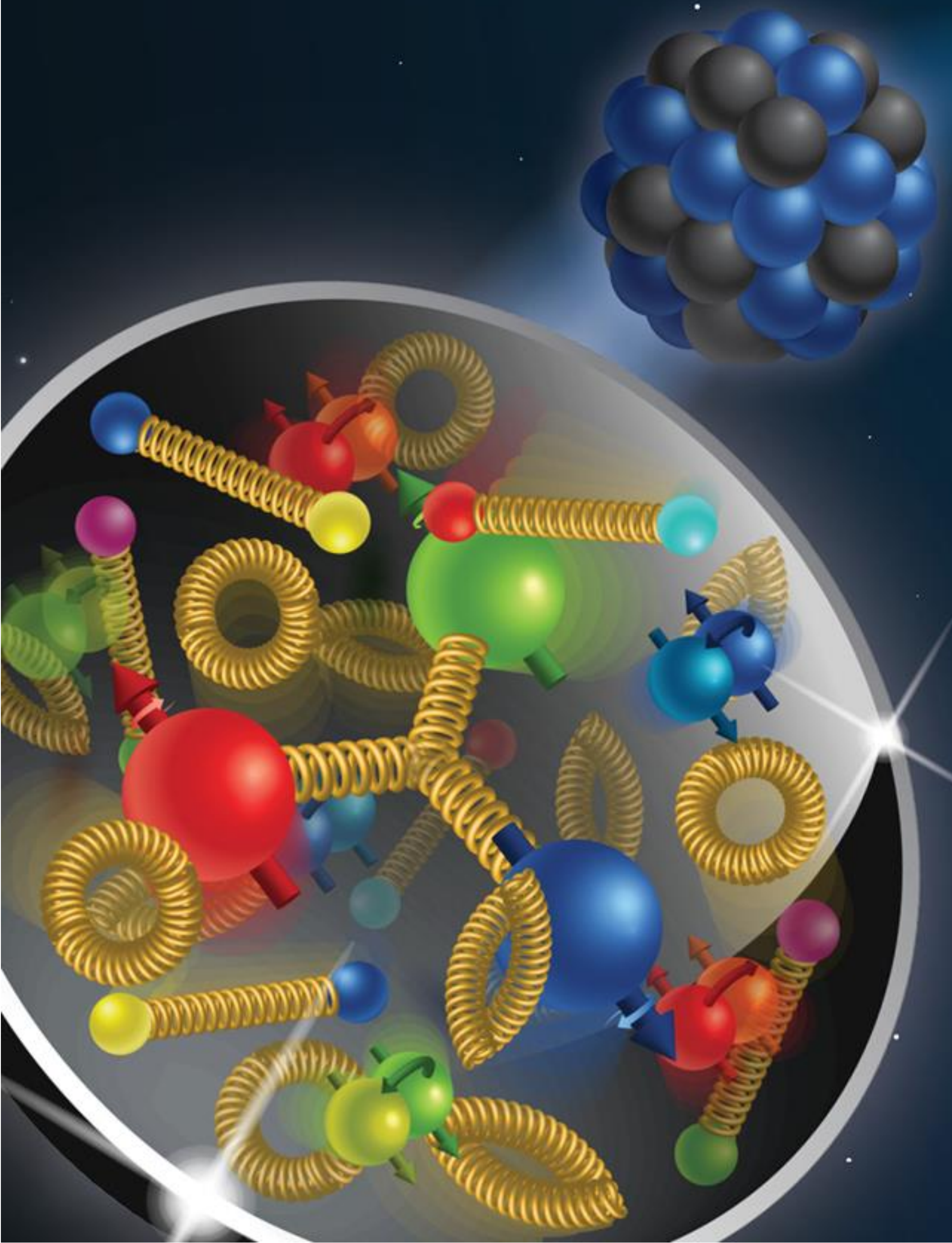
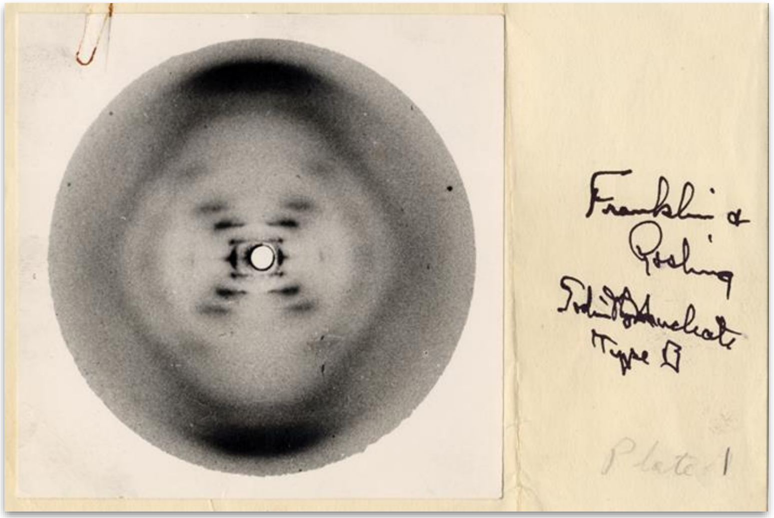


Shedding Light on Visible Matter: An Overview of the EIC Science

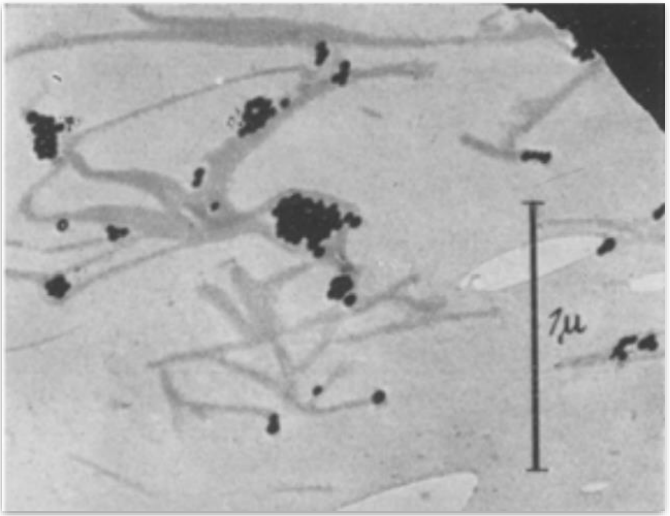
Maria Żurek

Argonne National Laboratory

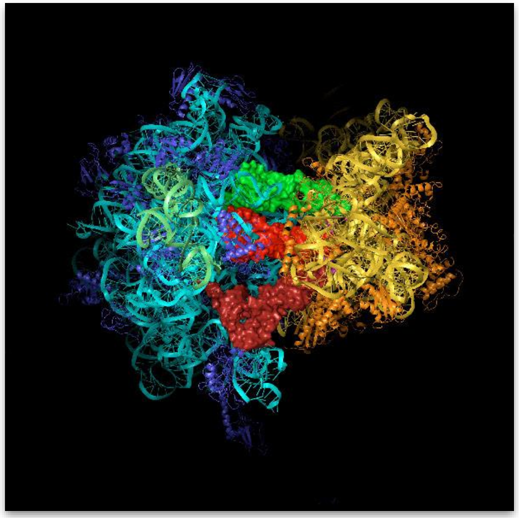
Electron-Ion Collider



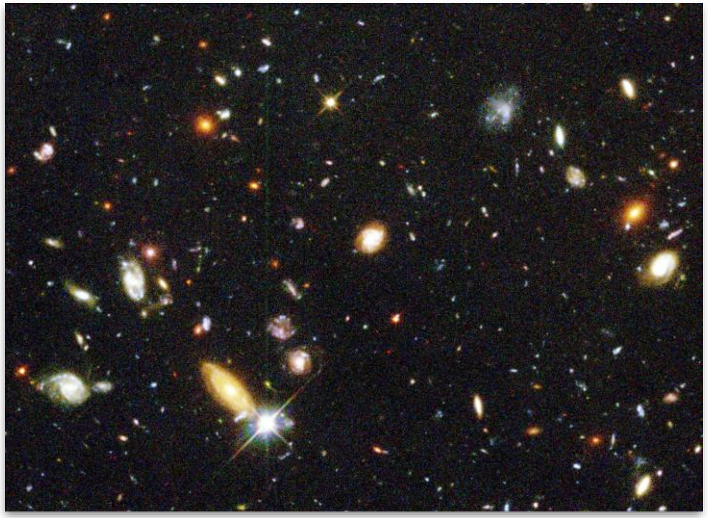
Rosalind Franklin’s “Photo 51” (1952) – DNA Double Helix



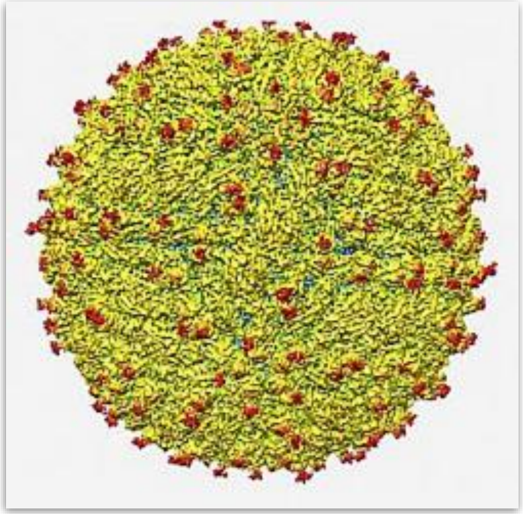
First Electron Microscope Image of a Virus (1939)



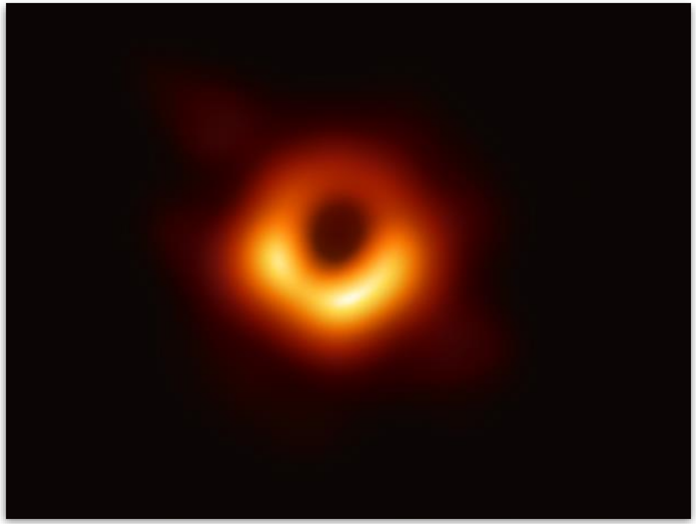
High-resolution Ribosome Structure (2000)



Hubble Deep Field Picture (1995)



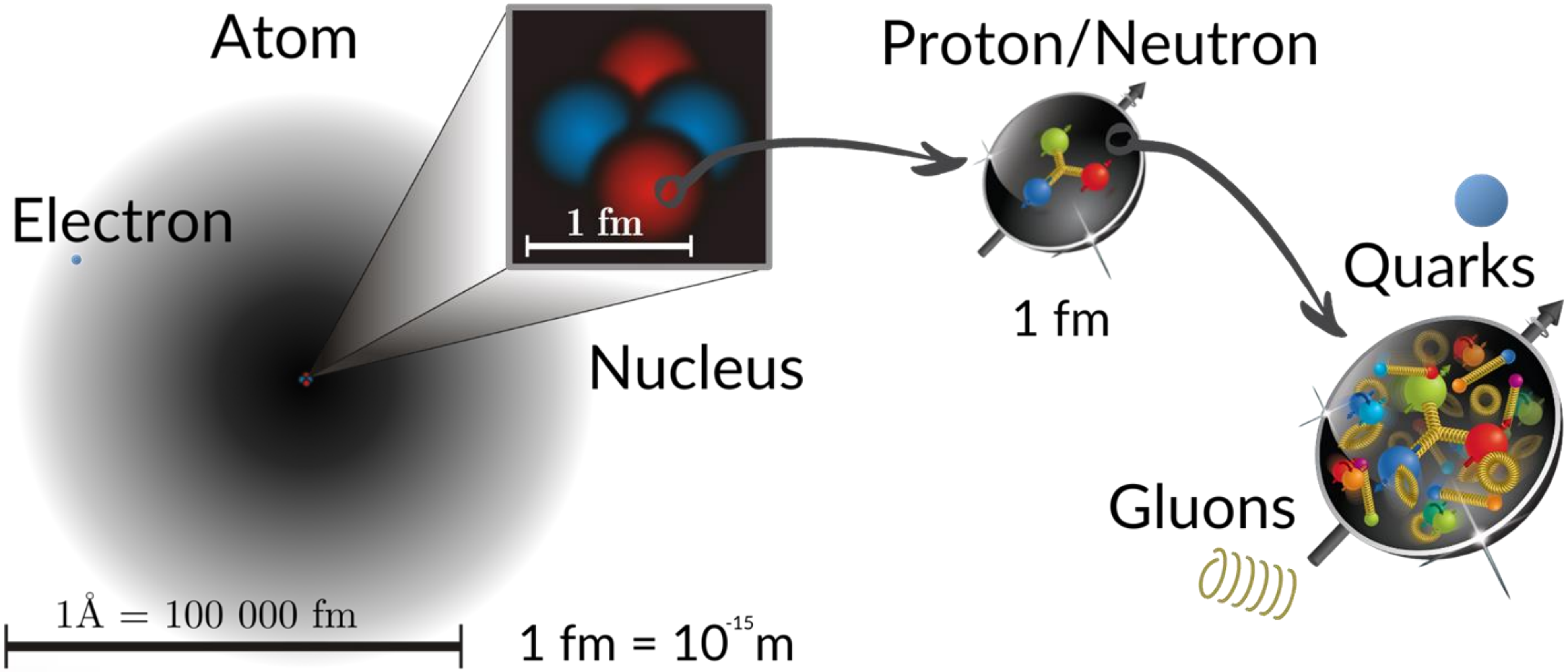
Cryo-EM Image of Zika Virus (2016)



First Image of a Black Hole (2019)

Pictures: See Bibliography on Slide 21

Imaging the Structure of Visible Matter

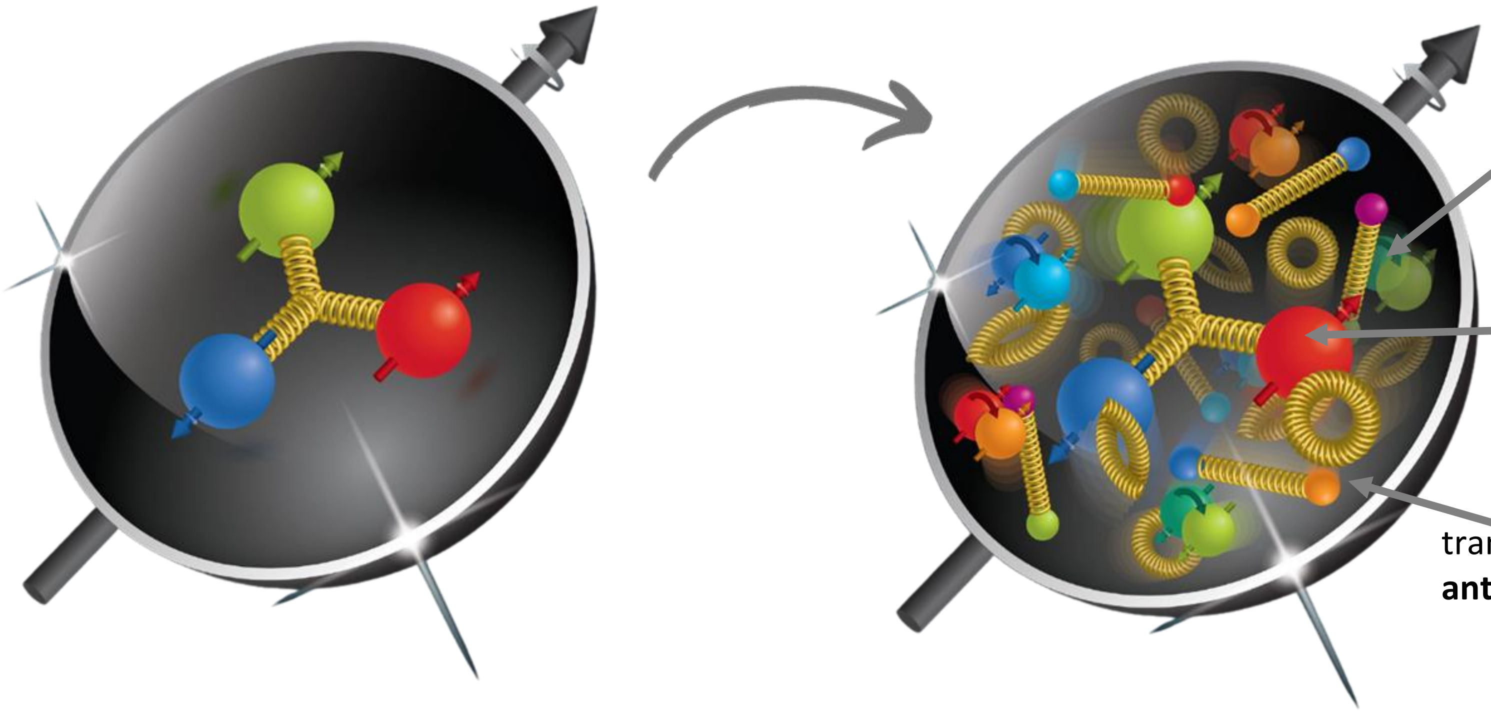


The EIC will uncover the hidden structure of protons and nuclei in 3D with precision akin to how atomic imaging transformed modern technology, offering new insights into the fundamental fabric of matter

Understanding the Glue that Binds Us All

Pictures: adapted from Brookhaven National Laboratory, Wikimedia Commons

The Evolving Understanding of the Structure of the Proton



Quantum Chromodynamics describes the **strongest force in the universe, binding quarks and gluons** with such intensity that they cannot be isolated, although at very high energies, they interact as if they were nearly free

Protons and nuclei **gain their fundamental properties**, like mass and spin, from the **intricate interactions between quarks and gluons** within this complex system

Pictures: adapted from Brookhaven National Laboratory

The EIC will explore matter through high-energy electron-ion collisions

How the EIC Will Study the Structure of Visible Matter

Deep Inelastic Scattering

Electrons, with no internal structure, are ideal probes for precisely imaging protons and nuclei through well-understood interactions.

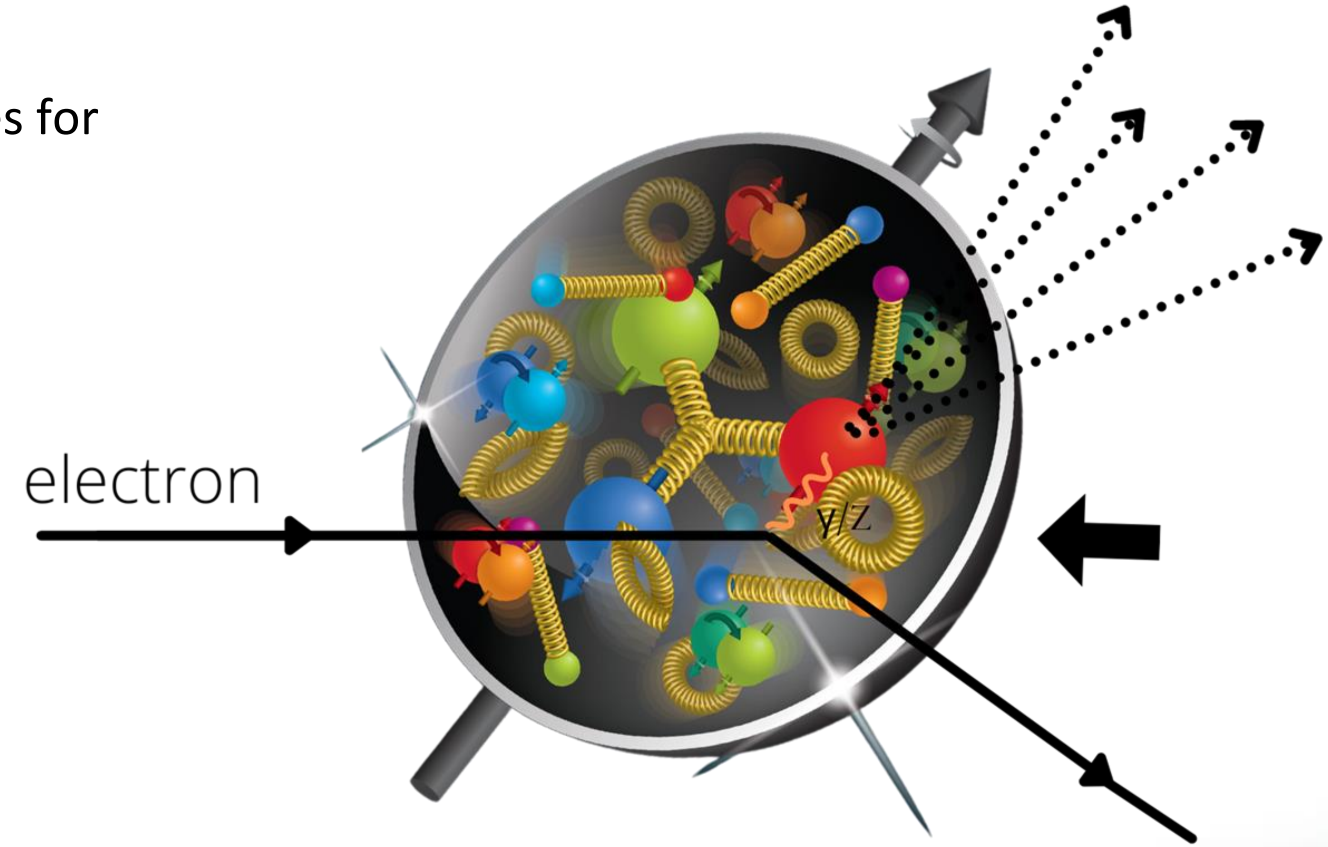
Q^2 – "resolution" of a microscope

Higher Q^2 – "zooming in" more closely

Lower Q^2 – looking at the proton at a coarser level

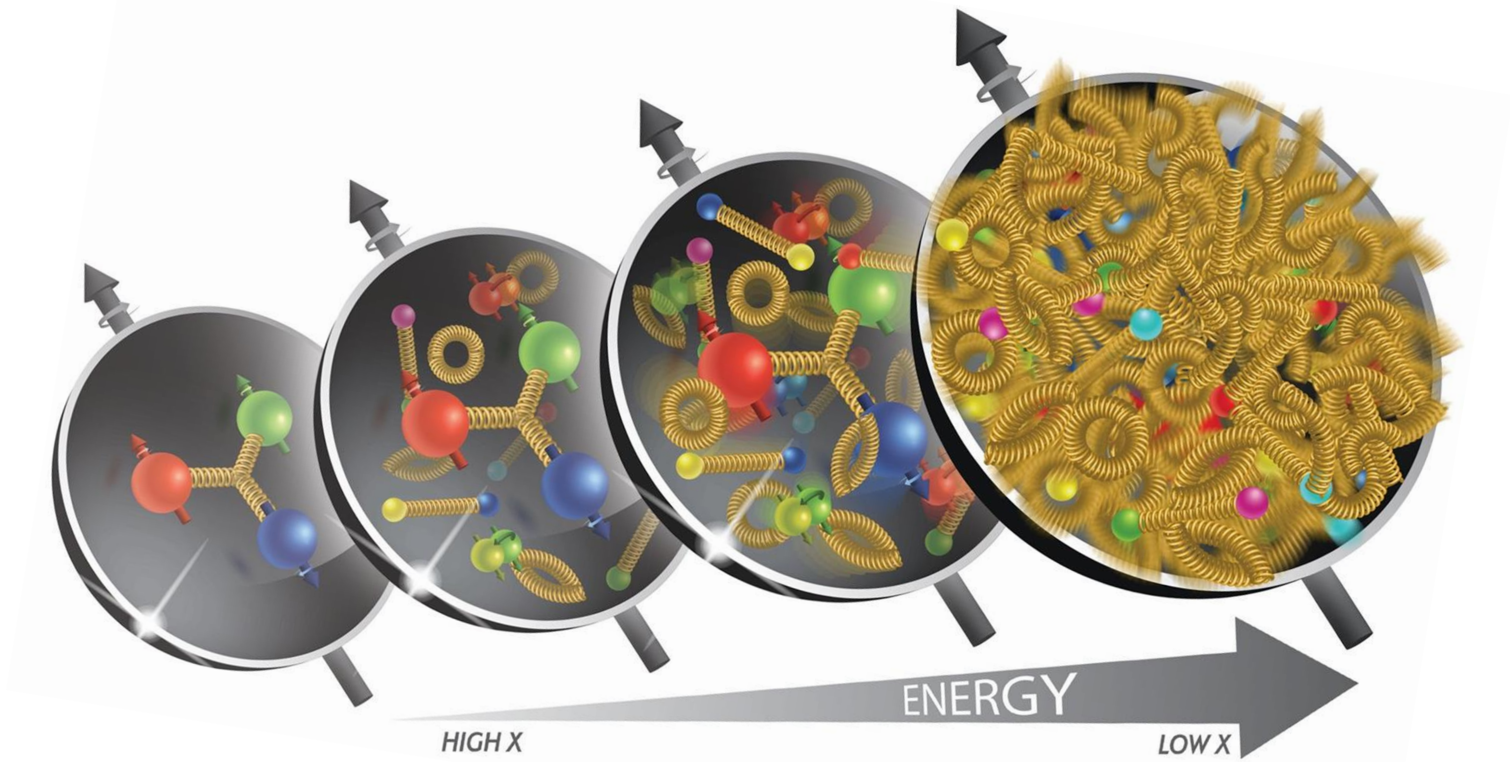
x – fraction of the proton’s momentum carried by the quark that is struck

It reveals how the proton's momentum is divided between its quarks and gluons



Pictures: adapted from Brookhaven National Laboratory

How the EIC Will Study the Structure of Visible Matter



Wide range of energies in electron-proton/nucleus collisions, optimized for precision in resolving their internal structure: EIC will explore matter over large range of resolution (Q^2) and quark/gluon densities (1/x)

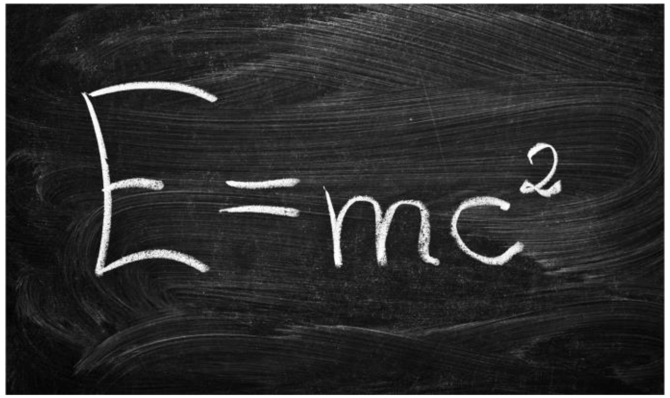
EIC – "microscope" to explore from the region where a proton is (mostly) an up-up-down quark system to the region where gluons dominate

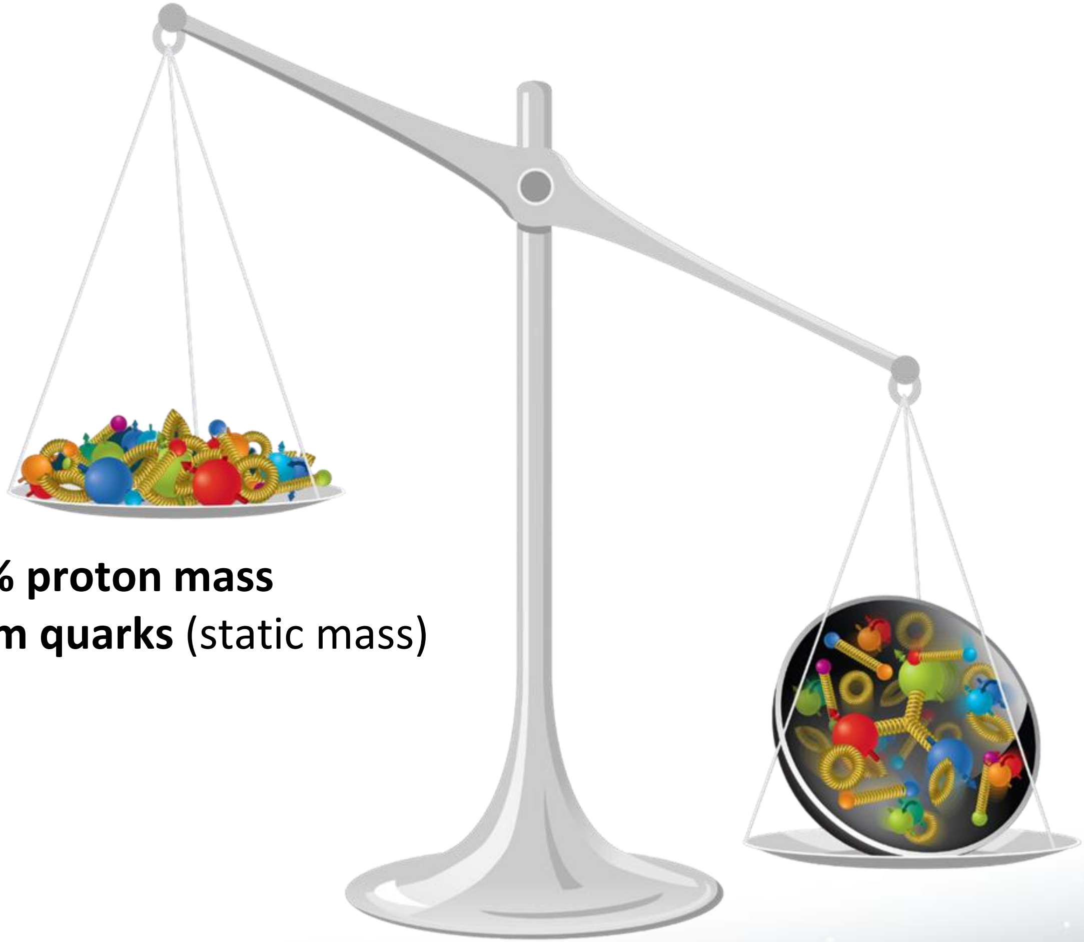
Pictures: adapted from Brookhaven National Laboratory

How do Protons and Neutrons Acquire Mass?

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

Where does the mass of the visible world come from?





<1% proton mass from quarks (static mass)

99% from interactions

Our mass arises from the energy of the strong force between quarks and gluons!

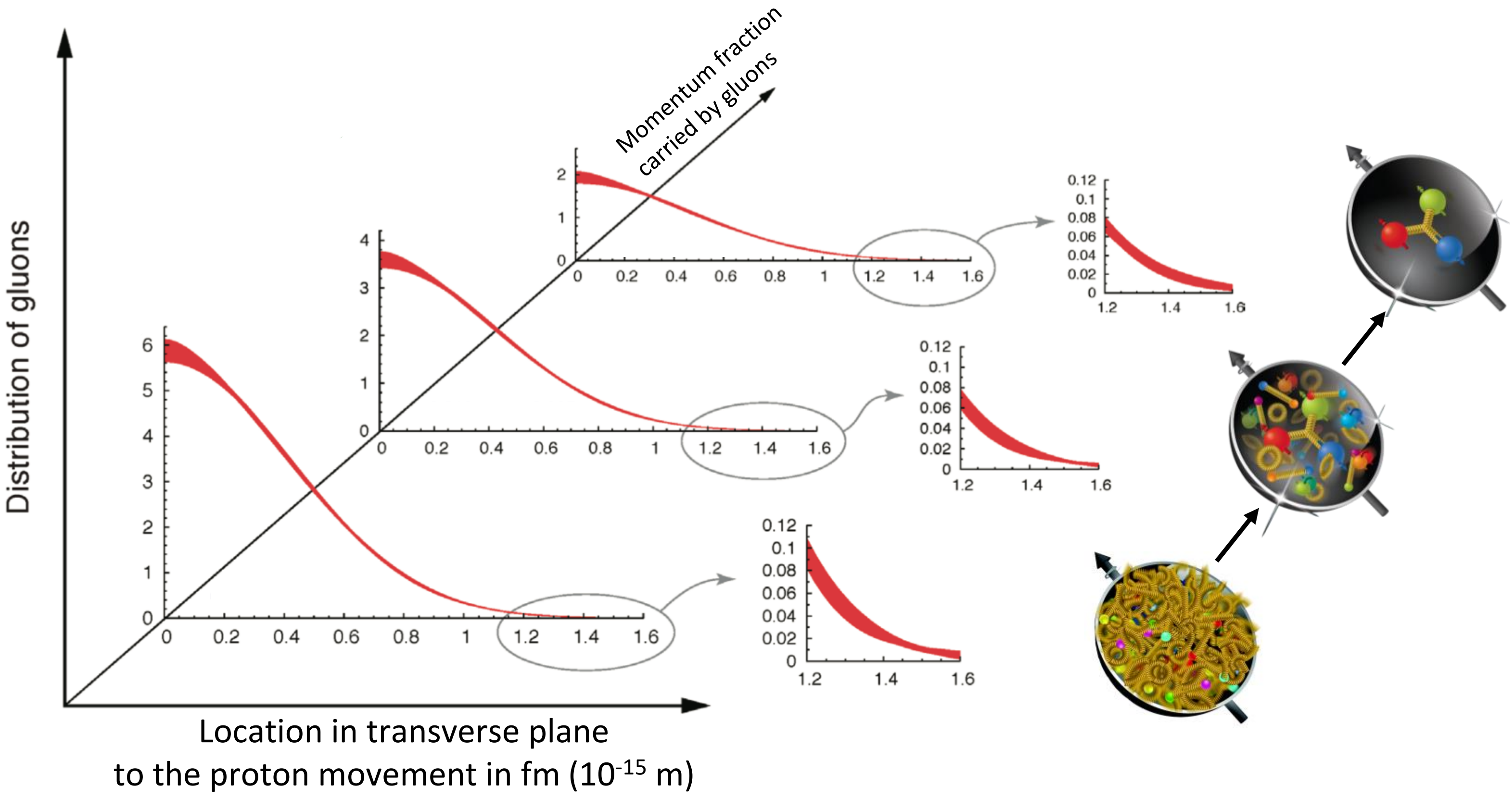
Pictures: adapted from Brookhaven National Laboratory

3D Mapping of Gluons Inside Matter

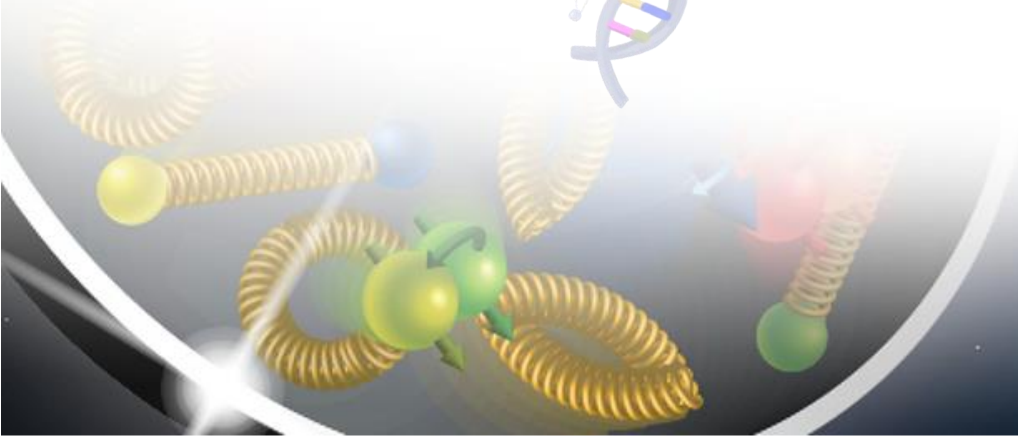
EIC will provide **first ever 3D images of gluons inside protons:**

- How their interactions contribute to the **proton's mass**?
- How they mediate the forces that **bind quarks together**?

- Much like how the discovery of DNA's double helix unveiled the structure and organization of genetic information



EIC will **3D map gluons inside protons** using special reactions that keep the proton intact and produce a quark-antiquark bound state



Electron-Ion Collider

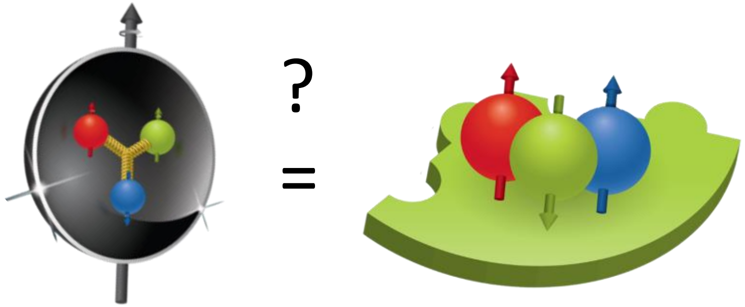
Pictures: EIC NAS Assessment and Brookhaven National Laboratory

Unraveling the Mystery of the Origin of the Proton Spin

The **proton's spin** — its internal "rotation" — **fundamental property like its charge and mass**

- Influences proton's behavior in magnetic fields, which **plays a key role in technologies like MRI machines and particle accelerators**

What creates the proton's spin?



Proton Spin Puzzle

After decades of experiments: **quark spins account for only about 30%** of the proton's spin

Pictures: adapted from Brookhaven National Laboratory

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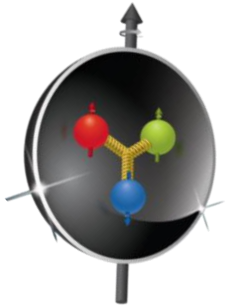

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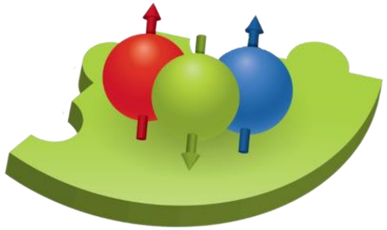
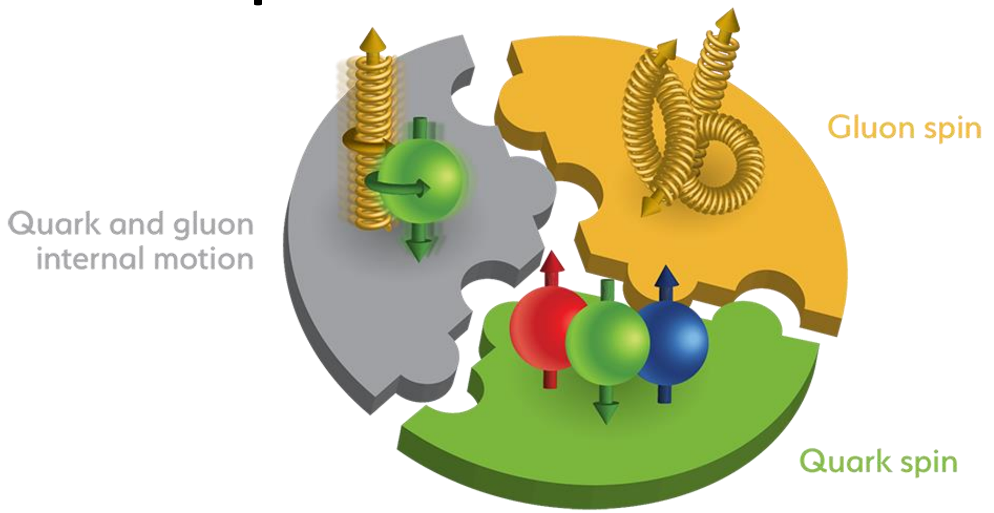


Proton Spin Puzzle



After decades of experiments: **quark spins account for only about 30%** of the proton's spin

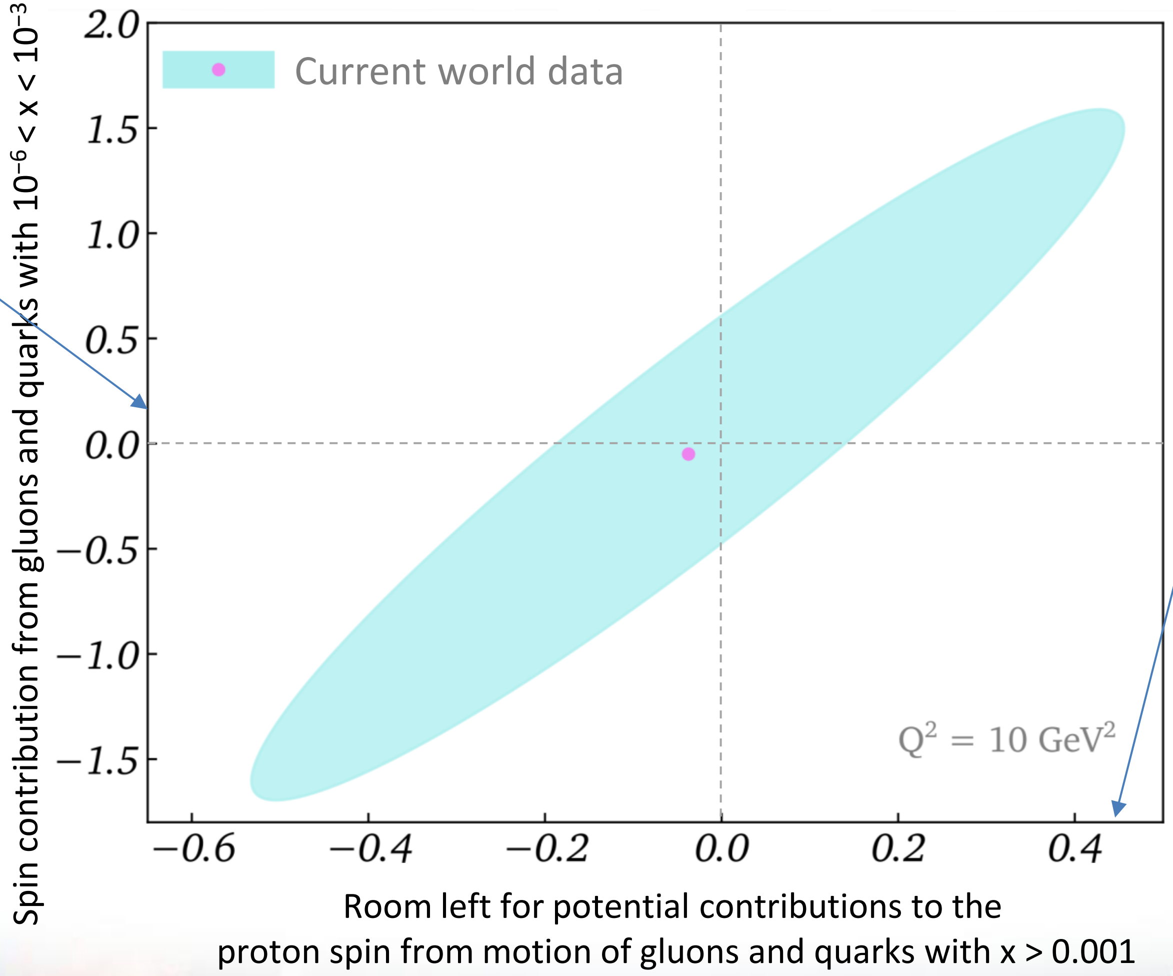
We now know that **quarks, gluons**, and **their motion** all contribute, but the full picture remains elusive

Pictures: adapted from Brookhaven National Laboratory

Unraveling the Mystery of the Origin of the Proton Spin

How much do the **spins of quarks and gluons very “deep” inside the proton** contribute to its spin?

Massive uncertainty range from -300% to +300% of the total proton spin!



How much do **the motion of quarks and gluons** contribute to the proton’s spin?

Close to zero—but with a huge uncertainty ranging from -100% to +80% of the total proton spin!

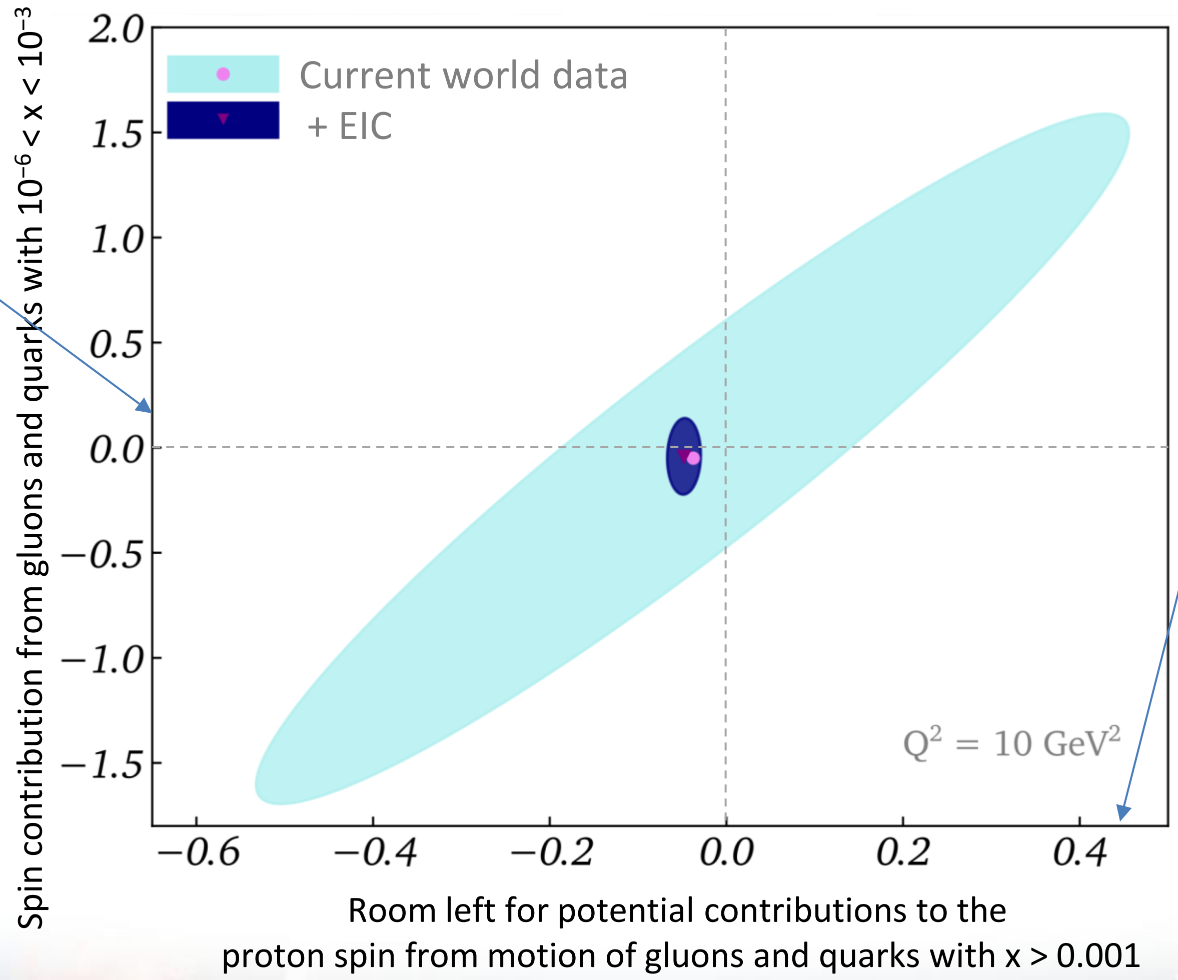
Electron-Ion Collider

Pictures: adapted from arXiv:2007.08300

Unraveling the Mystery of the Origin of the Proton Spin

How much do the **spins of quarks and gluons very "deep" inside the proton** contribute to its spin?

EIC aims to shrink this uncertainty by factor of 10!



How much do **the motion of quarks and gluons** contribute to the proton's spin?

EIC aims to shrink this uncertainty by factor of 22!

With its ability to collide electrons and protons at various spin orientations, EIC will be crucial in finally uncovering how different contributions to the proton spin add up

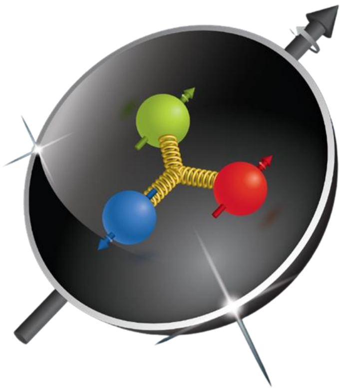
Electron-Ion Collider

Pictures: adapted from arXiv:2007.08300

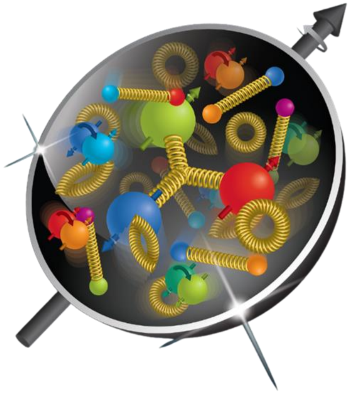
Peering into the Heart of Nuclear Matter

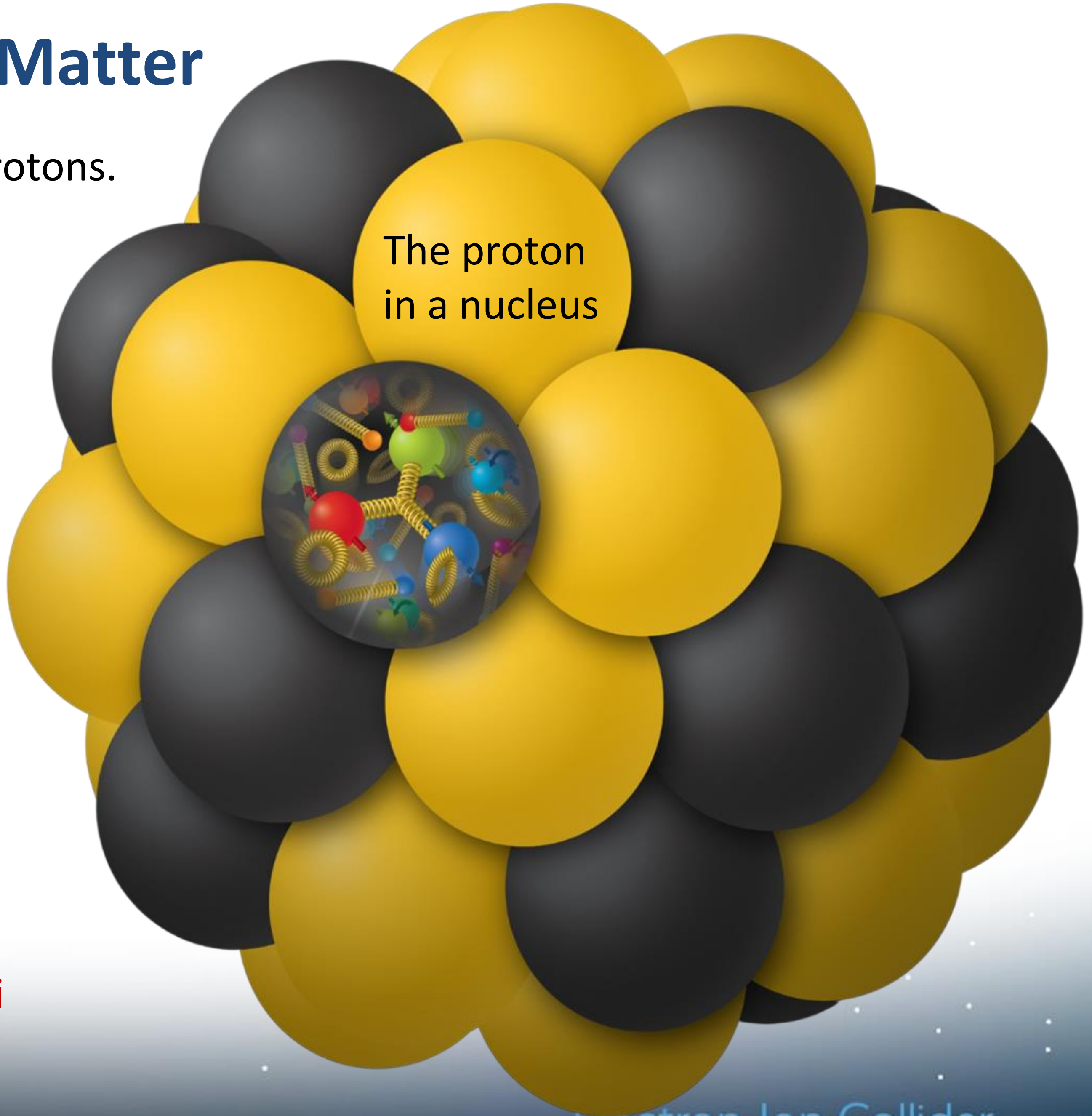
We are made of atoms, with heavier nuclei, not just protons.

The proton (1980s)



The proton (2020s)





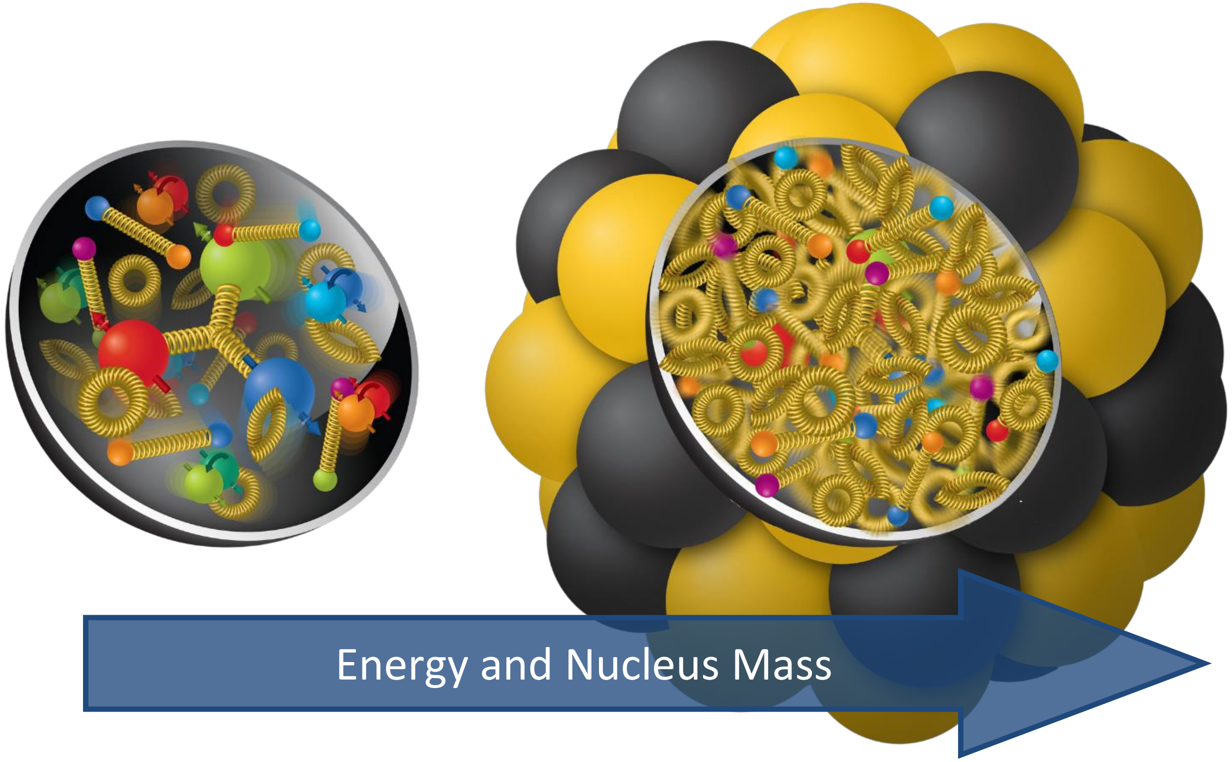
How does a high-density nuclear environment affect the behaviors of quarks and gluons?

The EIC will provide a complete view of the nucleus with insights into interactions that give rise to the forces binding protons and neutrons together in nuclei

Pictures: adapted from Brookhaven National Laboratory

New State of Gluonic Matter

- High-energy protons are packed with **increasing numbers of gluons**
- At extreme densities, gluon multiplication halts, **giving rise to a new state of matter**—this is gluon saturation
- **Heavy ion beams** at the EIC are key to creating the extreme conditions needed to study and **magnify this effect**



The EIC will probe the unexplored dense gluon environments, potentially unveiling new states of matter and deepening our understanding of the fundamental forces that bind everything in the visible Universe

Pictures: adapted from Brookhaven National Laboratory

Summary

Transformative Impact: The EIC will revolutionize our understanding of the fundamental structure of matter

Deep Insights Into Gluons That Bind Us All:

- Explore how nucleons and nuclei obtain their mass and spin from the dynamics of their constituent particles
- Investigate high gluon densities to uncover fundamental interactions in unexplored regions of nuclear matter

Unique Capabilities: Utilize high-energy collisions with varying spin orientations and diverse heavy ions to probe new dimensions of matter

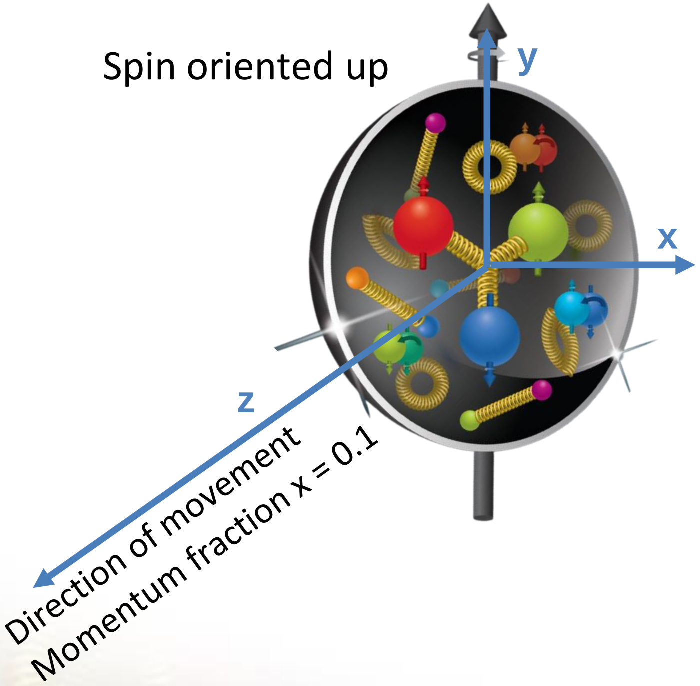
Pictures: adapted from Brookhaven National Laboratory

EIC will zoom in on the fundamental details of the matter that makes up our visible world

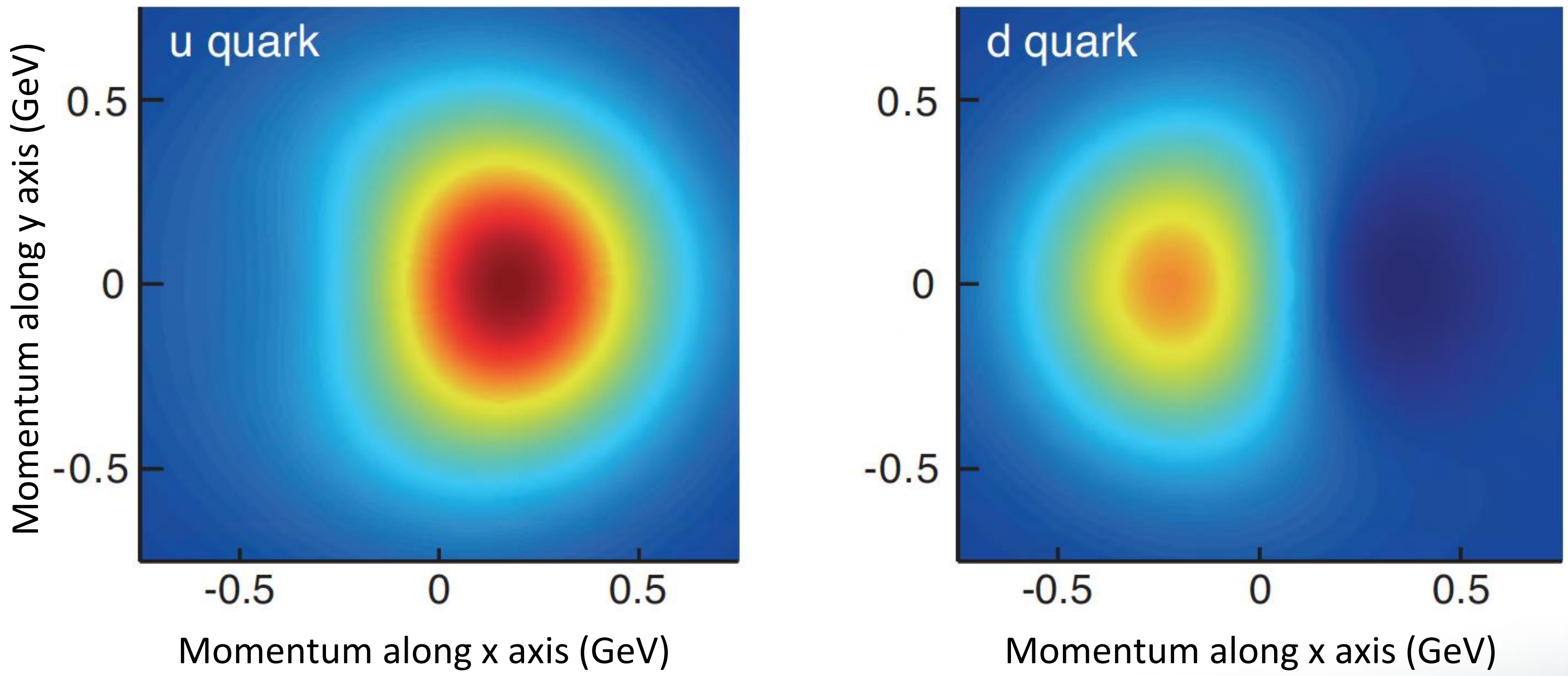
Backup

Motion of Gluons and Quarks Inside the Proton

The EIC will create the first 3D map of gluon and sea quark motion inside the proton, revealing their correlation with the proton's spin.



The color code indicates the probability of finding the up and down quarks



Current Understanding: Existing 3D maps only illustrate the motion of quarks, leaving the dynamics of gluons and sea quarks completely unexplored

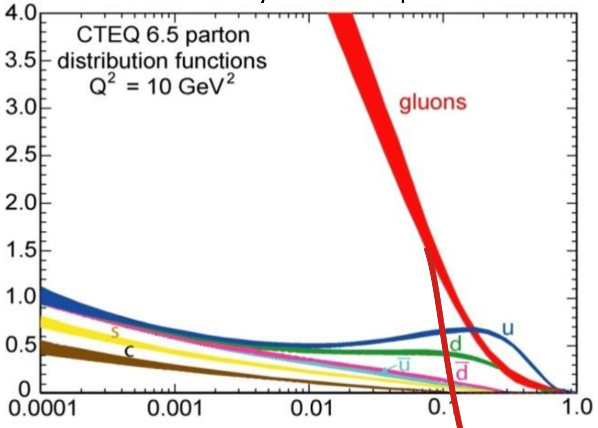
Electron-Ion Collider

Pictures: adapted from Brookhaven National Laboratory and EIC White Paper

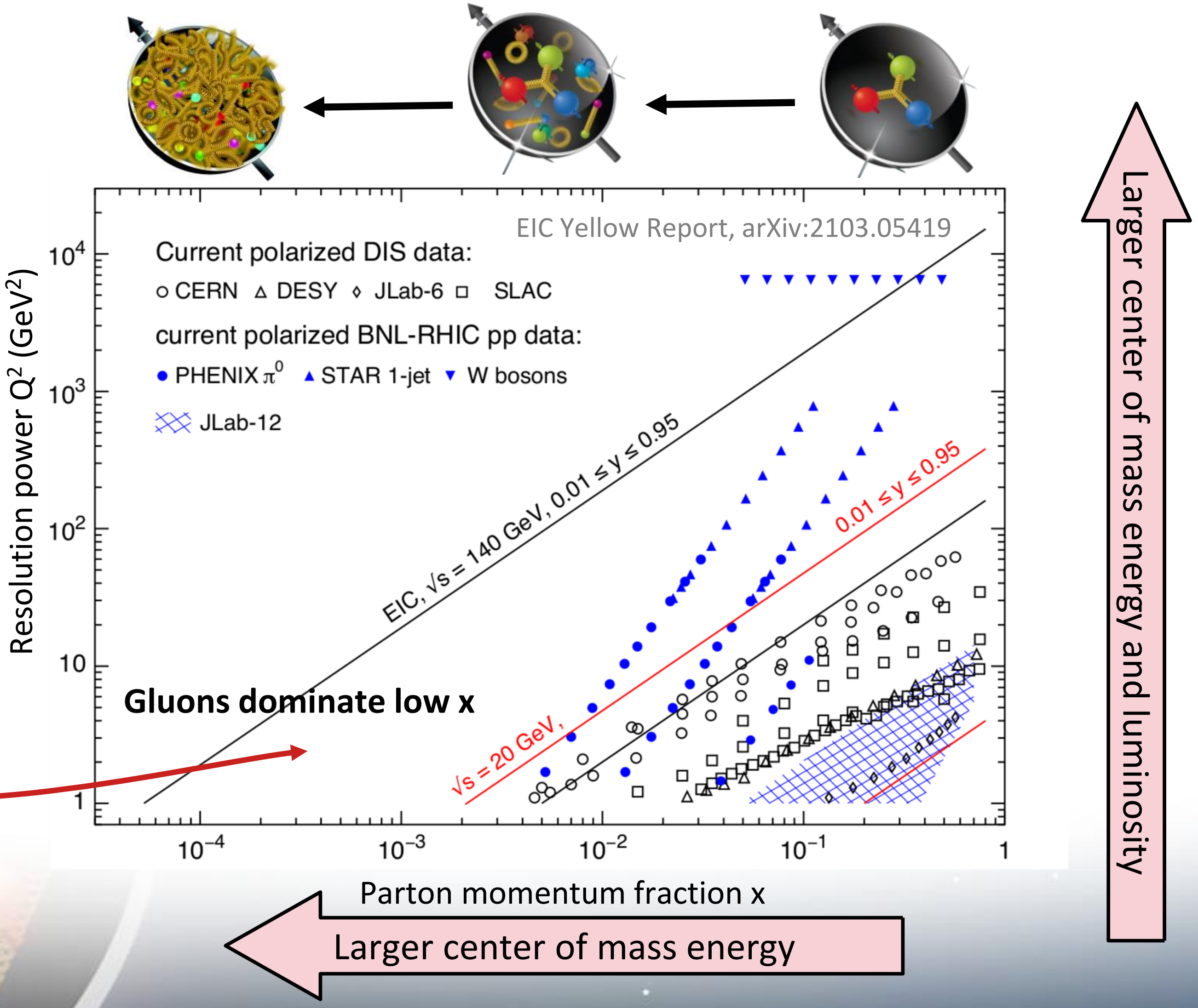
Probing Uncharted Territory

Unprecedented Access to Nucleon and Nucleus Structure

Quarks and gluons momentum fraction times their density inside the proton



Parton momentum fraction x



Electron-Ion Collider

Pictures: adapted from Brookhaven National Laboratory

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Pictures on Slide 2

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   - **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
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5. **Cryo-EM Image of Zika Virus**
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   - **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