



Stony Brook University



The promise and progress of the Electron Ion Collider:

Studying the glue that binds us all!

Abhay Deshpande

Brookhaven National Laboratory

Stony Brook University

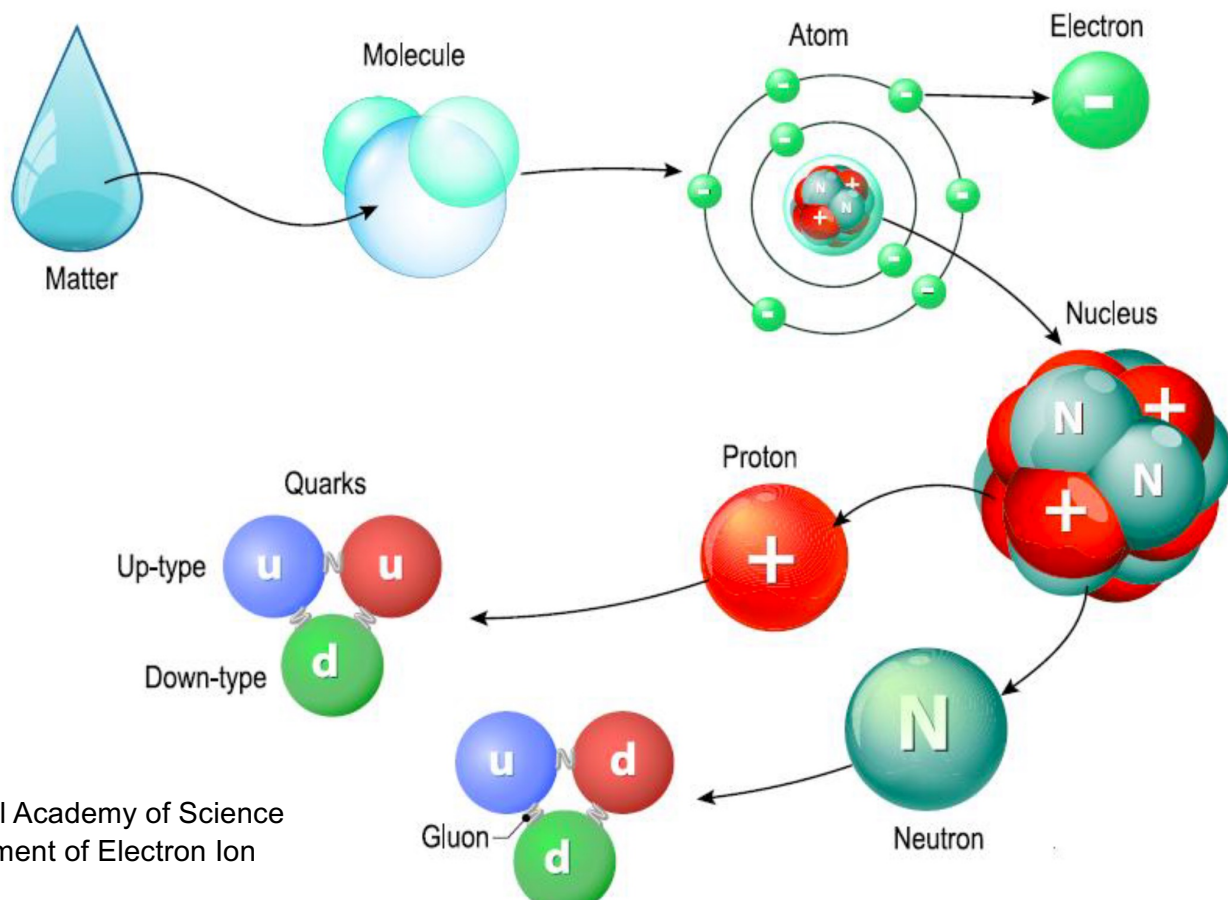
June 15, 2026

BNL Summer Student Lecture Series



@BrookhavenLab

Quest for the fundamental structure of matter

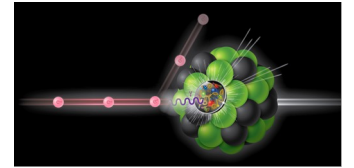


What's in there?

What are we made up of?

What is the "smallest"?

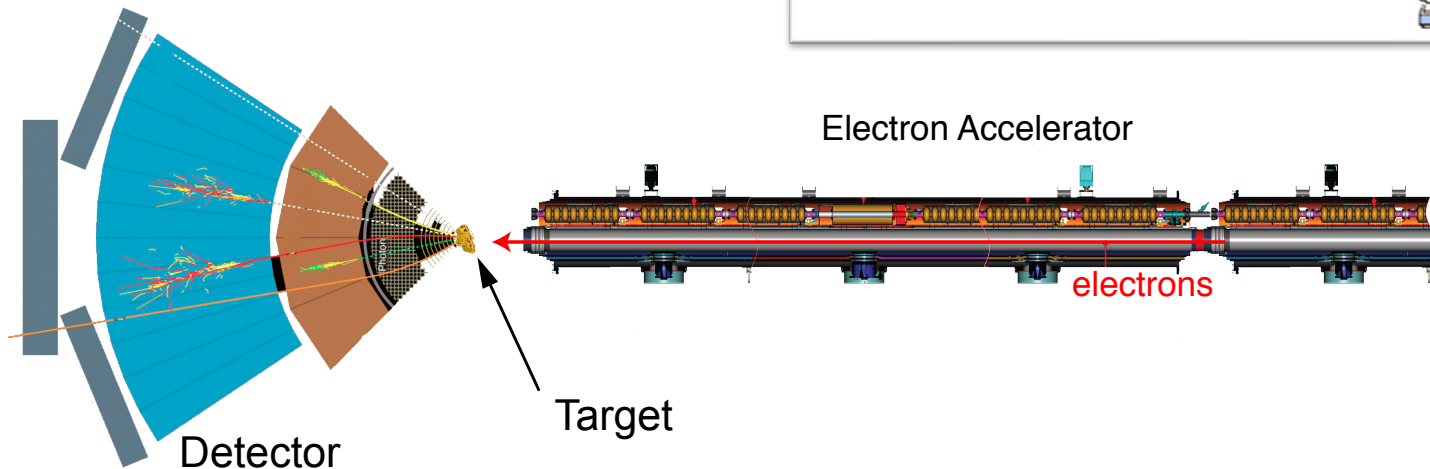
What is "fundamental" that can't be divided further?



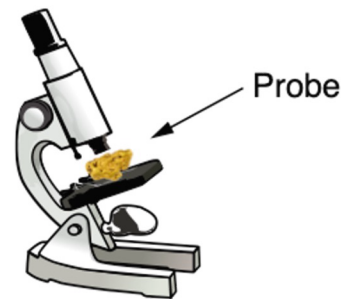
How do we know this?

Studying smaller and smaller things...

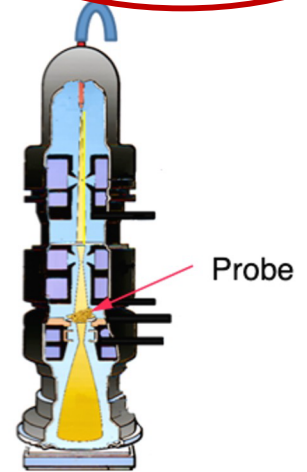
Fixed Target Particle
Accelerator Experiments
Wave length: 0.01 fm (20 GeV)
Resolution: ~ 0.1 fm

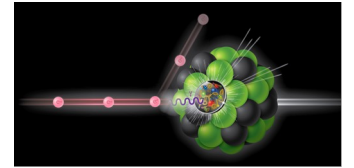


Light Microscope
Wave length: 380-740 nm
Resolution: > 200 nm



Electron Microscope
Wave length: 0.002 nm (100 keV)
Resolution: > 0.2 nm





What do we know now?

Standard Model (SM) of physics: Fundamental building blocks

$+2/3$	1968: SLAC u up quark	1975: SLAC c charm quark	1995: Fermilab t top quark	1983: DESY g gluon
$-1/3$	1968: SLAC d down quark	1947: Manchester University s strange quark	1977: Fermilab b bottom quark	1923: Washington University γ photon
0	1956: Savannah River Plant ν_e electron neutrino	1962: Brookhaven ν_μ muon neutrino	2000: Fermilab ν_τ tau neutrino	1983: CERN W W boson
-1	1897: Cavendish Laboratory e electron	1937: Caltech and Harvard μ muon	1976: SLAC τ tau	1983: CERN Z Z boson



18 Nobel
Prizes
since 1950

2015: Gravitational waves

**Einstein
gravity**

LIGO

What distinguishes **QCD** from QED?
Quantum **Chrom**odynamics $\leftrightarrow$ Quantum Electrodynamics

What distinguishes QCD from QED?

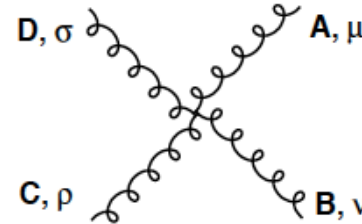
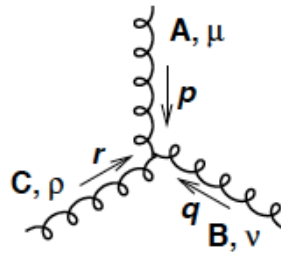
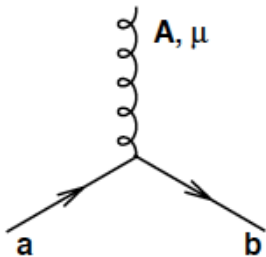
Gluons (g) and photons (γ): can only interact with other charged particles
 Gluons carry color charge, Photons carry no charge

$g \rightarrow q + \text{anti-quark}$



Only in QCD

(gluons) g
in QCD



Color Charge of gluons
 Enables self-interactions
 $g \rightarrow g + g$
 Or
 $g + g \rightarrow g + g$

Neutral photons
 Can NOT self-interact!
 $\gamma \rightarrow \gamma + \gamma$ (**NOT ALLOWED**)
 Or
 $\gamma + \gamma \rightarrow \gamma + \gamma$ (**NOT ALLOWED**)

March 3, 2026

QCD Asymptotic Freedom 1974



Nobel Prize in Physics 2004

David J. Gross, H. David Politzer, Frank Wilczek

*"for the discovery of asymptotic freedom
in the theory of the strong interaction".*

Quantum Chromodynamics (QCD)

Theory of strong interactions includes color confinement, asymptotic freedom

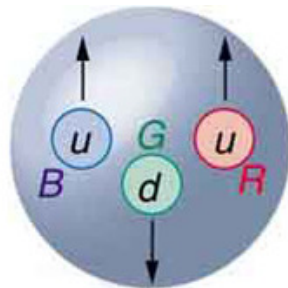
2004 Nobel Prize for explaining asymptotic freedom: q's free @ small distances

Confinement (force increases as a function of distance) observed, but not understood..... Many facets to it and need much experimental input

What is the quark structure of protons, neutrons and pions?

Quark Masses. $u = 3 \text{ MeV}$, $d = 5 \text{ MeV}$

Gluon mass: 0 MeV

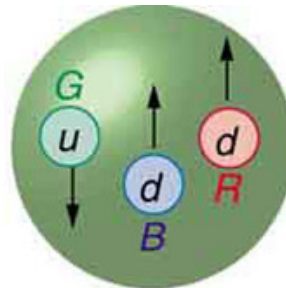


Proton

Spin $\frac{1}{2} + \frac{1}{2} - \frac{1}{2} = \frac{1}{2}$

Charge $+\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = 1$

938.27 MeV

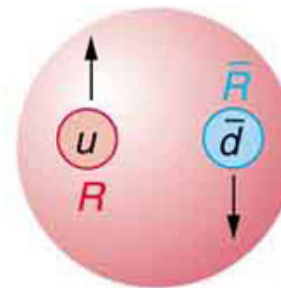


Neutron

Spin $-\frac{1}{2} + \frac{1}{2} + \frac{1}{2} = \frac{1}{2}$

Charge $+\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$

940.60 MeV

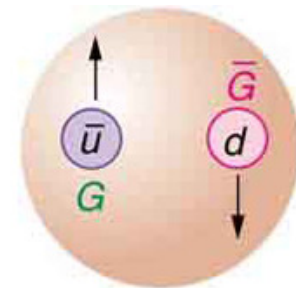


π^+

Spin $+\frac{1}{2} - \frac{1}{2} = 0$

Charge $+\frac{2}{3} + \frac{1}{3} = +1$

139.57 MeV

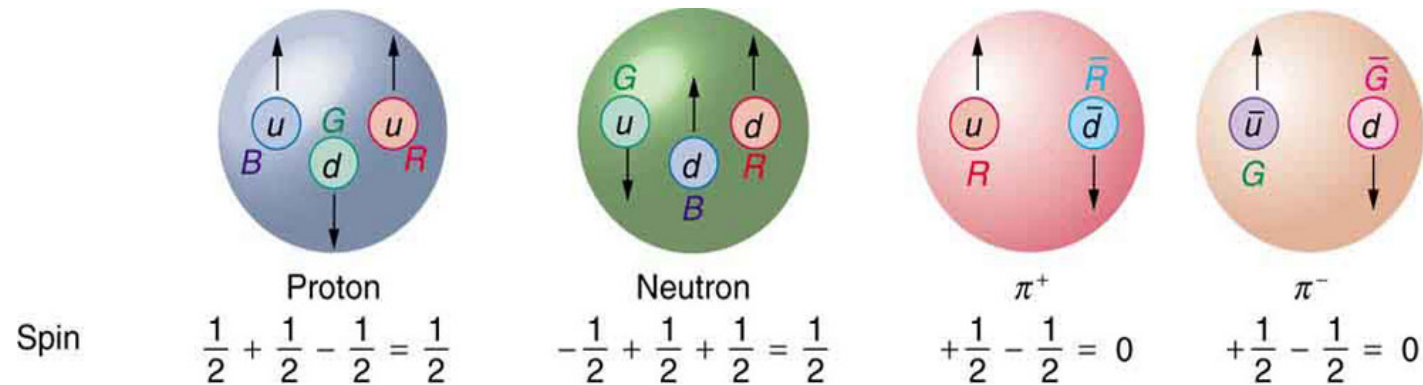


π^-

Spin $+\frac{1}{2} - \frac{1}{2} = 0$

Charge $-\frac{2}{3} - \frac{1}{3} = -1$

139.57 MeV

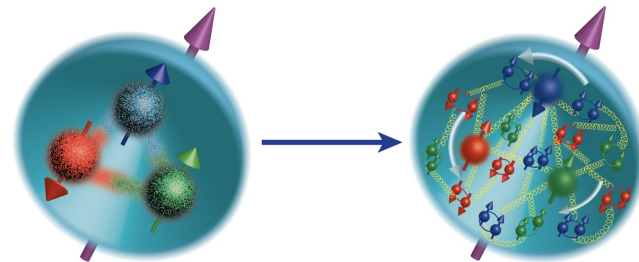
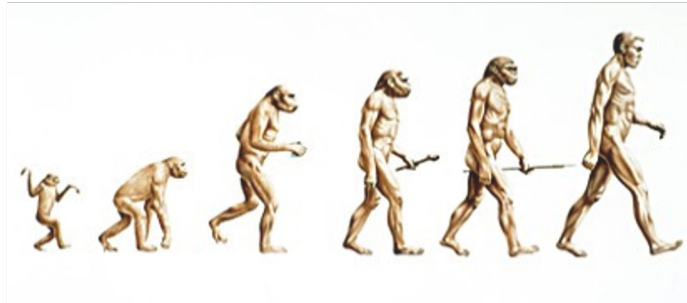


What about the origin of spin?

Proton has a fundamental property of spin = $\frac{1}{2}$ (unit of Planck's constant)

It should emerge from the spins of the quarks – proton's constituents

Spin “Crisis” (1989 @ CERN & 1990’s SLAC/DESY) → Spin Puzzle (after RHIC@BNL)



$$\frac{1}{2} = \left[\overset{0.12}{\frac{1}{2} \Delta \Sigma} \text{ [Quark's Orbital Ang. Motion] } \right] + \left[\overset{0.15}{\text{[Gluon's spin and Gluon's Orbital Ang. Motion]}} \right]$$

Quark's spin
Quark's Orbital Ang. Motion
Gluon's spin
Gluon's Orbital Ang. Motion

"Spin" always leads to surprises and intrigue



- If theorists had their way, they would ban all experiments with "spin"
 - J. D. Bjorken (SLAC)
 - June 1934 - August 2024



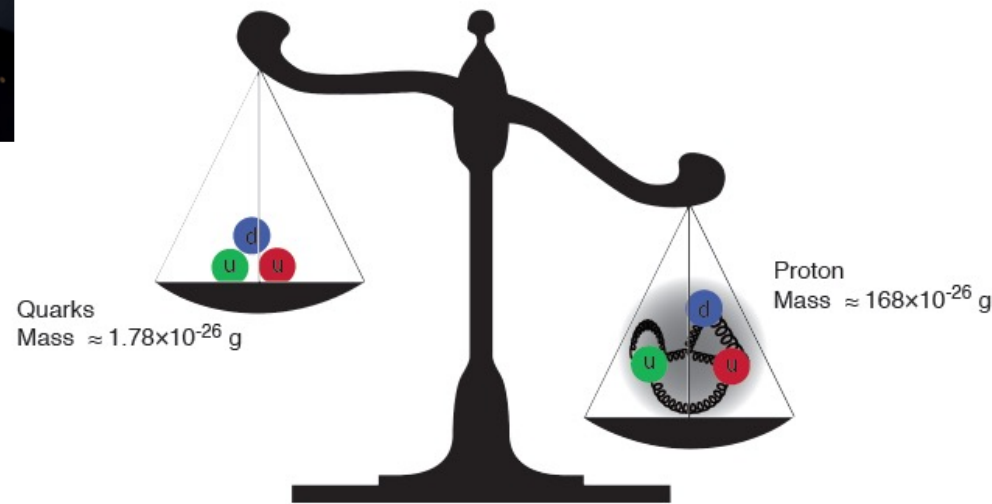
© Nobel Media AB. Photo: A. Mahmoud
François Englert



© Nobel Media AB. Photo: A. Mahmoud
Peter W. Higgs

Nobel 2013:
Peter Higgs &
François Englert
“Higgs Boson” that gives
mass to quarks, electrons,....

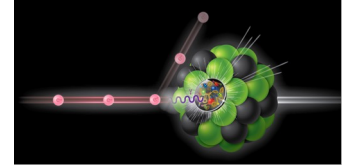
Visible Mass: Proton/Neutron mass puzzle



99% of the proton's
mass comes from
**energy of gluon
interactions**

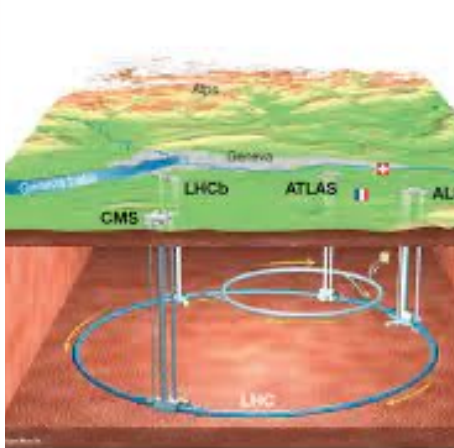
Masses of the quarks together 1.78×10^{-26} grams ← This mass comes from **HIGGS mechanism**
But the proton's mass (which is made of 3 dominant quarks and **massless gluons**) is 168.00×10^{-26} grams

- Only ~1% of the mass of the protons (neutrons) and
- hence that of the visible universe comes from Higgs mechanism
- Where does the rest (99%) of the mass come from?

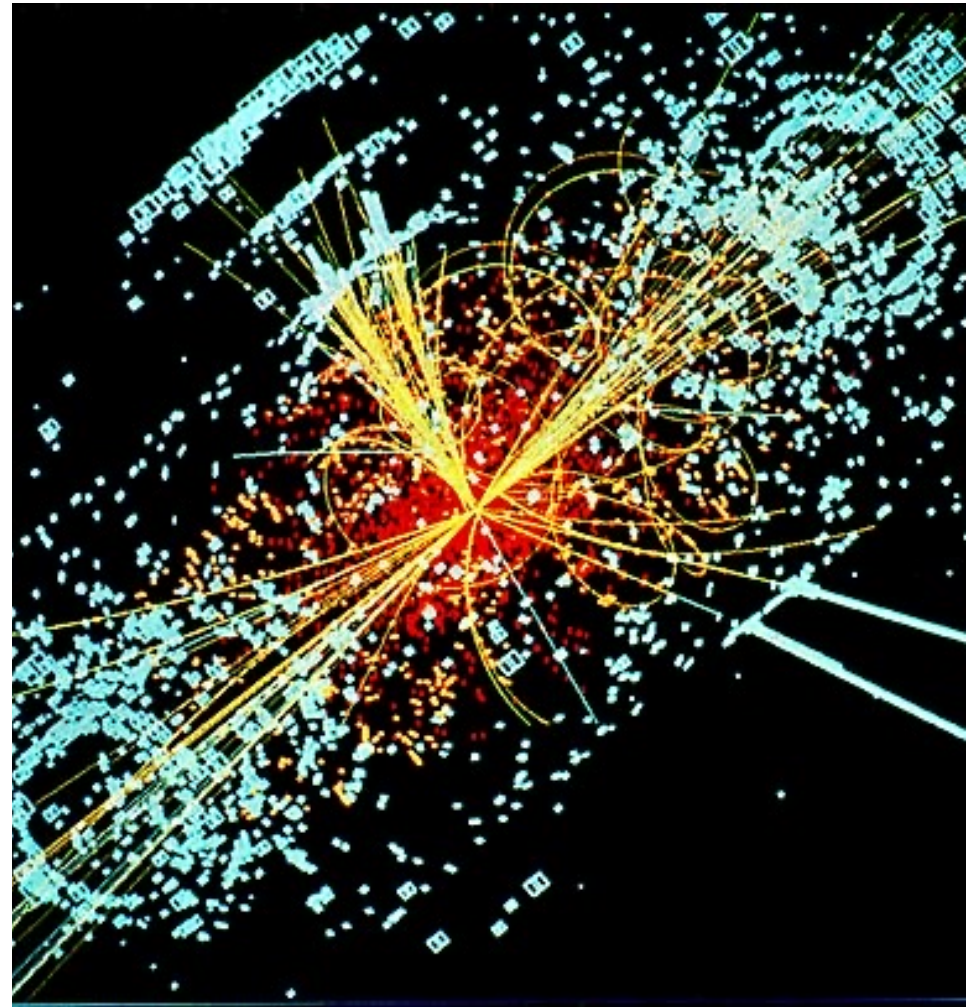


Deep Inelastic Scattering (DIS)

The best technique to understand the internal structure of protons, neutrons and the nuclei and exploring the intricacies of QCD



Brookhaven
National Laboratory



Study of internal structure of a watermelon:



A-A (RHIC/LHC)

1) Violent collision of melons



2) Cutting the watermelon with a knife

Violent DIS e-A (EIC)



Deep Inelastic Scattering

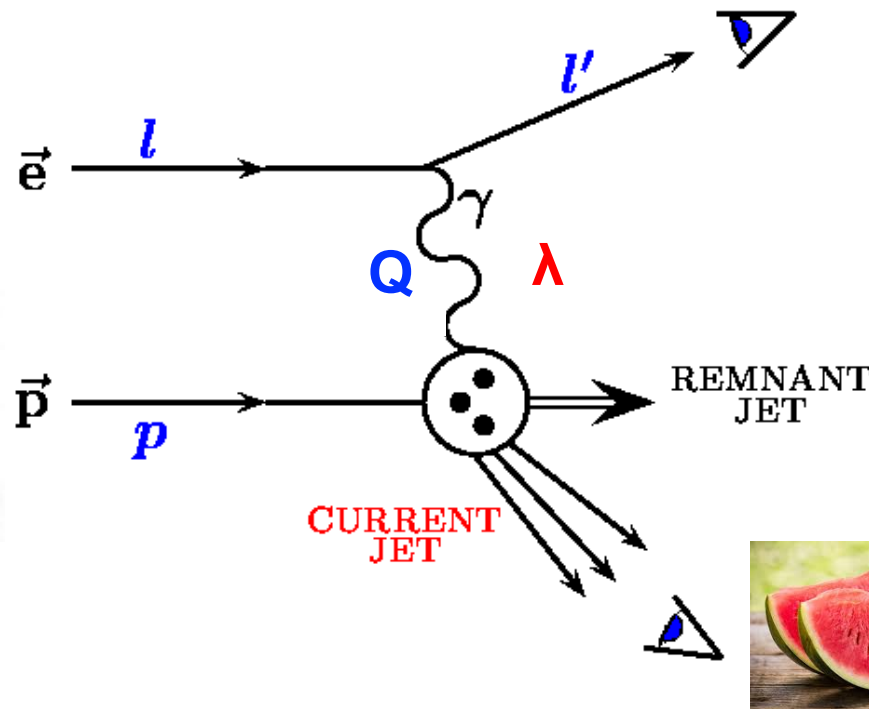


$$\lambda = h/Q^2$$

h = constant

λ = wavelength

Q^2 = momentum transferred



Deep Inelastic: ($\lambda \ll$ Proton Size)

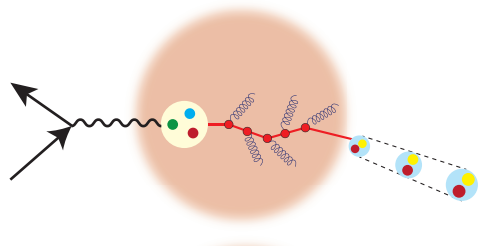
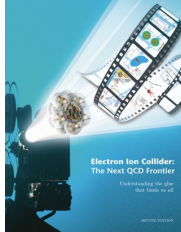
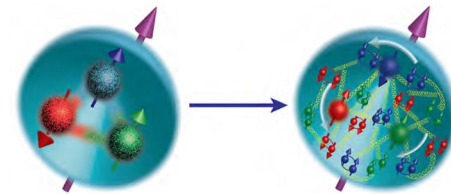
EIC Science

Electron-Ion Collider



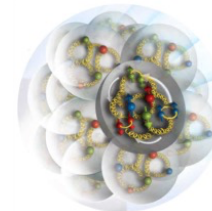
A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

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?

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?



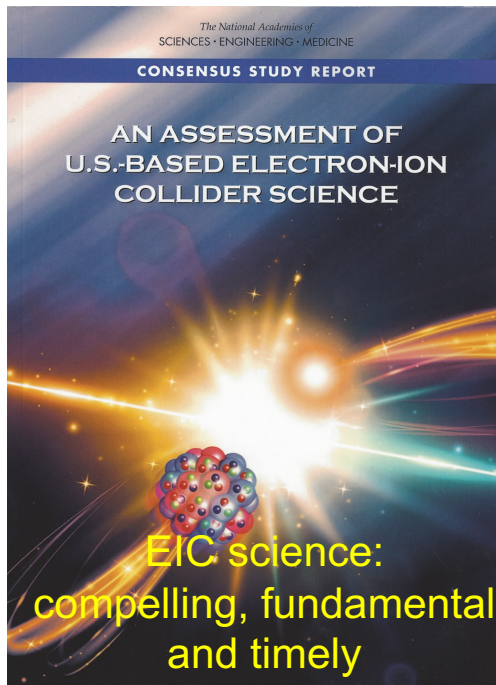
gluon
emission

?

gluon
recombination



US National Academy of Sciences, Engineering and Medicine: Assessment & Consensus Report



Physics of EIC

Emergence of Spin

Emergence of Mass

Physics of high-density gluon fields

Machine Design Parameters:

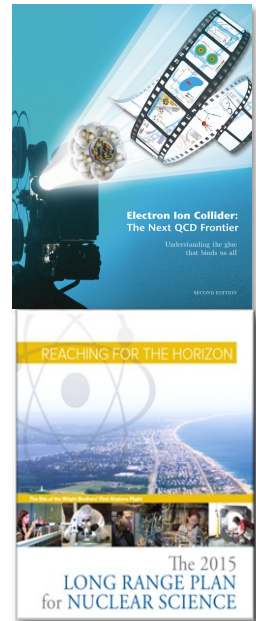
High luminosity: up to 10^{33} - 10^{34} cm⁻²sec⁻¹

Broad range in center-of-mass energy: ~20-140 GeV

Polarized beams e-, p, and light ion beams

Broad range in hadron species: protons.... Uranium

Up to two detectors well-integrated detector(s) into the machine lattice



Three-dimensional structure of the proton:

**What if we have no intuition?
Then things get difficult.**

One can not extrapolate based on our prior knowledge...

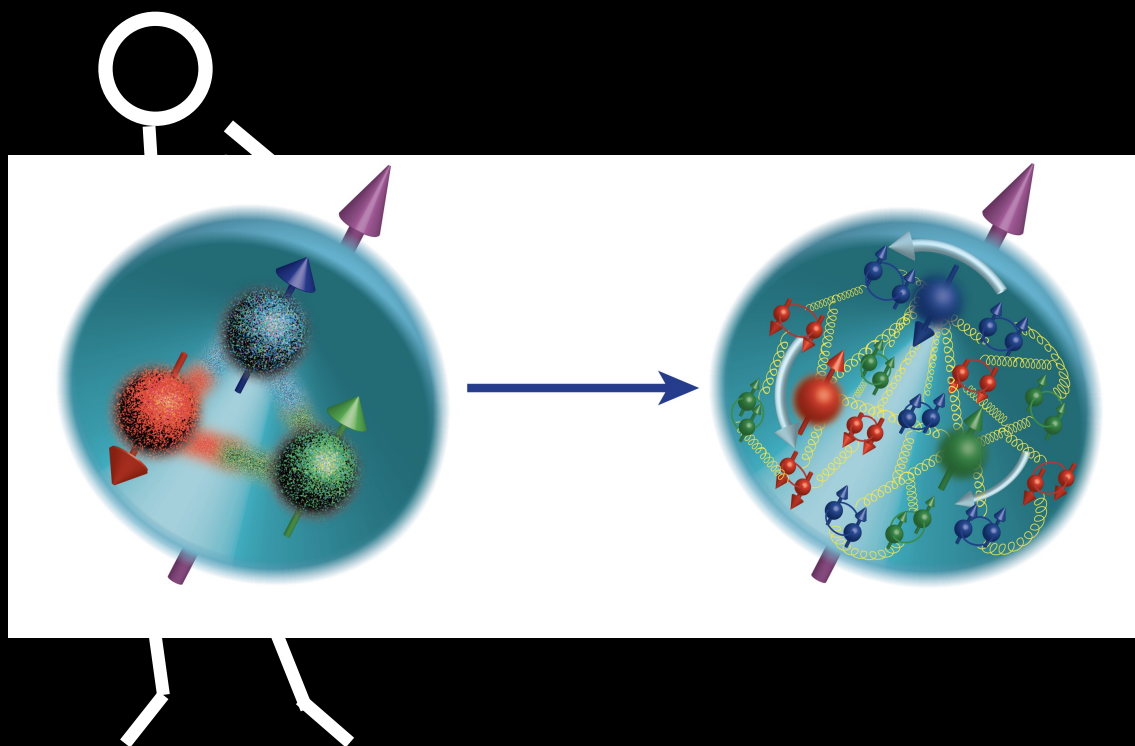
**With a roadmap in your
mind little data needed**



**Statue of Liberty
New York**

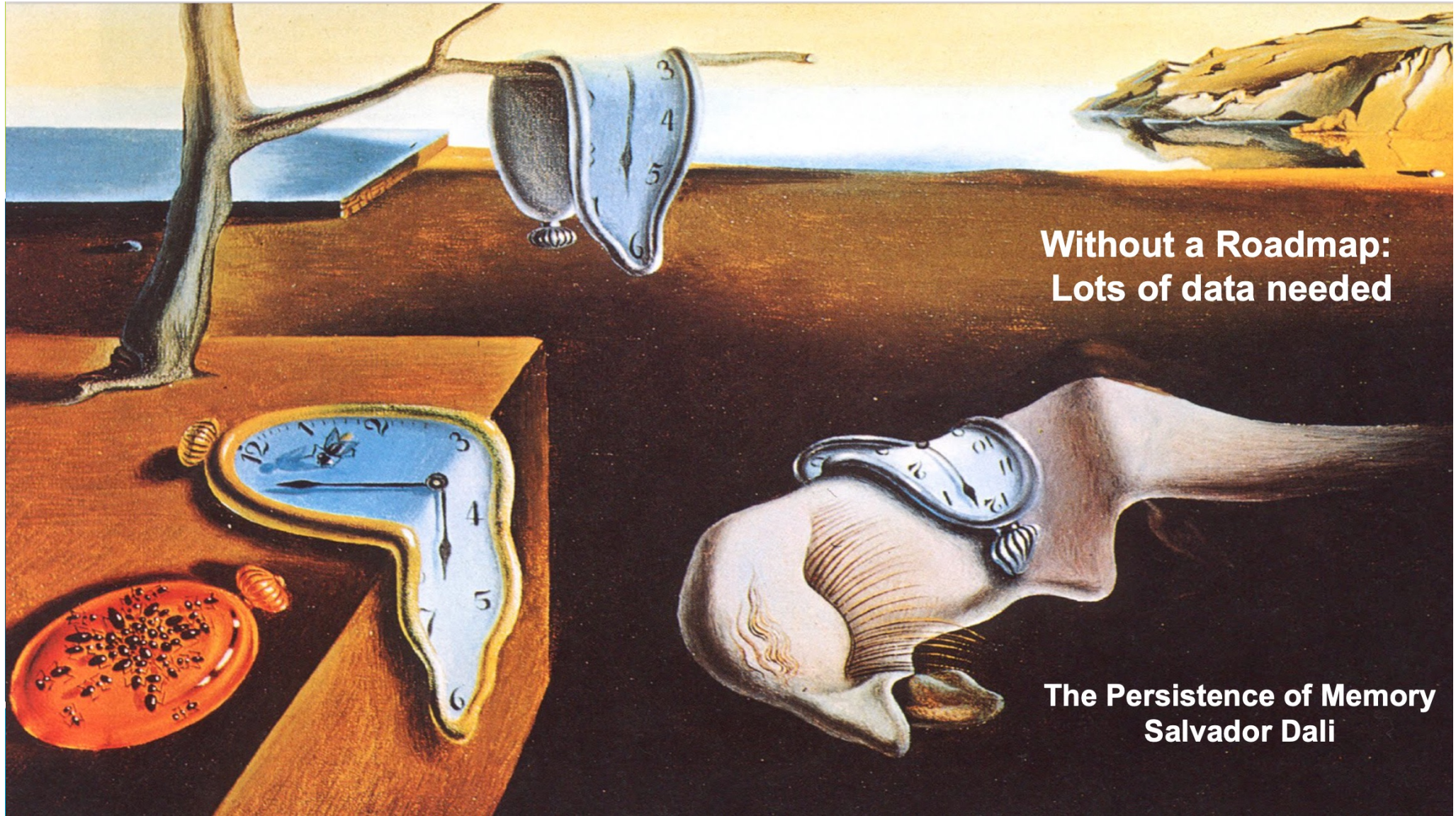
1D

3D



Courtesy: Alessandro Bacchetta

EIC at Tohoku University

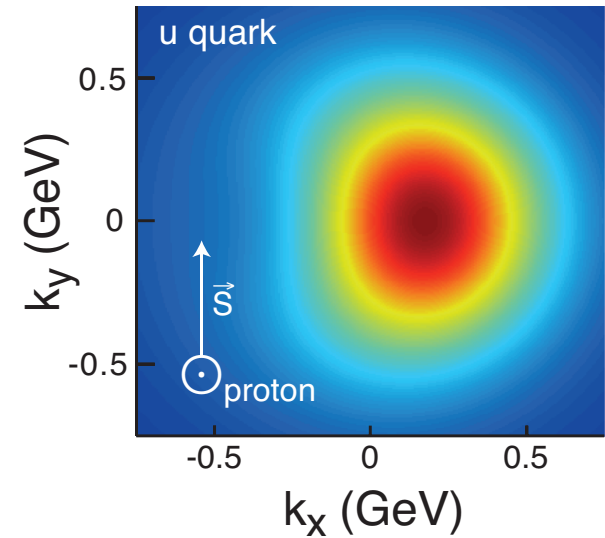
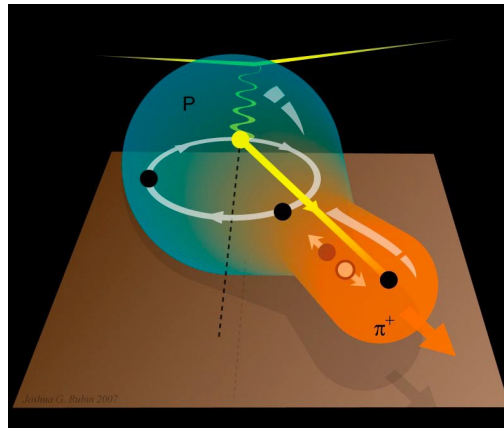
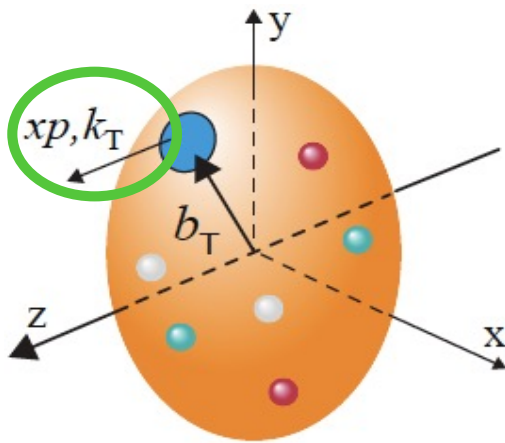


**Without a Roadmap:
Lots of data needed**

**The Persistence of Memory
Salvador Dali**

Measurement of Transverse Momentum Distribution

Semi-Inclusive Deep Inelastic Scattering

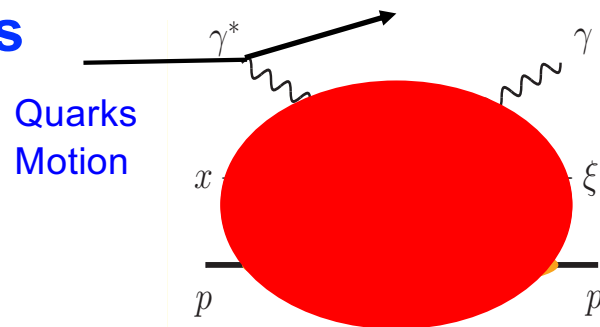
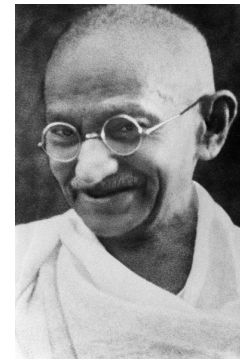


Spatial Imaging of quarks & gluons

Generalized Parton Distributions

Historically, investigations of nucleon structure and dynamics involved breaking the nucleon.... (exploration of internal structure!)

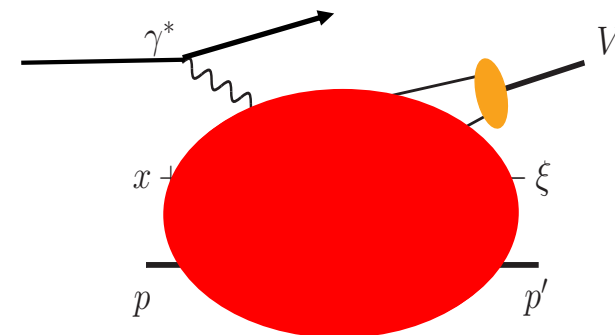
To get to the **orbital motion (position and momentum)** of quarks and gluons we need **non-violent collisions**



Deeply Virtual Compton Scattering

Measure all three final states

$$e + \mathbf{p} \rightarrow e' + \mathbf{p}' + \gamma$$



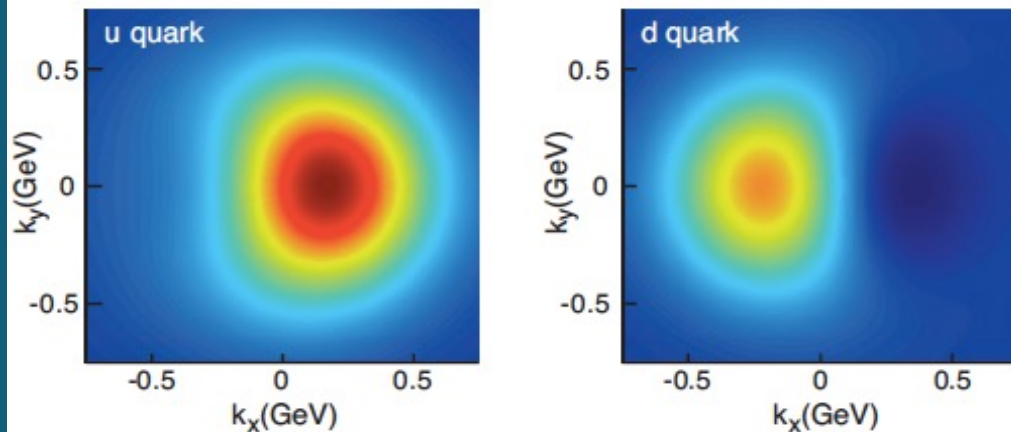
Gluons:
Only @
Collider

Fourier transform of momentum
transferred= $(p-p')$ $\rightarrow$ Spatial distribution

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

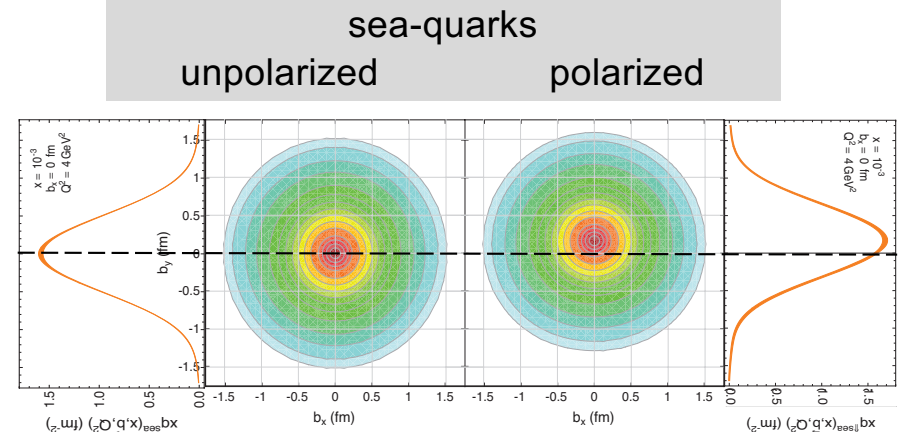
Spin-dependent 3D **momentum space** images from semi-inclusive scattering

Transverse **Momentum** Distributions

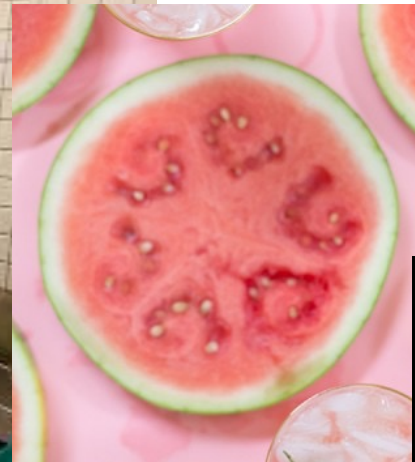


Spin-dependent 2D **coordinate space** (transverse) + 1D (longitudinal momentum) images from exclusive scattering

Transverse **Position** Distributions



Study of internal structure of a watermelon:



A-A (RHIC)

1) Violent collision of melons

2) Cutting the watermelon with a knife

Violent DIS e-A (EIC)

3) MRI of a watermelon

Non-Violent e-A (EIC)

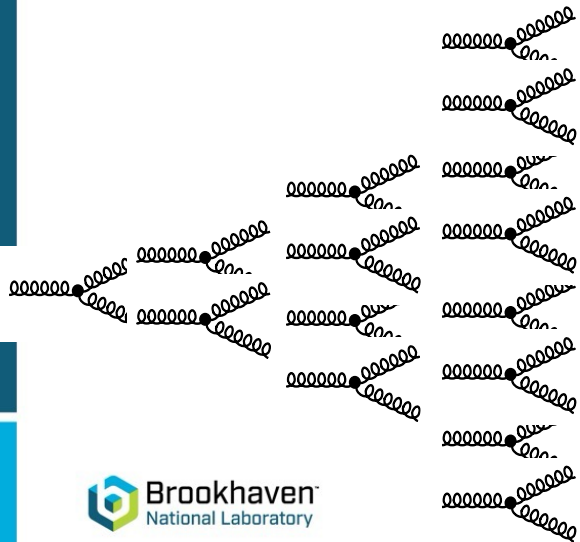
EIC at Tohoku University

Gluon and the consequences of its interesting properties:

Gluons carry color charge → Can interact with other gluons!

“...The result is a self catalyzing enhancement that leads to a runaway growth.
A small color charge in isolation builds up a big color thundercloud...”

*F. Wilczek, in “Origin of Mass”
Nobel Prize, 2004*



?

Infinity?

No!

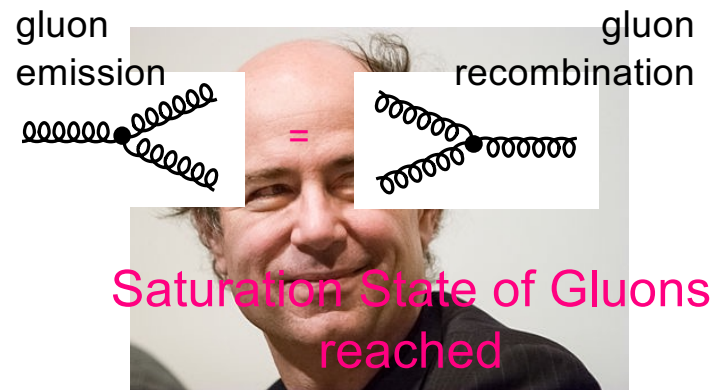
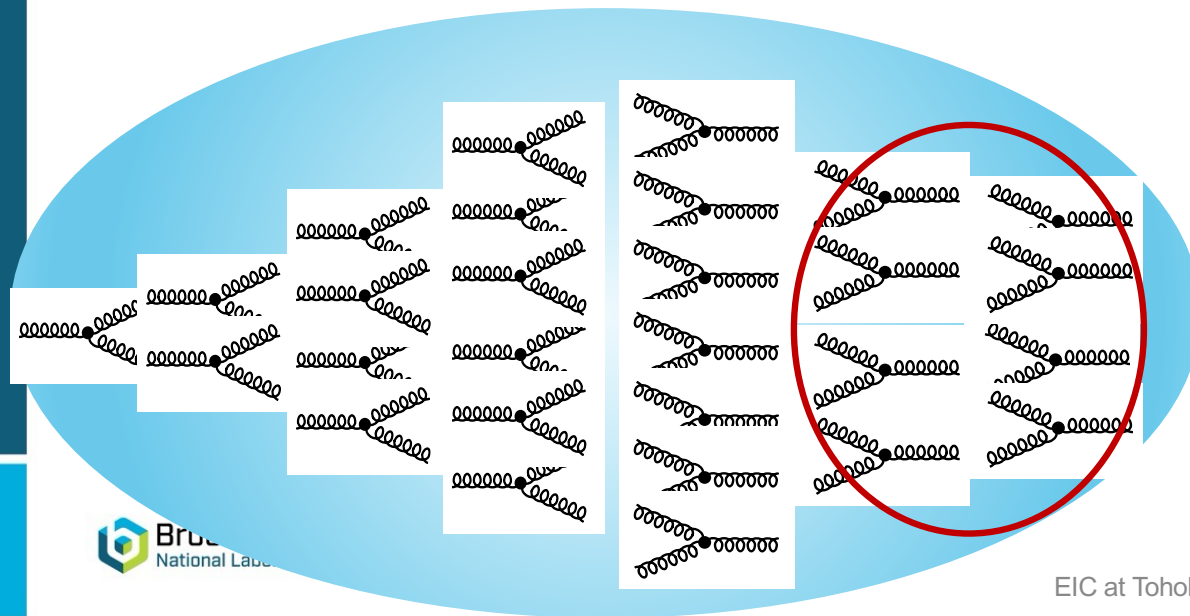


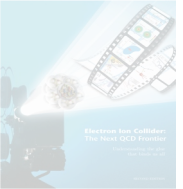
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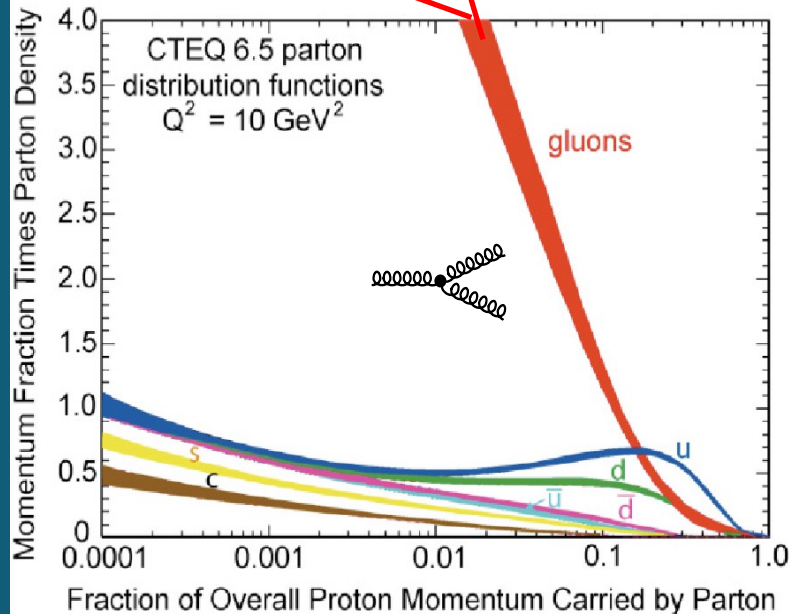




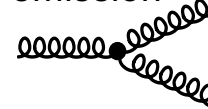
In search of a new state of matter!

What could tame the low-x rise?
Can EIC access this region?

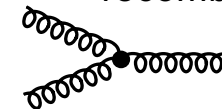
QCD inherently has the needed mechanism for this taming but we don't know when it gets triggered.



gluon emission



gluon recombination



=

At Q_s

Observation of gluon recombination effects

→ Is there such new state of matter?

→ “Color Glass Condensate”

→ 50-100 times higher energy density than the core of the neutron star

Experimental evidence needed





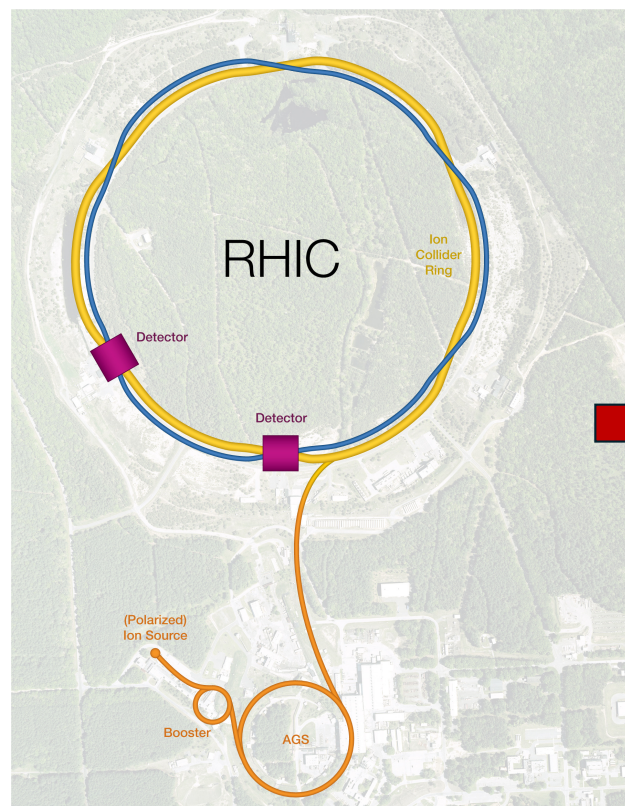
EIC Project and Realization



Stony Brook University



Transition from RHIC to Electron Ion Collider (EIC) in 2026

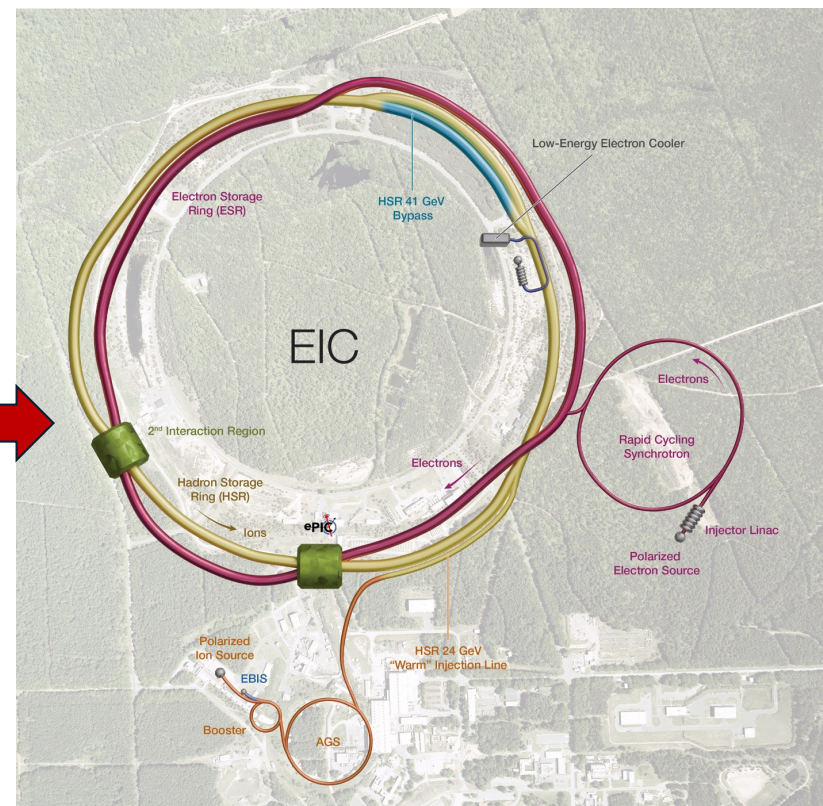


Re-Use the
existing tunnel

Minimal
modification to
the hadron beam
complex (yellow)

New electron
beam facility

Build on the
~\$2B+
investment



Present EIC Concept (2025)

Ultimate EIC Performance Parameters:

- High Luminosity: $L = 10^{33} - 10^{34} \text{cm}^{-2}\text{sec}^{-1}$
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: $E_{\text{cm}} = 28 - 140 \text{ GeV}$
- Large Ion Species Range: protons – Uranium
- Large Detector Forward Acceptance and Low-Background Conditions
- Possibility to Implement a **Second Interaction Region (IR)**

Accelerator Status at a glance:

- ✓ Polarized ion/proton source
- ✓ Ion injection and initial acceleration systems – Linac (200 MeV), Booster (1.5 GeV), AGS (25 GeV)

UPGRADE Hadron Storage Ring (40-275 GeV) – **HSR**

NEW Electron Pre-Injector (750 MeV linac)

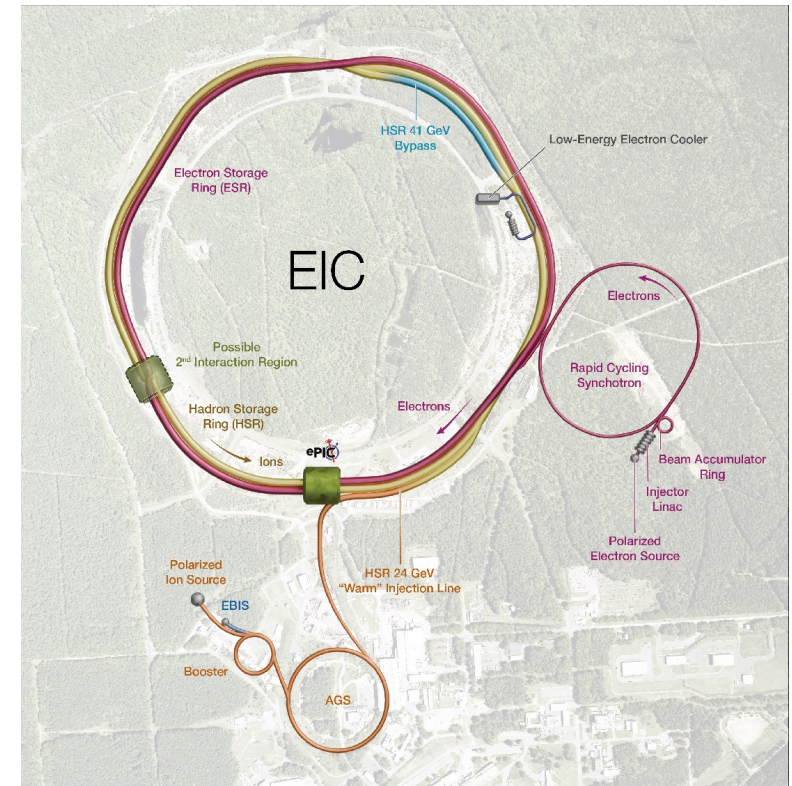
NEW Beam Accumulation Ring (750 MeV) – **BAR**

NEW Electron Rapid Cycling Synchrotron (0.75 GeV – top energy) – **RCS**

NEW Electron Storage Ring (5 GeV – 18 GeV) – **ESR**

NEW Interaction Region(s) – **IR**

NEW Hadron Cooling System



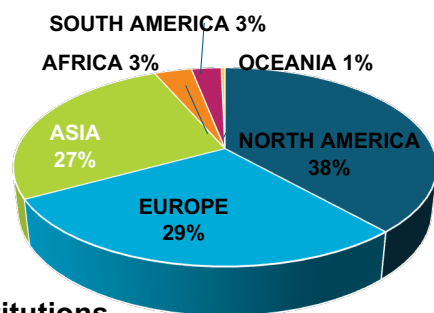
Protons: ~40 – 275 GeV

Electrons: 5 – 18 GeV

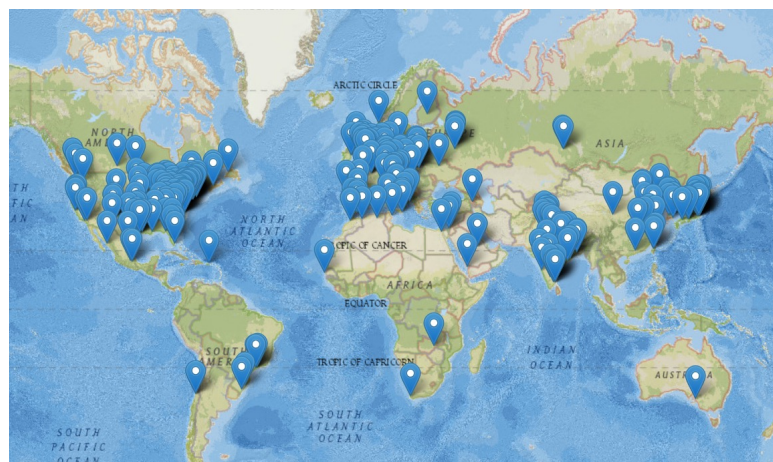
Current EIC US Partners (performing work and/or providing materials)

- ### EIC Collaborators (developing experiments, contributing expertise)

- ## Department of Energy Lab Partners

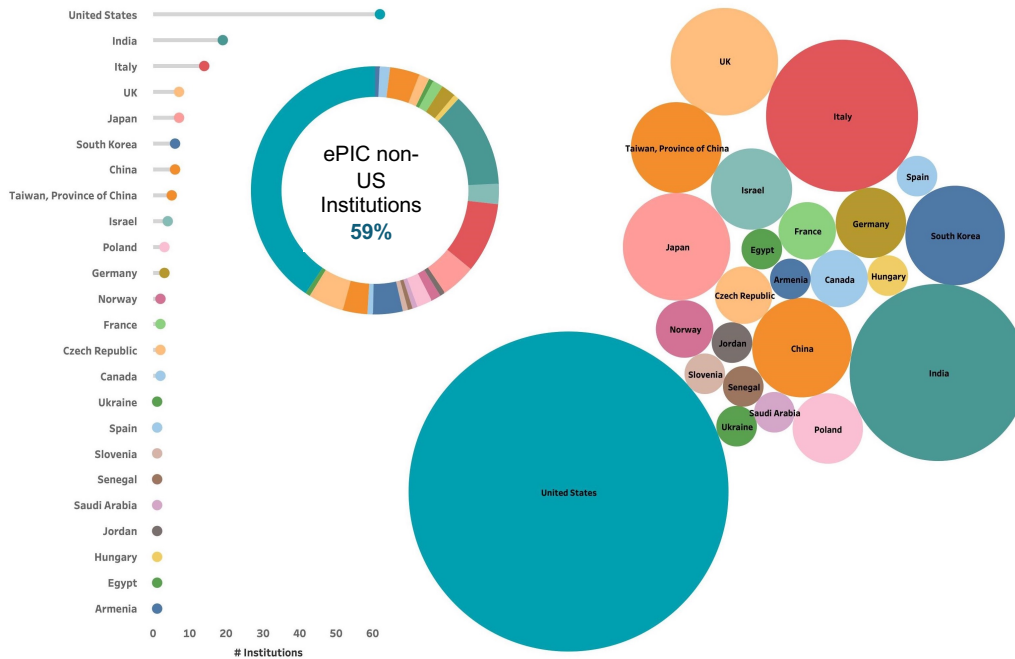


Institutions



The EIC design and construction has many scientific and technical challenges, creating opportunities for a worldwide collaboration to become part of this exciting endeavor.

The ePIC Collaboration



ePIC Spokesperson:
John Lajoie (ORNL)
ePIC Deputy Spokesperson & Interim Technical Director
Silvia Dalla Torre (INFN Trieste)



EIC at Tohoku University

ePIC formed in 2022

ePIC is now 176 institutions.

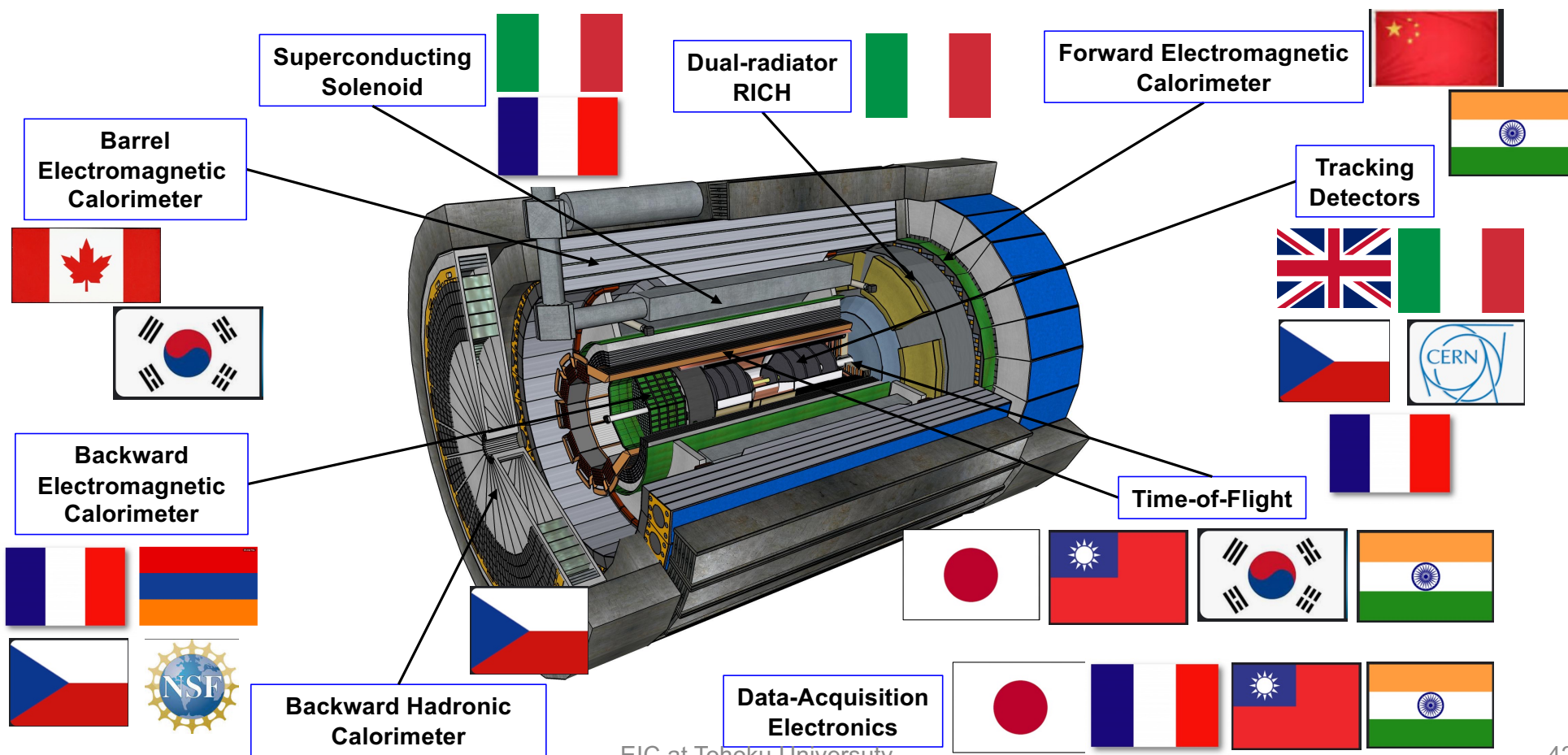
Representing 40+ countries

1000+ participants

A global pursuit for a new experiment at the EIC!

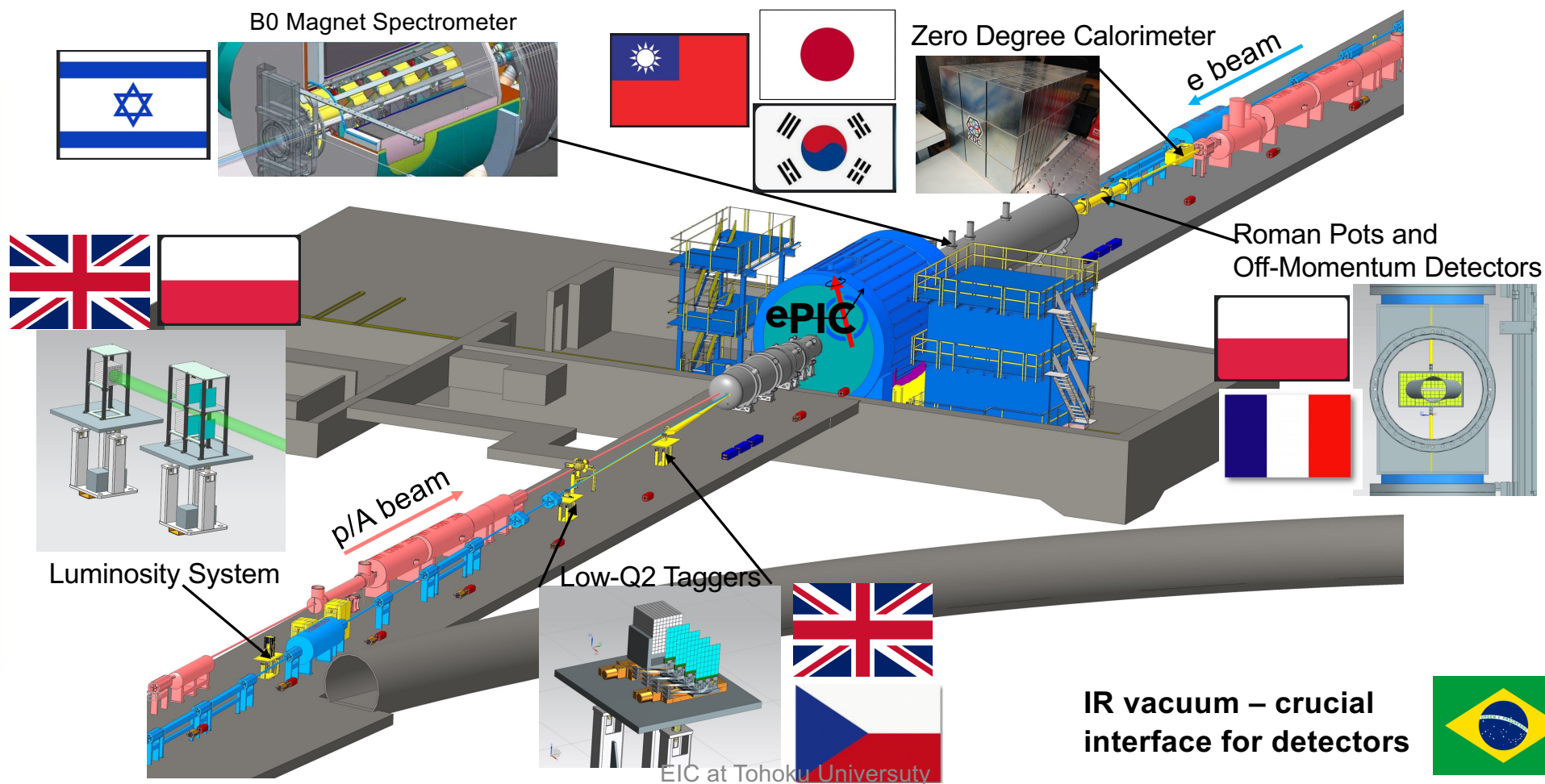


Central Detector Non-DOE Interest & In-Kind



EIC at Tohoku University

Far-Forward/Far-Backward Detectors Non-DOE Interest & In-kind



EIC Partner Highlights

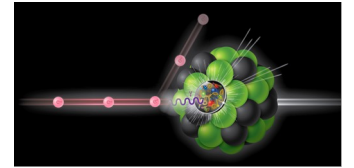
- **New York State** committed **\$100M** toward construction of buildings and infrastructure for the EIC.
- **In-kind contributions** developing with **Canada, France, Italy, and Japan**.
- **Statements of Interest** signed between DOE and **French** agencies.
- **EIC Accelerator Collaboration Kick-Off at IPAC'24**, Satellite Meeting held at IPAC'25 in Taiwan garnering growing interest.



- **5th EIC Resource Review Board Meeting** held in Prague in June 2025.
- **7th RRB @ MEXT Japan, June 9,10, 2026**; Strong support from **Canada, Czech Republic, France, Italy, Japan, South Korea, and Taiwan**.

In-kind contribution goals represent 30% of the Detector and 5% of the Accelerator

Outlook



The only new collider in the US (and for another 20-30 years in the “world”) is being planned at BNL – **high luminosity, energy, polarized beams, variable CM energy and all nuclei** – make this a rather unique and versatile machine

The EIC project has significant momentum on all fronts right now. First collisions and early physics starts around 2034/5

Science of EIC: **Gluons** – that bind us all...

- Understanding the origin of mass, spin and high-gluon-density state of matter!
- Possible complementary searches for BSM – 2nd detector? New technology?

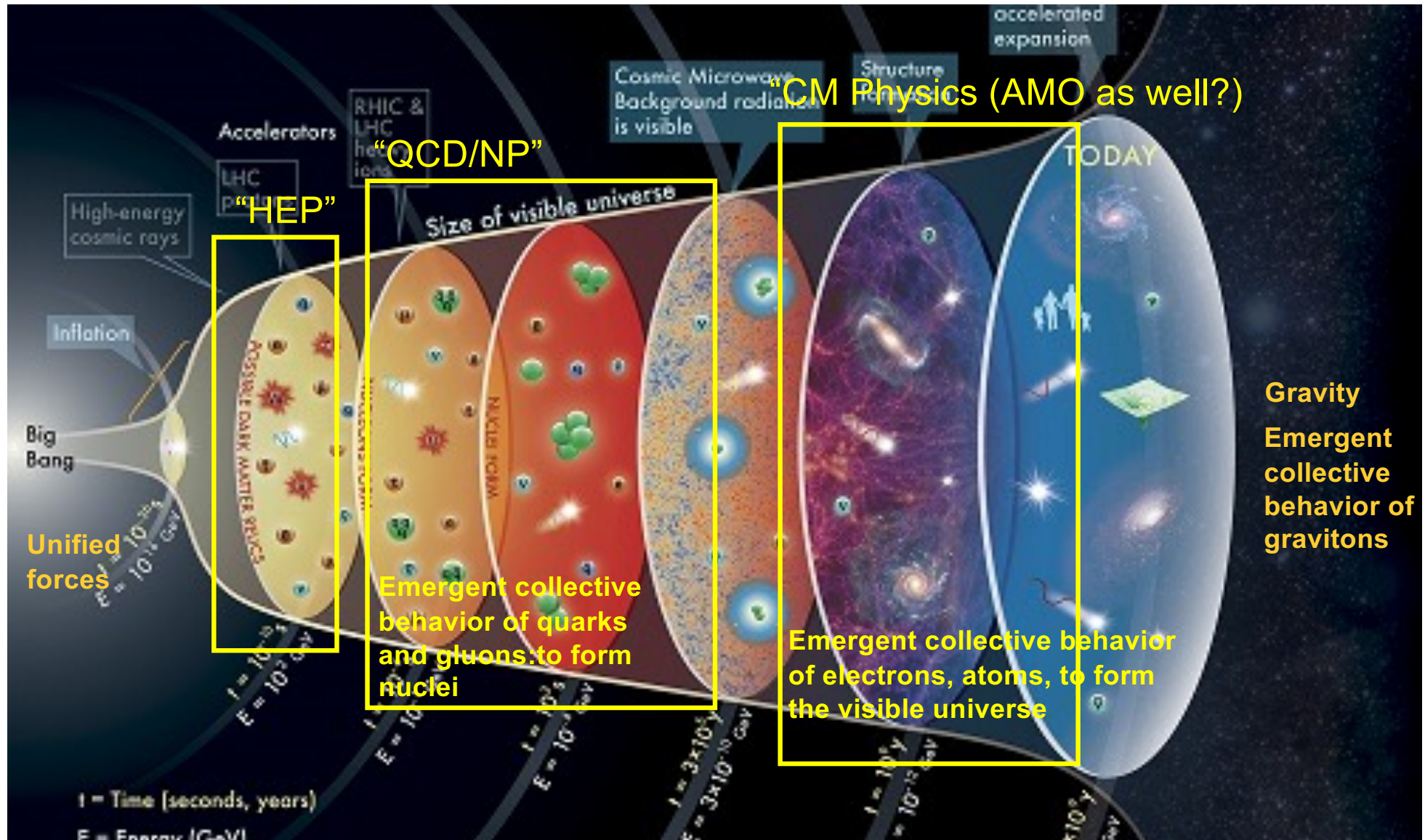
Exciting times ahead.... Join us! (eicug.org & bnl.gov)

Great opportunities for early career scientists in this audience

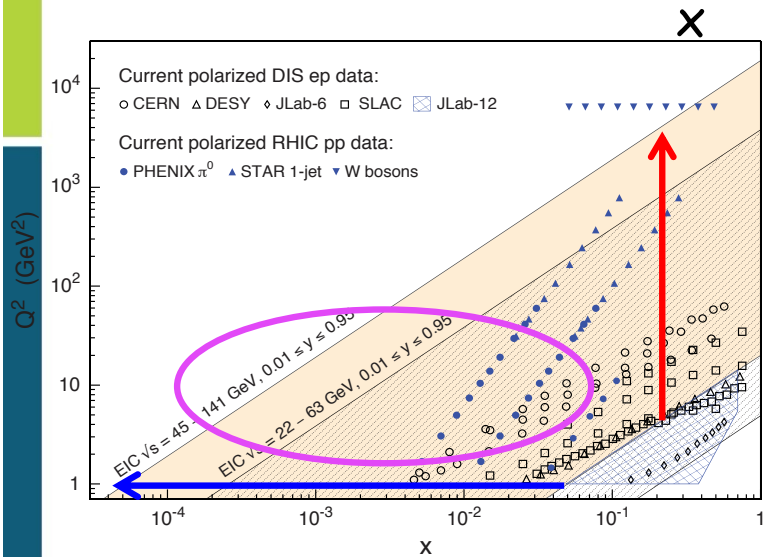
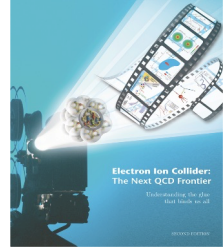


***"New directions in science are
launched by new tools much more
often than by new concepts."***

Freeman Dyson



EIC: **NEW** Kinematic reach & properties



For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/ ^3He
- ✓ Variable center of mass energy
- ✓ **Wide Q^2 range $\rightarrow$ evolution**
- ✓ **Wide x range $\rightarrow$ spanning valence to low-x physics**

For e-A collisions at the EIC:

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

