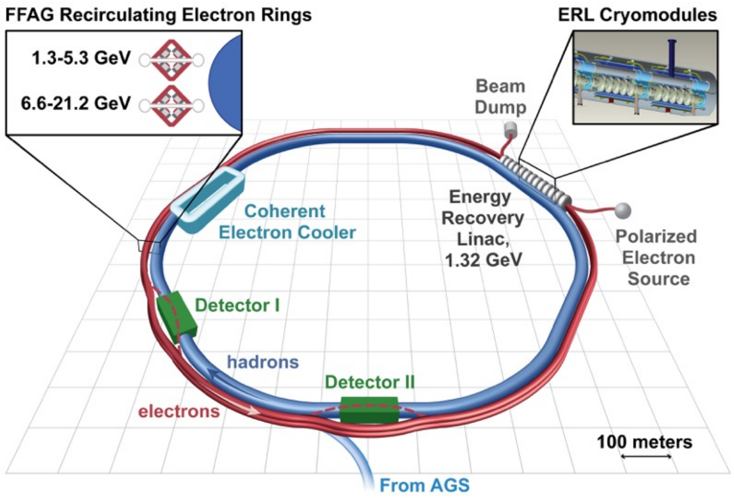
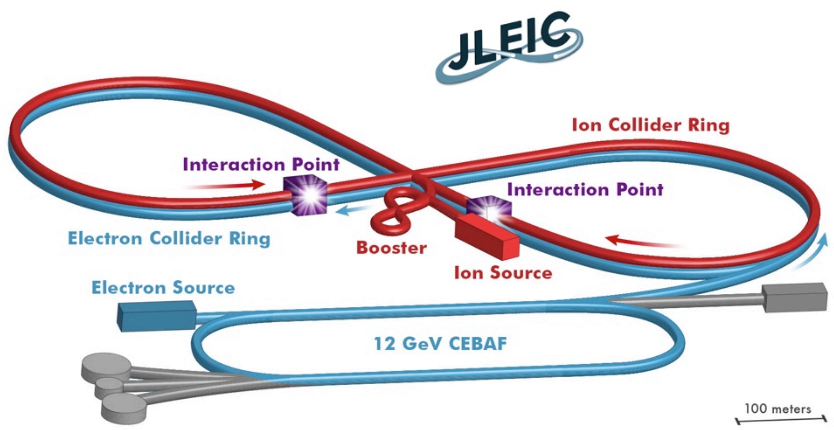
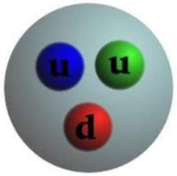
Electron Ion Collider: A New Science Frontier



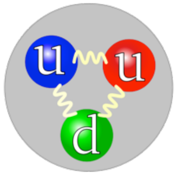


Rik Yoshida
Jefferson Lab
US QCD All-Hands Meeting
Newport News, Apr. 28, 2017

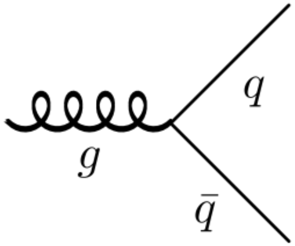
A short history: QCD and nucleons



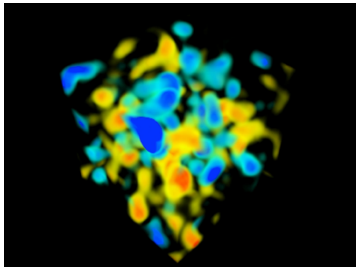
Quark Model: hadrons are made of quarks.



Quantum Chromodynamics: theory of quark and gluon interaction.



QCD is a strongly interacting theory except at short distances..
perturbative QCD: ok at short distances

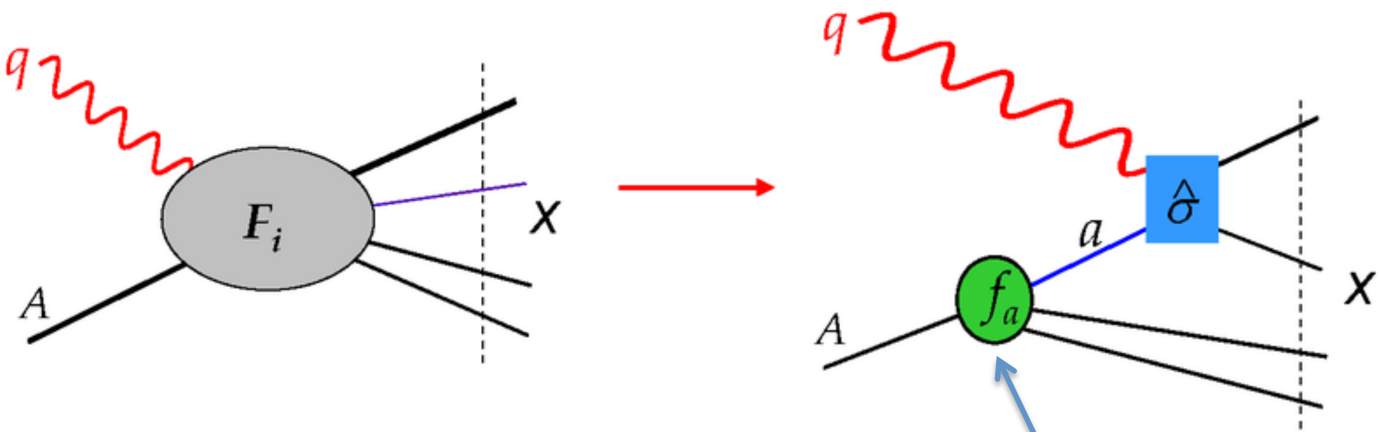


But nucleon size is long-distance in this scale:
perturbative theory cannot tell us about how nucleons come about from quarks and gluons.
(Lattice QCD. Nuclear Structure Theory)

Factorization

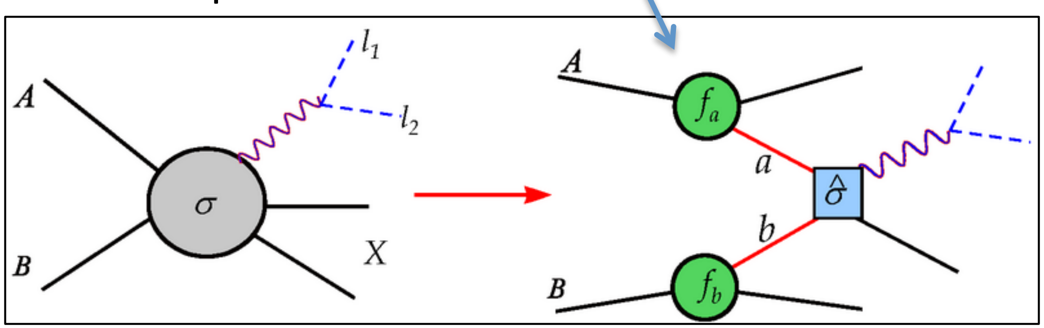
QCD-Factorization

$$\lim_{Q^2 \to \text{large},\, x\,\text{fixed}} F_i(x,Q^2) = f_a \otimes \hat{\sigma}$$



Same Parton Distributions

Different process

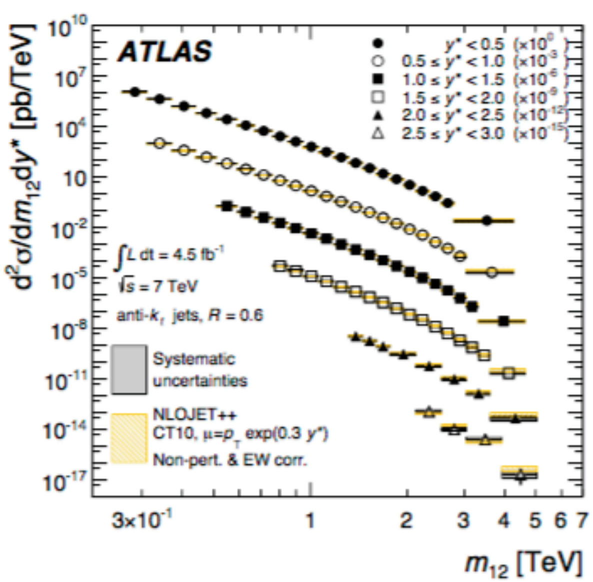


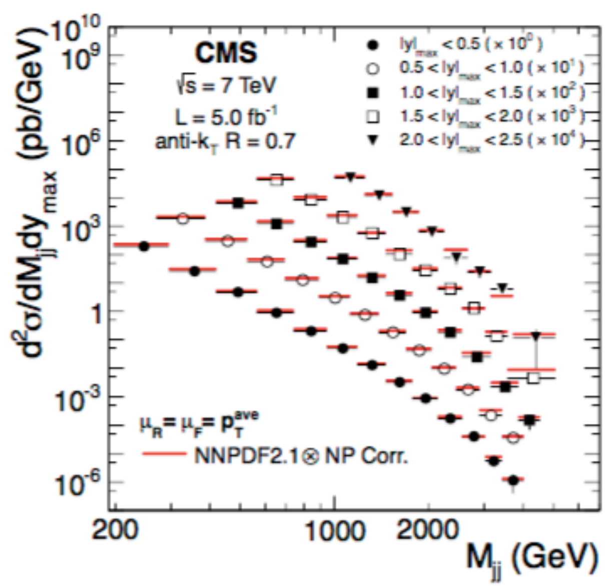
Parton distributions are process independent!

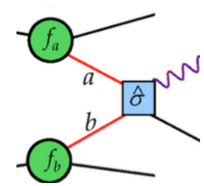
Using pQCD to understand protons: so far

- Protons at high momentum can be treated as a beam of partons— now identified as free quarks and gluons: (Asymptotic freedom!)
- QCD nature of quark and gluons make their densities “evolve” with Q^2
- This evolution itself is conceptually simple and the partons behave incoherently.
- You can measure DIS (and other) cross-sections -> extract pdfs -> predict cross-sections for another process. (Factorization!)

Jet cross-sections at the LHC predicted and measured

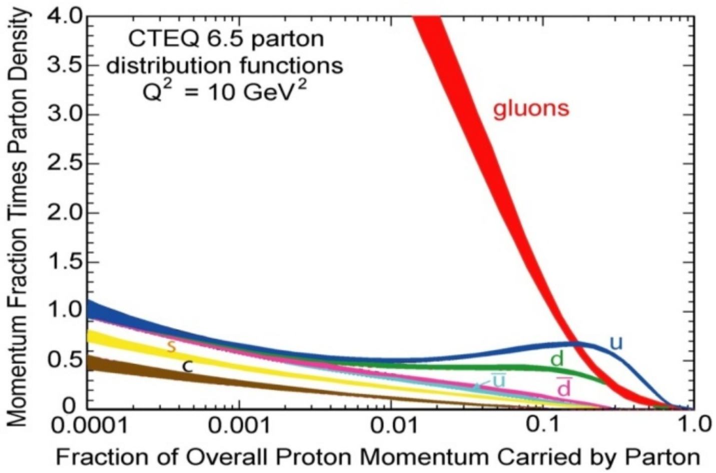




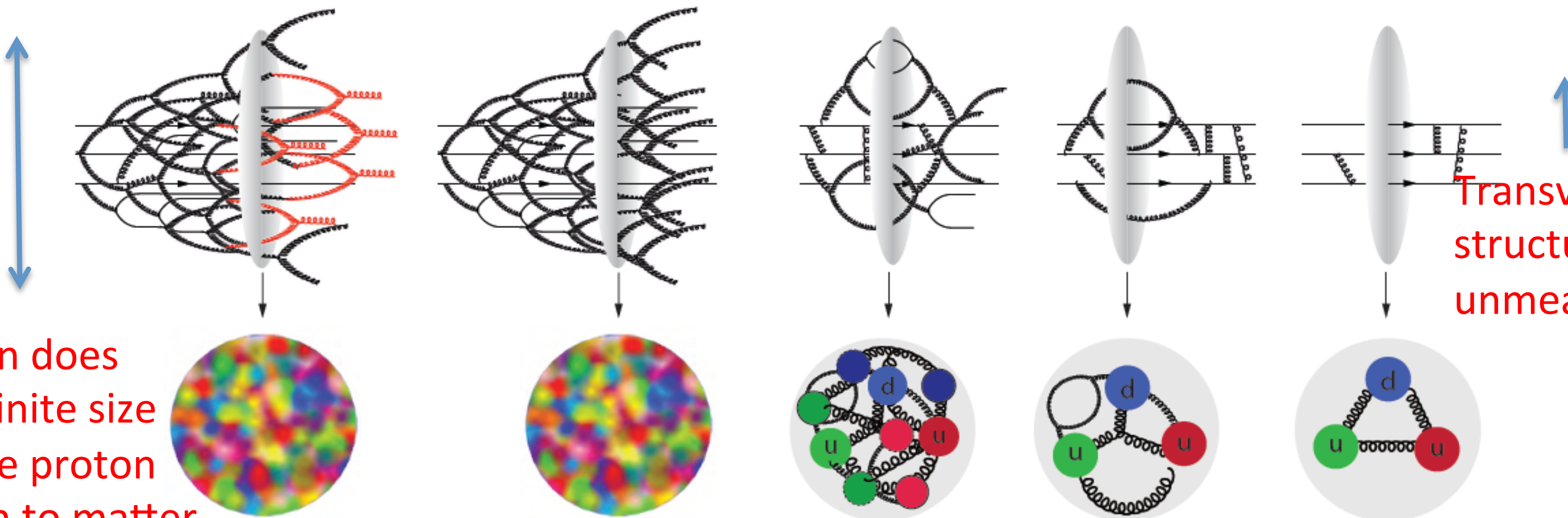


This is great if you are interested in studying the hard interaction (LHC physics)

What about the proton?



- Proton structure is embedded in the quark and gluon distributions.
- Gluons dominate below x of 0.1
- We imagine a proton looks something like the cartoon below..
- But we so far only have longitudinal information…

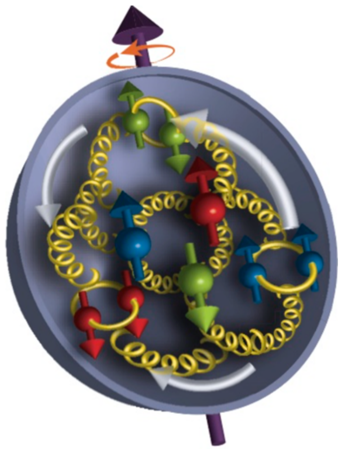


Transverse structure unmeasured

When does the finite size of the proton begin to matter (saturation! confinement!)

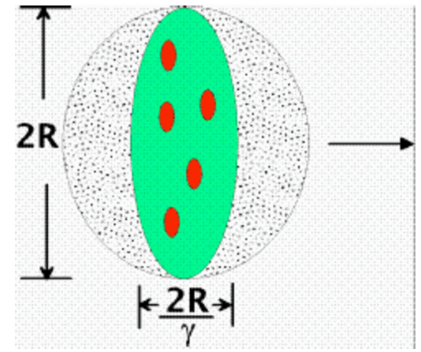
X (longitudinal) structure measured

Limits of Longitudinal Information



infinite
momentum
frame

What we know



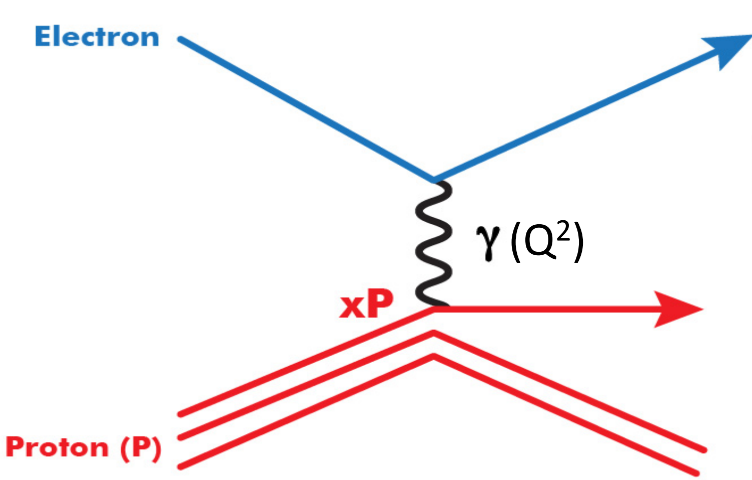
What is the quark and gluon structure of the proton?
-orbital motion?
-color charge distribution?
-spin?
-how does the mass come about?
-origin of nucleon-nucleon interaction?

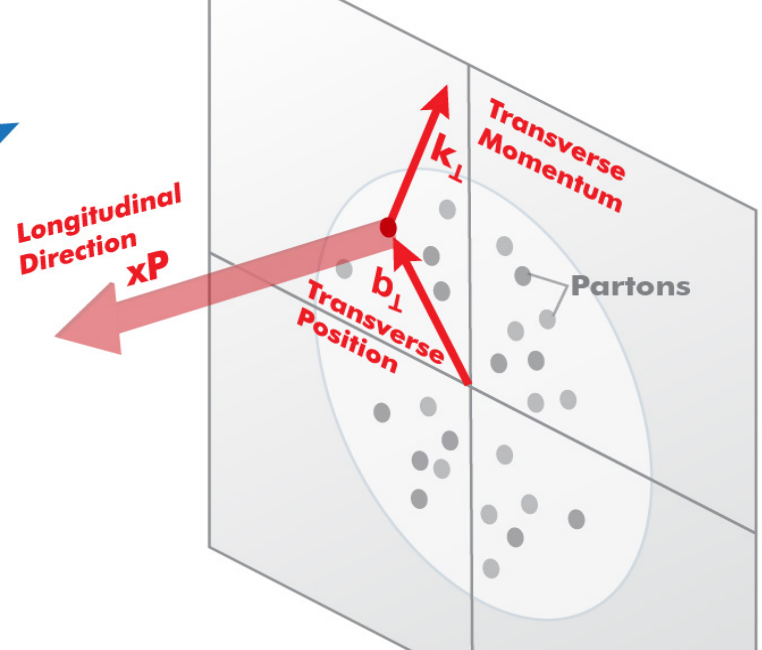
Parton frozen transversely. Framework does not incorporate any transverse information.

But this was the only way to define quark-gluon structure of proton in pQCD.

Progress in pQCD Theory (~1980-Now)

Factorization of TMD, GPD





Parton Distribution Functions:
Longitudinal only—
Pert. quarks and gluons can only be thought of longitudinally making up p.

3D (Transverse) Structure
TMD's, GPD's—
Now we know what to measure to understand the 3D structure of nucleons

Transverse Momentum Dependent Distributions (TMD): k_t
Generalized Parton Distributions (GPD): b_t

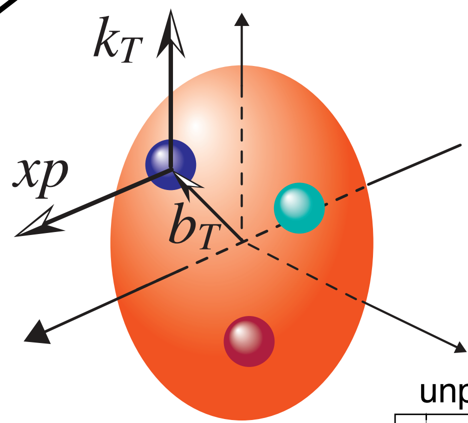
HERMES, COMPASS, JLAB 12

3D Imaging of Quarks and Gluons

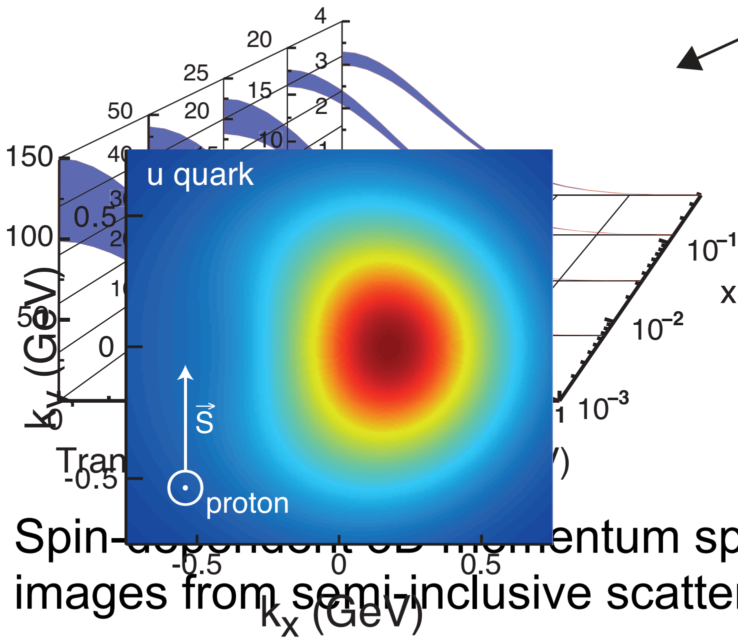
$W(x,b_T,k_T)$

Momentum space $\int d^2b_T$ → $f(x,k_T)$

$\int d^2k_T$ → $f(x,b_T)$ *Coordinate space*

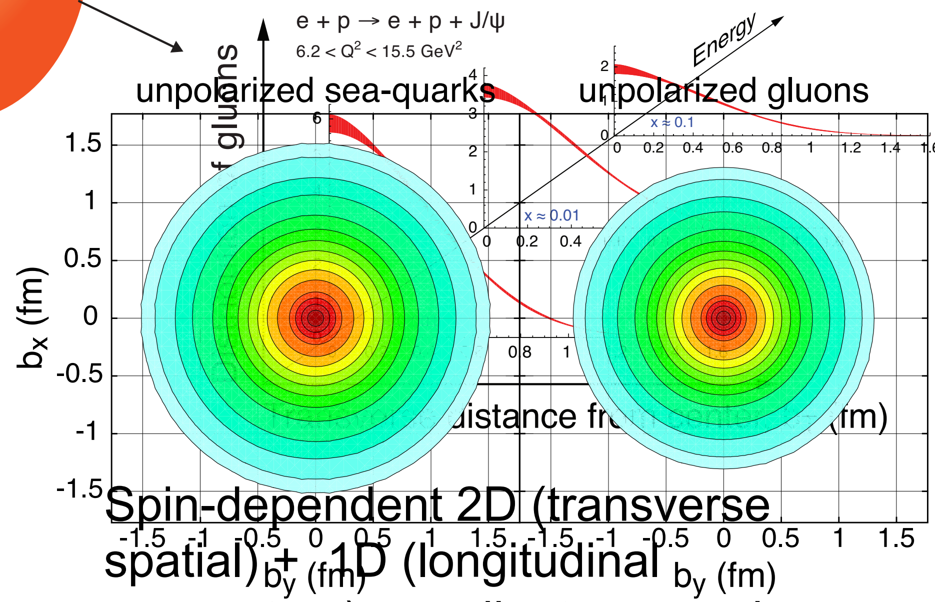


Quarks



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

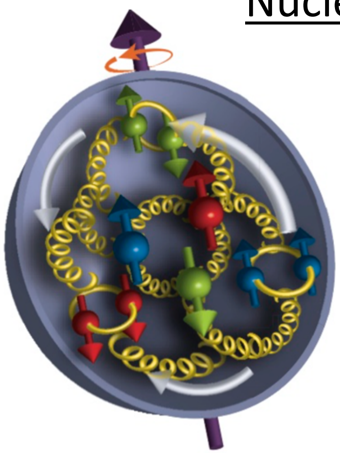
Gluons



Spin-dependent 2D (transverse spatial) + 1D (longitudinal momentum) coordinate space images

Position *r* X Momentum *p* → Orbital Motion of Partons

Understanding the Nucleon at the Next Level



Nucleon: A many-body system with challenging characteristics

Relativistic ($M_{proton} >> M_{quark}$)

Strongly Coupled (QCD)

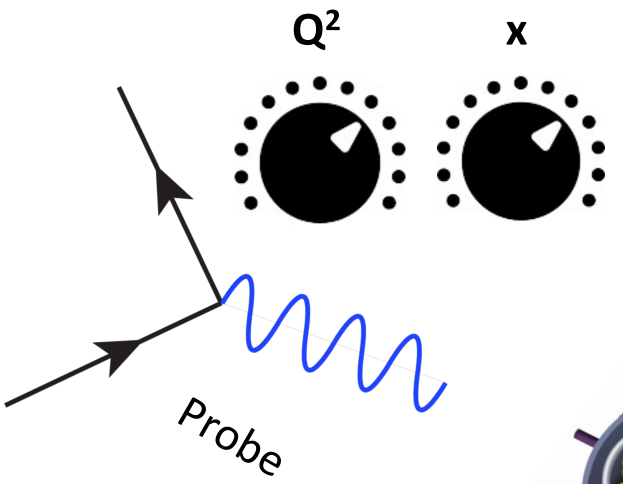
Quantum Mechanical (Superposition of configurations)

Measure in the Multi-Body regime:
- Region of quantum fluctuation + non-perturbative effects → dynamical origin of mass, spin.

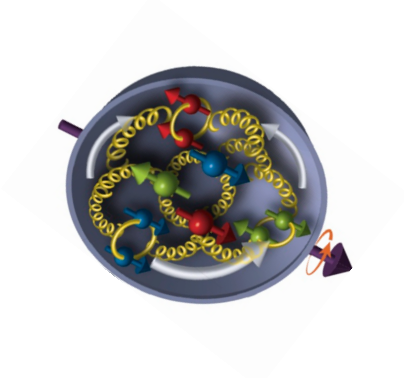
For the first time, get (almost?) all relevant information about quark-gluon structure of the nucleon

Designing EIC → Designing the right probe
- Resolution appropriate for quarks and gluons
- Ability to project out relevant Q.M. configurations

Parameters of the Probe

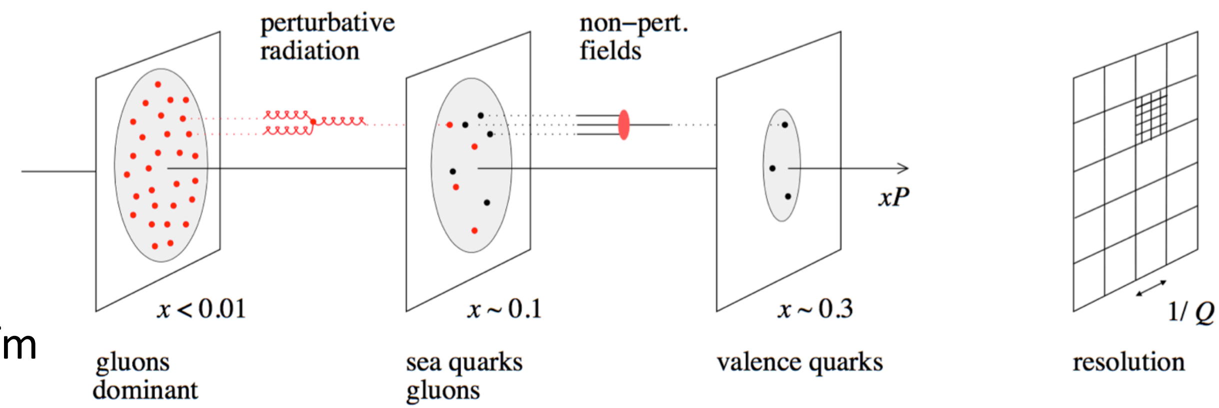


Ability to change **x** projects out different configurations where different dynamics dominate



Ability to change **Q²** changes the resolution scale

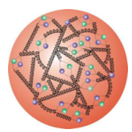
$Q^2 = 400\ \text{GeV}^2 \Rightarrow 1/Q = .01\ \text{fm}$



Where EIC Needs to be in x (nucleon)

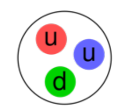
Saturation Regime: Needs to be Accessed via Ions (see later)

Collective Regime



Many-body Regime

Few-body Regime



10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 X (for proton)

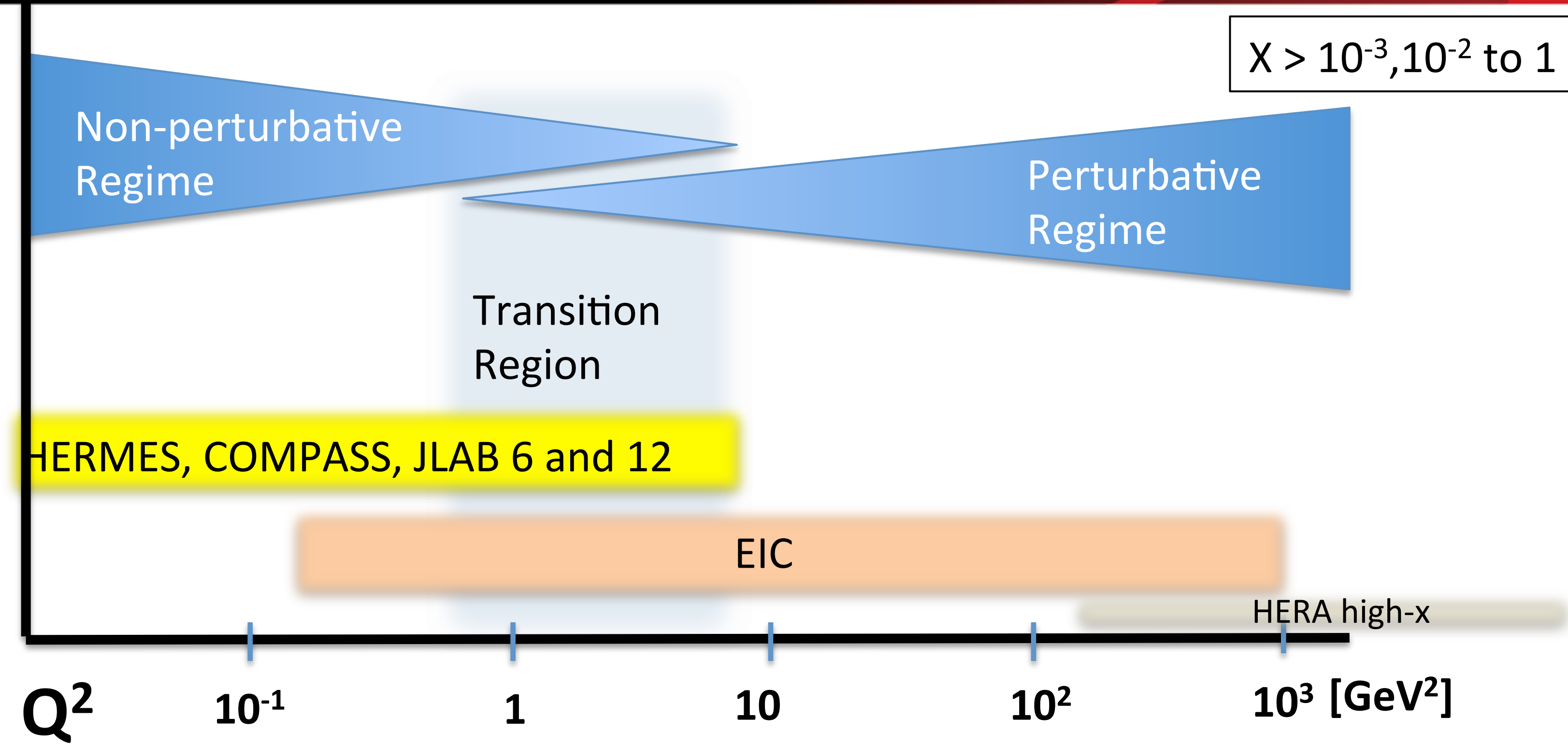
QCD Radiation Dominated (Studied at HERA)

Hadron Structure Dominated

Main interest for EIC Nucleon/Nuclear Program

Spin,TMD, GPD…

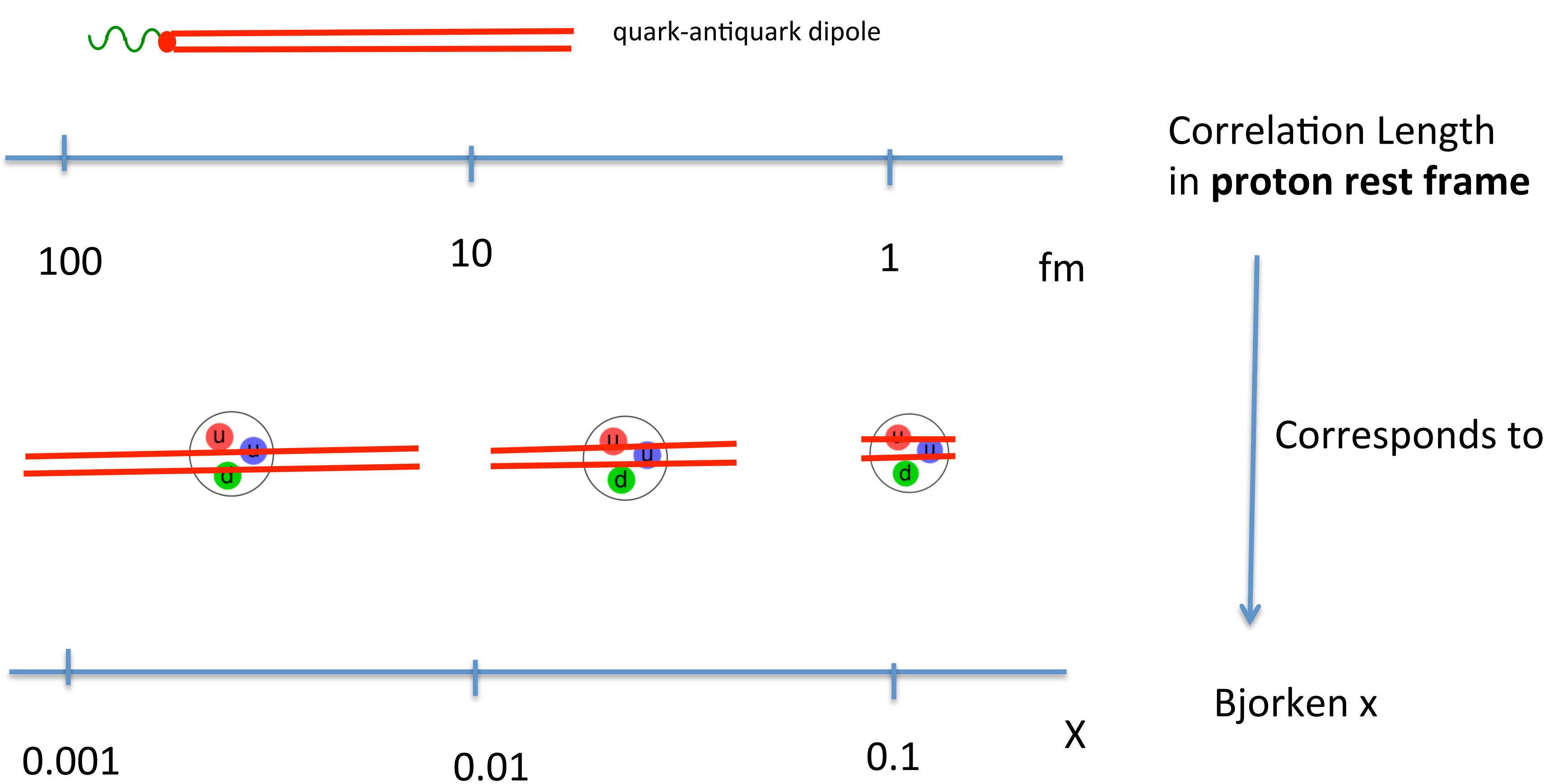
Where EIC needs to be in Q^2 (Q_1^2)



- Include non-perturbative, perturbative and transition regimes
- Provide long evolution length and up to Q^2 of ~1000 GeV^2 (~.005 fm)
- Overlap with existing measurements

Disentangle Pert./Non-pert., Leading Twist/Higher Twist

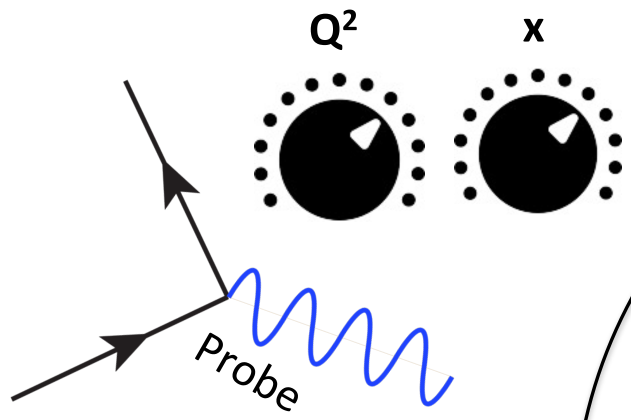
Bjorken x and length scale

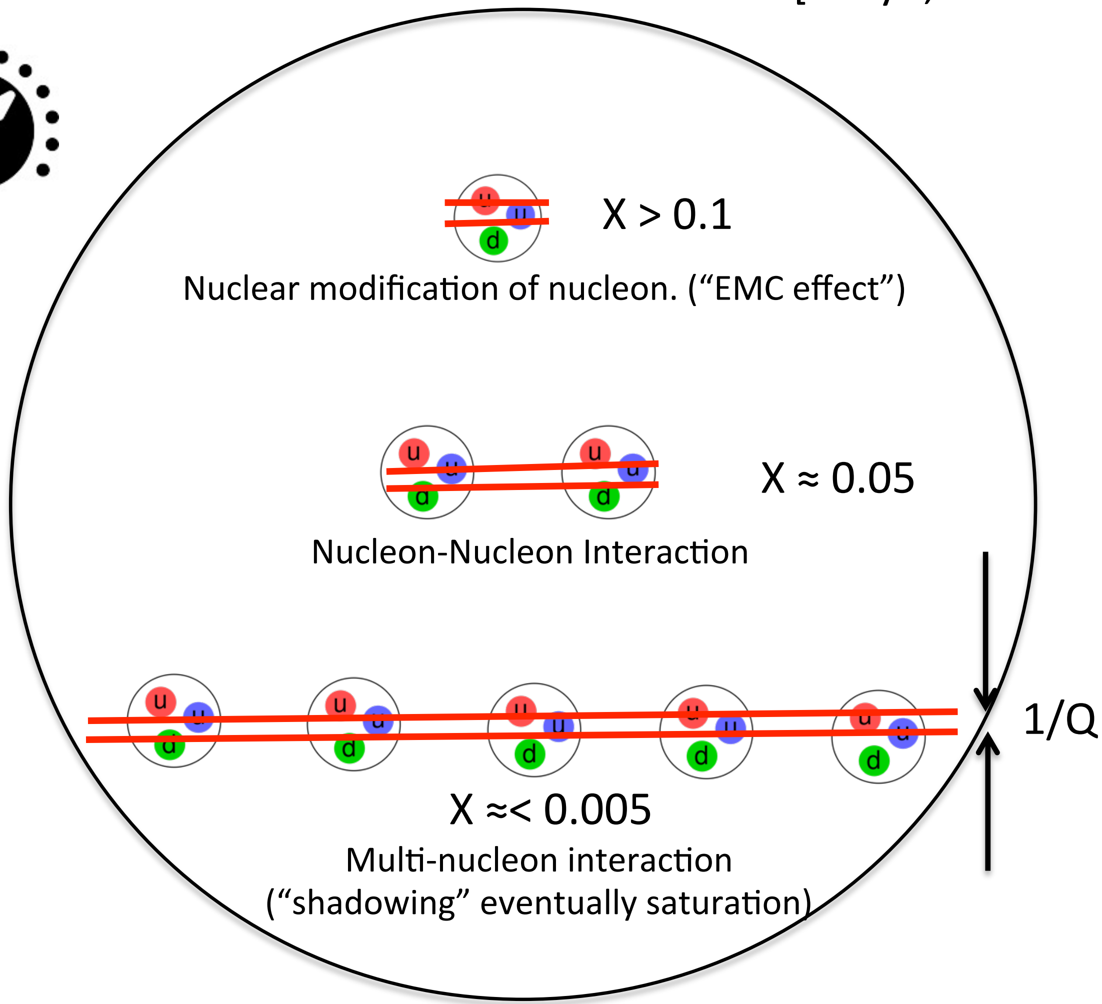


In the proton rest frame, dipole lifetime ($x < 0.1$) extends far beyond the proton charge radius

Parameters of the Probe (Nuclei)

[Cosyn, Armesto, Fazio]

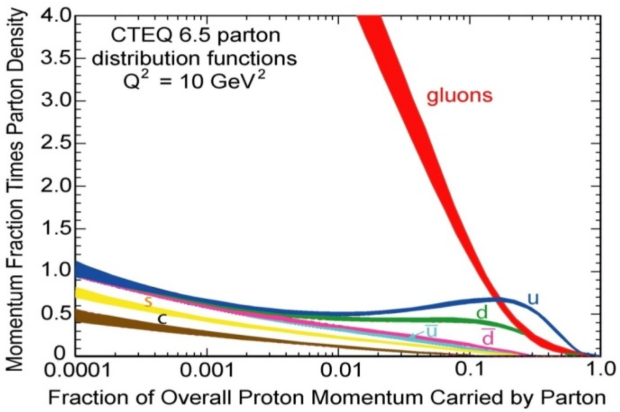




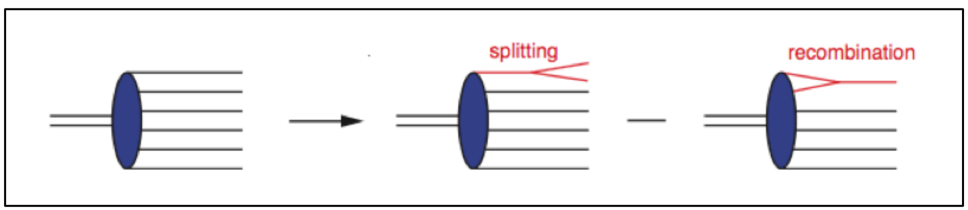
Probing the nucleon interaction in the nuclei (note this is different from correlation measurements)

Note: the x range for nuclear exploration is similar to the nucleon exploration

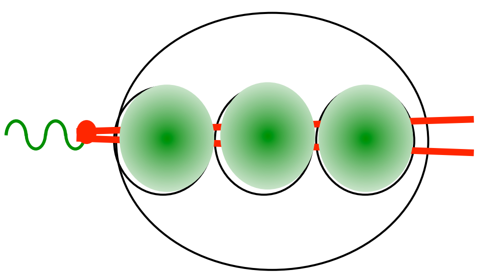
QCD at Extremes: Parton Saturation



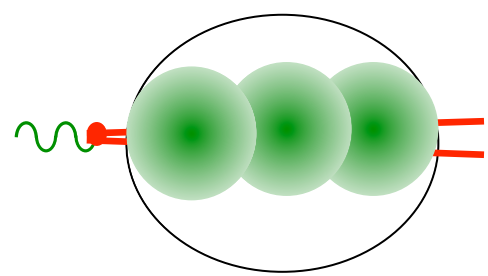
HERA discovered a dramatic rise in the number of gluons carrying a small fractional longitudinal momentum of the proton (i.e. small-x).



This cannot go on forever as x becomes smaller and smaller: parton recombination must balance parton splitting.
i.e. Saturation—unobserved at HERA for a proton. (expected at extreme low x)

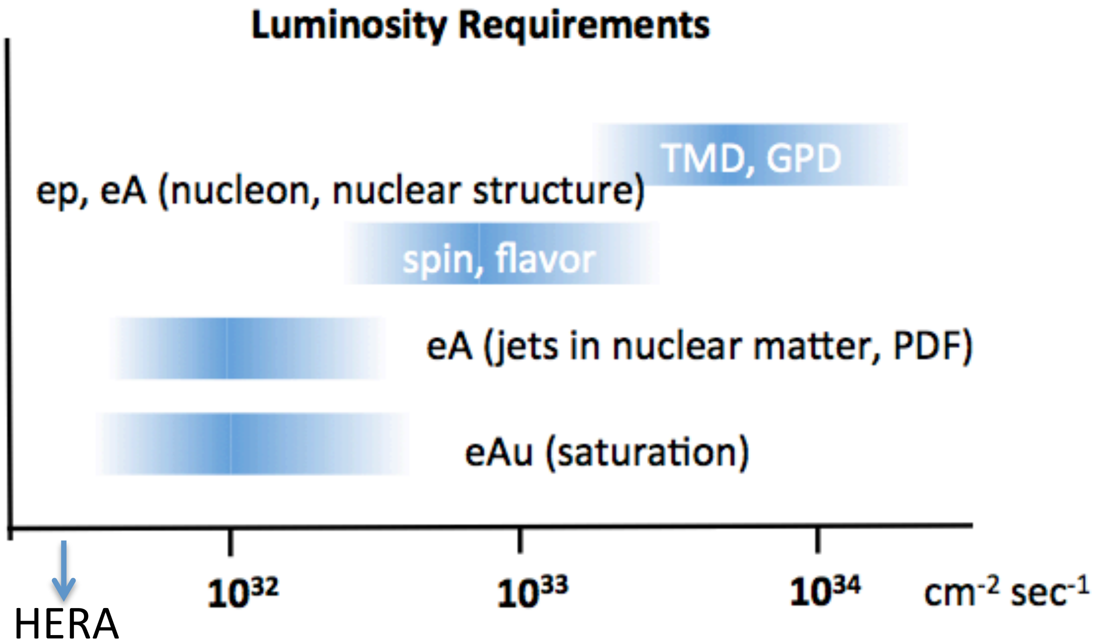


In nuclei, the interaction probability enhanced by $A^{1/3}$



Will nuclei saturate faster as color leaks out of nucleons?

Luminosity/Polarization Needed



Central mission of EIC (nuclear and nucleon structure) requires high luminosity and polarization (>70%).

The Electron Ion Collider

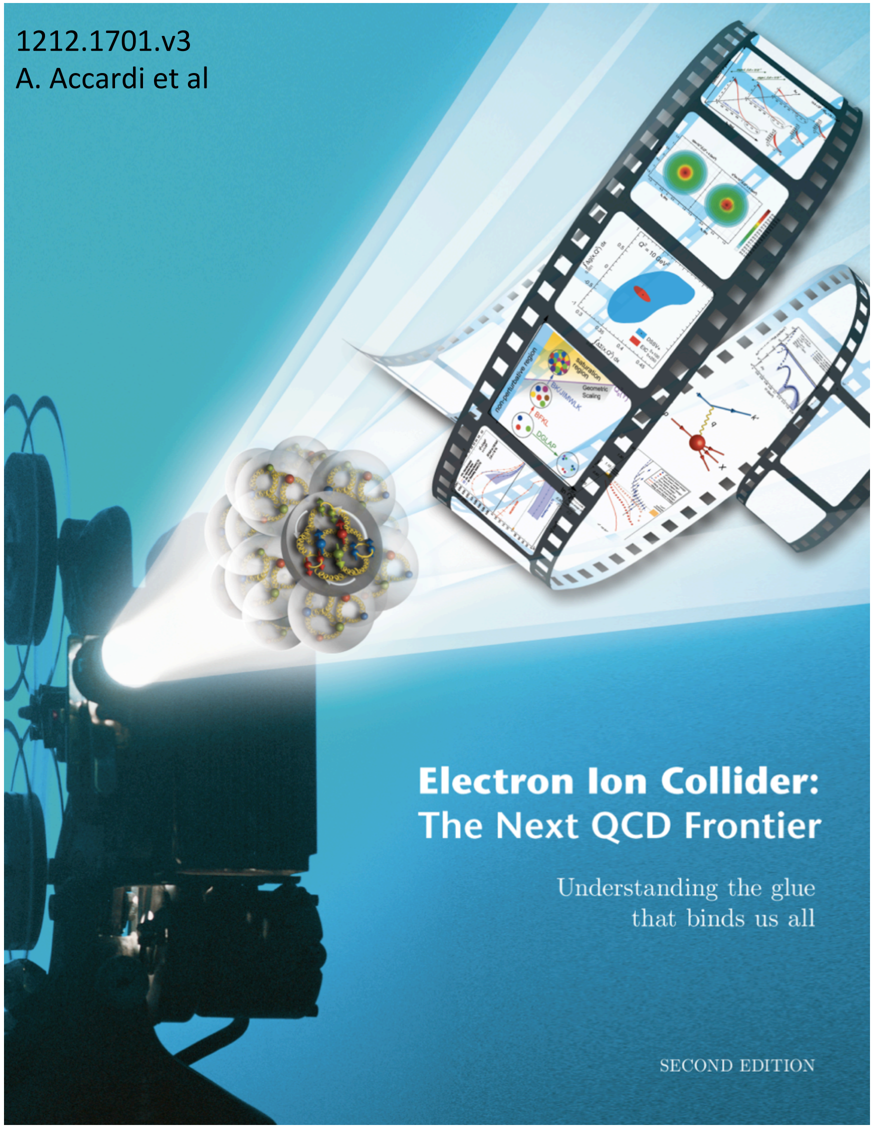
For e-N collisions at the EIC:
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 3-10(20) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-~100 (~140) GeV Variable CoM

For e-A collisions at the EIC:
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

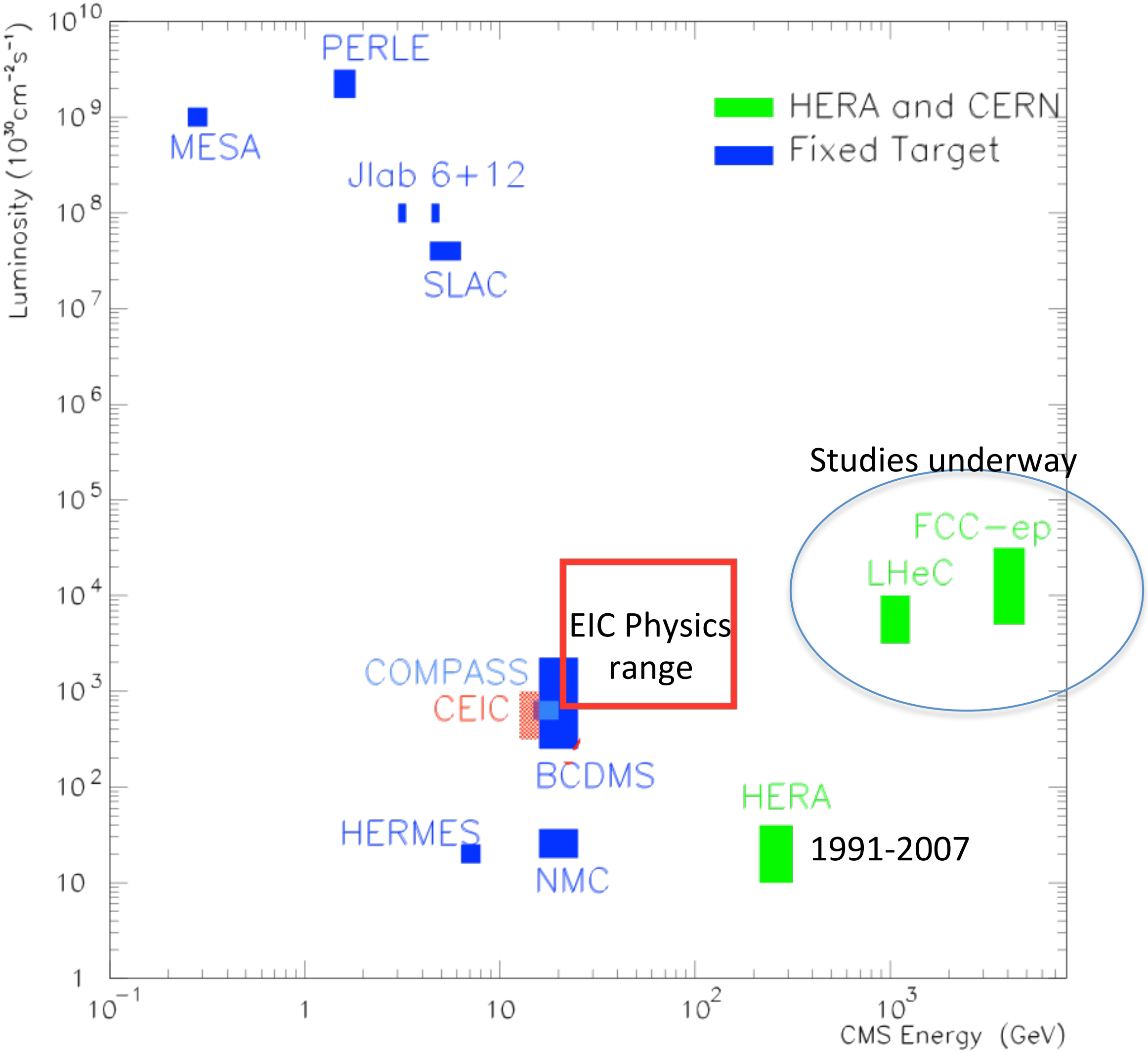
World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Two proposals for realization of the science case -
both designs use DOE's significant investments in infrastructure

1212.1701.v3
A. Accardi et al



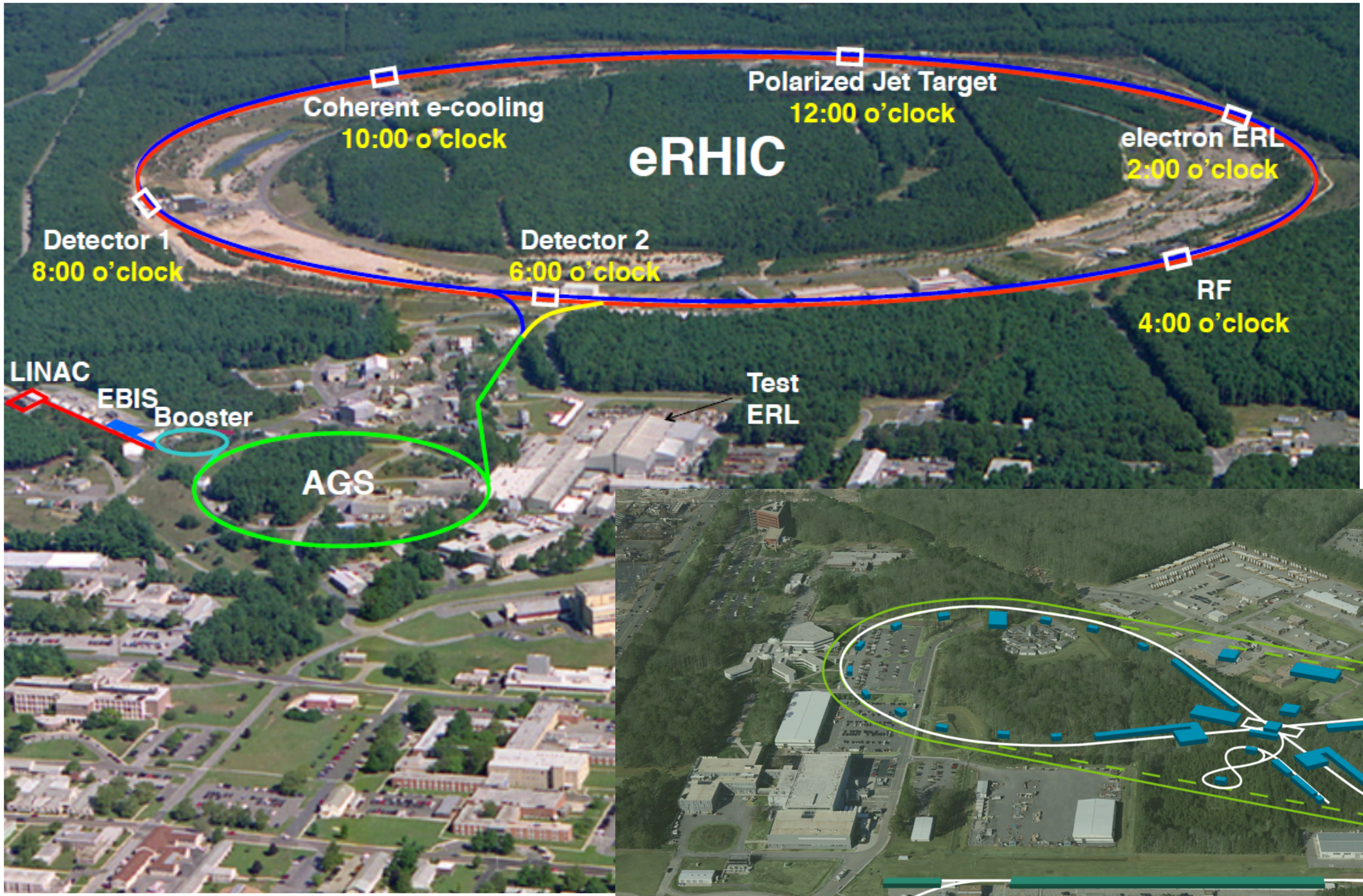
Past, Existing and proposed DIS Facilities



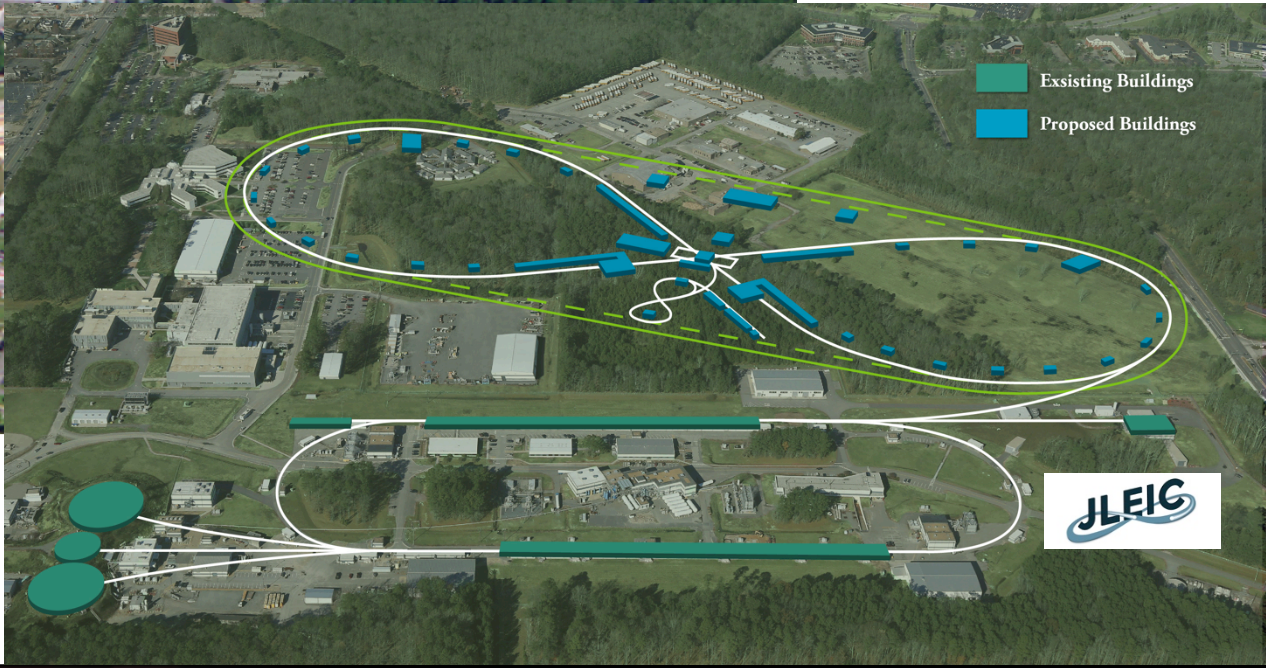
EIC will be a unique facility.

No other machine, existing or planned can address the physics of interest satisfactorily.

US-Based EIC Proposals

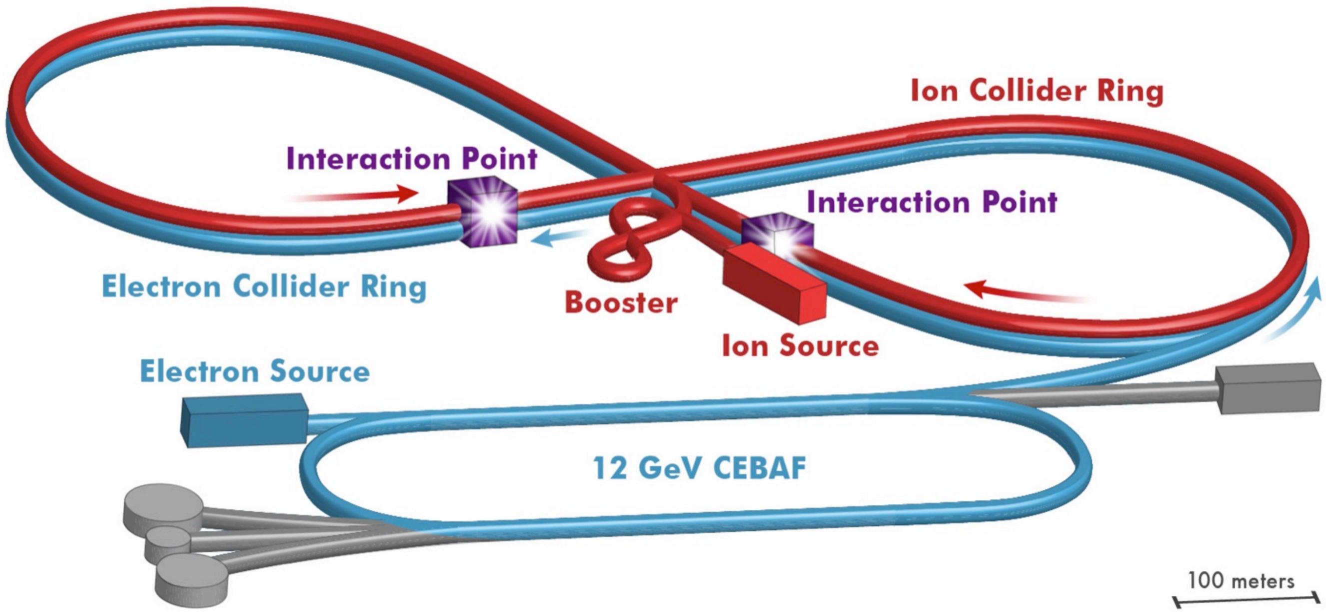


Brookhaven Lab
Long Island, NY



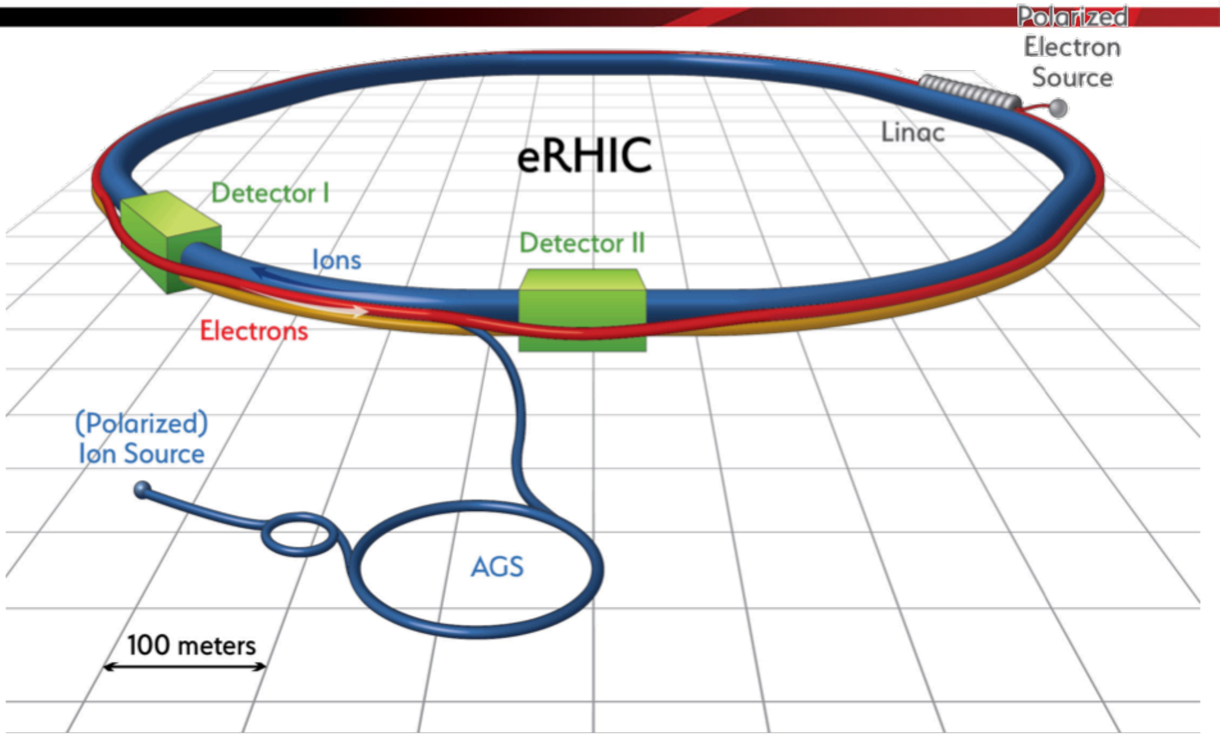
Jefferson Lab
Newport News, VA

JLEIC Realization



- Use existing CEBAF for polarized electron injector
- Figure 8 Layout: Optimized for high ion beam polarization → polarized deuterons
- Energy Range: √s : 20 to 65 - 140 GeV (magnet technology choice)
- Fully integrated detector/IR
- JLEIC achieves initial high luminosity, with technology choice determining initial and upgraded energy reach

eRHIC Realization



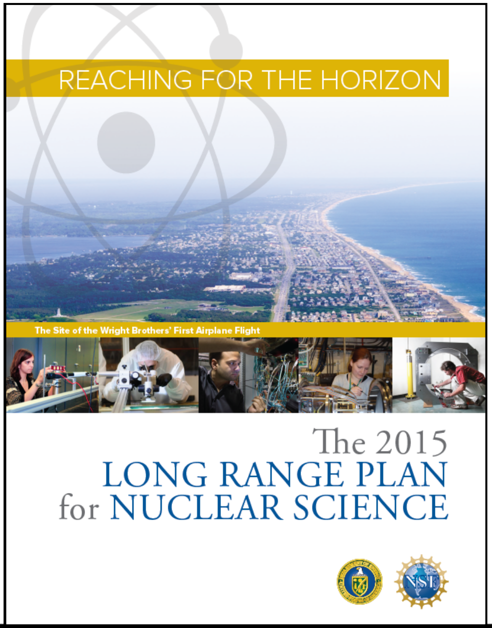
- Use existing RHIC
  - Up to 275 GeV protons
  - Existing: tunnel, detector halls & hadron injector complex
- Add 18 GeV electron accelerator in the same tunnel
  - Use either high intensity Electron Storage Ring or Energy Recovery Linac
- Achieve high luminosity, high energy e-p/A collisions with full acceptance detector
- Luminosity and/or energy staging possible

Nuclear Science Long-Range Planning

- Every 5-7 years the US Nuclear Science community produces a Long-Range Planning (LRP) Document
- The final document includes a *small* set of recommendations for the field of Nuclear Science **for the next decade**

October 2015 -> Report Finalized
(Including cost review of EIC)

USDOE (NP) is acting based on this planning
National Academy Science Review being commissioned
(Larger science case must be endorsed)



Recommendations - shorthand

1. **The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.**
    - **12 GeV** – unfold quark & gluon structure of hadrons and nuclei
    - **FRIB** – understanding of nuclei and their role in the cosmos
    - **Fundamental Symmetries Initiative** – physics beyond the SM
    - **RHIC** – properties and phases of quark and gluon matter

    The ordering of these four bullets follows the priority ordering of the 2007 plan

2. **We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.**

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

4. **We recommend increasing investment in small and mid-scale projects and initiatives that enable forefront research at universities and laboratories.**

EIC Realization Imagined

With a formal NSAC/LRP recommendation, what can we speculate about any EIC timeline?

- A National Academy of Sciences study has been initiated and the committee is now formed. Charge: “assess the scientific justification for a U.S. domestic electron ion collider facility, “ (Wider Science Community) Likely to take ~12 months. Our next challenge.

- DOE project “CD0” (Establish Mission Need) will be after the NAS study: i.e end 2017, early 2018.

- EIC construction has to start **after FRIB completion**, with FRIB construction anticipated to start ramping down near or in FY20.

→ Most optimistic scenario would have EIC construction start (CD3) in FY20, perhaps more realistic FY22-23 timeframe

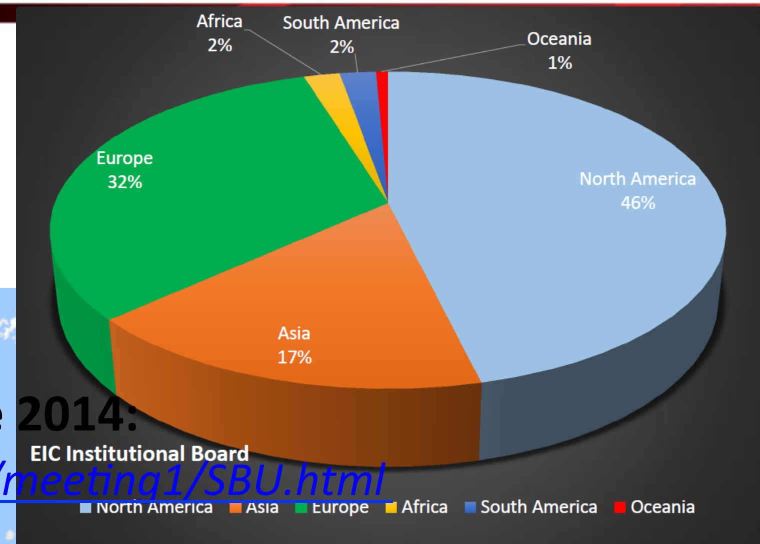
→ Best guess for EIC completion assuming formal NSAC/LRP recommendation would be 2025-2030 timeframe

The EIC Users Group: EICUG.ORG

(no students included as of yet)

670 collaborators, 28 countries, 150 institutions… (December, 2016)

Map of institution's locations



The EIC Users Meeting at Stony Brook, June 2014:

→ http://skipper.physics.sunysb.edu/~eicug/meeting1/SBU.html

The EIC UG Meeting at University of Berkeley, January 6-9, 2016

http://skipper.physics.sunysb.edu/~eicug/meeting2/UCB2016.html

Recent EICUG Argonne National Laboratory July 7-10, 2016

http://eic2016.phy.anl.gov

Remote/Internet: meeting: March 16th : For NAS Review preparation

Next meeting:

July 18-22, 2017 Trieste, Italy

New Users → New Physics → Lots of activities

Programs related to EIC

physical masses

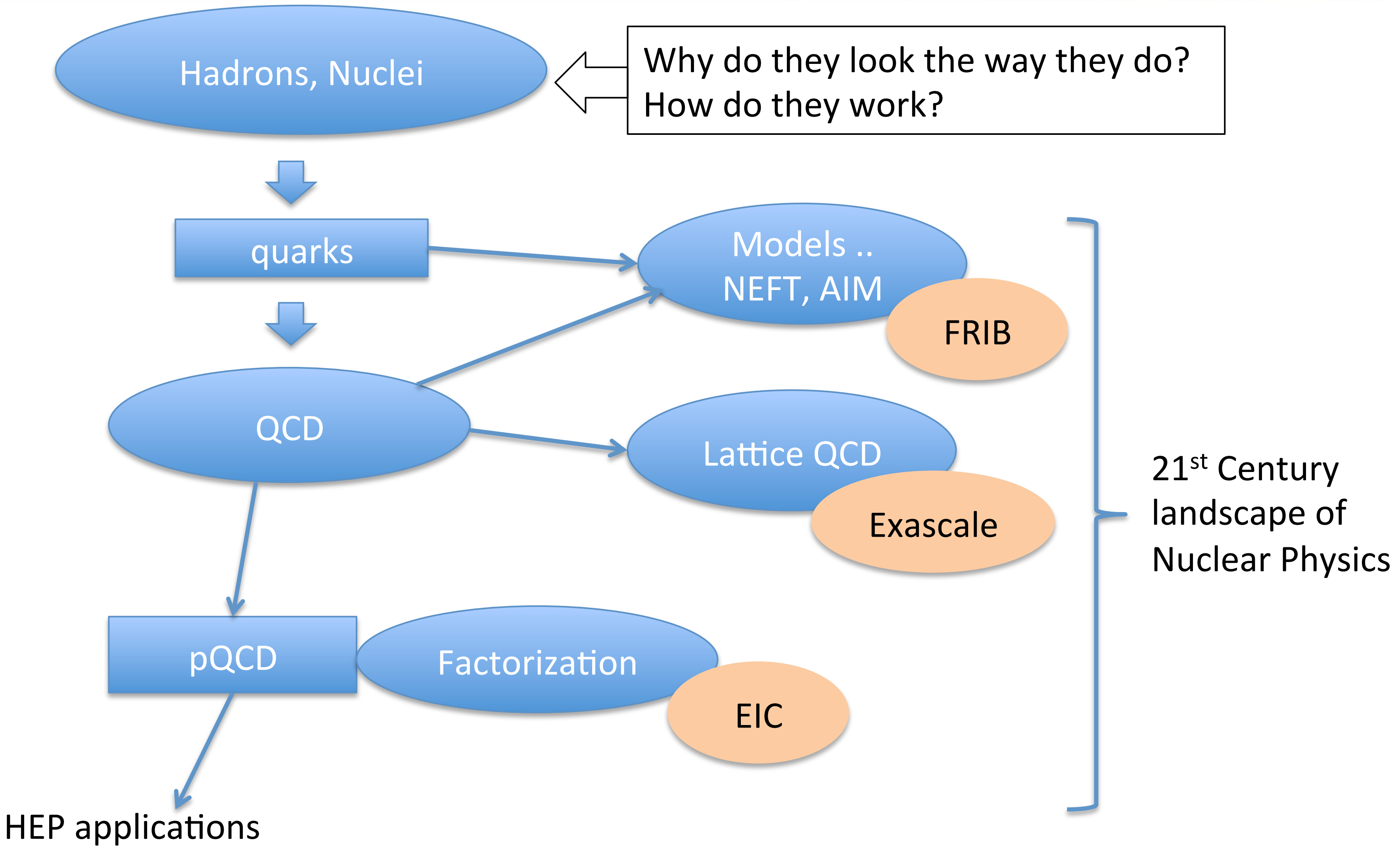
Highly Active EIC Community has evolved

…ia production with 1…

- In view of new discoveries of multi-quark XY…

EPILOGUE

Nuclear Science in the 21st C.



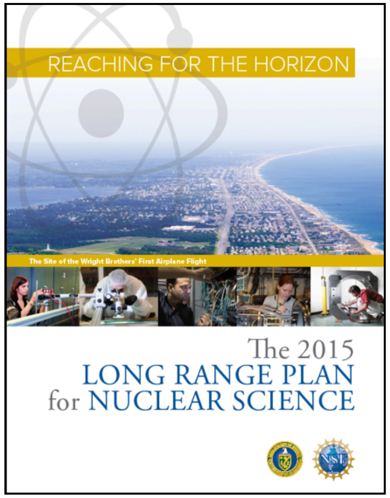
Conclusion

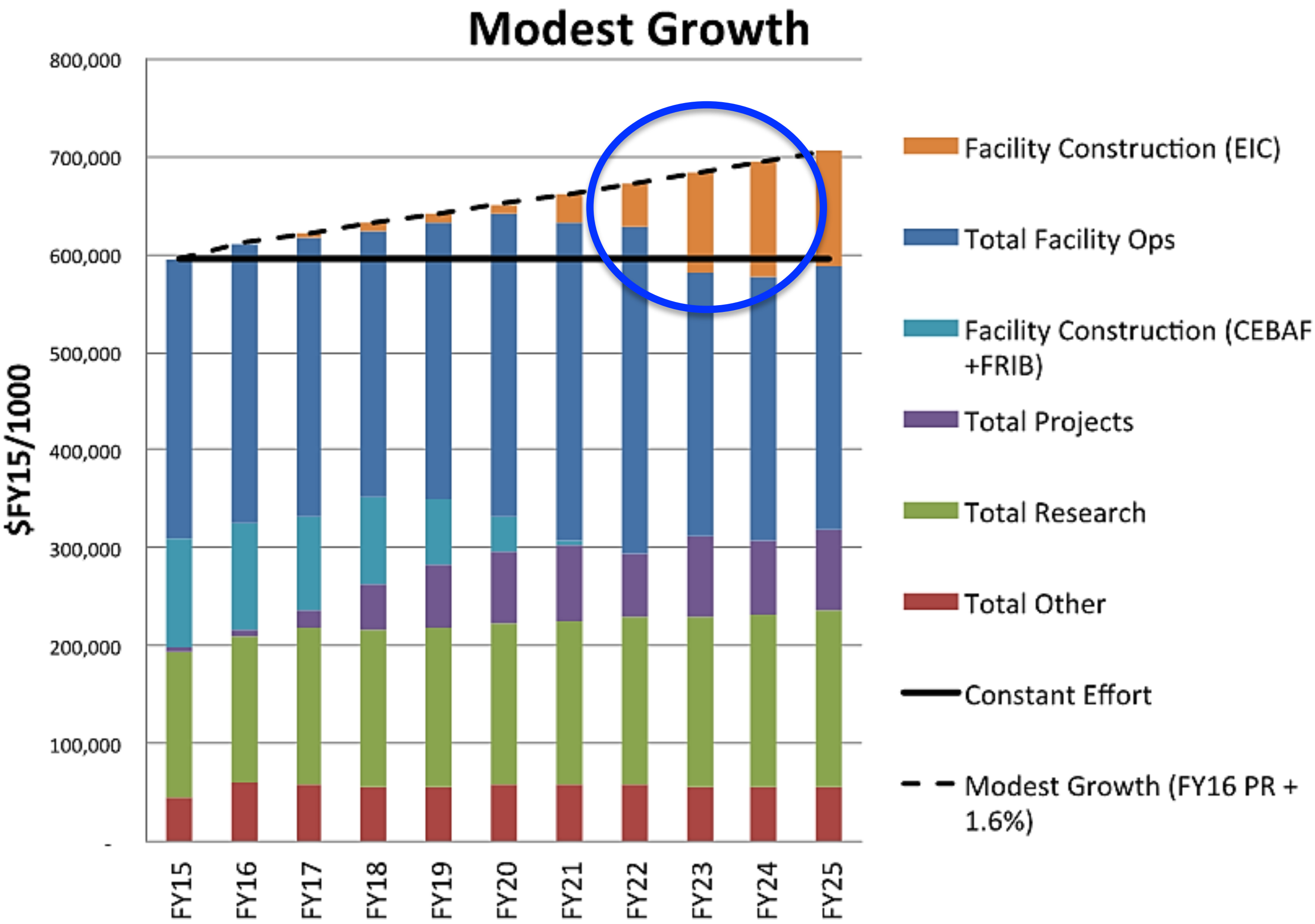
- EIC Program aim: Revolutionize the understanding of nucleon and nuclear structure and associated dynamics.
- For the first time, EIC will enable us to study the nucleon and the nucleus at the scale of quarks and gluons, over (arguably) all of the kinematic range that are relevant for exploring the nuclear and nucleon structure and the associated QCD dynamics.
- Outstanding questions raised both by the science at RHIC/LHC and at HERA/COMPASS/Jefferson Lab, have **naturally led to the science and design parameters of the EIC.**
- There exists **world wide interest** in collaborating on the EIC. Now we must turn this into real participation!
- In the next decades, with the advent of EIC, a new window will open to the quark-gluon structure of ordinary QCD matter.
- **EIC**(partons) + **FRIB** (nuclear structure) + **LQCD** will be a powerful set of tools in bringing our understanding of QCD matter to a new level.

The future of science demands an Electron Ion Collider

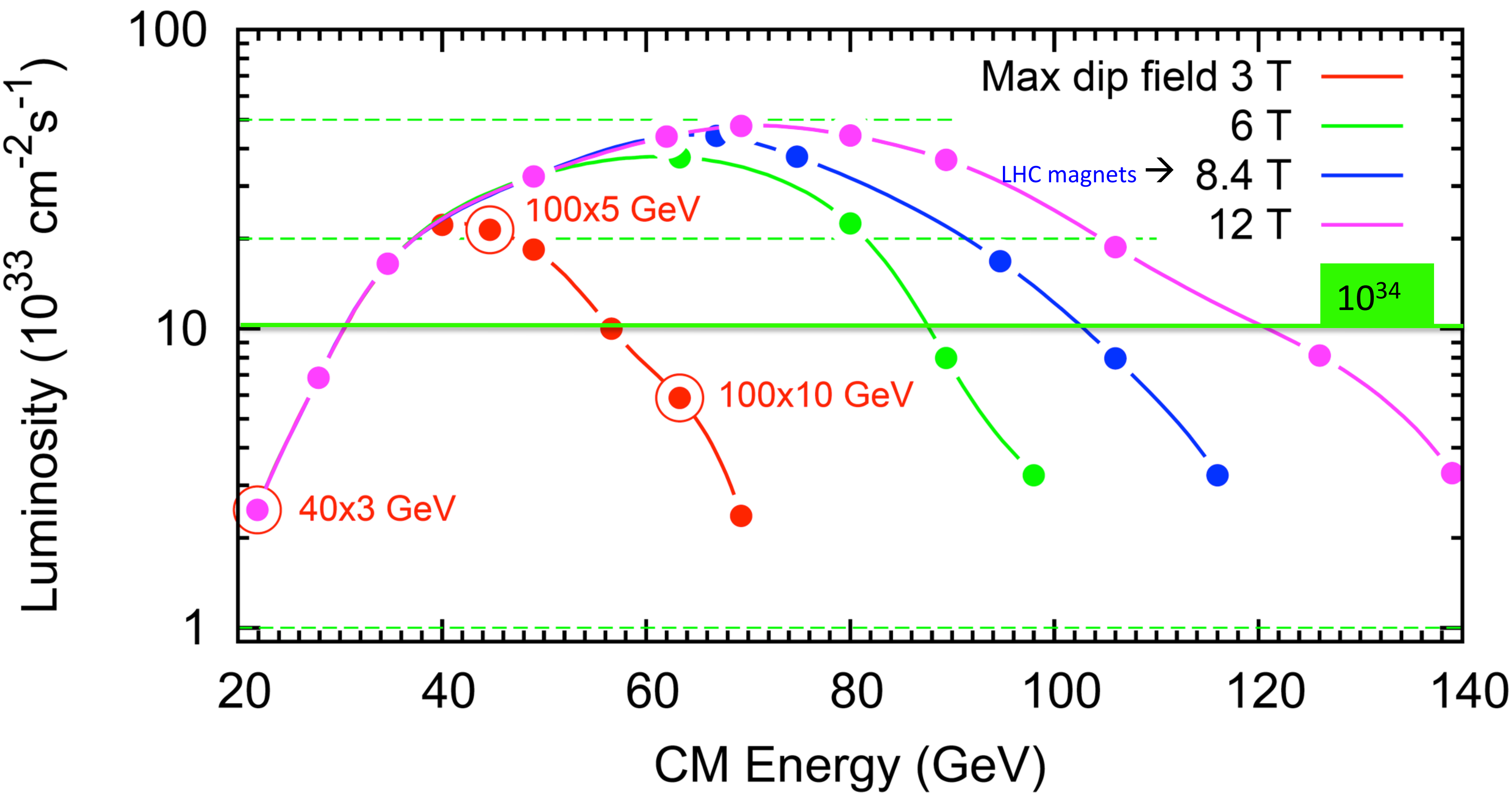
BACKUP

DOE budget in FY 2015 dollars for Modest Growth scenario

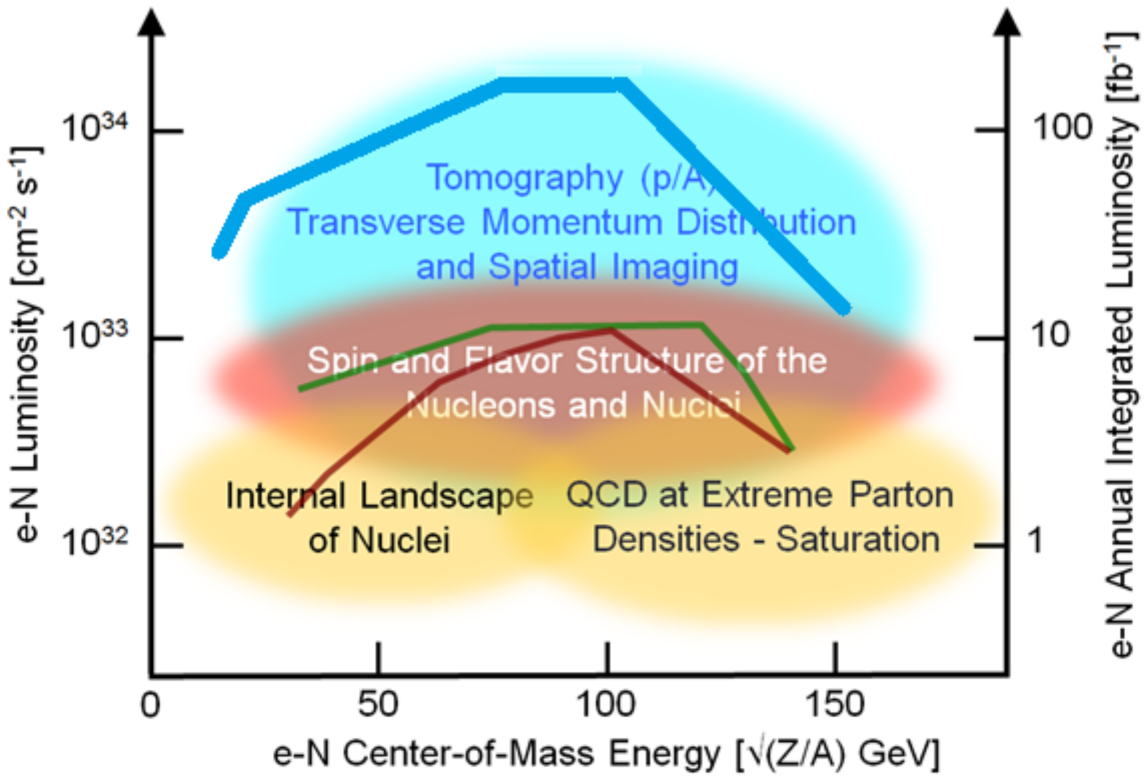




JLEIC energy reach and luminosity (log)



eRHIC luminosity

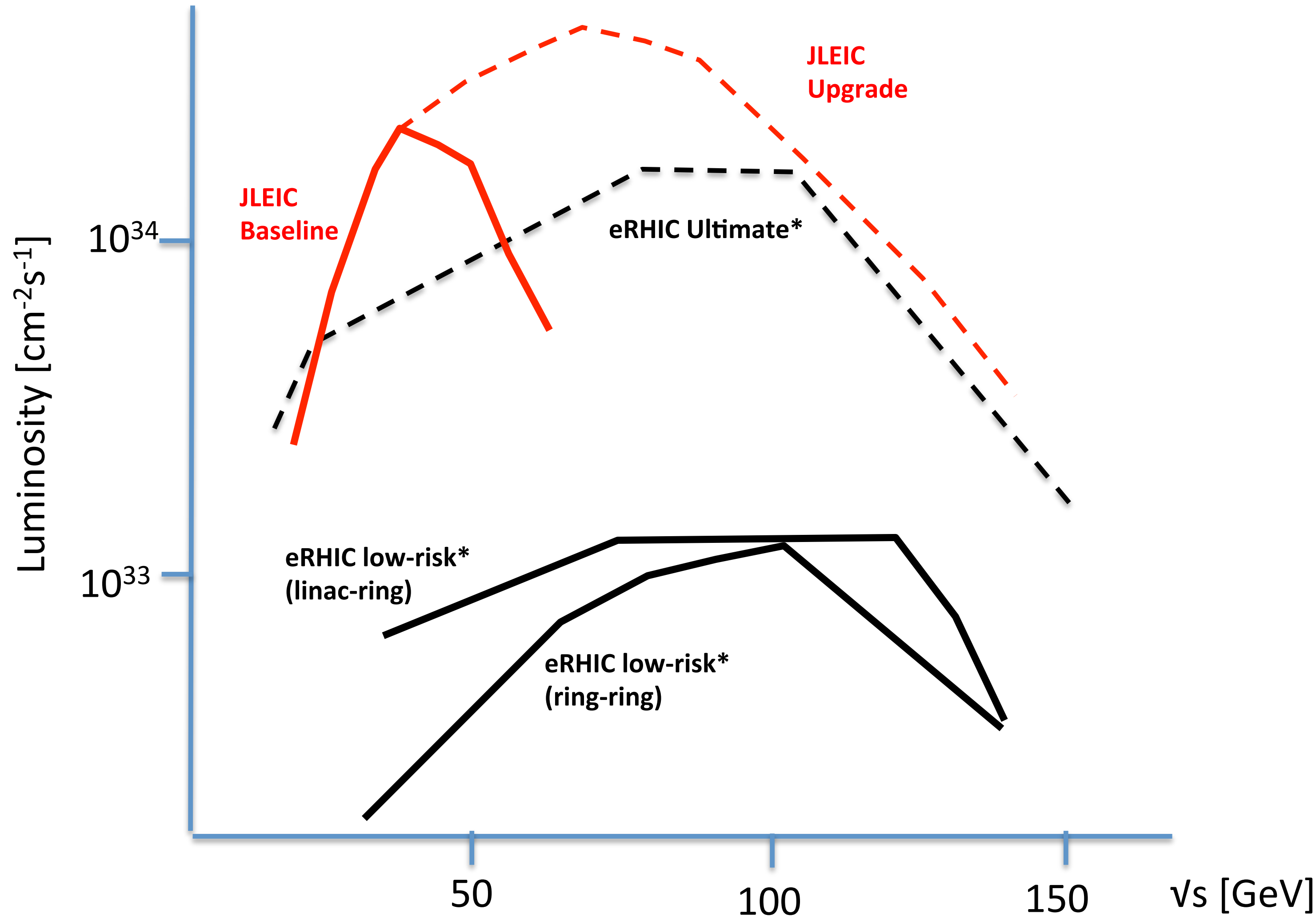


eRHIC is designed for an ultimate luminosity of $L = 10^{34} cm^{-2} s^{-1}$

but it needs **Strong Hadron Cooling** to reach full luminosity

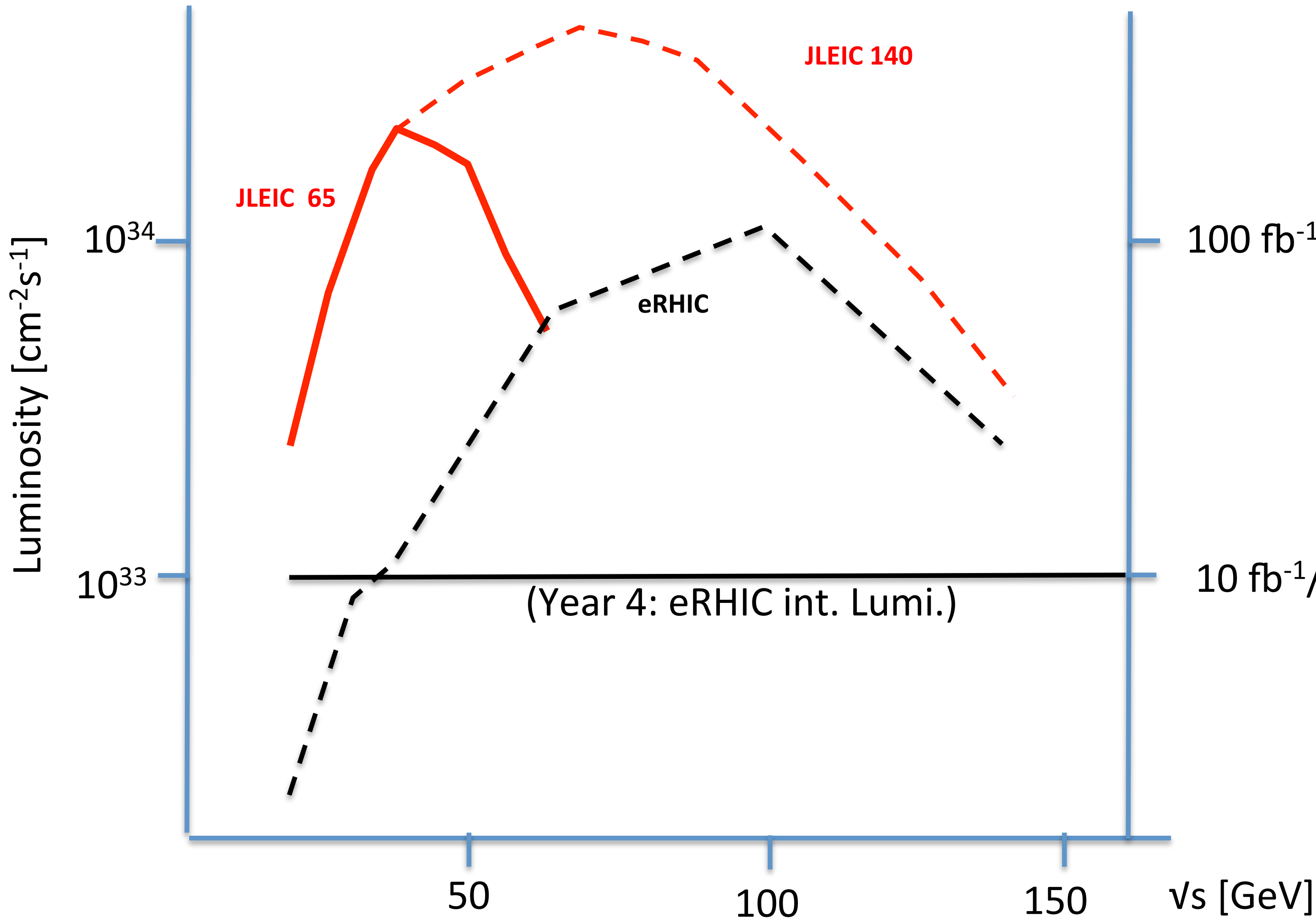
Lower luminosity design started to reduce overall technical risk

Comparison JLEIC and eRHIC (Jan. 2017)



*eRHIC parameters taken from F. Willike slides (F. Pilat talk) from [EIC opportunities meeting for INFN, Genova](#) (17 January, 2017)
JLEIC parameters can be found at [eic.jlab.org/wiki](#) (January, 2017 update)

Comparison JLEIC and eRHIC (Apr. 2017)



JLEIC parameters can be found at eic.jlab.org/wiki (January, 2017 update)

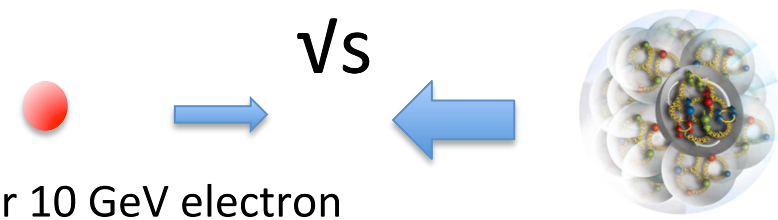
Designing The Right Probe: $\sqrt{s}$

What are the right parameters for the collider for the EIC science program?

We know the x range: down to ~ $10^{-3\text{-}4}$

We know the Q^2 range: up to ~1000 GeV^2

$Q^2 = sxy$, $s = 4E_eE_{hadron}$: so we know the energies we need.

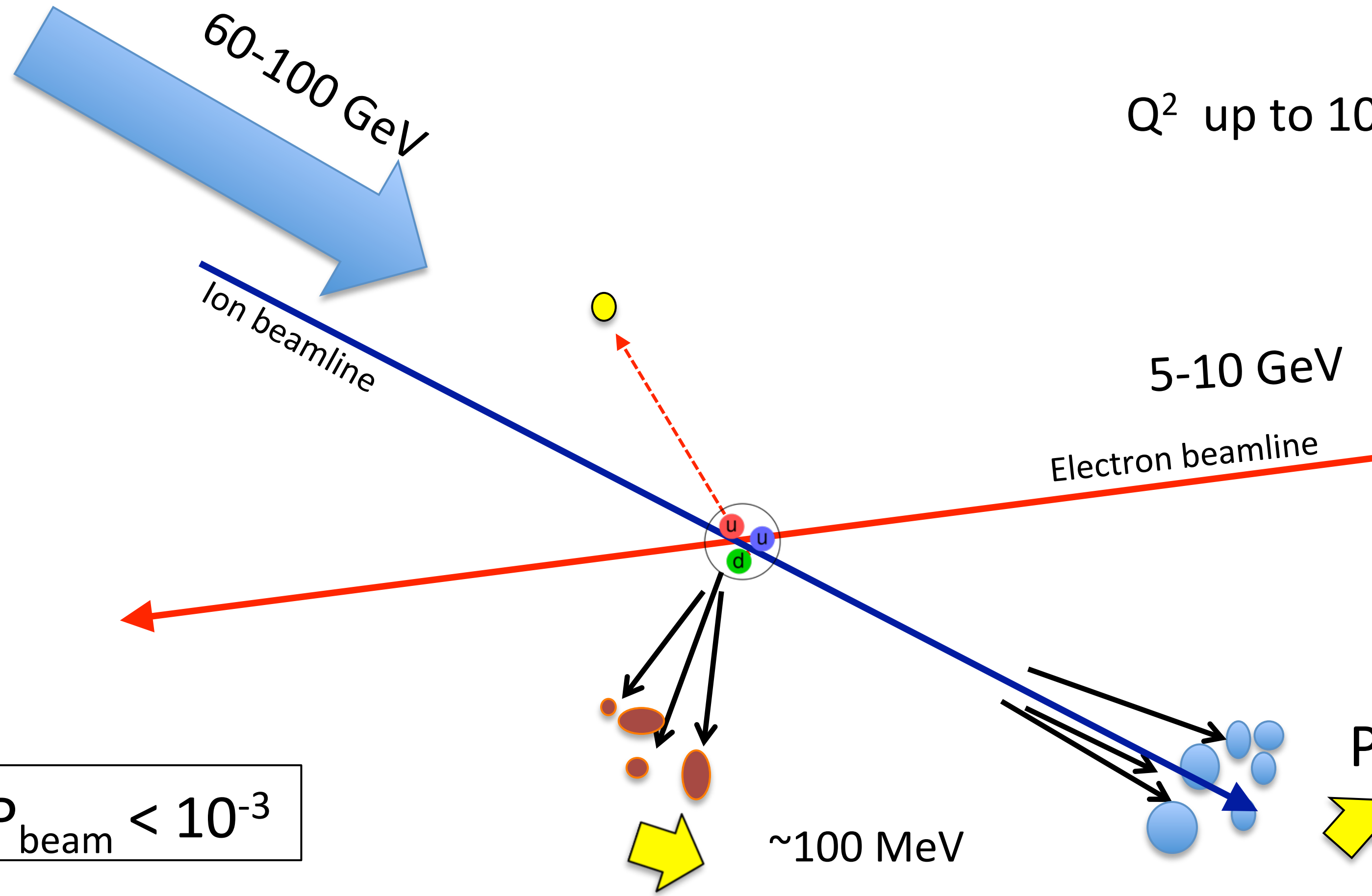


order 10 GeV electron realizable

order 100 GeV/u ion

$P_T/E_{proton} > 10^{-3}$

Measuring k_t and b_t



Q^2 up to 1000 GeV^2

P_t wrt beam

$P_t/P_{beam} < 10^{-3}$

P_t wrt scattering plane.
+ particle ID

JLEIC Detector and IR Document


JLEIC Documentation Series – 001

Jefferson Lab
Electron-Ion Collider (JLEIC):

An Introduction to the Interaction Region and Detector Design

Authored by the JLEIC Detector and Interaction Region Study Group

Existing Buildings
Proposed Buildings

Jefferson Lab Electron-Ion Collider is a proposed realization of the Electron-Ion Collider (EIC) [1]. The EIC has been chosen as the highest priority new construction for Nuclear Physics in the US [2]. We discuss the main drivers for design of the JLEIC interaction region and the detectors, and the layout that was developed in response to these drivers.

[1] A. Accardi et al., *Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all*, JLAB-PHY-12-1652, 2012.
[2] A. Aprahamian et al., *Reaching for the horizon: The 2015 long range plan for nuclear science*, 2015.

Jefferson Lab JLEIC

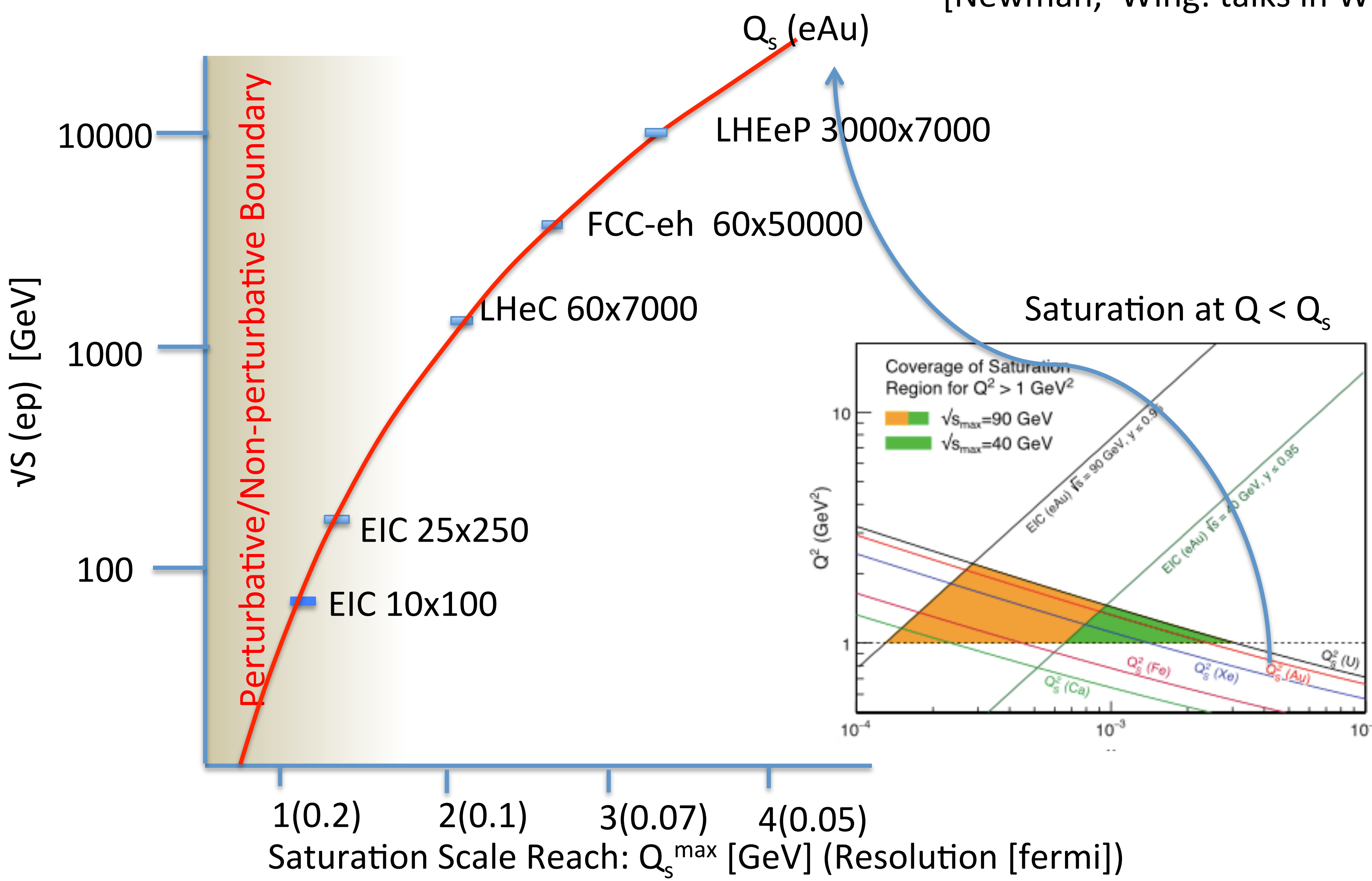
Can be found at the JLEIC Public Wiki page at: https://eic.jlab.org/wiki

This a short 9-page general introduction for people new to JLEIC.

More specific and detailed documents to follow.

Parton Saturation at eA colliders

[Newman, Wing: talks in WG2]



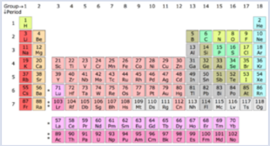
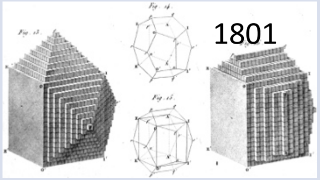
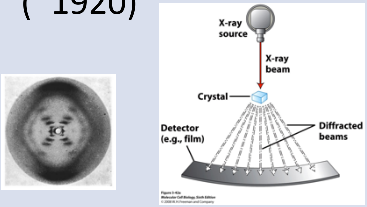
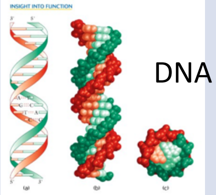
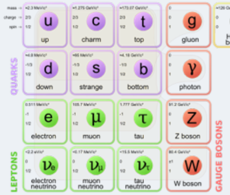
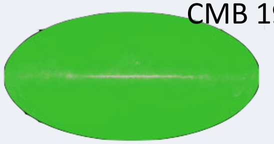
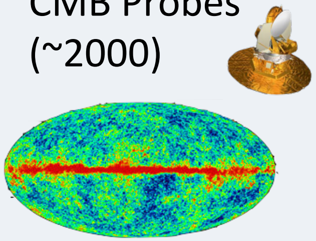
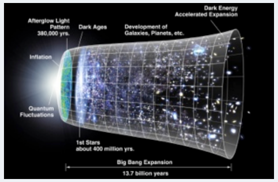
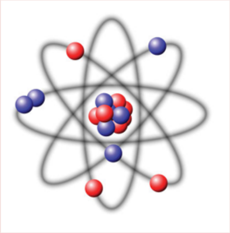
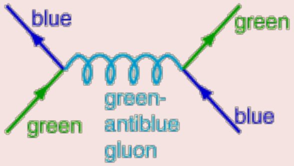
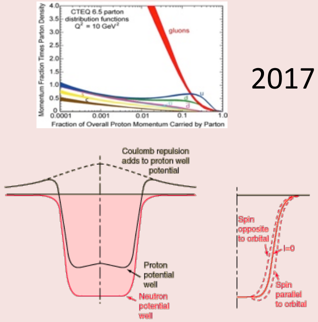
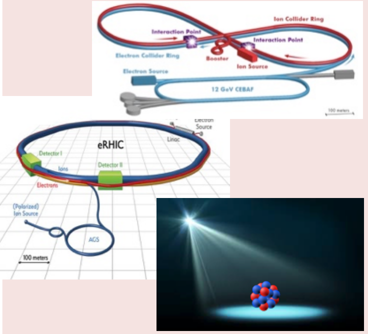
Why an Electron Ion Collider?

Nuclear matter is made of quarks that are bound by gluons that also bind themselves. Unlike with the more familiar atomic and molecular matter, the interactions and structures are inextricably mixed up, and the observed properties of nucleons and nuclei, such as mass & spin, emerge out of this complex system. Gaining detailed knowledge of this astonishing dynamical system at the heart of our world will be transformational, perhaps in an even more dramatic way than how the understanding of the atomic and molecular structure of matter led to new frontiers, new sciences and new technologies.

The Electron Ion Collider:

A new US-based facility, EIC, with a versatile range of beam energies, polarizations, and species, as well as high luminosity, is required to precisely image the quarks and gluons and their interactions, to explore the new QCD frontier of strong color fields in nuclei – to *understand* how matter at its most fundamental level is made.

EIC: A Portal to a New Frontier

Dynamical System	Fundamental Knowns	Unknowns	Breakthrough Structure Probes (Date)	New Sciences, New Frontiers
Solids 	Electromagnetism Atoms 	Structure  1801	X-ray Diffraction (~1920) 	Solid state physics Molecular biology  DNA
Universe 	General Relativity Standard Model 	Quantum Gravity, Dark matter, Dark energy. Structure  CMB 1965	Large Scale Surveys CMB Probes (~2000) 	Precision Observational Cosmology 
Nuclei and Nucleons 	Perturbative QCD Quarks and Gluons $\mathcal{L}_{QCD} = \overline{\psi}(i\partial\!\!\!/ - gA\!\!\!/)\psi - \frac{1}{2}\mathrm{tr}\, F_{\mu\nu}F^{\mu\nu}$ 	Non-perturbative QCD Stucture  2017	Electron-Ion Collider (2030) 	Structural QCD Nuclear Physics