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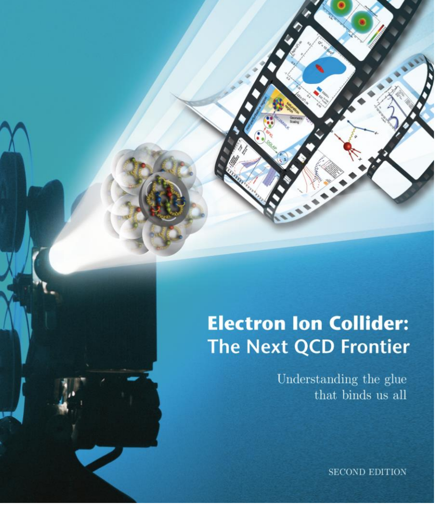
A. Accardi *et al.*

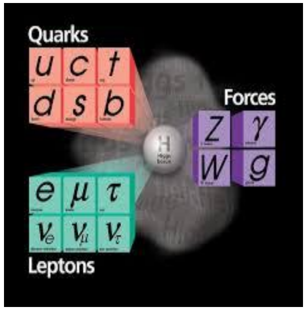


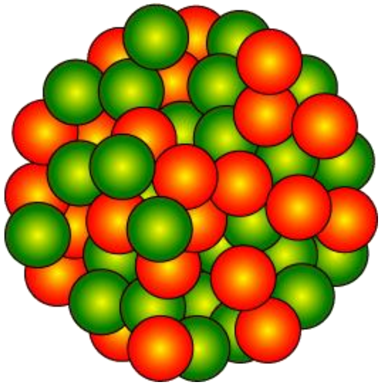
Electron Ion Collider: The next QCD frontier

Understanding the Glue that Binds Us All

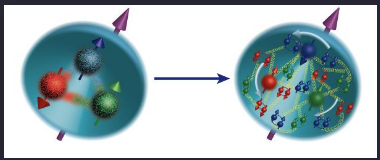
Why the EIC?

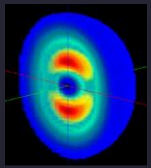
To understand the role of gluons in binding quarks & gluons into Nucleons and Nuclei

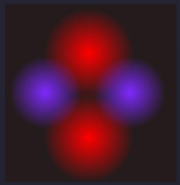




21st Century Nuclear Science: Probing nuclear matter in all Its forms & exploring their potential for applications

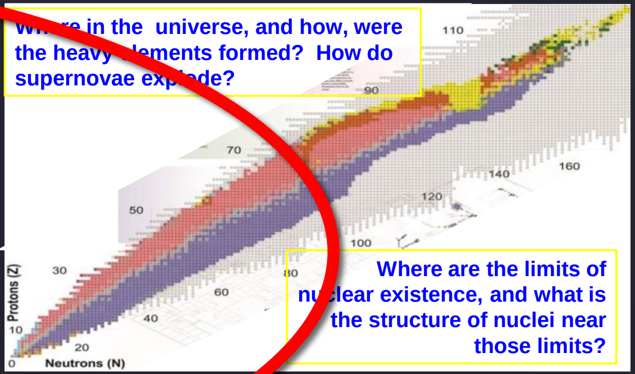




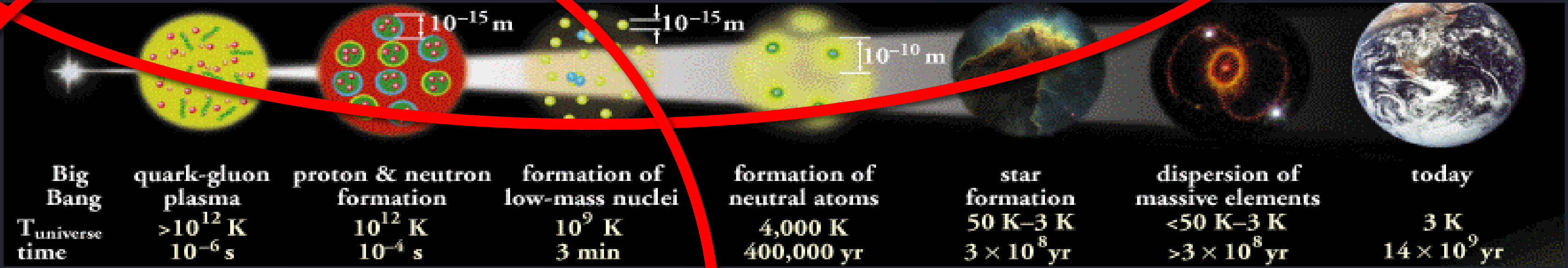


How are the properties of protons and neutrons, and the force between them, built up from quarks, antiquarks and gluons? What is the mechanism by which these fundamental particles materialize as hadrons?

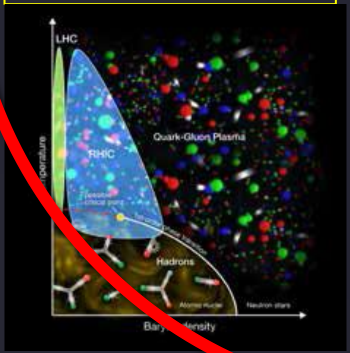
Where in the universe, and how, were the heavy elements formed? How do supernovae explode?



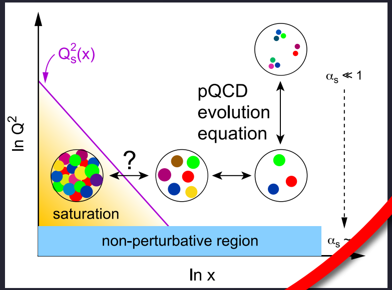
Where are the limits of nuclear existence, and what is the structure of nuclei near those limits?



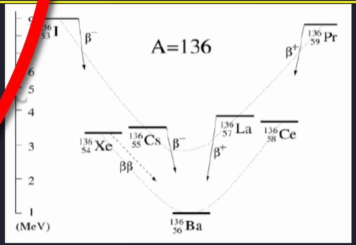
What is the nature of the different phases of nuclear matter through which the universe has evolved?



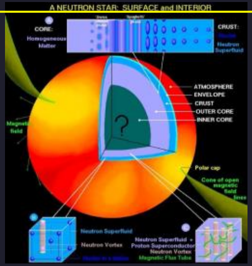
Do nucleons and all nuclei, viewed at near light speed, appear as walls of gluons with universal properties?



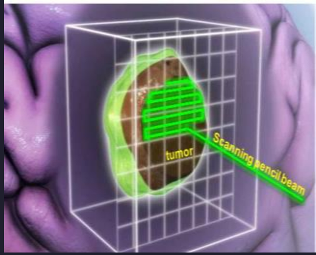
How can the properties of nuclei be used to reveal the fundamental processes that produced an imbalance between matter and antimatter in our universe?



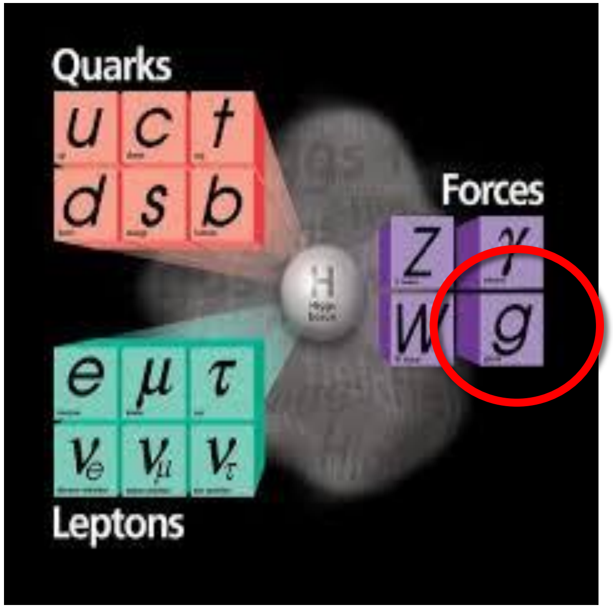
How are the nuclear building blocks manifested in the internal structure of compact stellar objects, like neutron stars?



How can technologies developed for basic nuclear physics research be adapted to address society's needs?



Gluon in the Standard Model of Physics



- Gluon: carrier of the strong force (QCD)
- No electric charge, massless, but carries color-charge
- Binds the quarks and gluons inside the hadrons with tremendous force! (Strong force)

At the heart of many poorly understood phenomena:

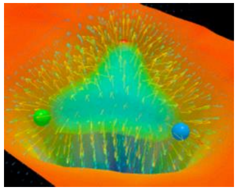
Color Confinement, composition of nucleon spin, quark-gluon plasma at RHIC & LHC…

Role of gluons in hadron & nuclear structure

Dynamical generation of hadron masses & nuclear binding

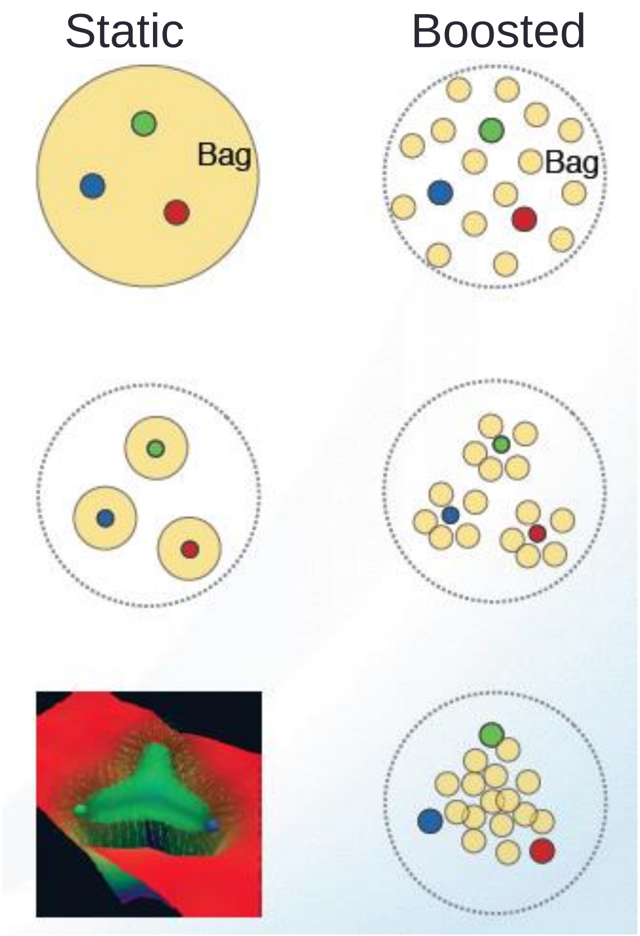
- Massless gluons & almost massless quarks, through their interactions, generate more than 98% of the mass of the nucleons:

  Without gluons, there would be no nucleons,
  no atomic nuclei… no visible world!



- Gluons carry ~50% the proton's momentum, ?% of the nucleon's spin, and are responsible for the transverse momentum of quarks
- The quark-gluon origin of the nucleon-nucleon forces in nuclei not quite known
- Lattice QCD can't presently address dynamical properties on the light cone
- **Experimental insight and guidance crucial for complete understanding of *how* hadron & nuclei emerge from quarks and gluons**

What does a proton look like?



Bag Model: Gluon field distribution is wider than the fast moving quarks.
Gluon radius > Charge Radius

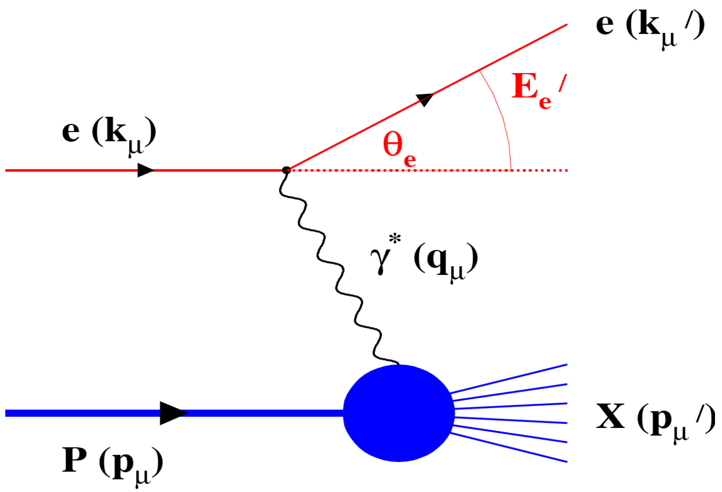
Constituent Quark Model: Gluons and sea quarks hide inside massive quarks.
Gluon radius ~ Charge Radius

Lattice Gauge theory (with slow moving quarks), gluons more concentrated inside the quarks:
Gluon radius < Charge Radius

Need transverse images of the quarks and gluons in protons

Tool: Deep Inelastic Scattering

Precision microscope with exquisite control



Q^2 → Measure of spatial resolution

y → Measure of inelasticity

x → Measure of momentum fraction of the struck quark in a proton: "*shutter speed*"

$\sqrt{s}$ → CM energy

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

Rigorous theoretical description in quantum field theory

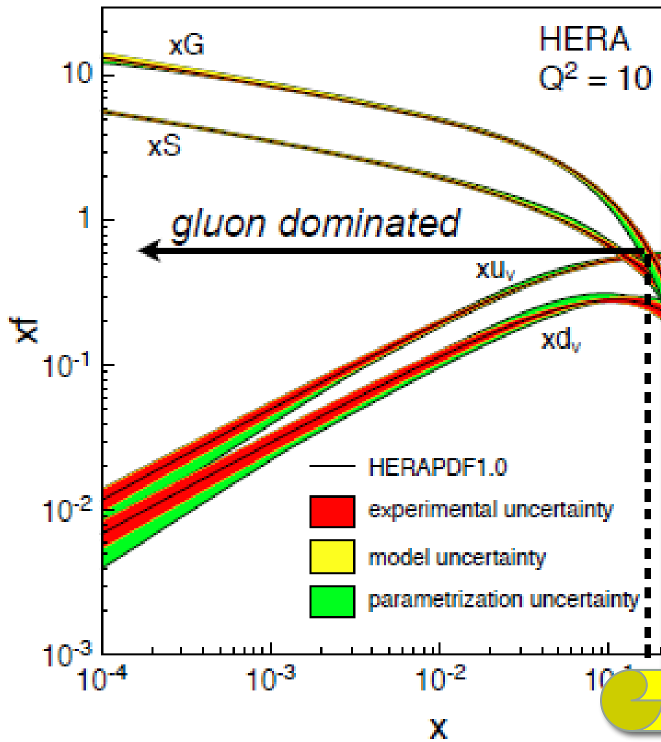
Inclusive events: e+p/A → e'+X
Detect only the scattered lepton in the detector

Semi-Inclusive events: e+p/A → e'+h(π,K,p,D,jet)+X
Detect the scattered lepton in coincidence with identified hadrons/jets in the detector

Exclusive events: e+p/A → e'+ h(γ,π,K,p,J/ψ,jet)
Detect every thing including scattered proton/nucleus (or its fragments)

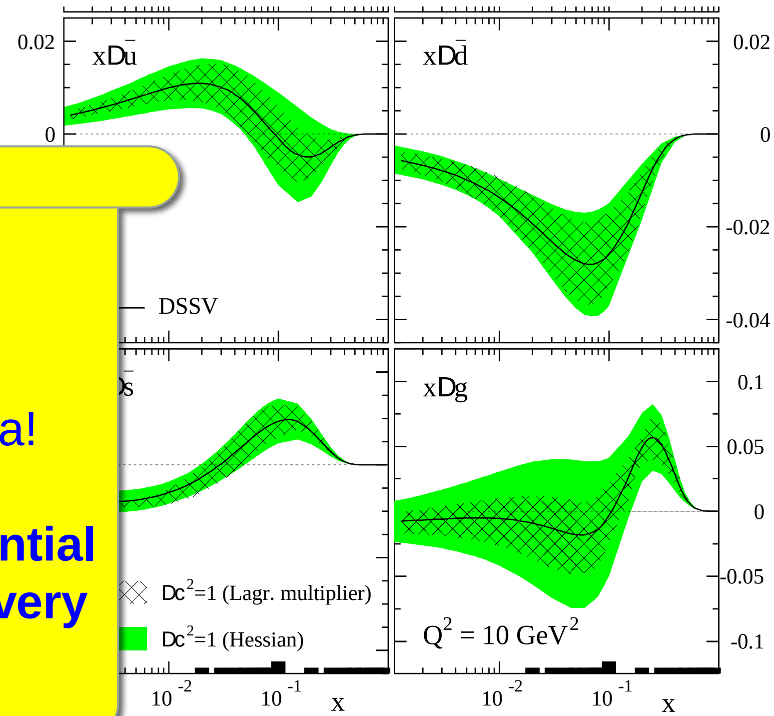
What does a proton look like? Unpolarized & polarized

We only *have a 1-dimensional picture!*



QCD Terra-incognita!

High Potential for Discovery

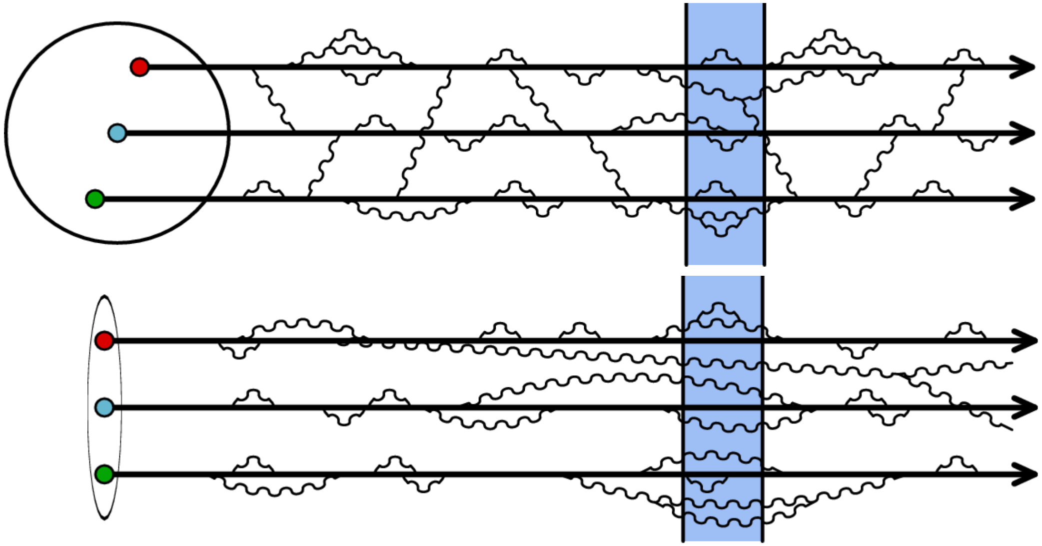


- ***Need to go beyond 1-dimension!***
- **Need 3D Images of nucleons in <u>momentum & coordinate</u> space**
- ***Could they give us clues on orbital motion of partons? → Finally help solve the spin puzzle?***

Proton at low and high energy:

Low energy
High x
Regime of Jlab

High energy
Low- x
Regime of a Collider

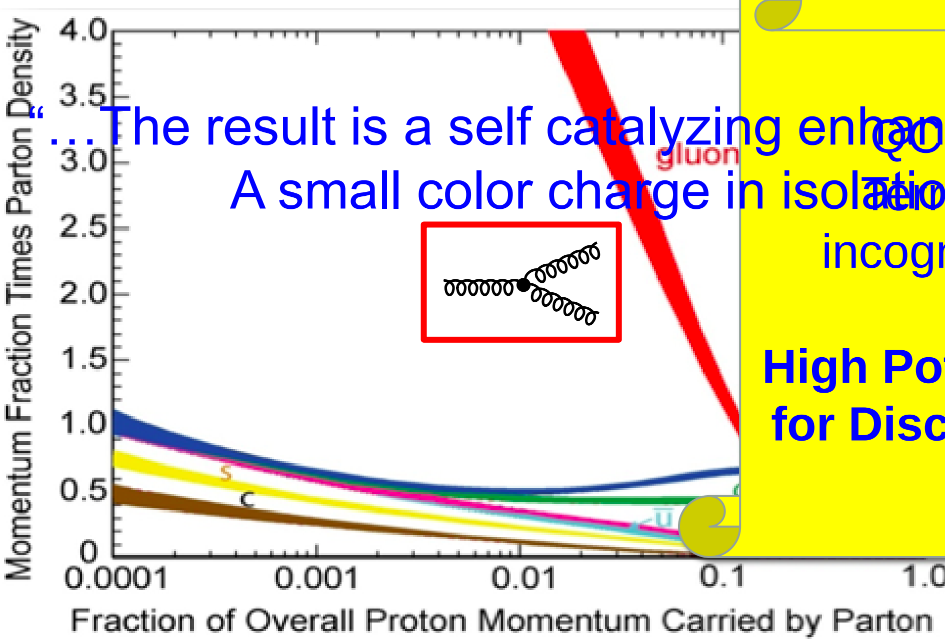


At high energy:

- Wee partons fluctuations time dilated in strong interaction time scales
- Long lived gluons can radiate further smaller x gluons → **runaway growth?**

Gluon and the consequences of its interesting properties:

Gluons carry color charge ➔ Can interact with other gluons!



QCD
Terra incognita!

High Potential for Discovery

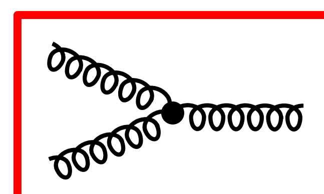
…parent "indefinite rise" in gluon …tribution in proton!

"…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"

…hat could **limit this indefinite** …**e?** → saturation of soft gluon …nsities via gg→g recombination …ust be responsible.

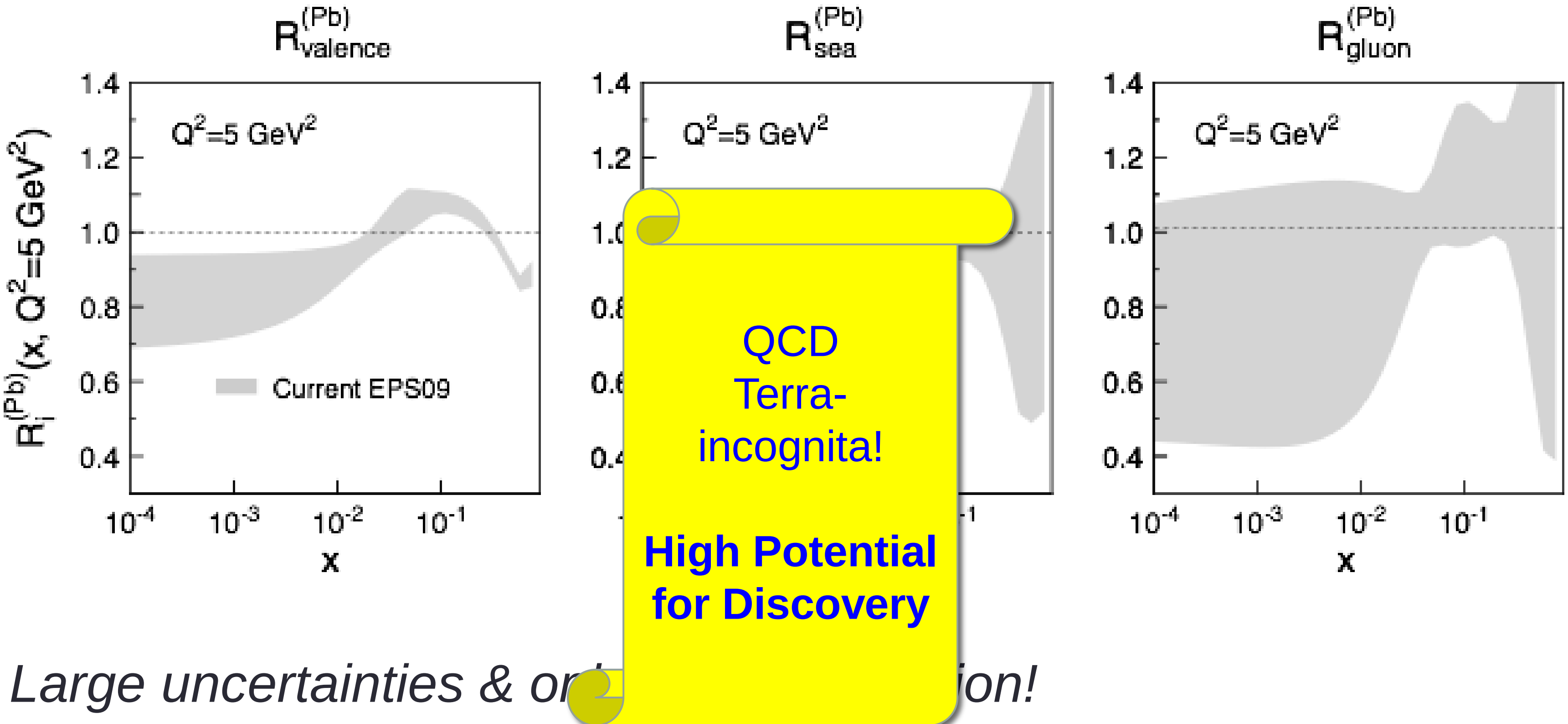
recombination



Where? No one has unambiguously seen this before!

If true, effective theory of this →"**Color Glass Condensate**"

What does a nucleus look like?



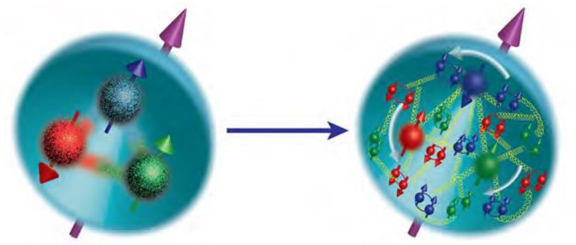
- *Large uncertainties & or* *ion!*
- *Need to reduce uncertainties &* ***go beyond the 1-dimensions***
- ***Need (2+1)D partonic images of nuclei****.*

- *To fully understand: emergence of hadrons in Cold QCD matter & initial state ←→ properties of QGP formed in AA collisions*

Puzzles and challenges in understanding this QCD many body emergent dynamics

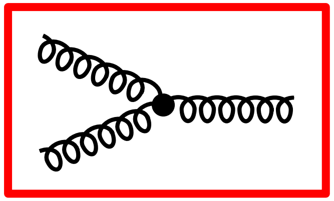
How are the gluons and sea quarks, and their intrinsic spins distributed in space & momentum inside the nucleon?

Role of Orbital angular momentum?



What happens to the gluon density in nuclei at high energy? Does it saturate, into a gluonic form of matter of universal properties?

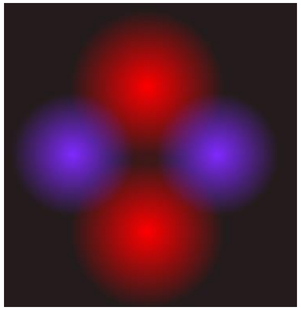
Is it clumpy or smooth?

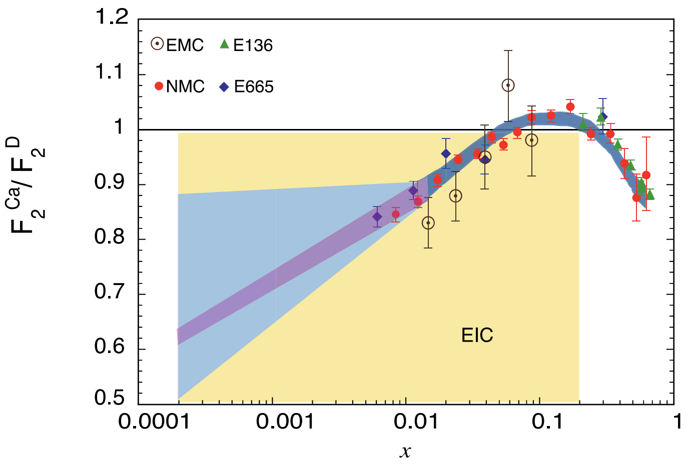


?

Puzzles and challenges….

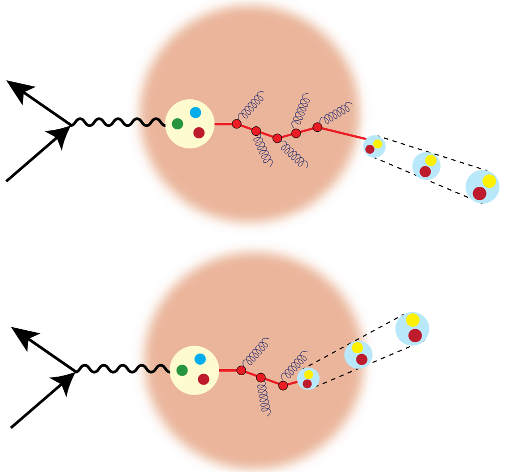
How do gluons and sea quarks contribute to the nucleon-nucleon force?





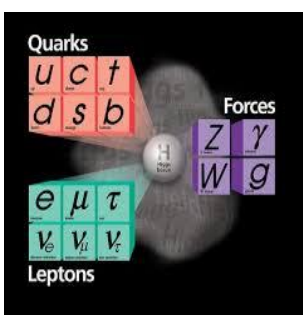
How does the nuclear environment affect the distributions of quarks and gluons and their interactions inside nuclei?

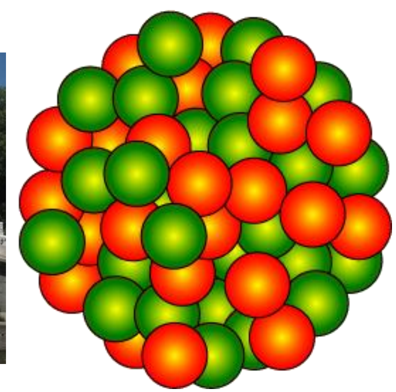
How does nuclear matter respond to fast moving color charge passing through it?



Why do we need an EIC?

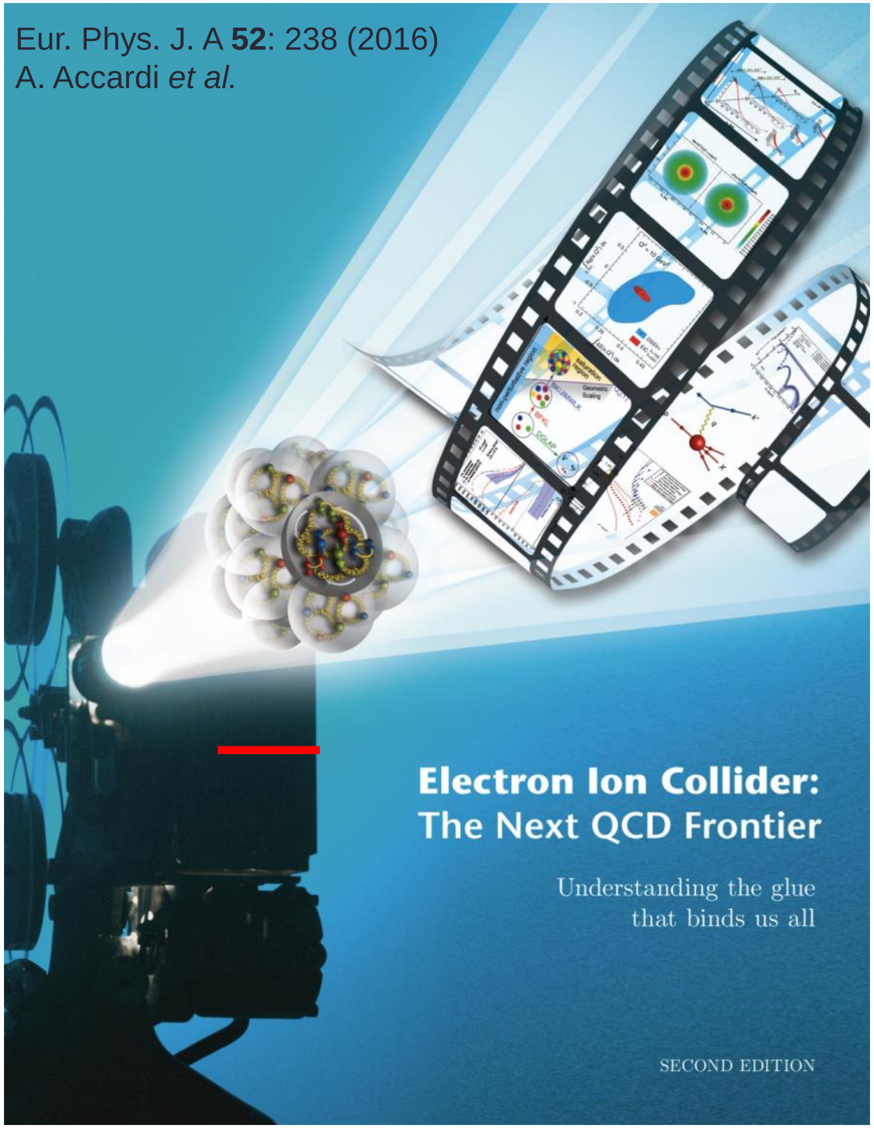
A new facility, EIC, with a versatile range of kinematics, beam polarizations, high luminosity and beam species, is required to ***precisely image*** *the sea quarks and gluons in nucleons and nuclei,* to explore the new QCD frontier of strong color fields in nuclei, and to resolve outstanding issues in understanding nucleons and nuclei in terms of fundamental building blocks of QCD

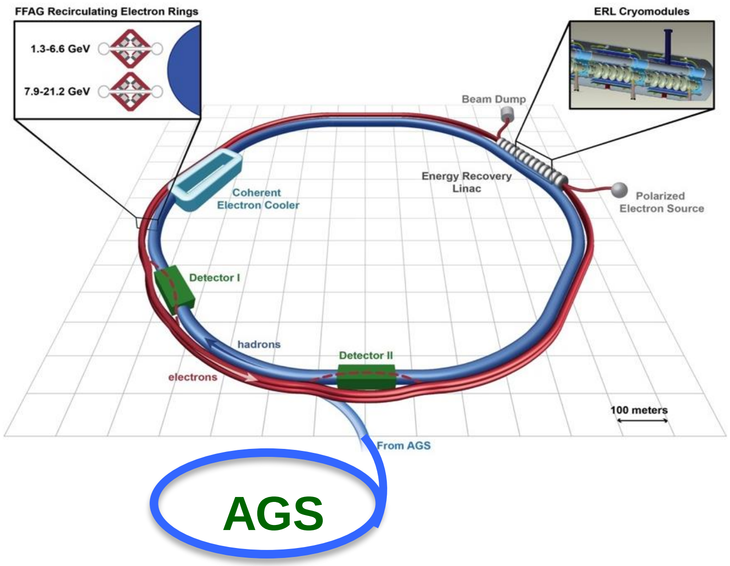


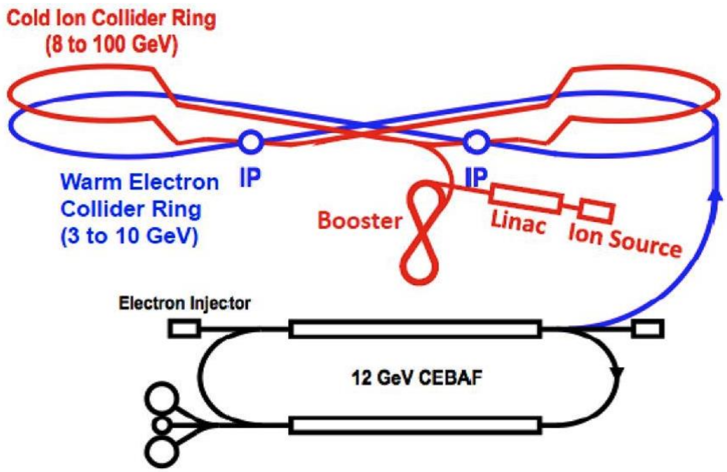


The Electron Ion Collider

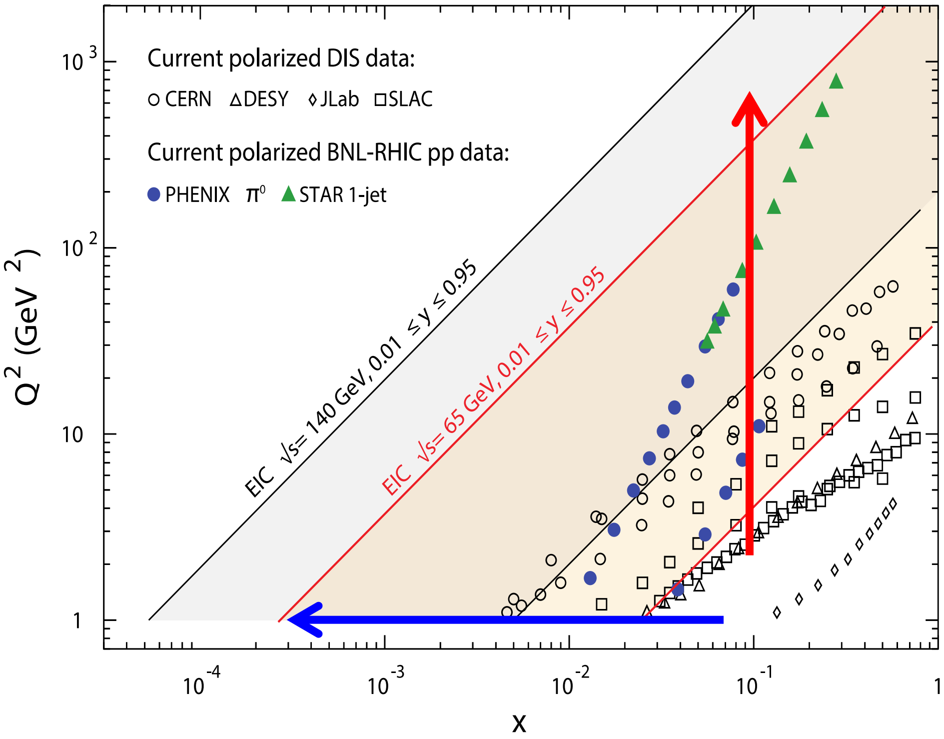
Two proposals for realization of the Science Case





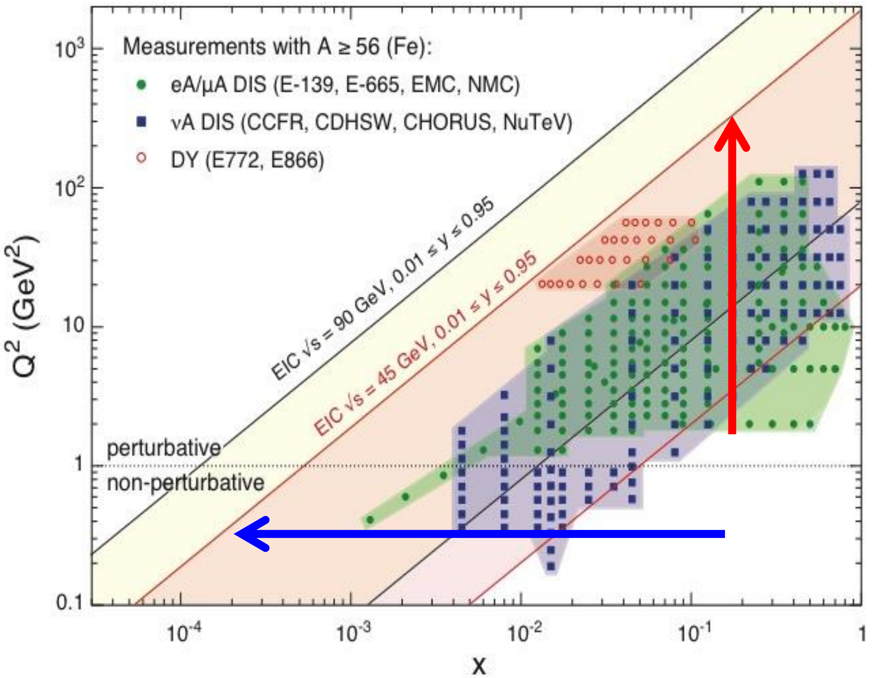


US EIC: Kinematic reach & properties



For e-N collisions at the EIC:

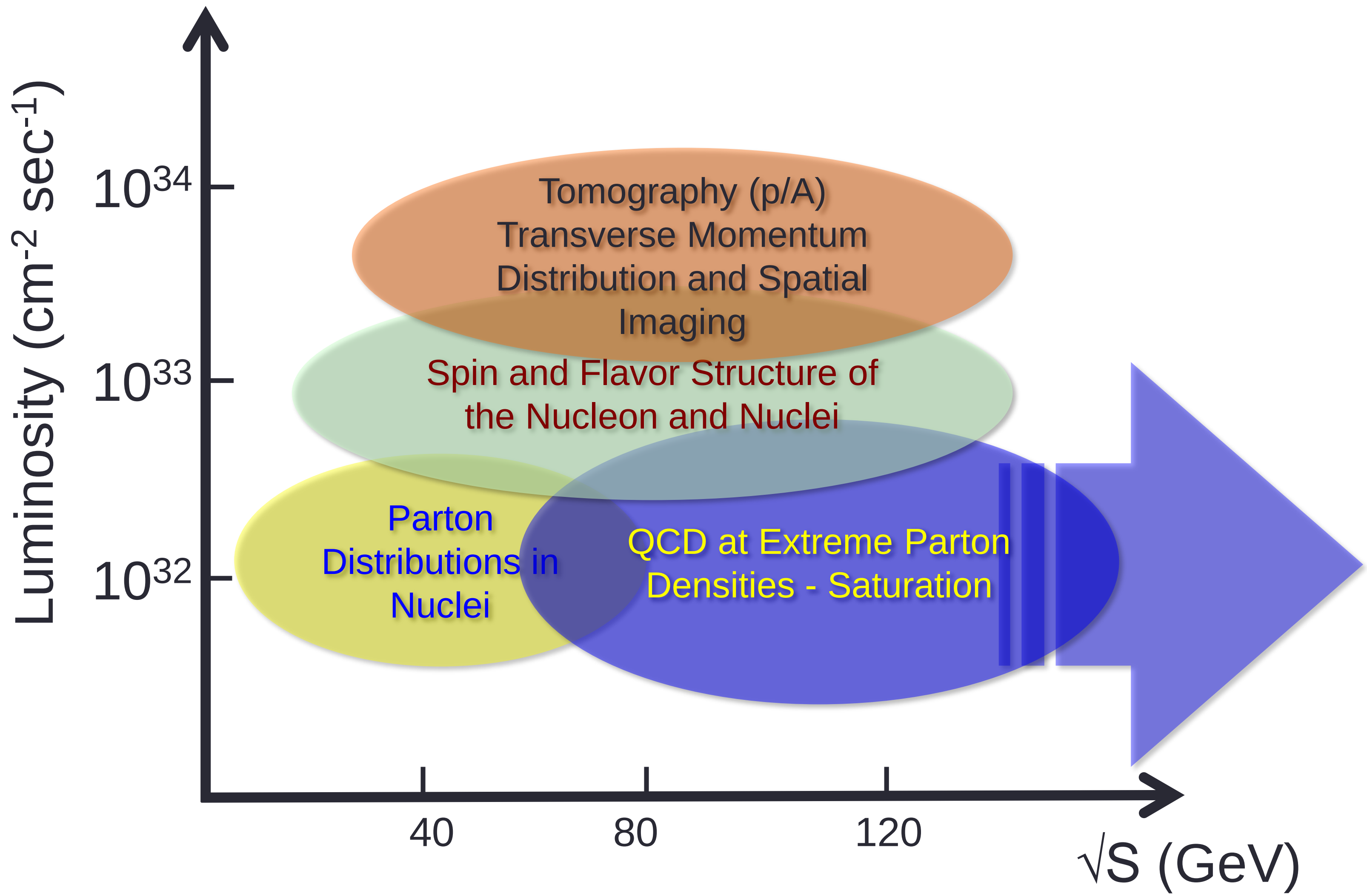
- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

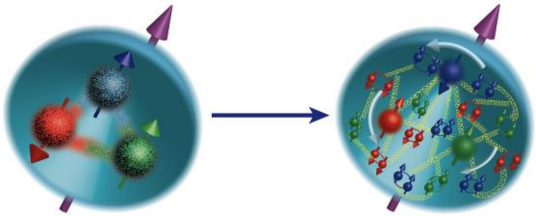


For e-A collisions at the EIC:

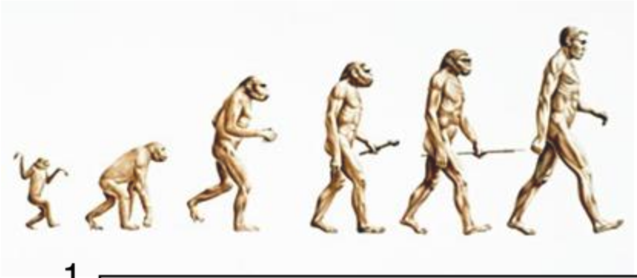
- ✓ **Wide range in nuclei**
- ✓ Lum. per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range (evolution)
- ✓ Wide x region (reach high gluon densities)

Physics vs. Luminosity & Energy

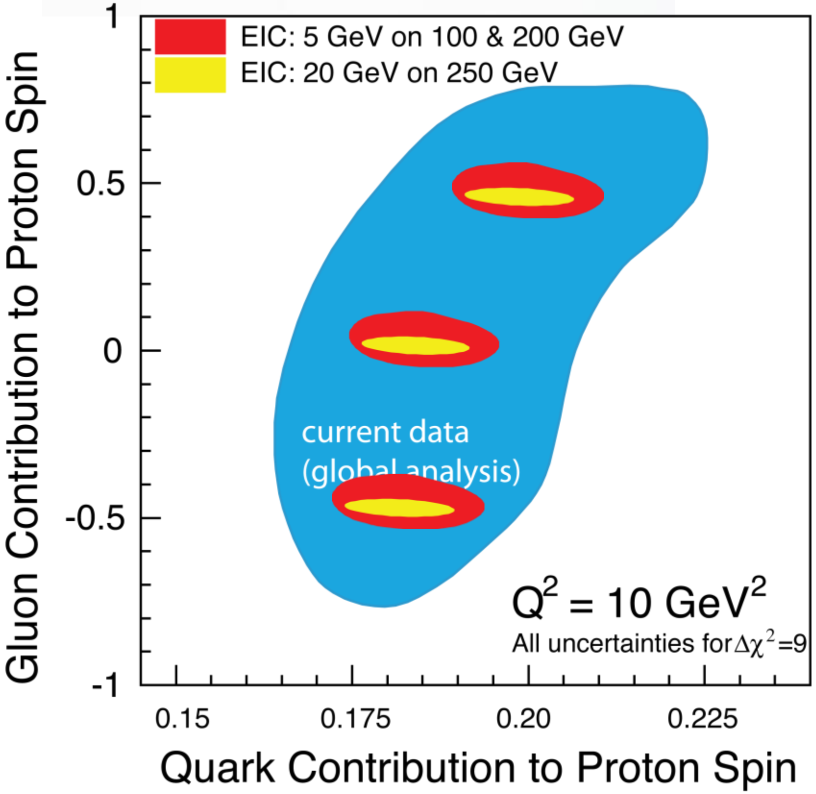




Our Understanding of Nucleon Spin



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



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

Precision in $\Delta\Sigma$ and Δg ➔ A clear idea of the magnitude of L_Q+L_G

3-Dimensional Imaging of Quarks and Gluons

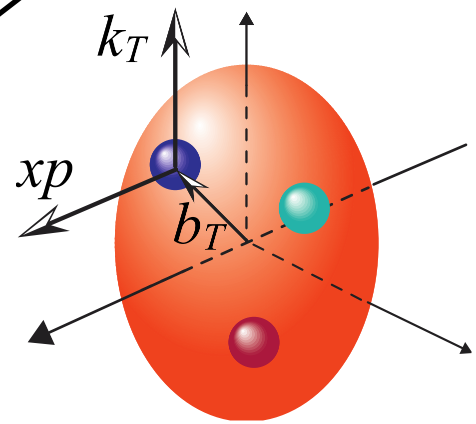
$$W(x,b_T,k_T)$$

Momentum space

$\int d^2b_T$

Coordinate space

$\int d^2k_T$

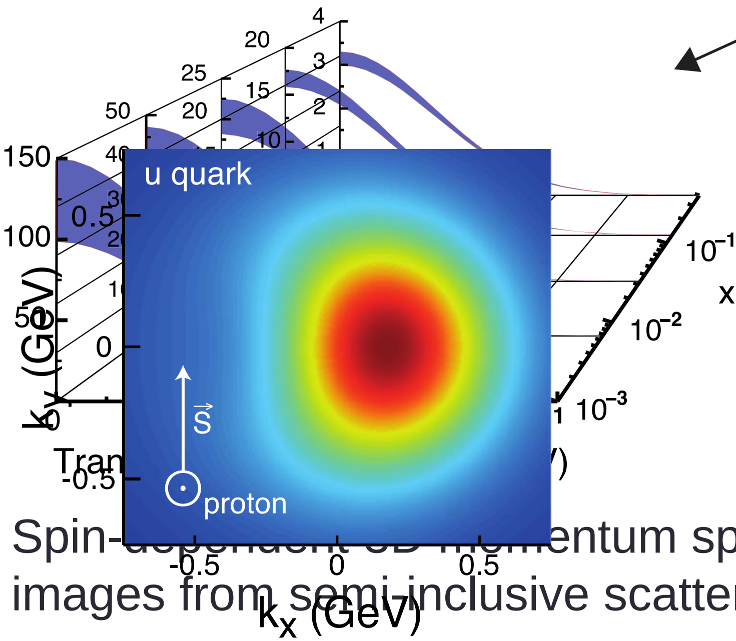


Quarks

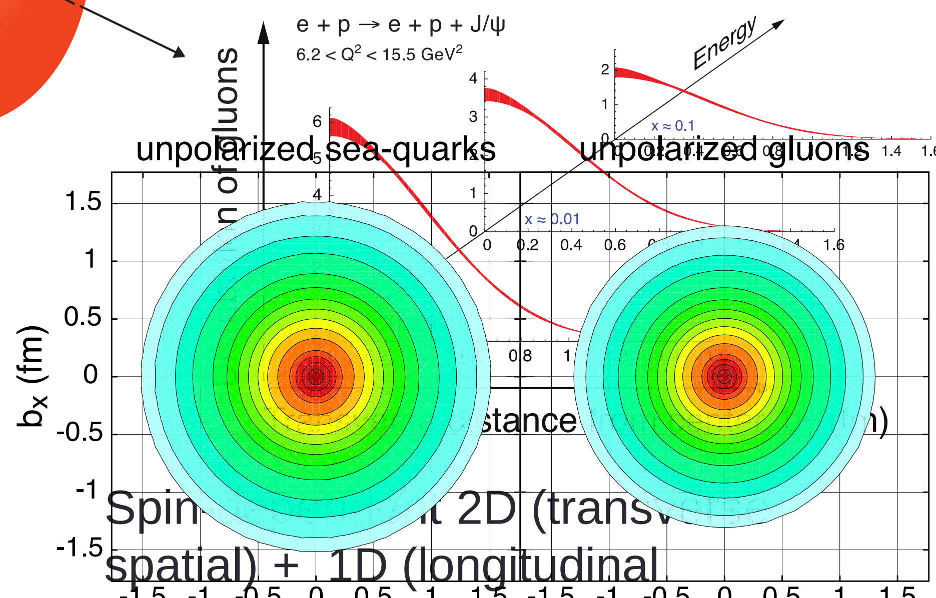
$f(x,k_T)$

$f(x,b_T)$

Gluons

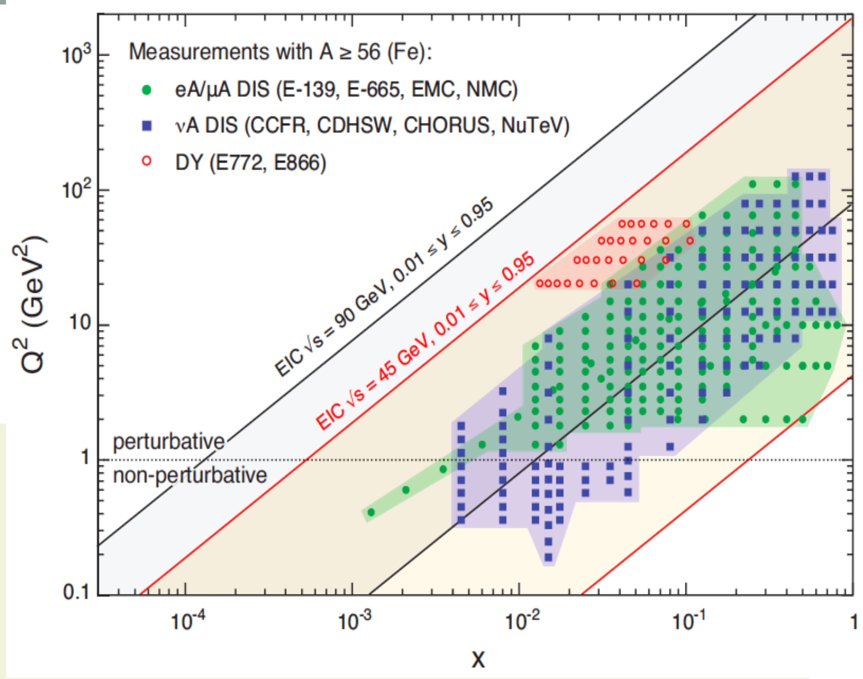


Spin-dependent 3D momentum space images from semi-inclusive scattering



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

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



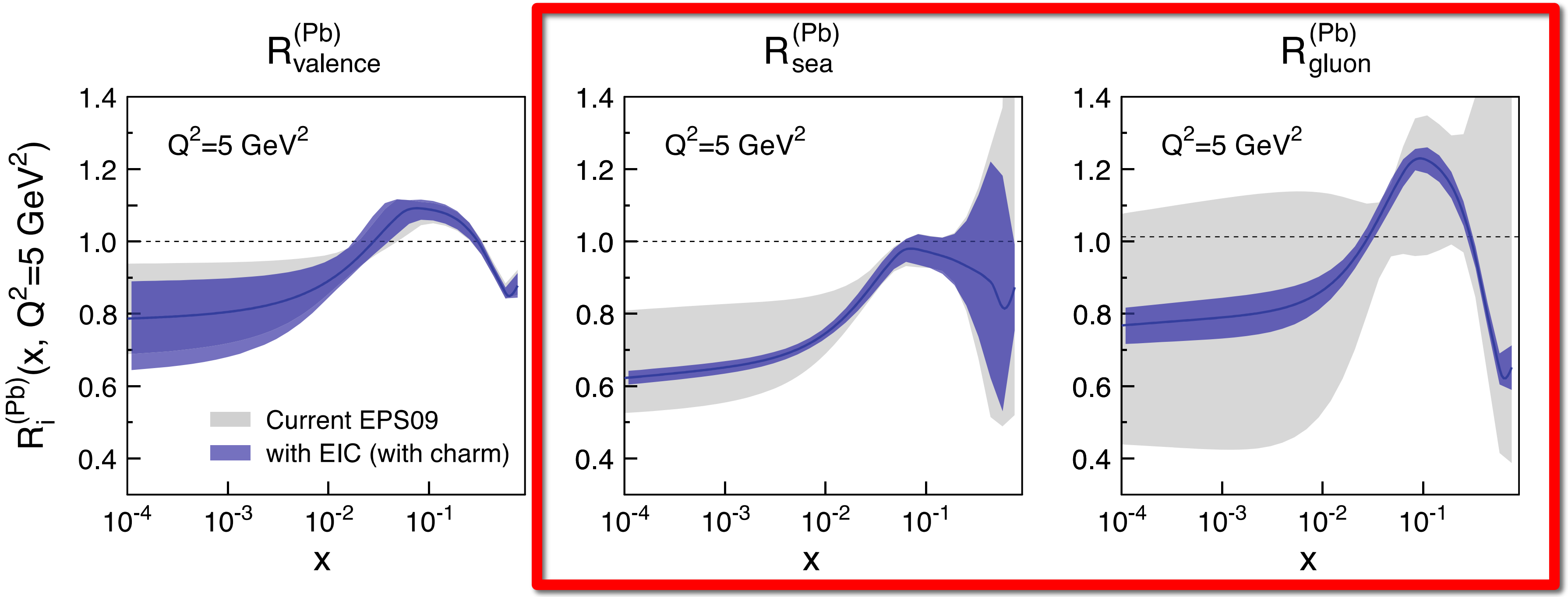
The Nucleus:
A laboratory for QCD

What do we know about the gluons in nuclei? Very little!

Does gluon density saturate? Does it produce a unique and universal state of matter?

Parton propagation and interaction in nuclei (vs. protons)

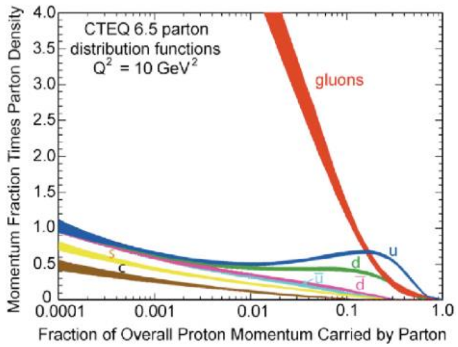
EIC: impact on the knowledge of nPDFs



Ratio of Parton Distribution Functions of Pb over Proton:

- Without EIC, large uncertainties in **nuclear sea quarks and gluons**
- With EIC significantly reduces uncertainties

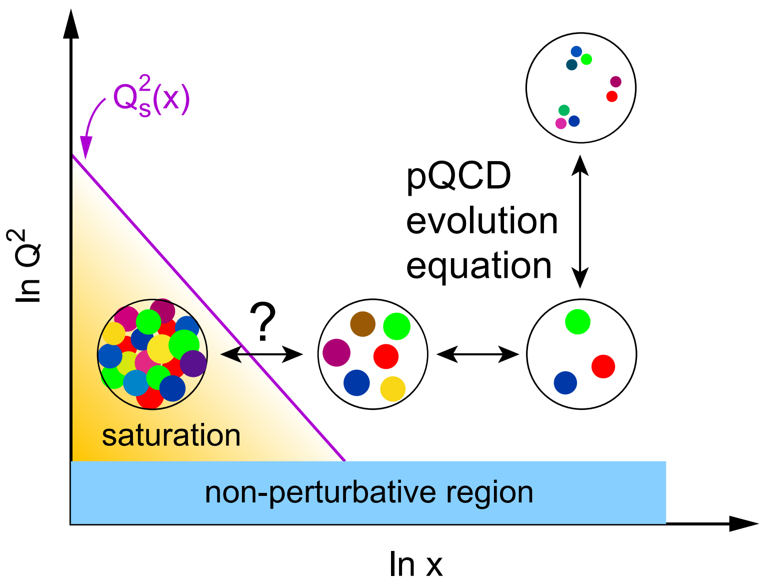
- Impossible for current and future pA data at RHIC & LHC data to achieve

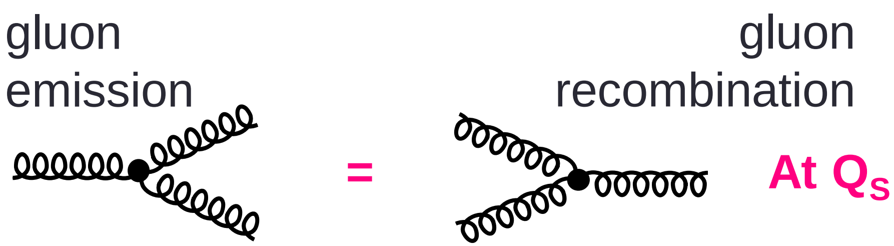


What do we learn from low-x studies?

What tames the low-x rise?

- New evolution eqn.s @ low x & moderate Q^2
- Saturation Scale $Q_S(x)$ where gluon emission and recombination comparable





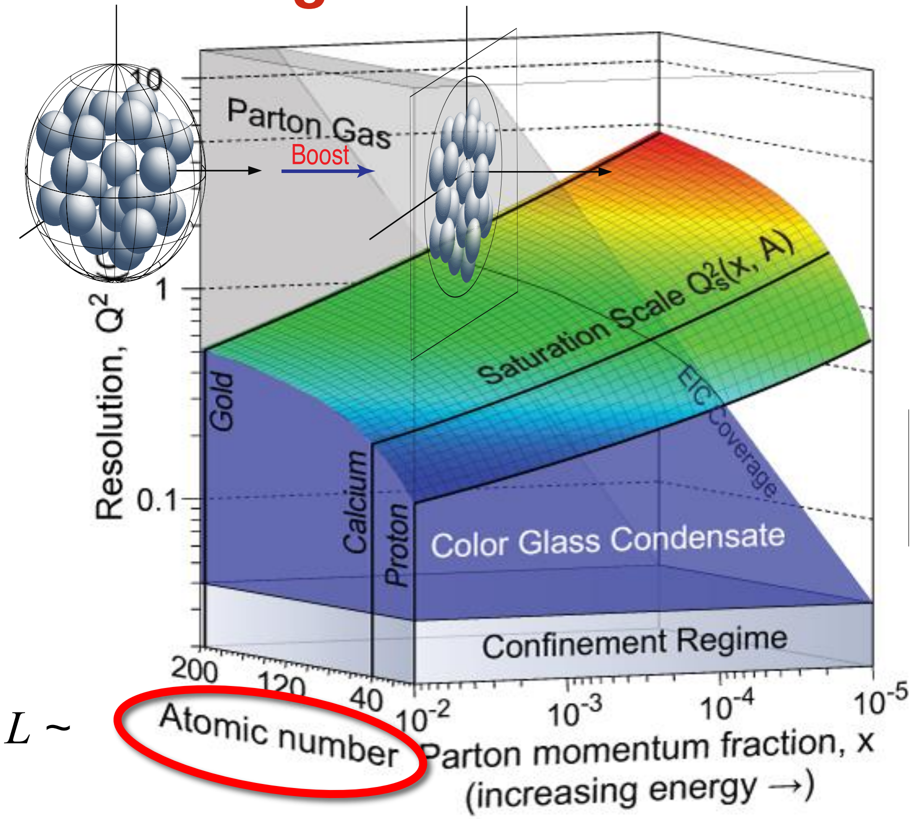
First observation of gluon recombination effects in nuclei:
➔leading to a collective gluonic system!

First observation of g-g recombination in different nuclei
→ Is this a universal property?
→ Is the Color Glass Condensate the correct effective theory?

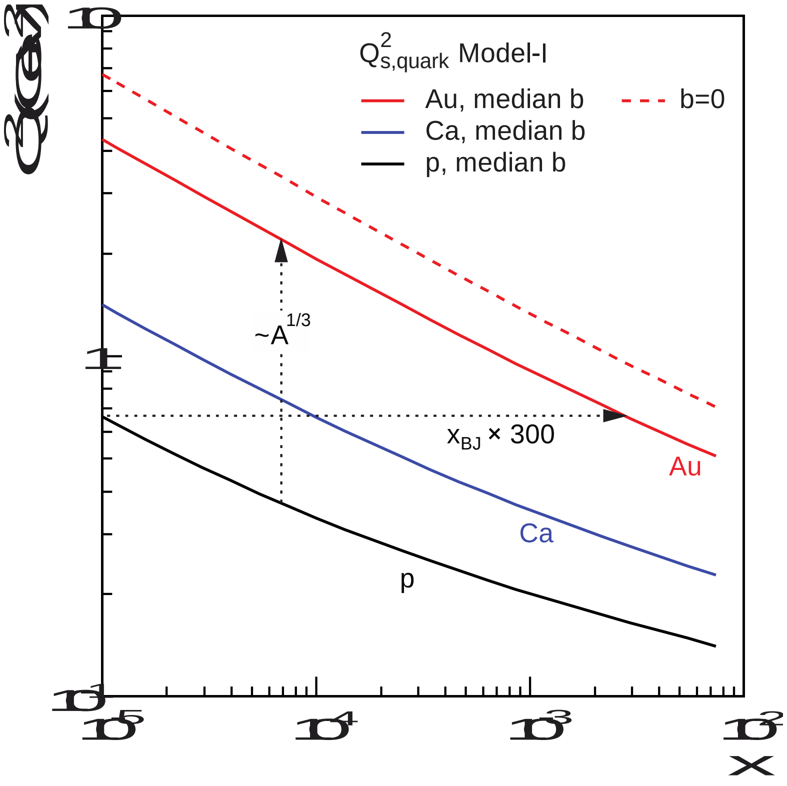
How to explore/study this new phase of matter?

(multi-TeV) e-p collider (LHeC) OR **a (multi-10s GeV) e-A collider**

Advantage of nucleus →



$L \sim$ $1/3$

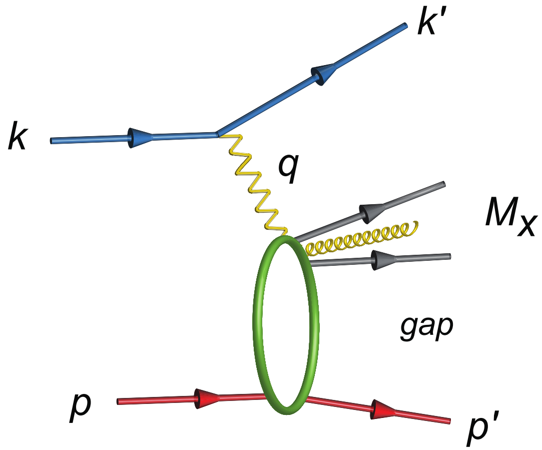


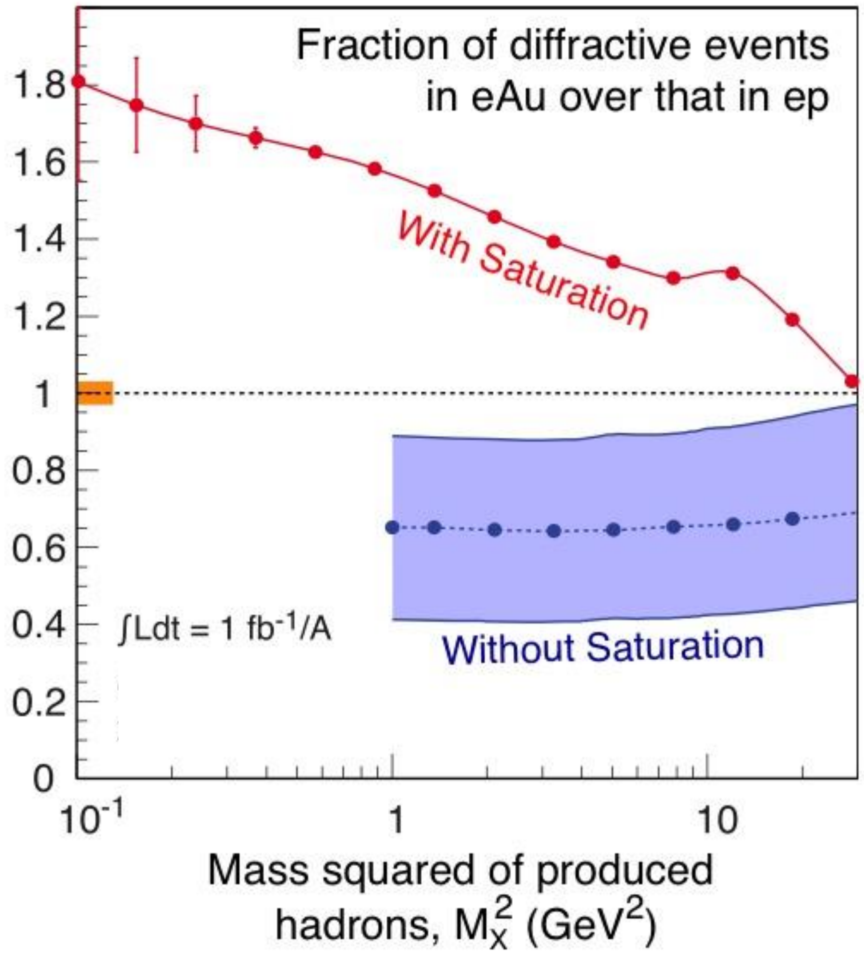
Enhancement of Q_S with A:
Saturation regime reached at significantly lower energy (*i.e* "cost") in nuclei

Saturation/CGC: What to measure?

Many ways to get to gluon distribution in nuclei, but diffraction most sensitive:

$$\sigma_{\text{diff}} \propto [g(x,Q^2)]^2$$





At HERA

ep: 10-15% diffractive

At EIC eA, if Saturation/CGC

eA: 25-30% diffractive

Exposing different layers of the nuclear landscape with electron scattering

History:

Electromagnetic

Elastic electron-nucleus scattering → charge distribution of nuclei

Present/Near-future:

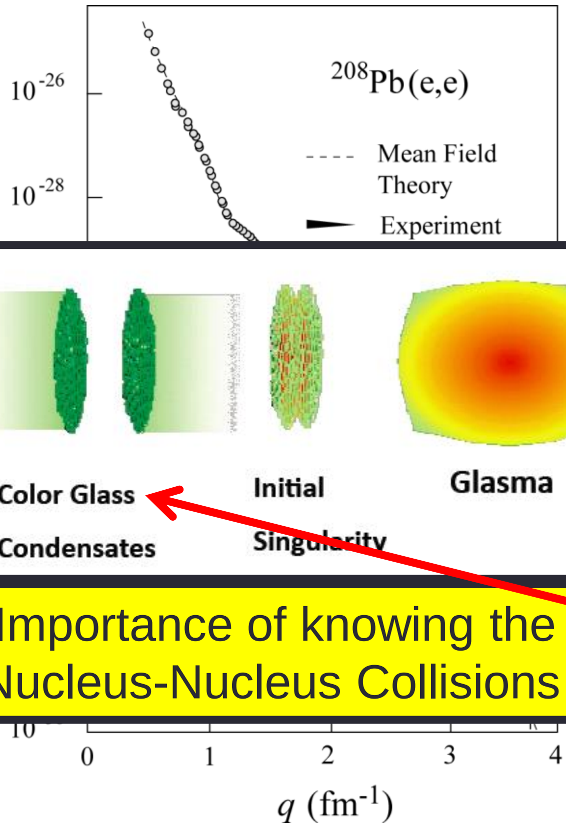
Electroweak

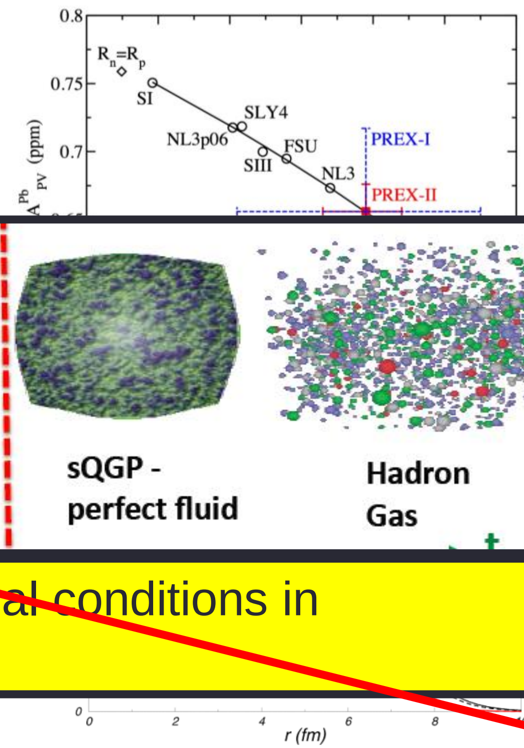
Parity-violating elastic electron-nucleus scattering (or hadronic reactions *e.g.* at FRIB) → neutron skin

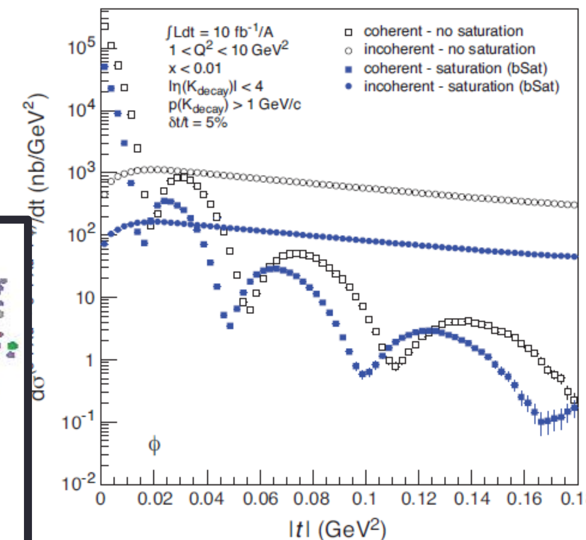
Future: at the EIC:

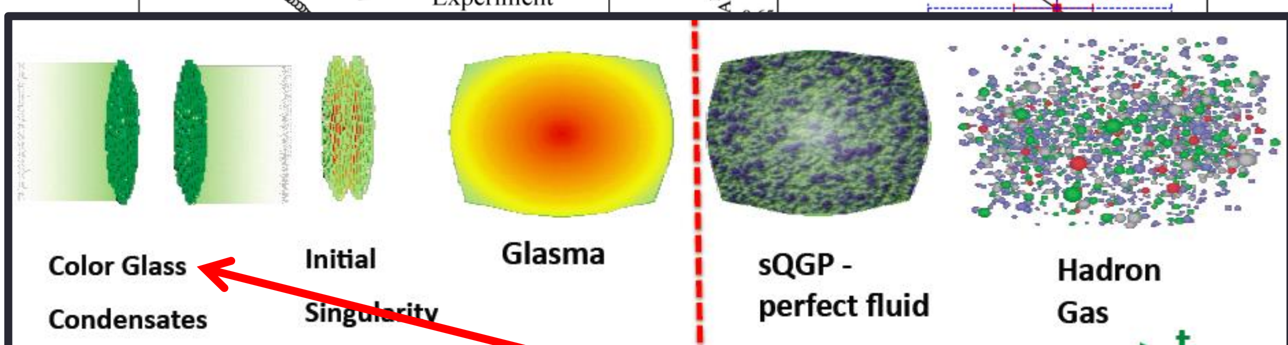
Color dipole

ϕ Production in coherent electron-nucleus scattering → gluon spatial distribution in nuclei









Importance of knowing the initial conditions in Nucleus-Nucleus Collisions

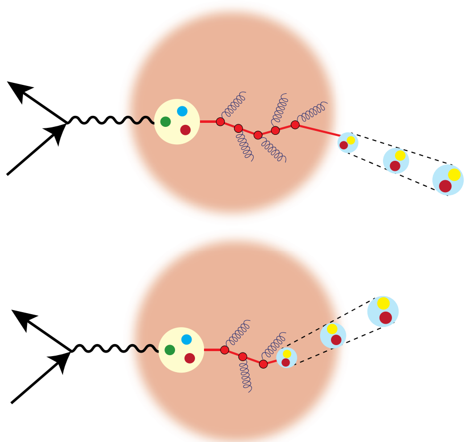
Fourier transform gives unprecedented info on gluon spatial distribution, including impact of gluon saturation

Emergence of Hadrons from Partons

Nucleus as a Femtometer sized filter

Unprecedented ν, the virtual photon energy range @ EIC : *precision & control*

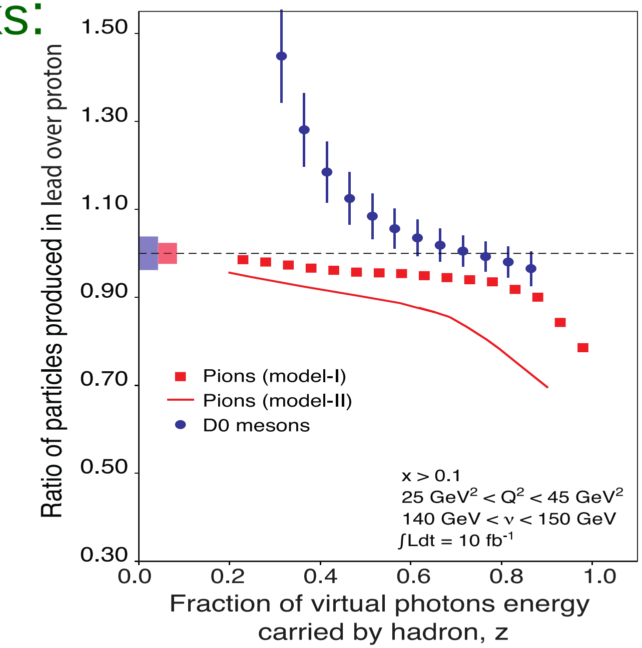
$$\nu = \frac{Q^2}{2mx}$$



Control of ν by selecting kinematics;
Also under control the nuclear size.

Colored quark emerges as color neutral hadron ➔ What is nature telling us about confinement?

Energy loss by light vs. heavy quarks:



Identify π 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

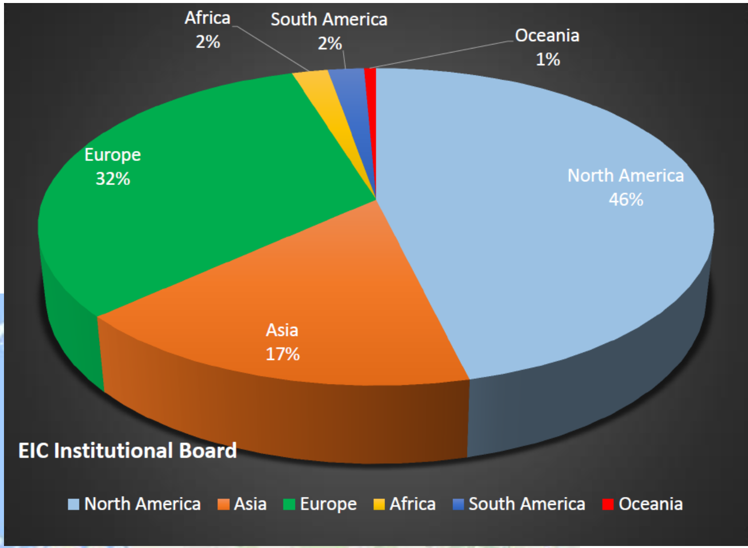
Need the collider energy of EIC and its control on parton kinematics

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



EICUG Organizational Structure

Membership

- 670 users including experimentalists, theorists and accelerator scientists

Institutional Board (IB)

- 150 institutional representatives form the Institutional Board (IB)

Steering Committee

- 7 steering committee members ***elected*** by the User Group (IB) + 2 nominated by the Labs

Physics Working Groups

- Physics Working Groups & their conveners: to be organized soon

EICUG Steering Committee

- Abhay Deshpande (SBU, Chair & Spokesperson)
- Bernd Surrow (Temple U, Vice-Chair)
- John Arrington (ANL)
- Charles Hyde (ODU)
- Marco Radici (INFN, Italy)
- Christine Aidala (U. Michigan, Chair-IB)
- Asia Representative (TBD)
- Europe Representative (TBD)

Lab Representatives:

- Elke Aschenaeur (BNL)
- Rik Yoshida (JLab)

Principle task: Communicate with the outside world to promote EIC science, and work with the Lab managements, (when necessary) with the funding agencies & international organizations to move the EIC to reality

Maintaining US Leadership in Accelerator Science

On going R&D on accelerator concepts and technologies:

- High current Energy Recovery Linac (ERL)
- High current polarized electron gun
- Coherent electron cooling
- High gradient crab cavities
- Fixed Field Acceleration Gradient beam transport
- Superferric magnets
- Figure-8 shaped e/h rings to aid polarization of beams

Most EIC R&D is of global interest!

Realizing these for the US EIC keeps the US on the cutting edge of accelerator science

EIC: Why now?

- A set of compelling physics questions about the gluon’s role in nucleons and nuclei has been formulated
- Measurements that provide answers to those compelling questions have been identified
- Powerful formalisms that connect the measurements to rigorously defined properties of QCD structure & dynamics of the nucleons and nuclei have been developed
- Based on the Accelerator R&D since the 2007 LRP, technical designs of an EIC using existing facility infrastructure now exist
- The international users are organizing to be in a position to design, propose and construct the necessary research equipment
- US nuclear physics has the laboratories and technical expertise in place to realize EIC

Summary

- The EIC will profoundly impact our understanding of the **structure of nucleons and nuclei in terms of sea quarks & gluons** (SM of Physics).
  → ***The bridge between sea quark/gluons to nuclei***
- The EIC will enable images of **yet unexplored regions of phase space in QCD** with its high luminosity/energy, nuclei & beam polarization
  → **There is a *high potential for discovery***
- **O**utstanding questions raised by the science at RHIC/LHC and Jefferson Lab, have **naturally led us to the Science and design parameters of the EIC**
- **There is world wide interest** in collaborating on the EIC
- Accelerator scientists at RHIC and JLab together ready to provide the **intellectual and technical leadership for to realize the EIC**, a frontier accelerator facility.

Future of nuclear science demands an Electron Ion Collider.
The U.S. must lead the way.