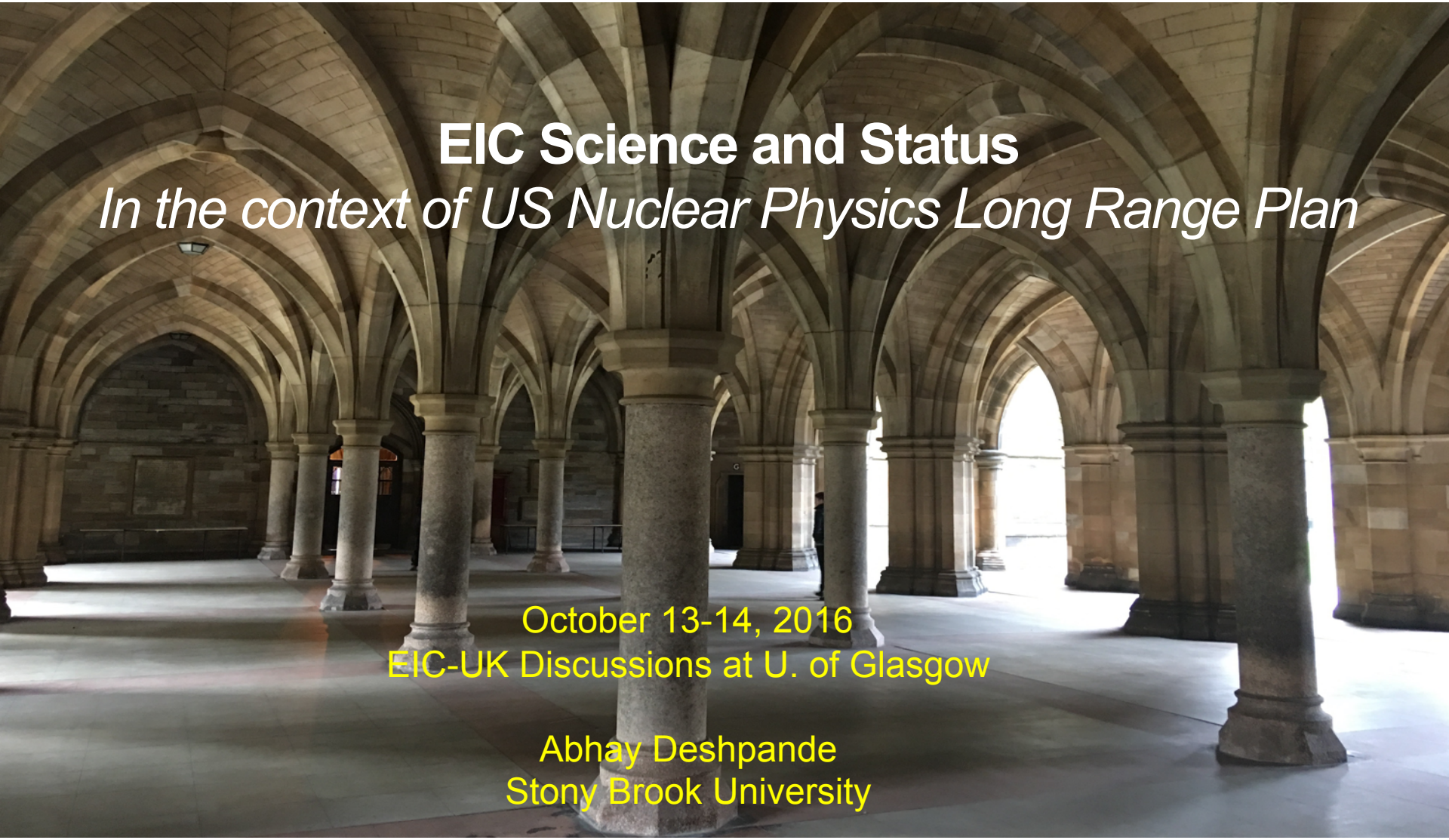


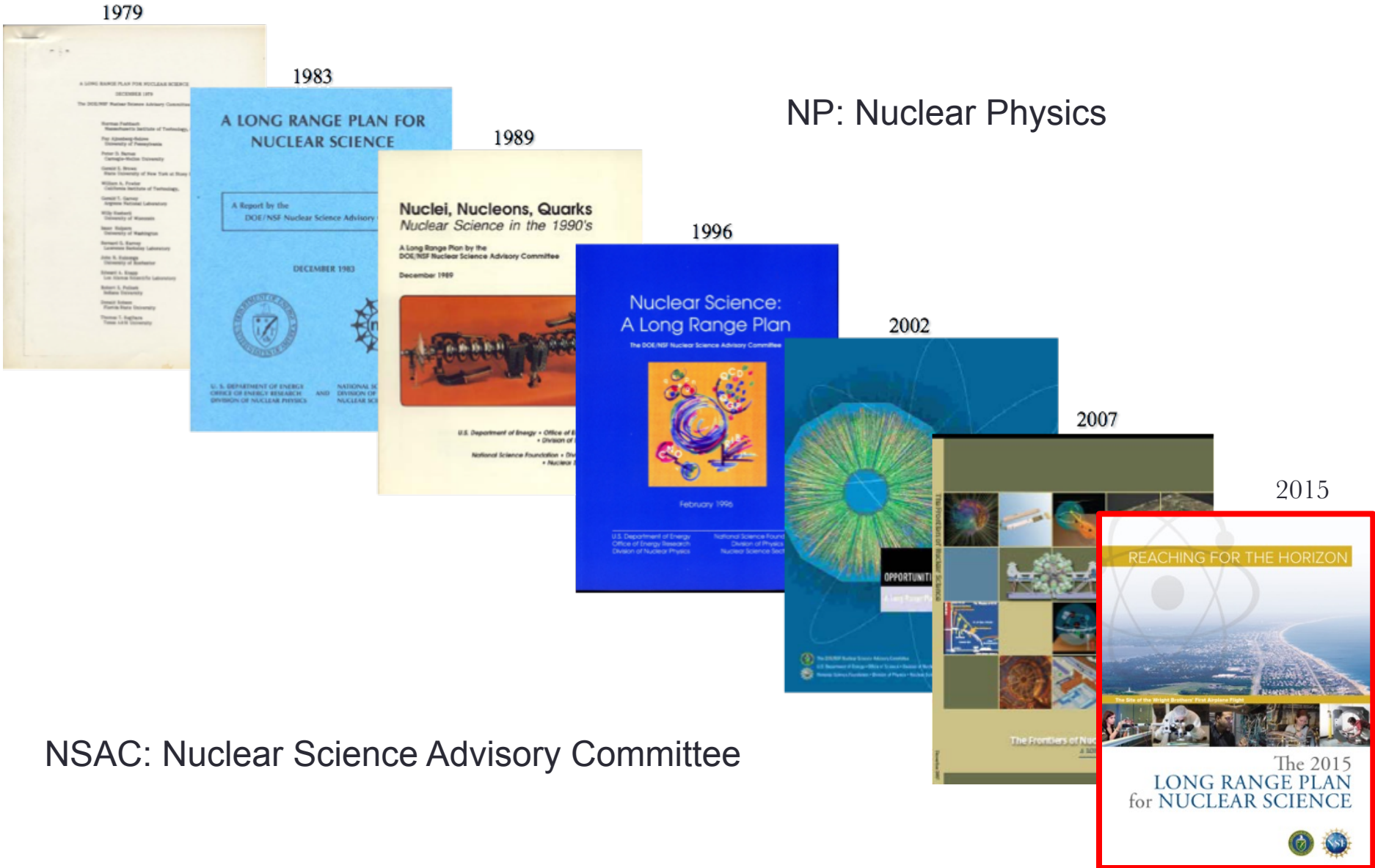
EIC Science and Status

In the context of US Nuclear Physics Long Range Plan

October 13-14, 2016
EIC-UK Discussions at U. of Glasgow

Abhay Deshpande
Stony Brook University

NP's long history of Long Range Plans (LRP)



NP: Nuclear Physics

NSAC: Nuclear Science Advisory Committee

The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

http://science.energy.gov/np/reports

Recommendations:

Finish programs at existing & **under construction** facilities (RHIC, **JLab**, NCLS, **FRIB**,…) & sustain a targeted program in fundamental symmetries & neutrino research

Invest in a ton-scale neutrino-less double beta decay experiment

Construct a high-energy high-luminosity polarized EIC with highest priority following the completion of FRIB.

10 yrs

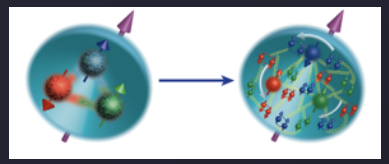
Invest in mid- and small-scale projects at universities and laboratories

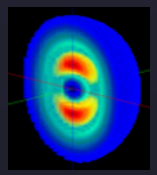
Initiatives:

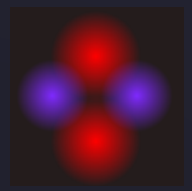
Theory & Computing

Detector & Accelerator R&D

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

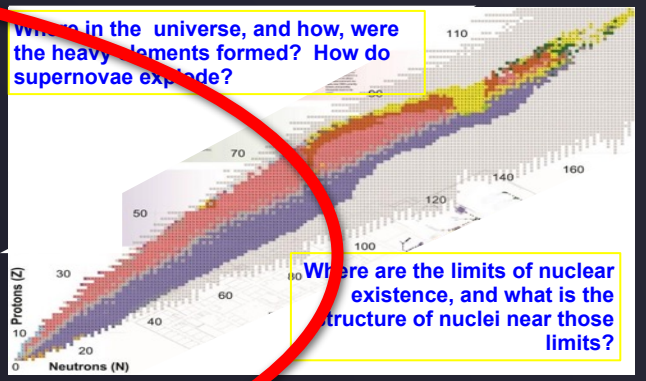




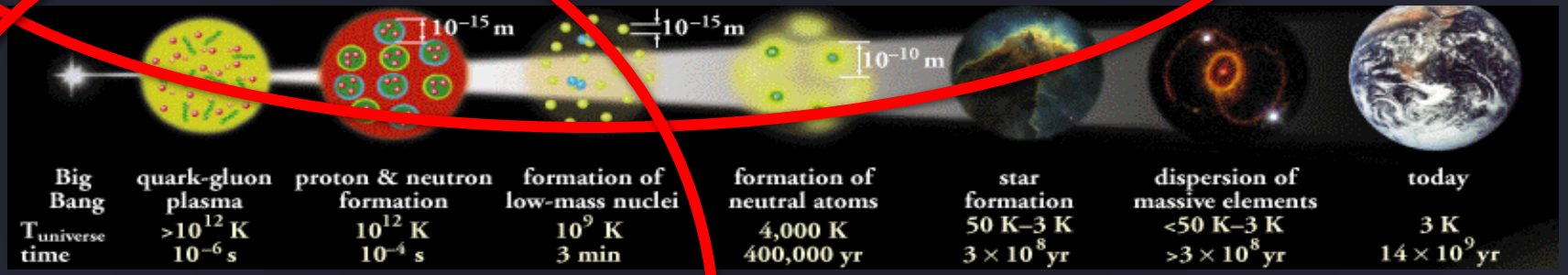


How are the properties of protons and neutrons, and the force between them, built up from quarks, antiquarks and gluons? What is the mechanism by which these fundamental particles materialize as hadrons?

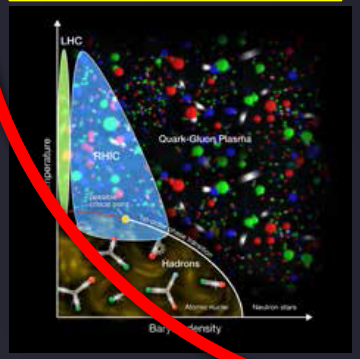
Where in the universe, and how, were the heavy elements formed? How do supernovae explode?



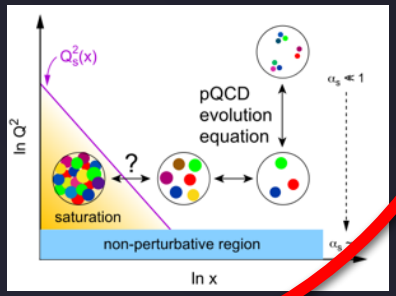
Where are the limits of nuclear existence, and what is the structure of nuclei near those limits?



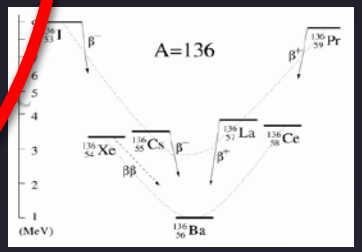
What is the nature of the different phases of nuclear matter through which the universe has evolved?



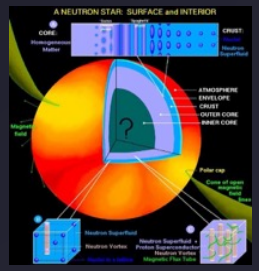
Do nucleons and all nuclei, viewed at near light speed, appear as walls of gluons with universal properties?



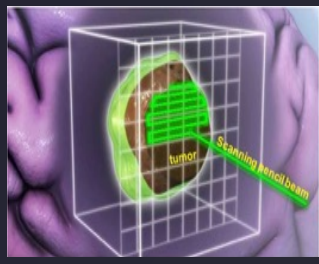
How can the properties of nuclei be used to reveal the fundamental processes that produced an imbalance between matter and antimatter in our universe?



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?

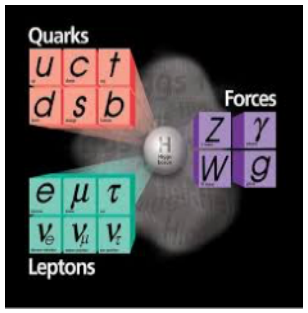


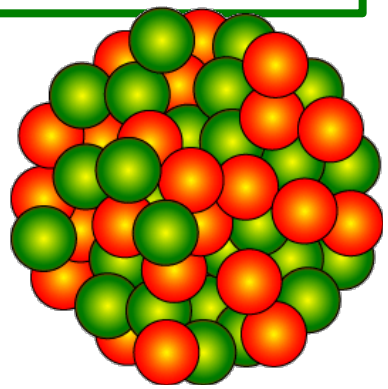
Electron Ion Collider: The next QCD frontier

Understanding the Glue that Binds Us All

Why the EIC?

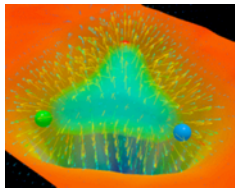
To understand the role of gluons in binding quarks & gluons into Nucleons and Nuclei





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 95% 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

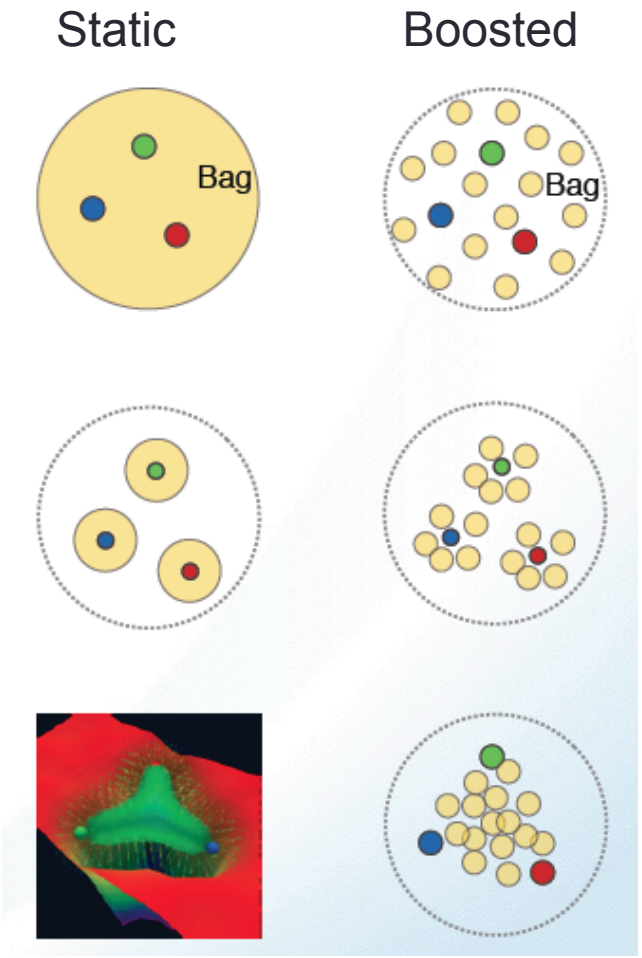
- The quark-gluon origin of the nucleon-nucleon forces in nuclei not quite known

- 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

CONFINEMENT!

What does a proton look like?



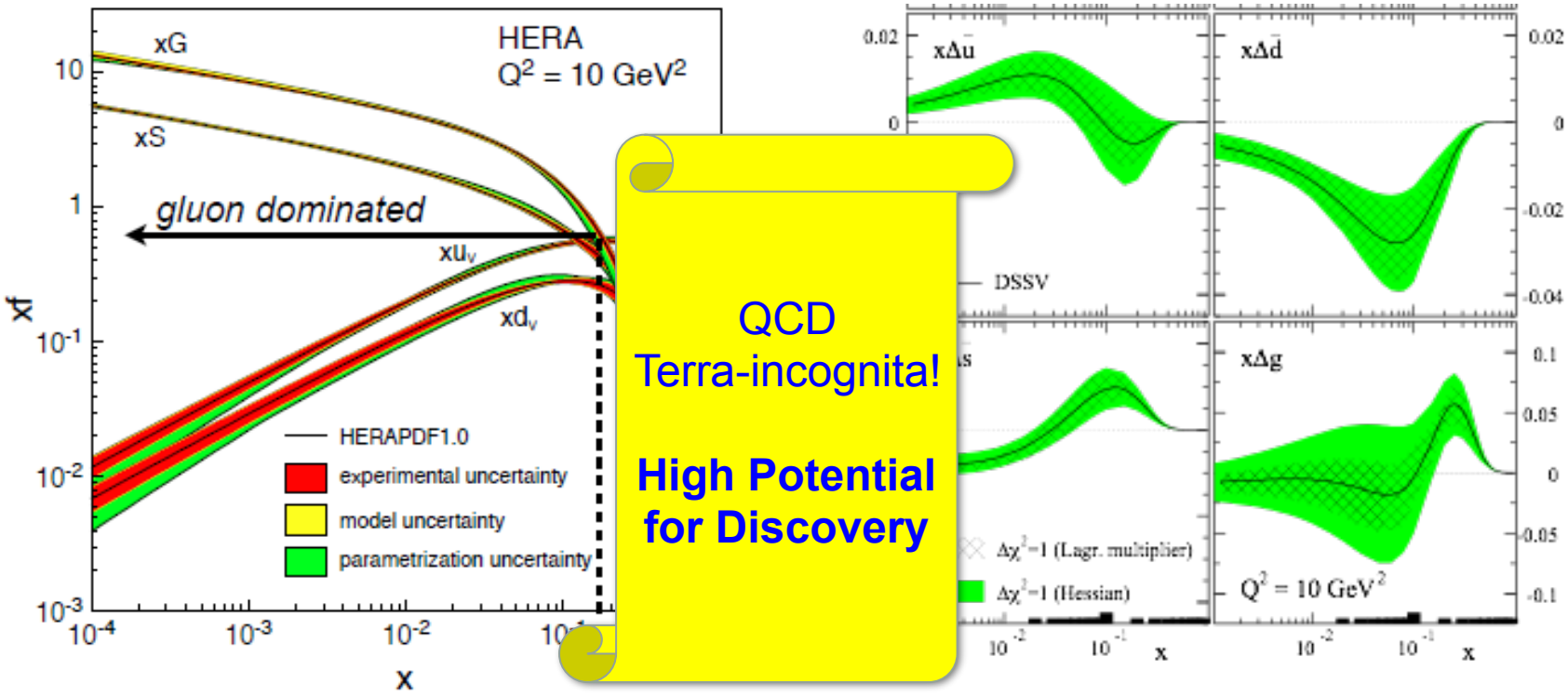
Bag Model: Gluon field distribution is wider than the fast moving quarks.
Gluon radius > Charge Radius

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

What does a proton look like?
Unpolarized & polarized parton distribution functions



QCD
Terra-incognita!

High Potential for Discovery

Need to go beyond 1-dimension!

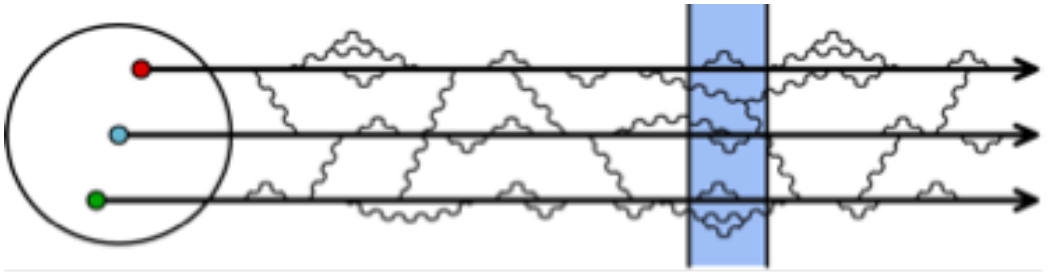
Need 3D Images of nucleons in Momentum & Position space

Could they give us clues on orbital motion of partons?

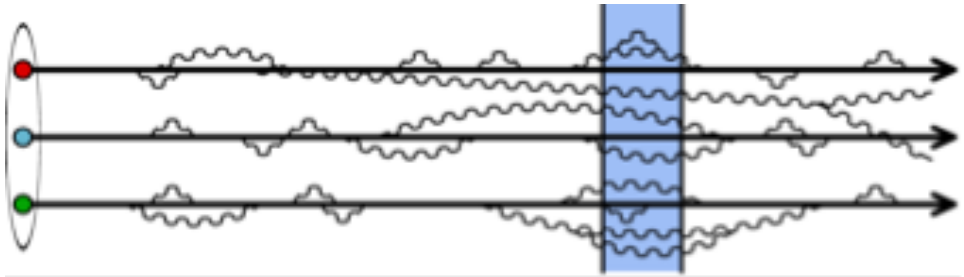
Understanding the nucleon spin

How does a Proton look at low and high energy?

Low energy
High x
Regime of fixed target exp.



High energy
Low- x
Regime of a Collider



At high energy:

- Wee partons fluctuations are time dilated in strong interaction time scales
- Long lived gluons radiate further smaller x gluons ➔ which intern radiate more……. Leading to a **runaway growth?**

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…."

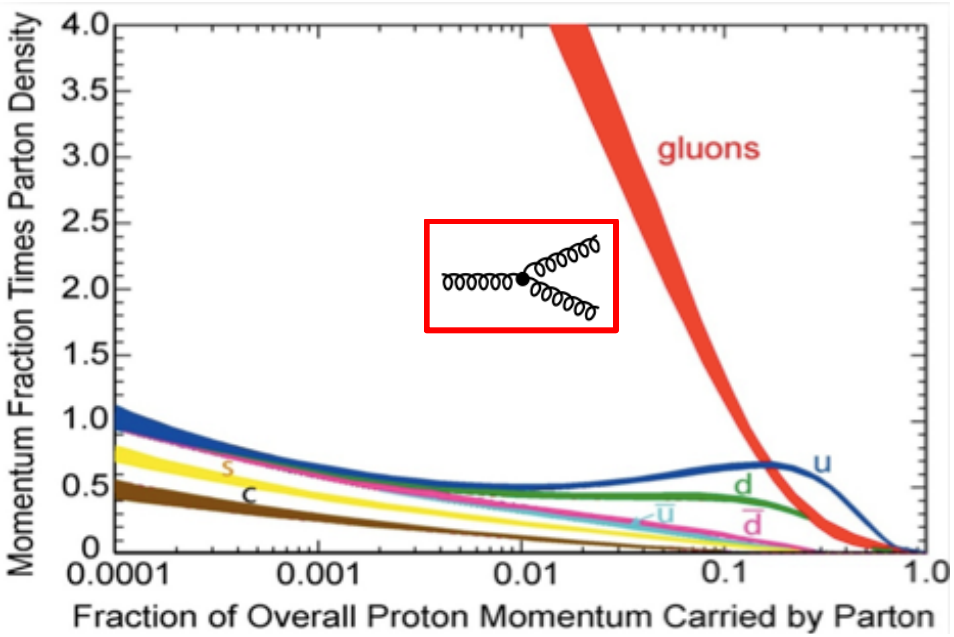
F. Wilczek, in "Origin of Mass"
Nobel Prize, 2004

Gluon and the consequences of its interesting properties:

Gluons carry color charge ➔ Can interact with othe

QCD Terra-incognita!

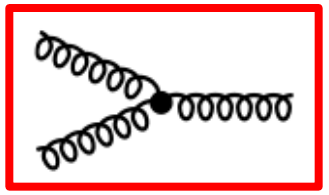
High Potential for Discovery



Apparen ” in gluon distributi

What ndefinite **rise?** → saturation of soft gluon densities via gg→g recombination must be responsible.

recombination

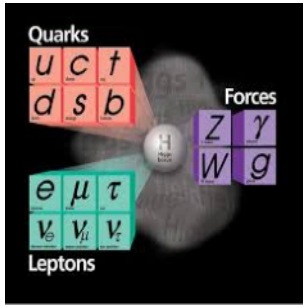


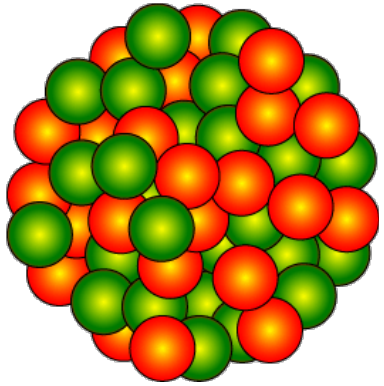
Where? No one has unambiguously seen this before!

If true, effective theory of this →“Color Glass Condensate”

Why an Electron Ion Collider?

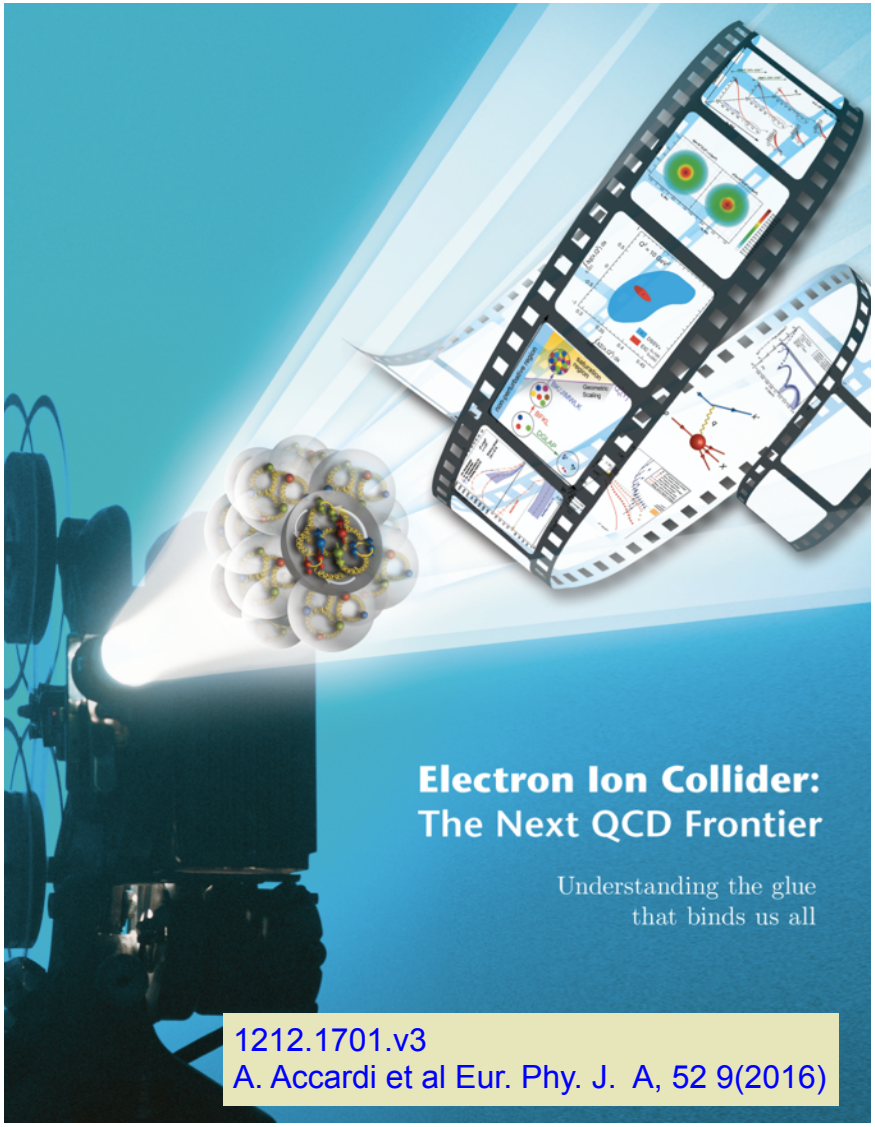
A new facility, EIC, with a versatile range of kinematics, beam polarizations, high luminosity and beam species, is required to ***precisely image*** *the sea quarks and gluons in nucleons and nuclei,* to explore the new QCD frontier of strong color fields in nuclei, and to resolve outstanding issues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



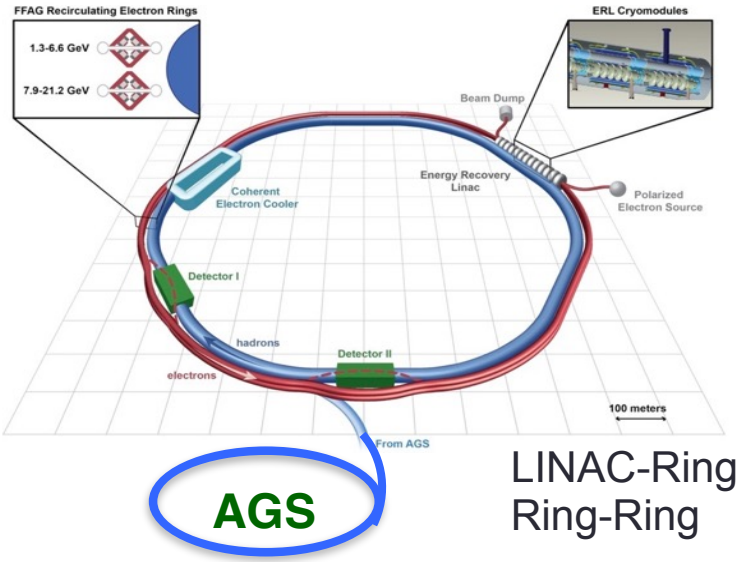


The Electron Ion Collider

Two options of realization!



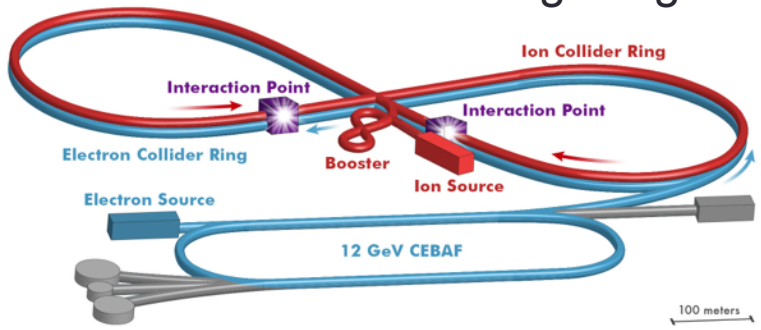
1212.1701.v3
A. Accardi et al Eur. Phy. J. A, 52 9(2016)



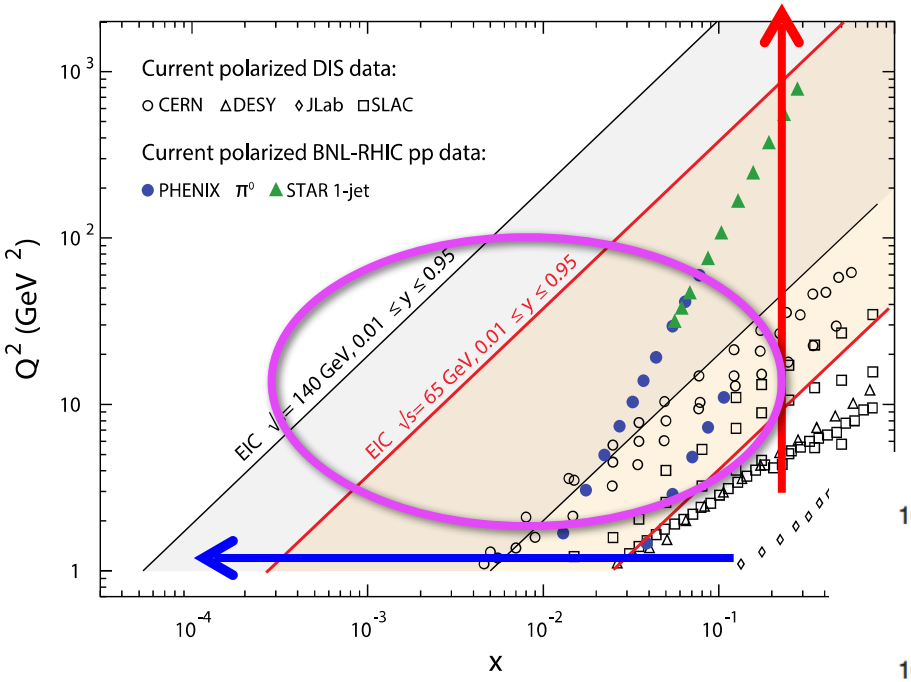
LINAC-Ring
Ring-Ring

Not to scale

Ring-Ring



EIC: Kinematic reach & properties

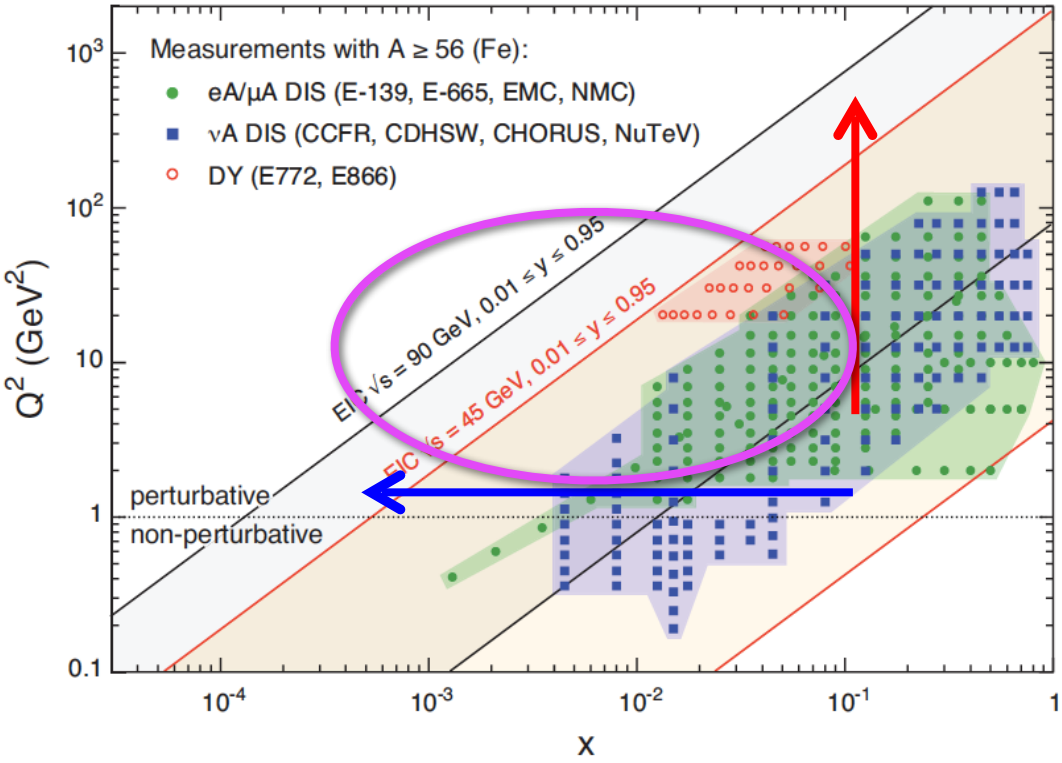


For e-N collisions at the EIC:

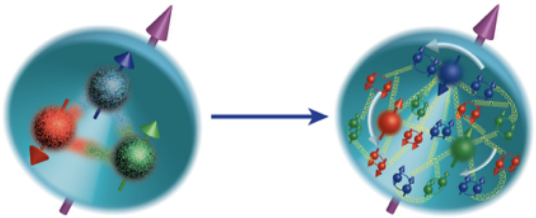
- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

For e-A collisions at the EIC:

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



NUCLEON SPIN



Our Understanding of Nucleon Spin

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

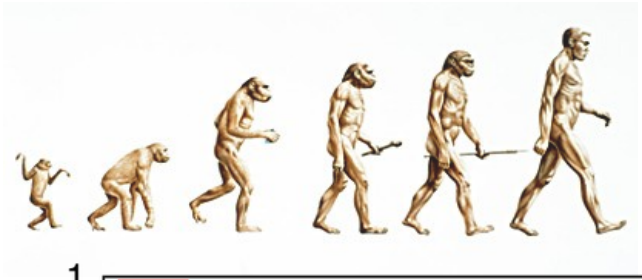
$\Delta\Sigma/2$ = Quark contribution to Proton Spin

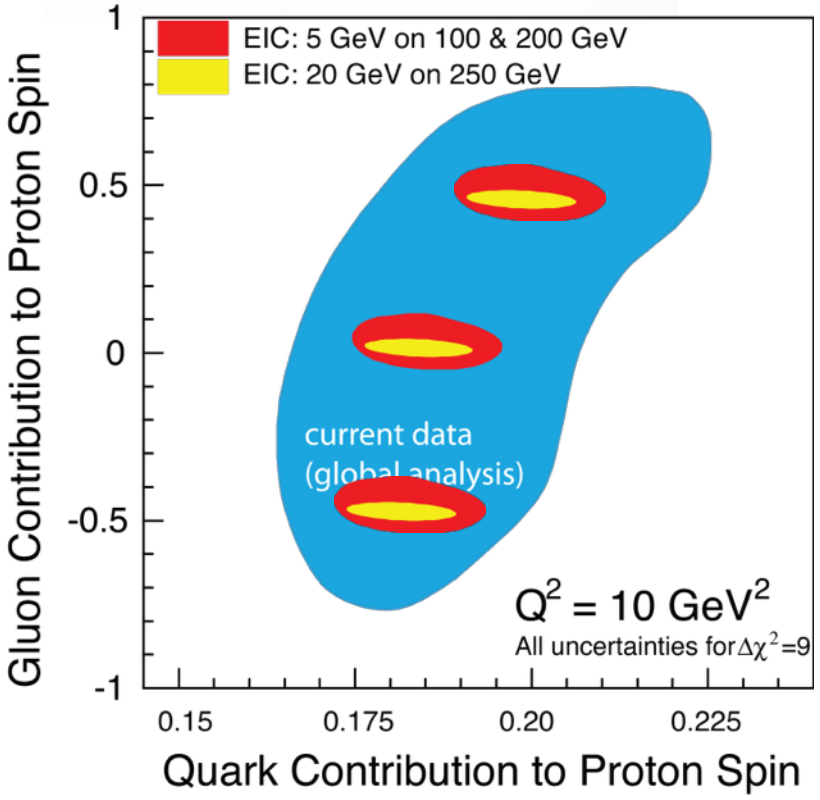
L_Q = Quark Orbital Ang. Mom

Δg = Gluon contribution to Proton Spin

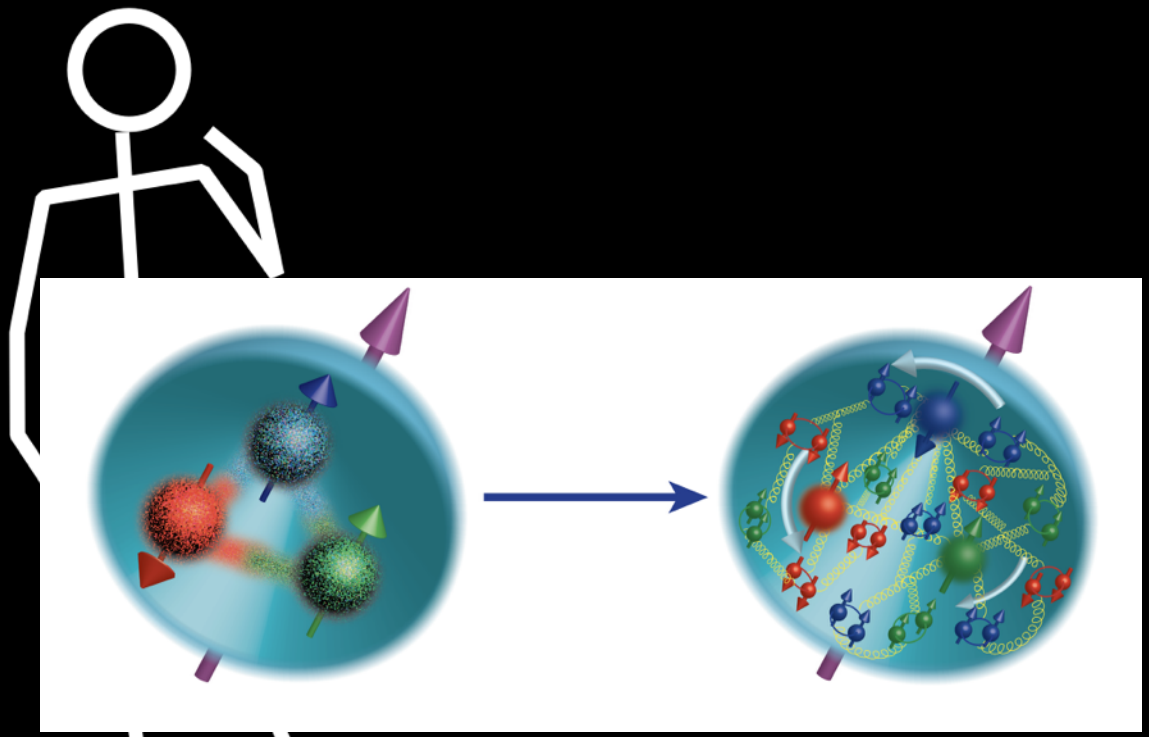
L_G = Gluon Orbital Ang. Mom

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





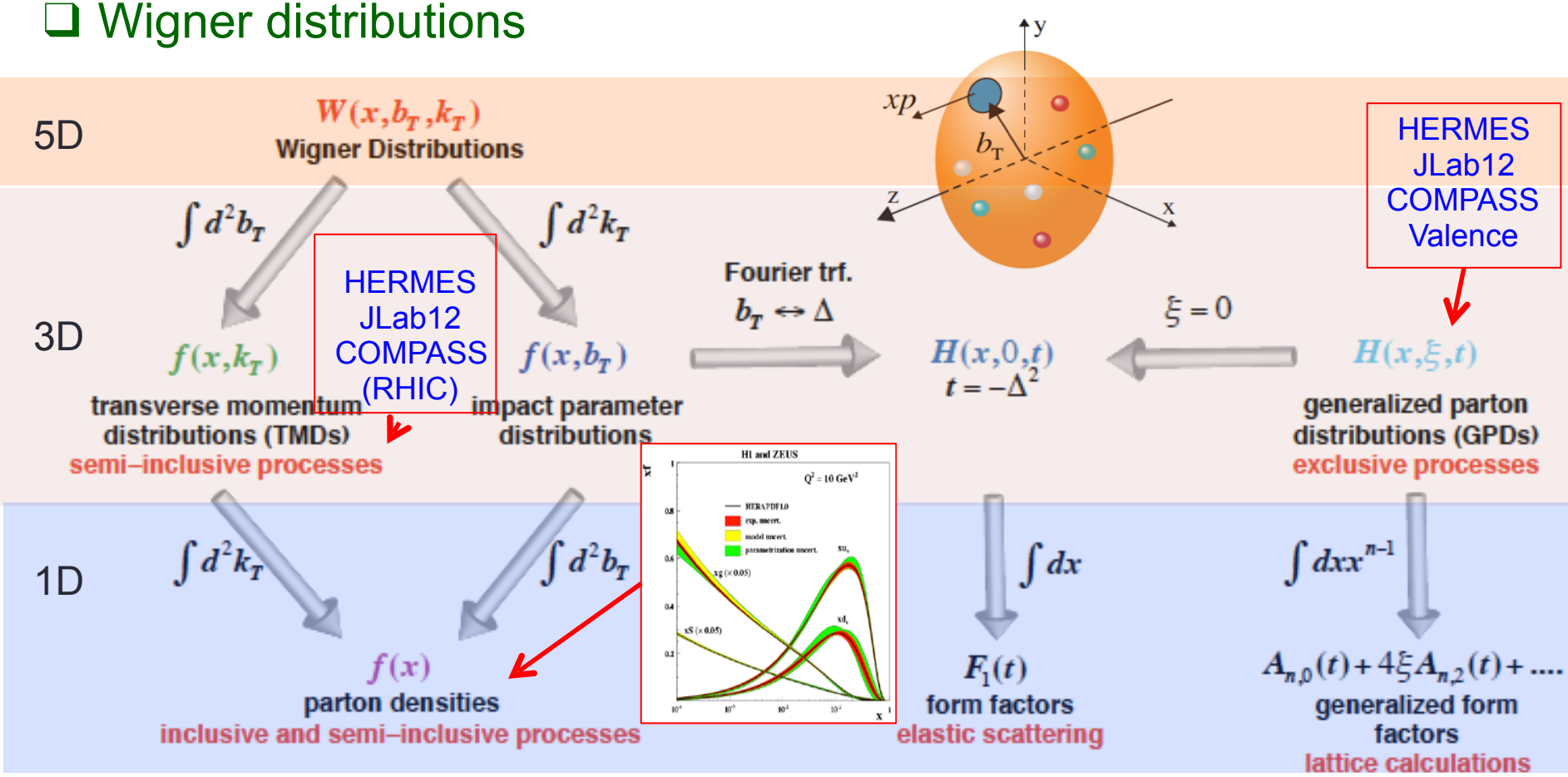
1D



Courtesy: Alssandro Bacchetta

Unified view of the Nucleon Structure

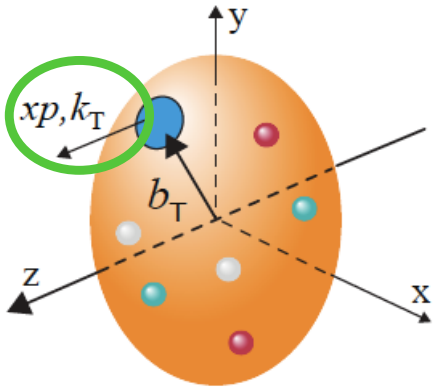
- Wigner distributions

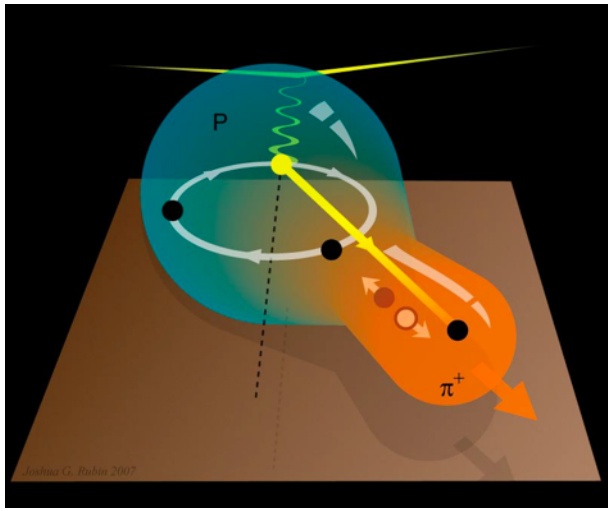


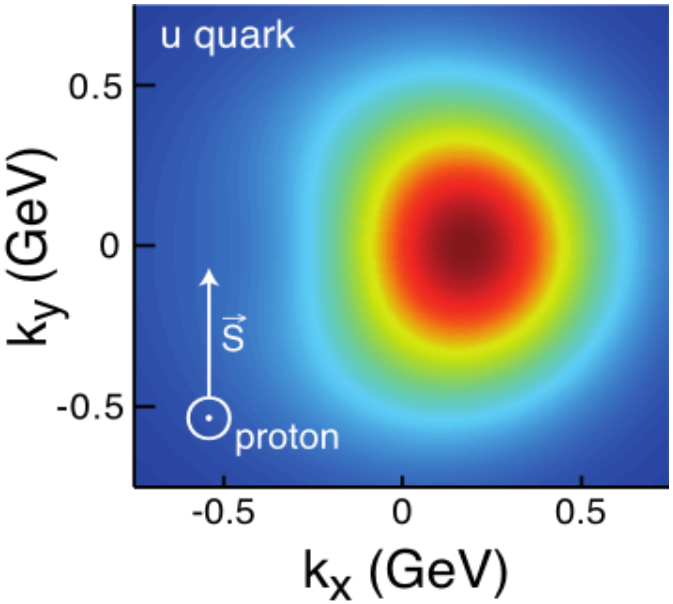
- (2+1)D imaging Quarks (Jlab/COMPASS) , **Gluons (EIC)**
  - TMDs – confined motion in a nucleon (semi-inclusive DIS)
  - GPDs – Spatial imaging of quarks and gluons (exclusive DIS & diffraction)

Measurement of Transverse Momentum Distribution

Semi-Inclusive Deep Inelastic Scattering



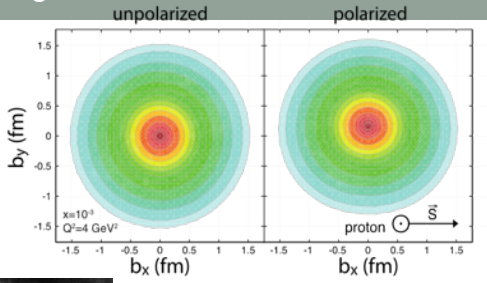




- Naturally, two scales:
  - high Q – localized probe
    To "see" quarks and gluons
  - Low p_T – sensitive to confining scale
    To "see" their confined motion
  - *Theory – QCD TMD factorization*

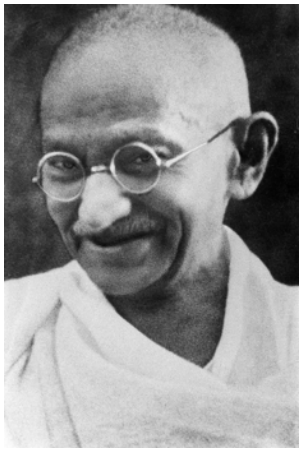
Spatial Imaging of quarks & gluons

Generalized Parton Distributions

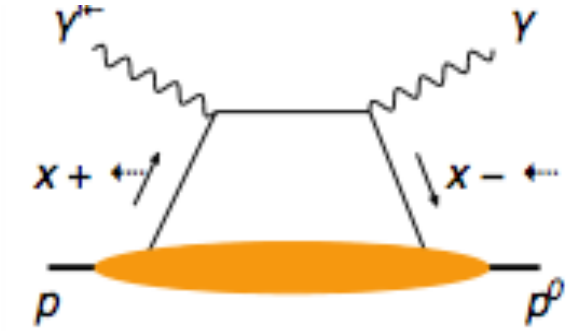


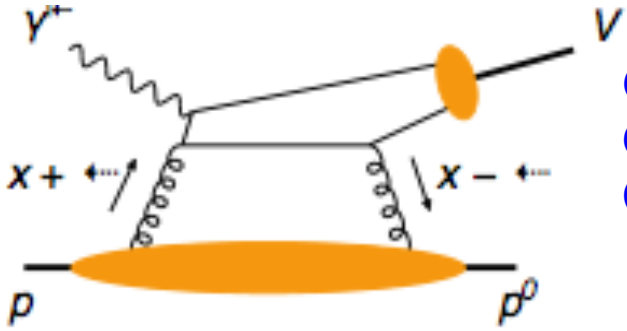
Historically, investigations of nucleon structure and dynamics involved breaking the nucleon…. (exploration of internal structure!)

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



Quarks Motion





Gluons: Only @ Collider

Deeply Virtual Compton Scattering
Measure all three final states
e + **p** → e'+ **p'**+ γ

Fourier transform of momentum transferred=(p-p') → Spatial distribution

Exclusive measurements → measure "everything"

3-Dimensional Imaging Quarks and Gluons

Momentum space

$W(x,b_T,k_T)$

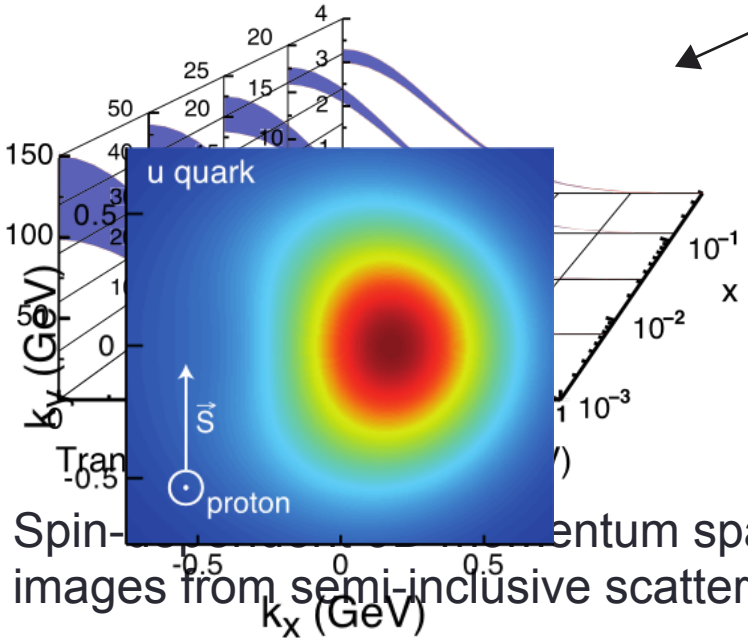
$\int d^2b_T$ $\int d^2k_T$

Coordinate space

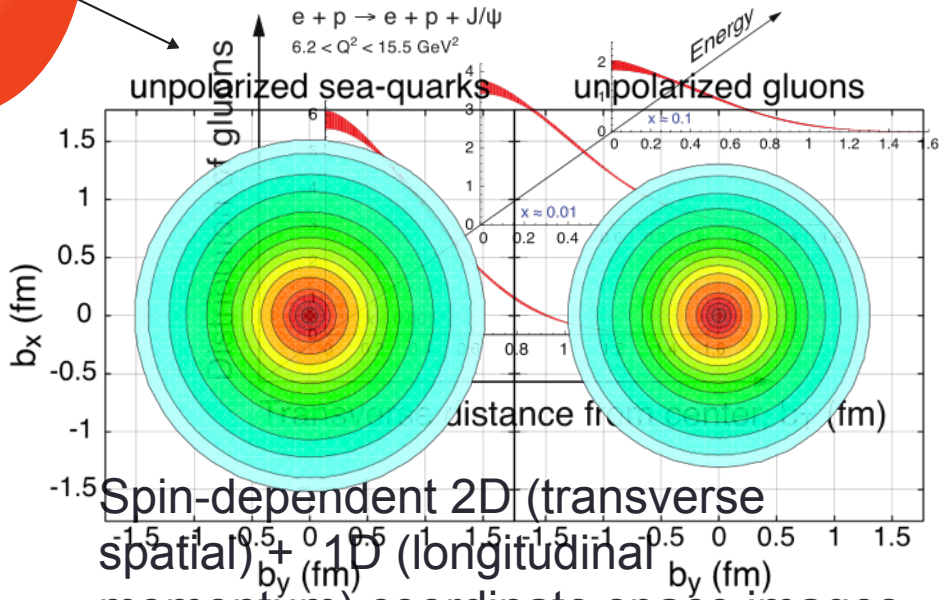
k_T xp b_T

$f(x,k_T)$ $f(x,b_T)$

Quarks 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

→ *Directly comparable with Lattice QCD Calculations*

Prospect of direct comparison with lattice QCD

➢ **Quark GPDs and its orbital contribution to the proton spin:**

$$J_q = \frac{1}{2}\lim_{t\to 0}\int dx\, x \;\; \text{(General. Parton Dist.s H,E)} \;\; = \frac{1}{2}\Delta q + L_q$$

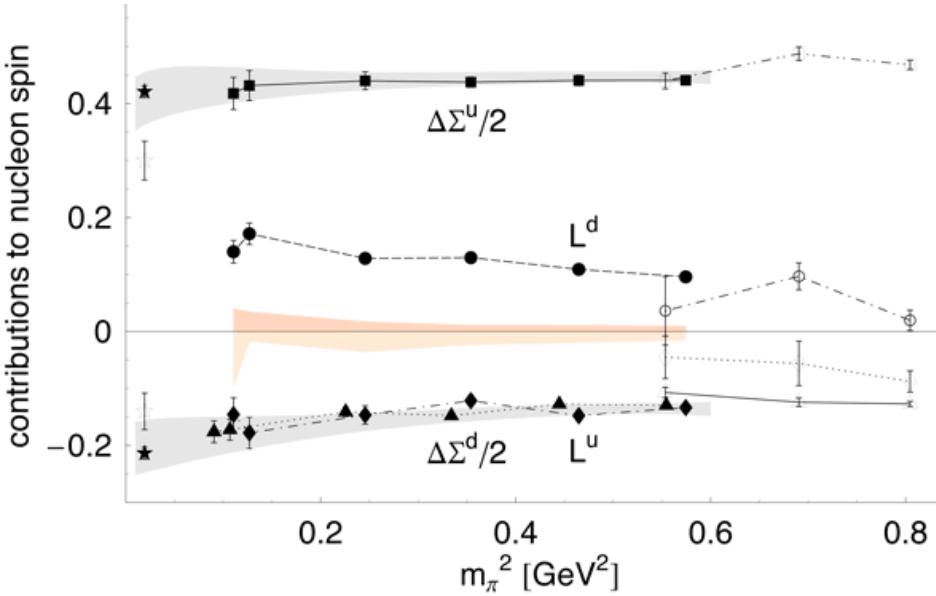
The first meaningful constraint on quark orbital contribution to proton spin by combining the sea from the EIC and valence region from JLab12/COMPASS

J_q, calculated on Lattice QCD:

Future:

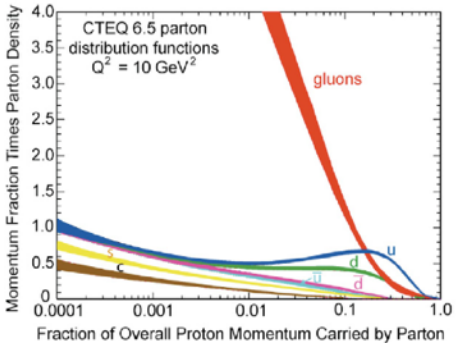
New developments on LQCD calculating parton distributions including gluon distributions:

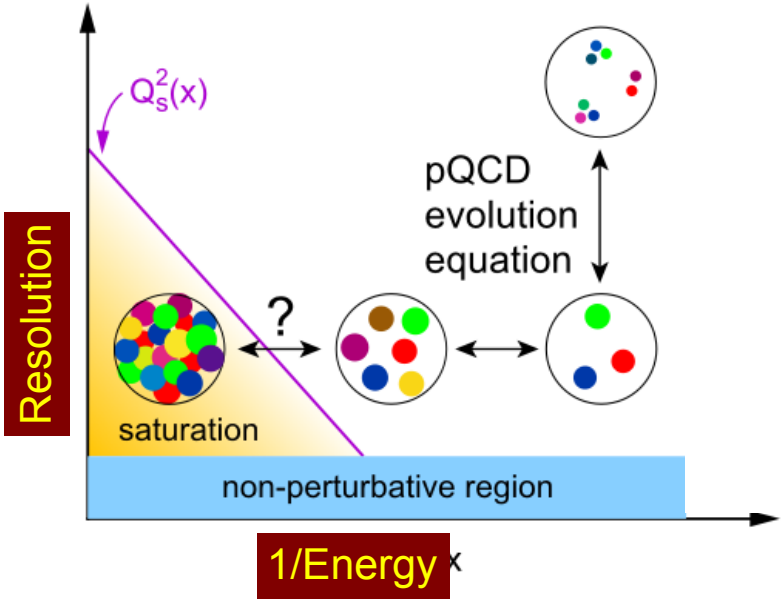
X. Ji et al. PRL 111 (2013) 112002
Y. Hatta, PRD89 (2014) 8, 085030
& Y.-Q. Ma, J.-W. Qiu 1404.6860



NUCLEONS AT HIGH ENERGY : GLUE, GLUE GLUE

What do we learn from low-x studies?

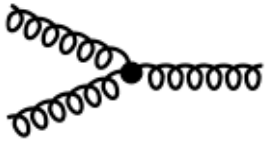




What tames the low-x rise?

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

gluon emission = gluon recombination



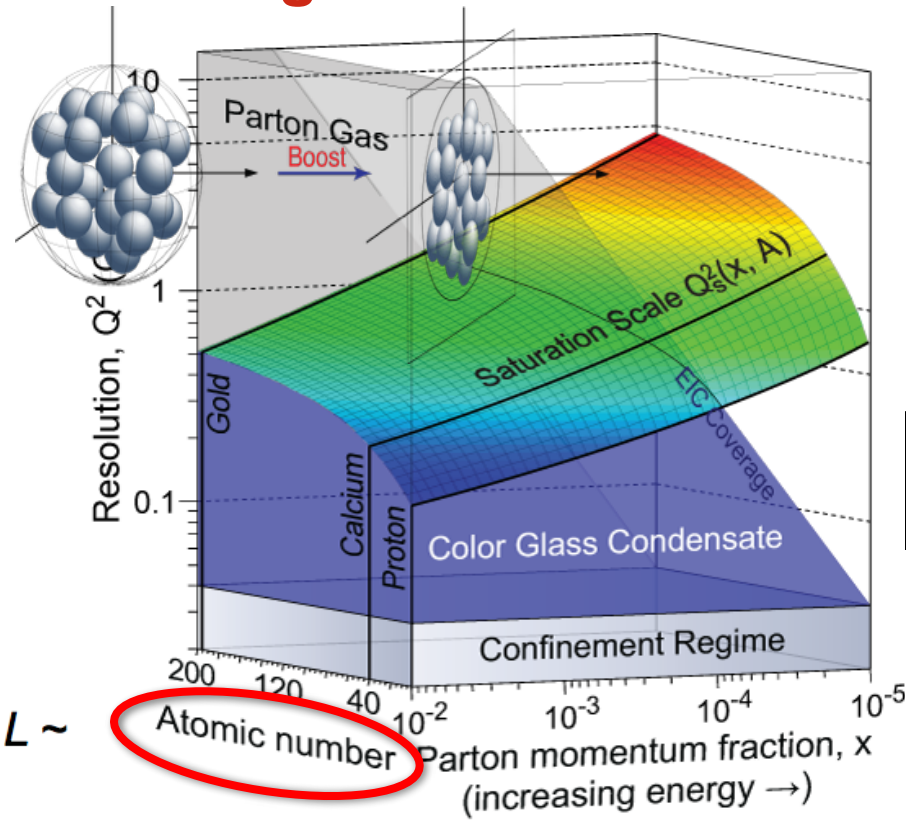
At Q_S

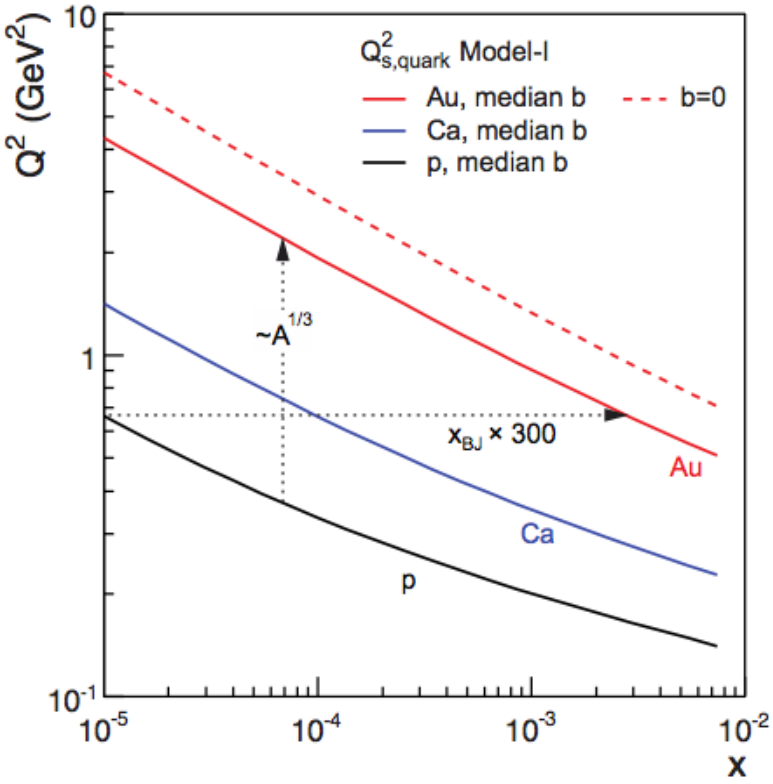
First observation of gluon recombination effects in nuclei:
➔leading to a *collective* gluonic system!
First observation of g-g recombination in *different* nuclei
à **Is this a universal property?**
à **Is the Color Glass Condensate the correct effective theory?**

How to explore/study this new phase of matter?

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

Advantage of nucleus →





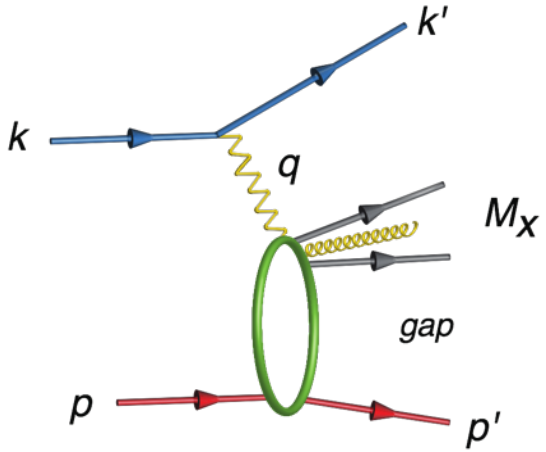
Enhancement of Q_S with A:

Saturation regime reached at significantly lower energy (read: "cost") in nuclei

Saturation/CGC: What to measure?

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

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

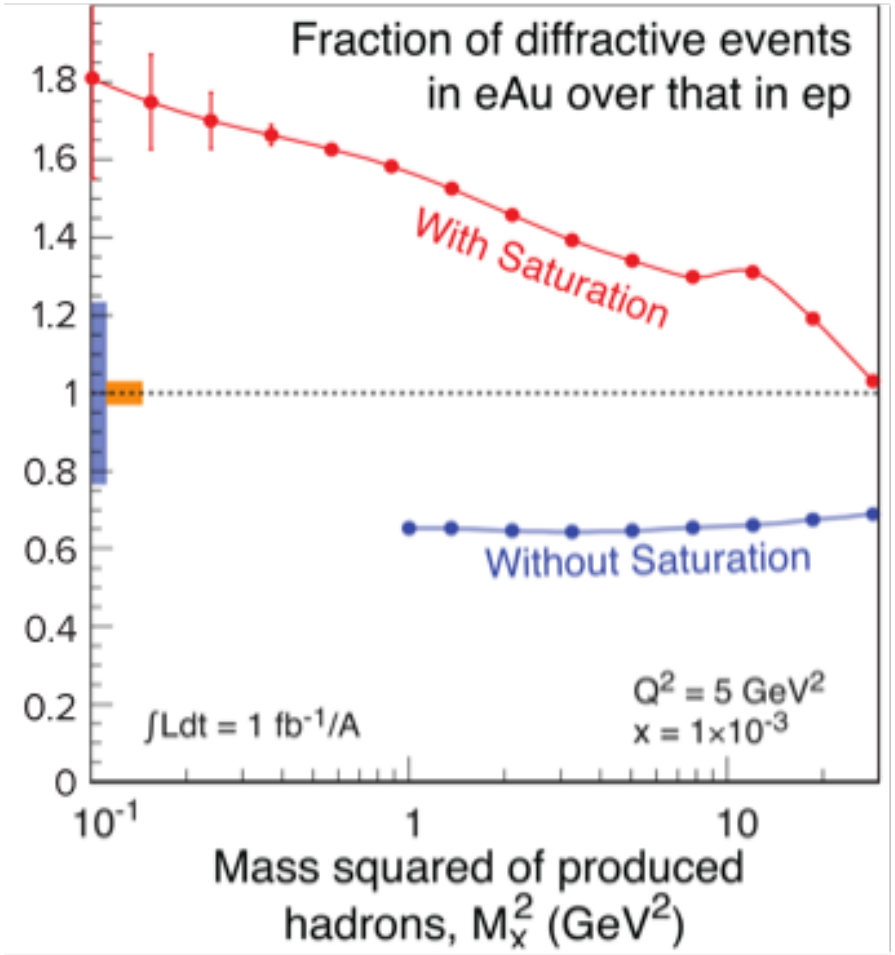


At HERA

ep: 10-15% diffractive

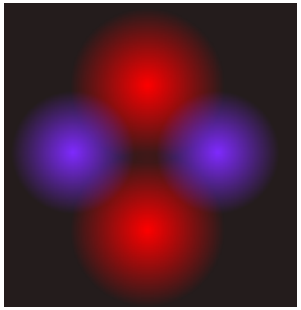
At EIC eA, if Saturation/CGC

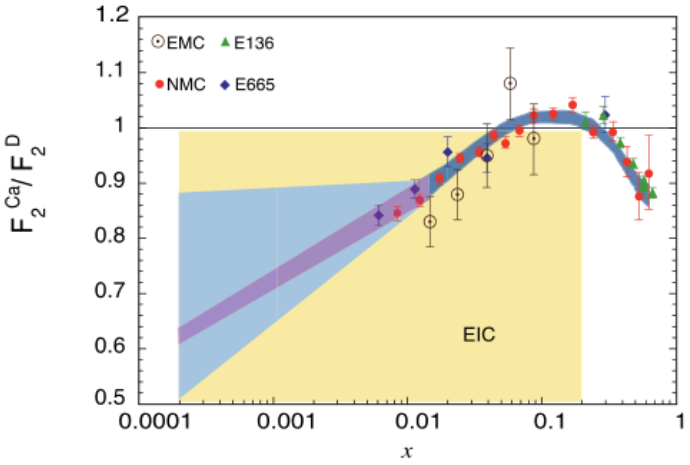
eA: 25-30% diffractive



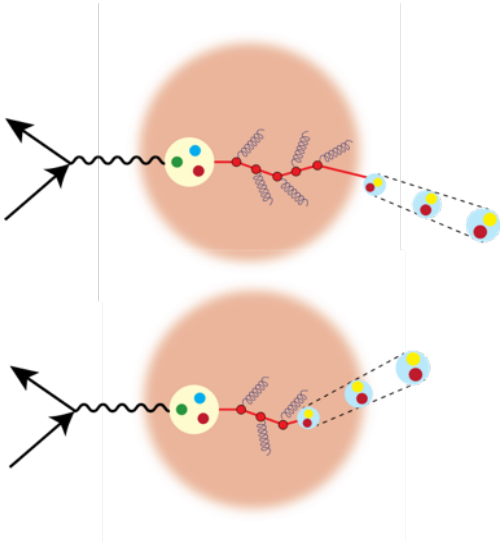
Puzzles and challenges….

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? (hadronization…. confinment?)

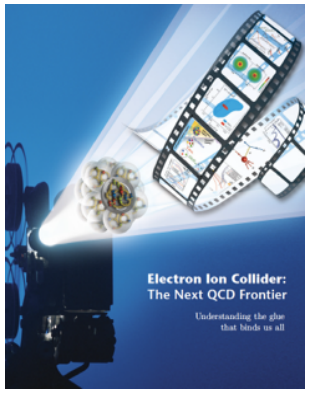
Other uncharted physics terrains for EIC Studies: Not in the EIC White Paper

- Impact of super-precise PDFs in $x > 0.001$, $1 < Q^2 < 100$ GeV^2 for future Higgs studies (some insight through LHeC studies, but serious effort on EIC beginning now).

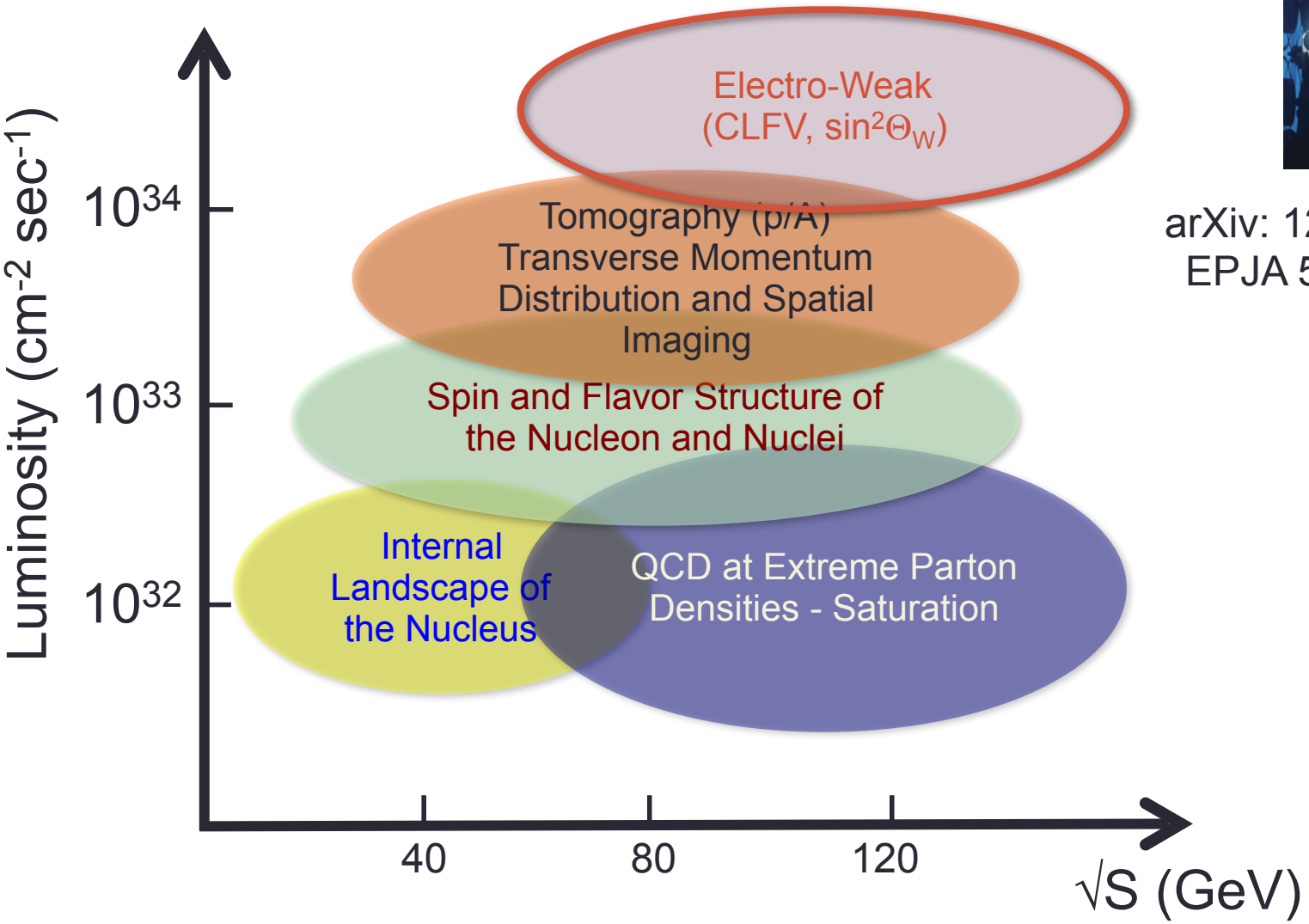
- Heavy quark and quarkonia (c, b quarks) studies beyond HERA, with 100-1000 times luminosities (??) [Of interest to Glasgow group? – from memories of ZEUS?]

- Internal structure of jets with variability of CM 50-140 GeV^2:
  - In comparison with HERA, Tevatron & LHC energies, and
  - Electron & proton polarizations (jet fragmentation studies) and comparison between jets in e+e- at BaBar/Belle & in future Super-Belle ("**Collins Functions**")

Physics vs. Luminosity & Energy



arXiv: 1212.1701.v3
EPJA 52, 9 (2016)



Electroweak & beyond….(?)

- Electro-weak deep inelastic scattering
  - Electroweak structure functions (including spin)
  - Significant contributions from W and Z bosons which have different couplings with *quarks and anti-quarks*

- Parity violating DIS: a probe of beyond TeV scale physics
  - Measurements at higher Q^2 than the PV DIS 12 GeV at Jlab
  - Precision measurement of $\mathrm{Sin}^2\Theta_W$

- New window for physics beyond SM through LFV search M. Gonderinger & M. Ramsey-Musolf, JHEP 1011 (045) (2010); arXive: 1006.5063 [hep-ph]

$$e^- + p \rightarrow \tau^- + X$$

REALIZATION….

EIC Distinct from (the past) HERA

- Luminosity 100-1000 times that of HERA
  - Enable 3D tomography of gluons and sea quarks in protons
- Polarized protons and light nuclear beams
  - Critical to all spin physics related studies, including precise knowledge of gluon's & angular momentum contributions from partons to the nucleon's spin
- Nuclear beams of all A (p→U)
  - To study gluon density at saturation scale and to search for coherent effects like the color glass condensate and test its universality
- Center mass variability with minimal loss of luminosity
  - Critical to study onset of interesting QCD phenomena
- Detector & IR designs mindful of "Lessons learned from HERA"
  - No bends in e-beam, maximal forward acceptance….

Innovative Accelerator Science

On going R&D on accelerator concepts and technologies:

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

eRHIC R&D

JLEIC R&D

Most of these are of global interest!

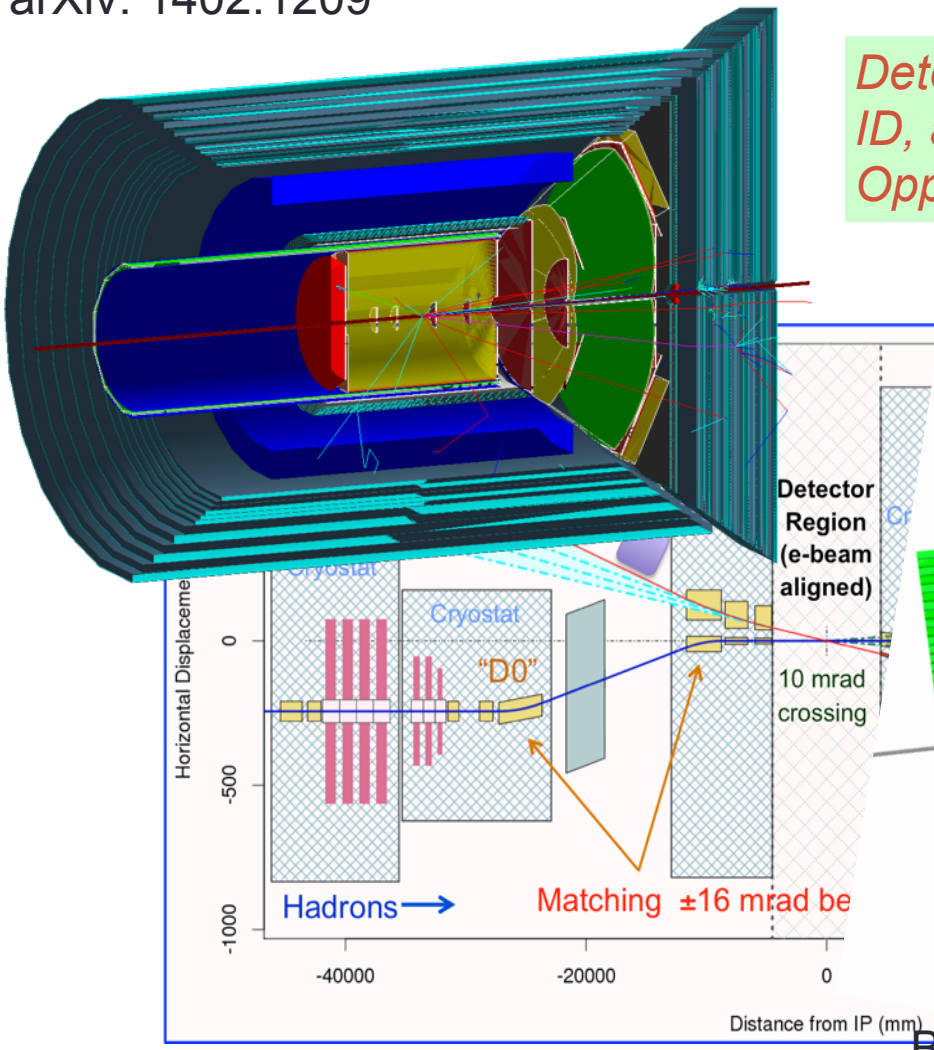
Realizing these for the US EIC requires *cutting edge accelerator science.*

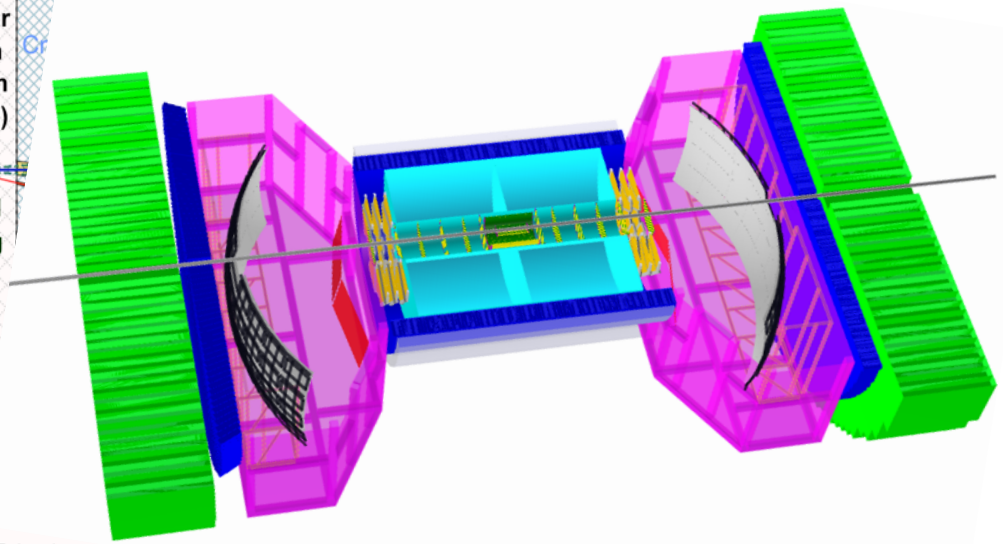
Office of NP, US DOE is initiating an Accelerator R&D program to address this ~$7M/year starting FY2017.

EIC IR & Detector Plan both at eRHIC & JLEIC

Day-1 Detector: CELESTE
A.K.A. “ePHENIX” with BaBar Solenoid
arXiv: 1402.1209

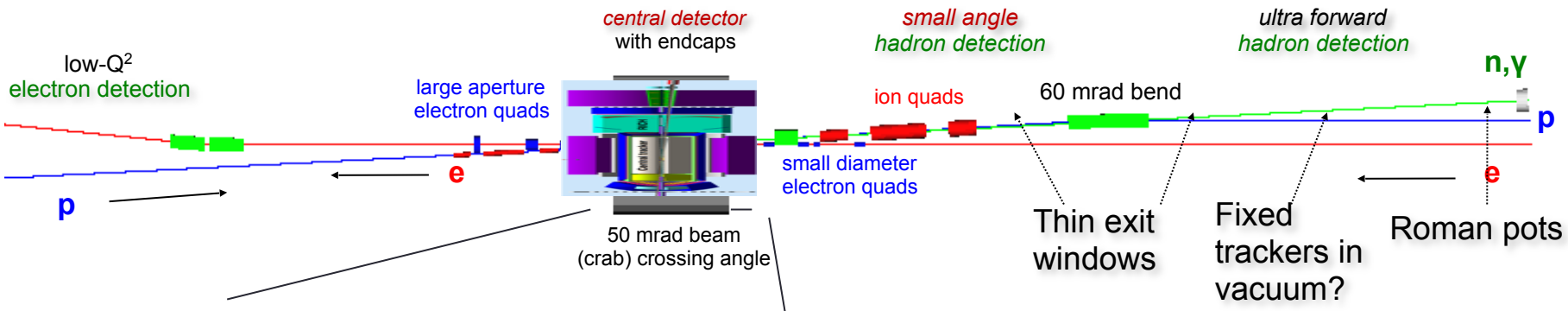
Detector: Low mass tracking technology, particle ID, asymmetric collisions (moving CM) are all in! Opportunities for HQ and Quarkonium physics.

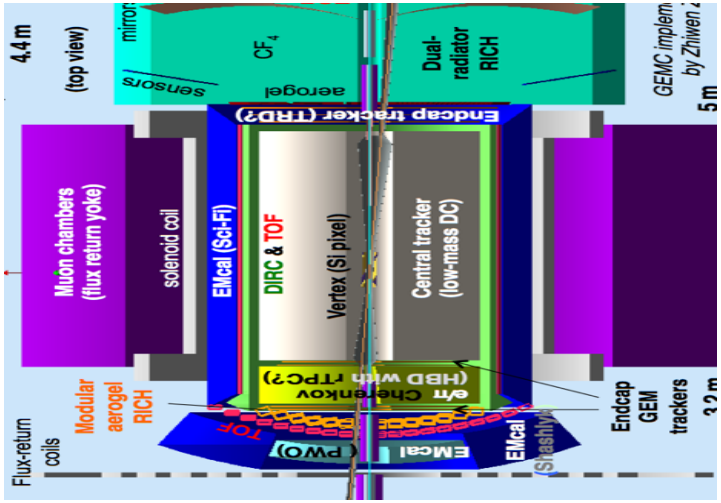




BEAST by BNL’s EIC Task Force
arXiv: 1409.1633

EIC at JLab: Integrated IR & Detector

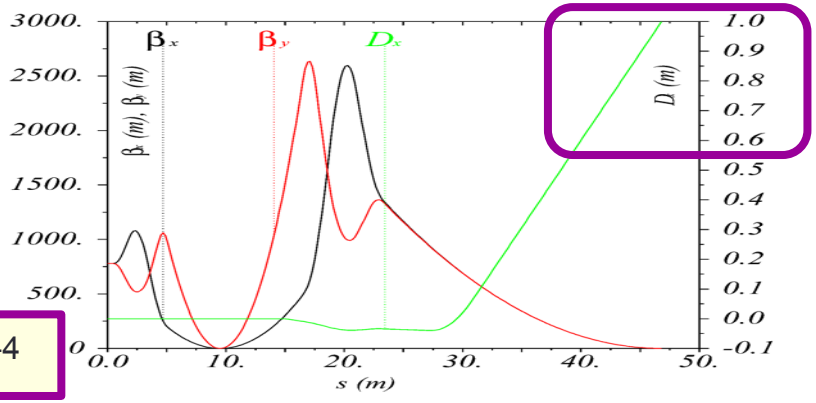




Cartoon of central detector based on dual solenoid a la ILC4 detector, but using the previous iteration interaction region design.

Hadron/Ion detection in 3 stages

- ❑ Endcap with 50 mrad crossing angle
- ❑ Small dipole covering angles to a few degrees
- ❑ Ultra-forward up to one degree, for particles passing accelerator quads



Beamline functions as spectrometer: dp/p < 3×10^{-4}

Detector R&D

An active Generic Detector R&D Program for EIC underway, (supported by DOE, administered by BNL, T. Ullrich):

An external committee of 8 peple reviews all proposals

~140 physicists, 31 institutes (5 Labs, 22 Universities, 9 Non-US Institutions) 15+ detector consortia exploring novel technologies for tracking, particle ID, calorimetry

- à *Weekly meetings, workshops and test beam activities already underway*
- à *https://wiki.bnl.gov/conferences/index.php/EIC_R%25D*
- à *MUCH TO BE DONE… despite many successes….*

Currently the program receives ~$1.3M annually. About to request **increase it to at least two times this amount in near future**, mainly dictated by **doubling of requests** from doubled **national & international requests.**

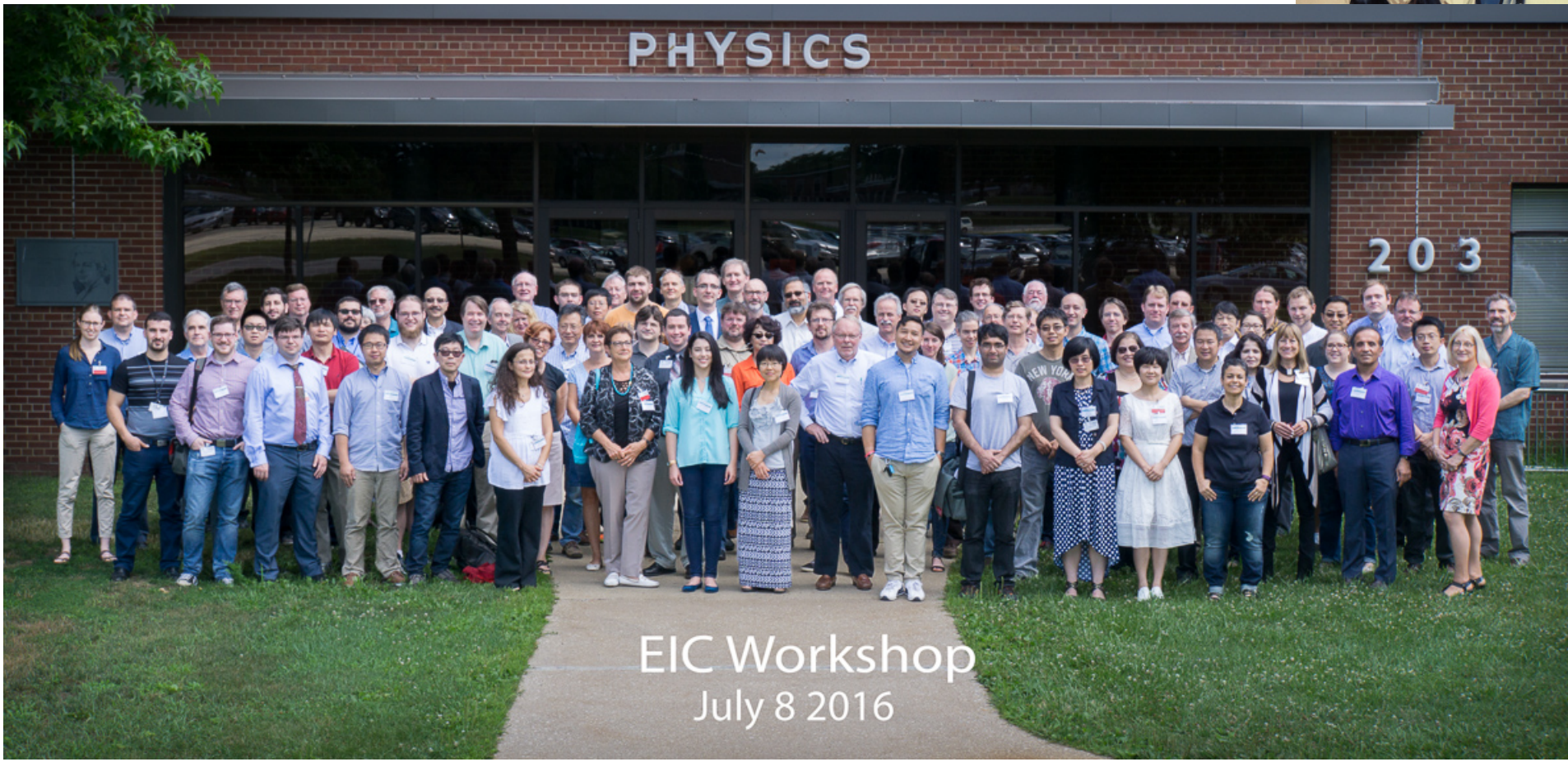
Opportunity for non-US Sources to make an impact!

EICUG Today: 656 Users, 137 Institutes, 27 Countries

355 experimentalists, 111 theorists, 141 accelerator-physicists, 43 unknowns

Community/Collaboration building:

EIC User Group → eicug.org (contact me!)



T. Hallman, Office of NP at the NSAC meeting March 23, 2016

Next Formal Step on the EIC Science Case

THE NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE
Division on Engineering and Physical Science
Board on Physics and Astronomy
U.S.-Based Electron Ion Collider Science Assessment

Summary

The National Academies of Sciences, Engineering, and Medicine ("National Academies") will form a committee to carry out a thorough, independent assessment of the scientific justification for a U.S. domestic electron ion collider facility. In preparing its report, the committee will address the role that such a facility would play in the future of nuclear science, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics. The need for such an accelerator will be addressed in the context of international efforts in this area. Support for the 18-month project in the amount of $540,000 is requested from the Department of Energy.

Mail reviews received; proposal approved for funding in PAMS; PR package in PAMS being processed.

Progress is also being made on a second Joint NAS study on Space Radiation Effects Testing

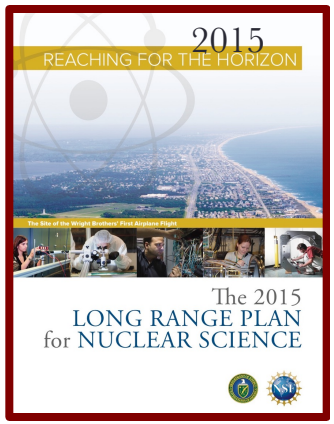
Charge to the National Academy for the review of EIC (2016) (my rendition of the charge to fit on 1 slide)

The committee will assess the scientific justification for a U.S. domestic electron ion collider facility

In particular, the committee will address the following questions:

- What is the merit and significance of the science? What is its importance in the overall context of research in nuclear physics and the physical sciences in general?
- Capabilities of other facilities, existing and planned, domestic and abroad? What would be the unique scientific role of the US EIC complementary to existing and planned facilities?
- What are the benefits to (US) leadership in nuclear physics?
- What are the benefits to other fields of science and to society?

INT Program 2010 → EIC in the LRP2015



- 2010 INT workshop on the Science of EIC critical to making the case in the 2015 LRP. (500+ page document, 150+ participants and 500+ authors) : **arXiv:1108.1713**, D. Boer et al.

- Next LRP in ~2020, just before EIC Construction begins.
- We have already started preparing for this, through the ***EIC Users Group***, with the support of BNL and Jefferson Lab

INT Program Approved: 2018

A 7-week program "Probing Nucleons and Nuclei in High Energy Collisions" dedicated to the **physics of the Electron Ion Collider has been approved by the Institute for Nuclear Theory** in Seattle with the tentative dates of **October 1 - November 16, 2018**. The topics to be covered include Spin and Three-Dimensional Structure of the Nucleon (GPDs, TMDs, longitudinal spin) and QCD in a Nucleus (small-x physics and saturation, connections to heavy ions, large-x physics in a nucleus).

The program organizers will be Yoshitaka Hatta, **Yuri Kovchegov**, Cyrille Marquet, and Alexei Prokudin. They plan to have ample discussion time and lectures aimed at young researchers. Both **theorists and experimentalists** are welcome to participate in the program. Young researchers, women and underrepresented minorities are strongly encouraged to apply.

Path forward for the EIC:

- Science Review by National Academy of Science (& Engineering & Arts) (National Research Council)

- Positive NAS review will trigger the DOE's CD process
  - CD0 (acceptance of the critical need for science by DOE) FY18
  - EIC-Proposal's Technical & Cost review → FY19 (site selection)
  - CD2 requires site selection
  - Major Construction funds ("CD3") by 2022/23"
  - Assuming 1.6% sustained increase over inflation of the next several years (Long Range Plan)

Assumption: "Modest Growth" ➔ 1.6% growth/year above constant effort

The 2015 Long Range Plan for Nuclear Science

Not much time!

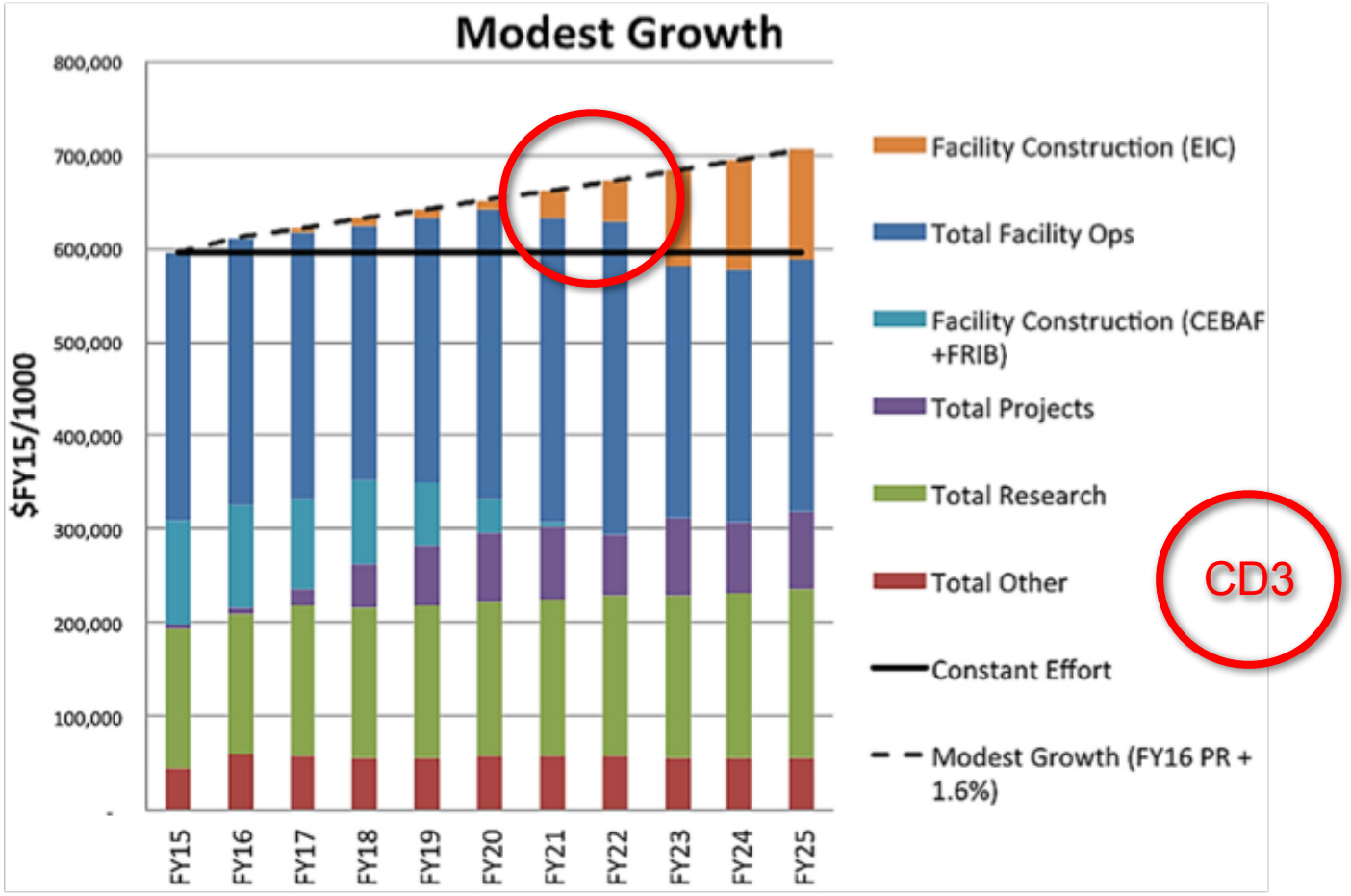


Figure 10.4: DOE budget in FY 2015 dollars for the Modest Growth scenario.

Summary:

The EIC (with its precision and control) will profoundly impact our understanding of **the many body structure of nucleons and nuclei in terms of sea quarks & gluons** → ***The bridge between sea quark/gluons to Nuclei***

The EIC will enable **IMAGES** of **yet unexplored regions of phase spaces in QCD** with its high luminosity/energy, nuclei & beam polarization
→ ***High potential for discovery***

Outstanding questions raised by world wide experiments at CERN, BNL and Jeff Lab, have **naturally led us to the science and design parameters of the EIC: World wide interest and opportunity** in collaborating on the EIC

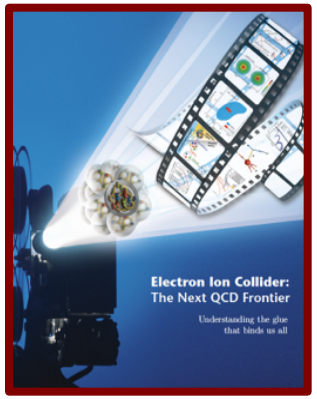
Accelerator scientists at RHIC, Jlab in collaboration with **many from outside accelerator experts** will provide the **intellectual and technical leadership for to realize the EIC** -- *a frontier accelerator facility.*

Future QCD studies, particularly for Gluons, demands an Electron Ion Collider

NSAC agrees and we are moving forward!

THANK YOU

Thanks to many of my EIC Collaborators and Enthusiasts who led many of the studies presented in this talk
See: arXiv:1108.1713, D. Boer et al.



Without the EIC White Paper Writing Group the EIC White Paper would not have existed.
Special thanks to Dr. Jianwei Qiu and Prof. Zein-Eddine Meziani, my Co-Editors for the EIC White Paper
See: arXiv:1212.1701.v3 , A. Accardi et al.
Eur. Phy. J. A 52, 9 (2016)

The eRHIC and JLEIC machine design teams

Also gratefully acknowledge recent input from: M. Diefenthaler, R. Yoshida