Studying the Glue that binds us all at e-RHIC

Berndt Mueller
Associate Laboratory Director
for Nuclear and Particle Physics
BNL

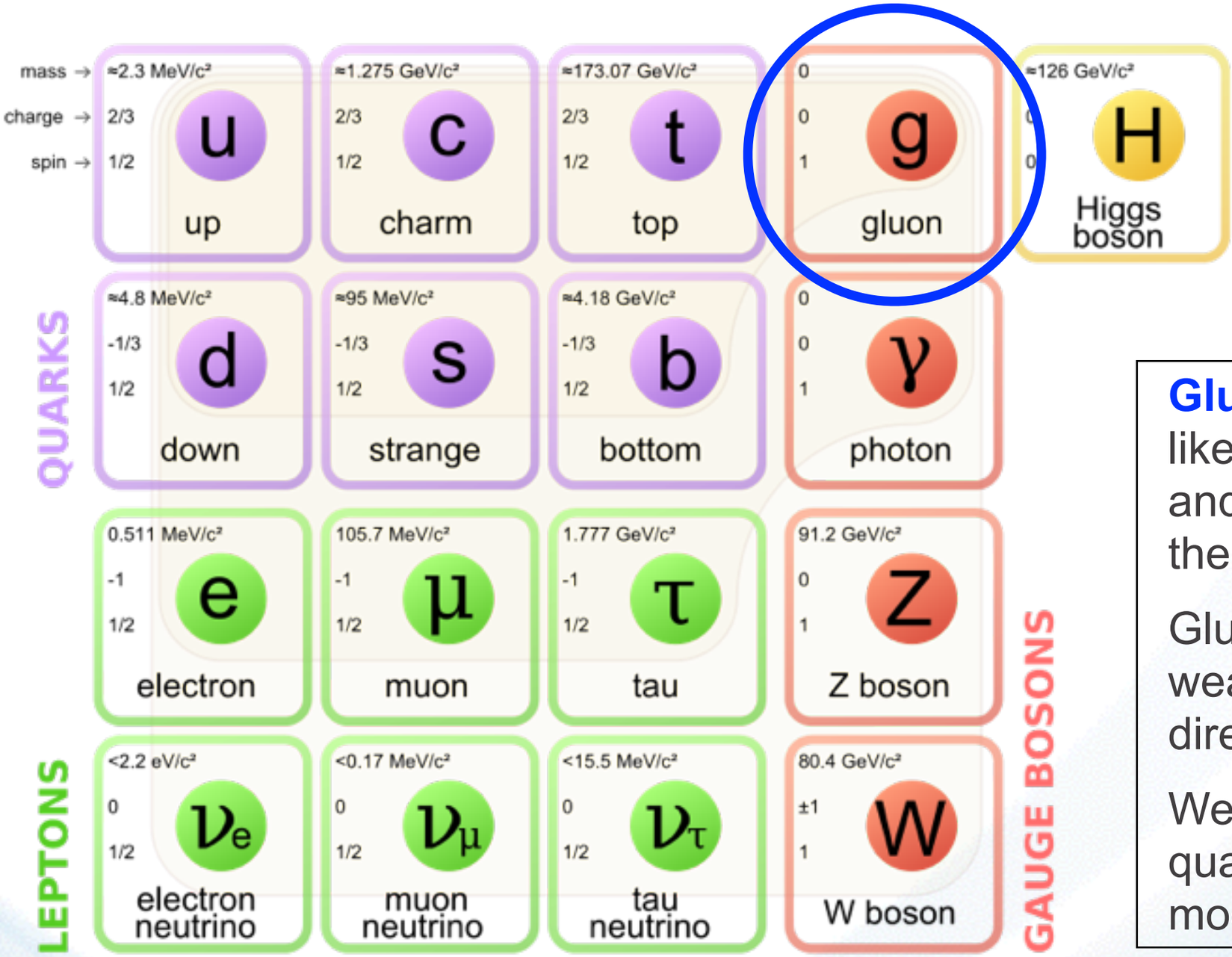
Community Action Council
11 December 2014

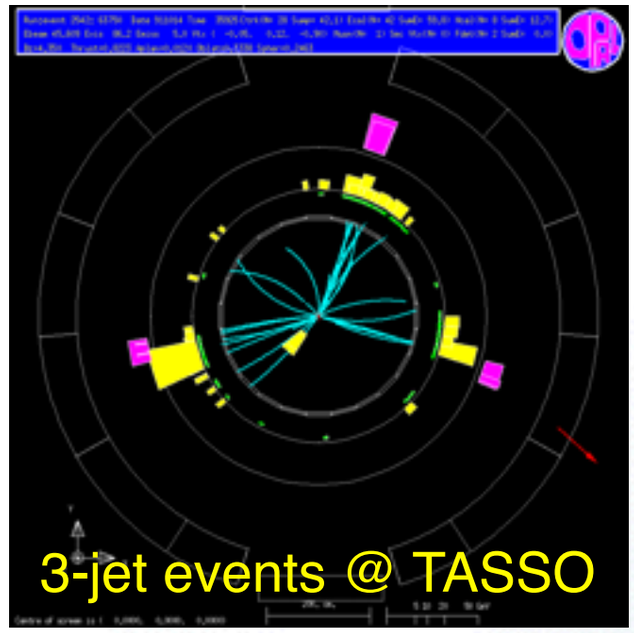
BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

The Mysterious Gluon

Standard Model particles





Gluons are **gauge bosons** like **photons** [massless (?) and spin 1], but they carry the SU(3) **color** charge.

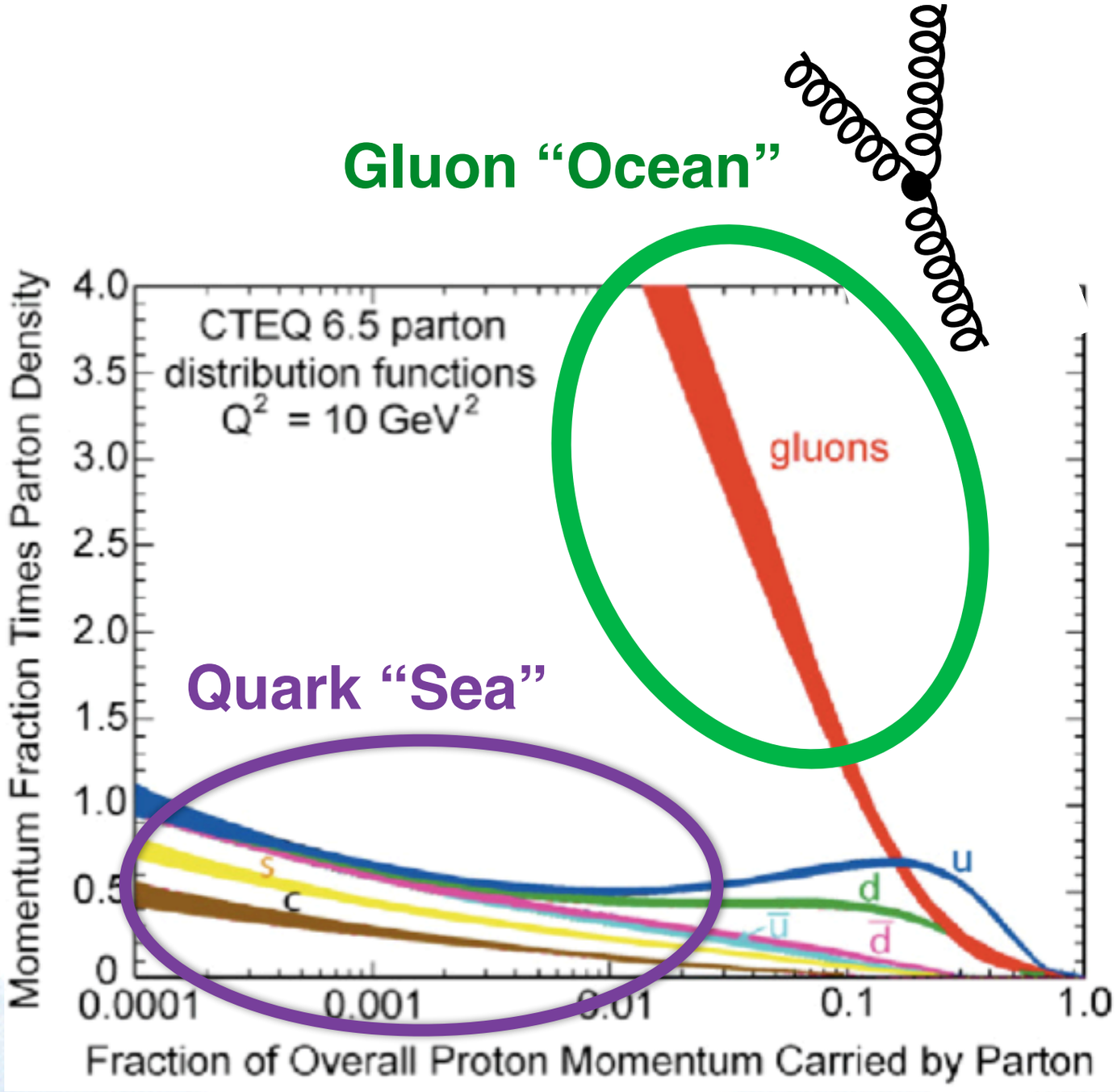
Gluons carry no electric or weak charge - they cannot directly interact with photons.

We know their coupling to quarks and self-coupling with moderate precision.

Gluons are weird particles

- Gluons, like quarks, never occur in isolation.
- So far, gluons have only been observed as short-lived, virtual quanta.
- States solely made of gluons (“glueballs”) should exist, but have never been unambiguously identified.
- Free space without glue fields is unstable against the spontaneous formation of chromo-magnetic fields.
- We are constantly immersed in a gluon condensate, similar to the Higgs condensate: $\langle G^2 \rangle^{1/4} \approx 0.6$ GeV.
- The detailed structure of the gluon condensate and the mechanism by which it creates quark confinement is still unknown - many different models compete.

Gluon Ocean and Quark Sea

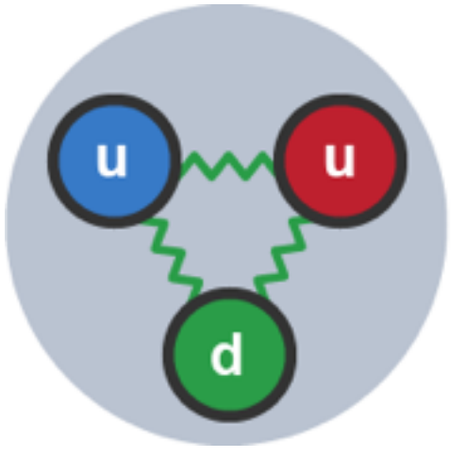


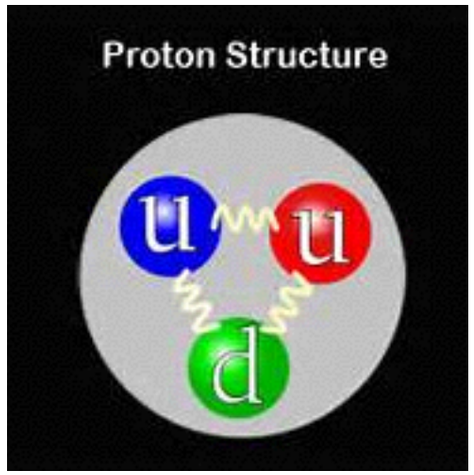
Quark Sea derives from Gluon Ocean via gluon splitting into a quark-antiquark pair: suppressed by factor $\alpha s/\pi$.

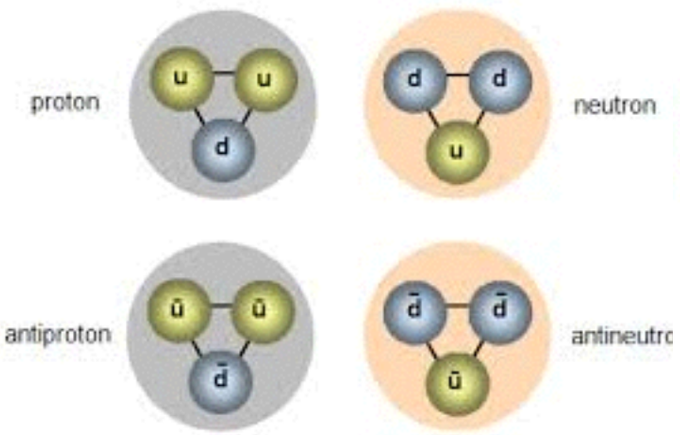
Clean separation from valence quarks requires experiments probing $x < 0.01$, or nucleon energies of order 100 GeV.

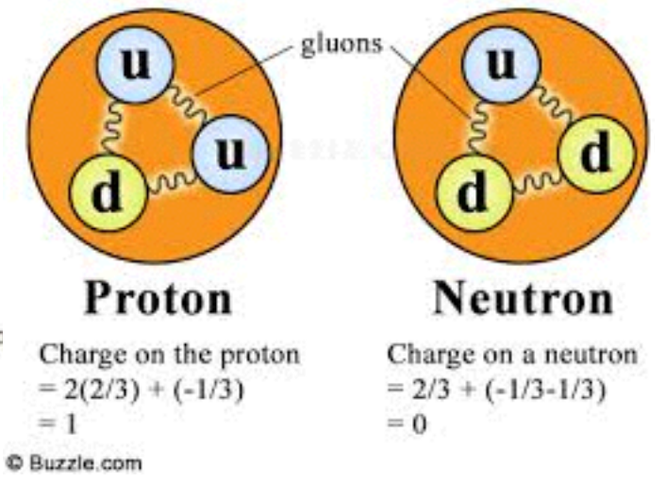
RHIC provides polarized protons of up to 255 GeV and nuclei up to uranium up 100 A GeV.

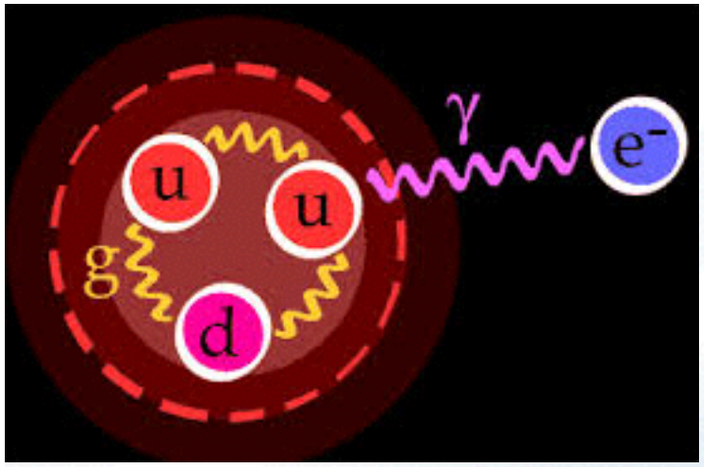
Where are the gluons?



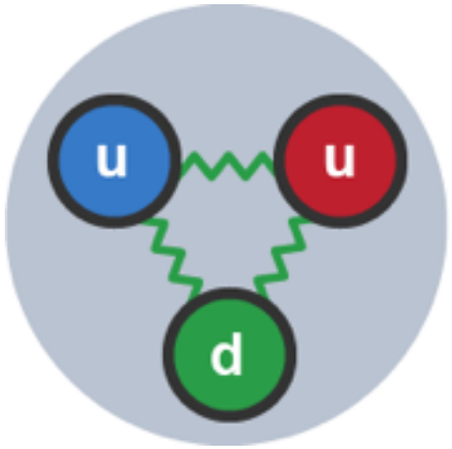


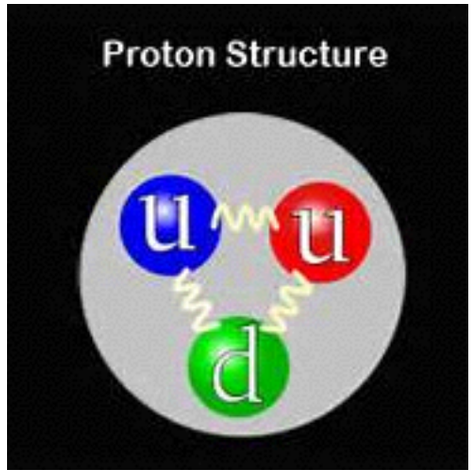


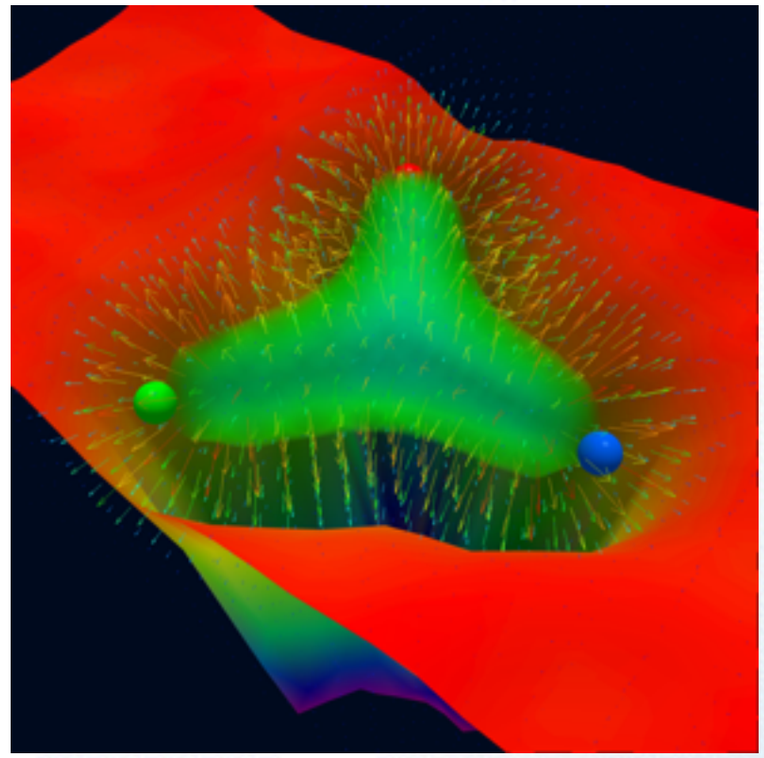




Where are the gluons?

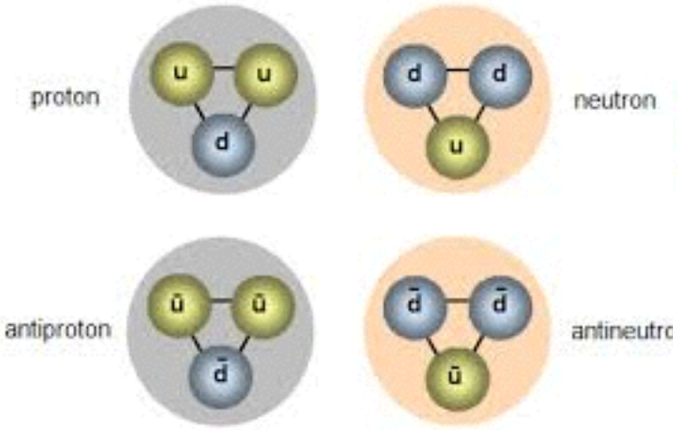


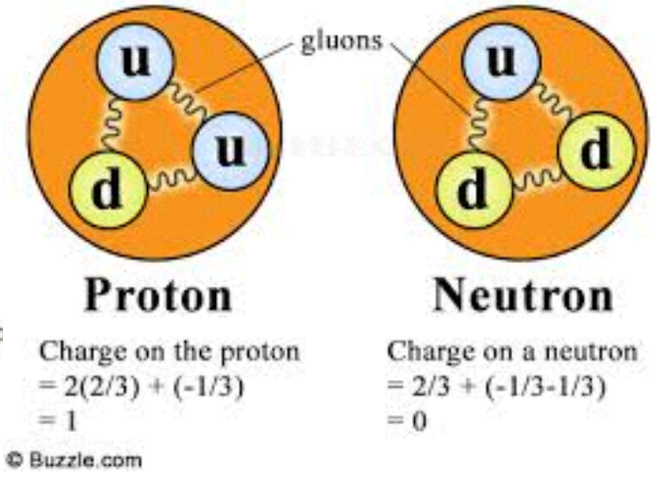


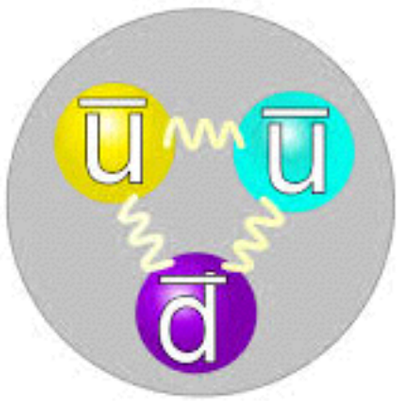


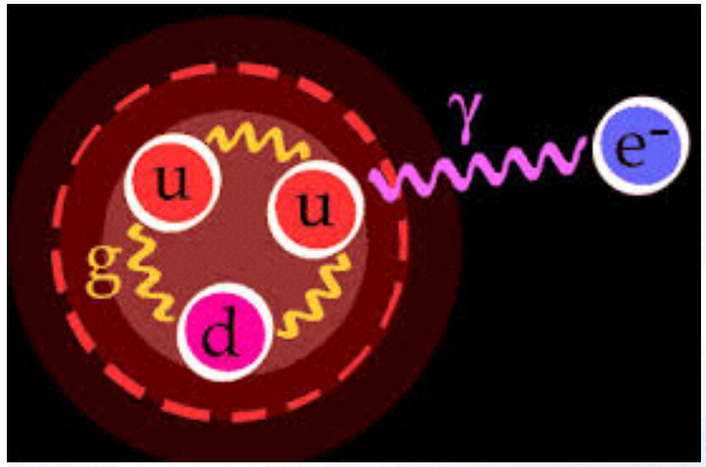
Lattice simulation with artificially frozen quarks

D. Leinweber (Adelaide)





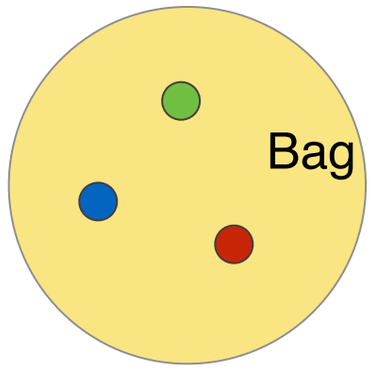




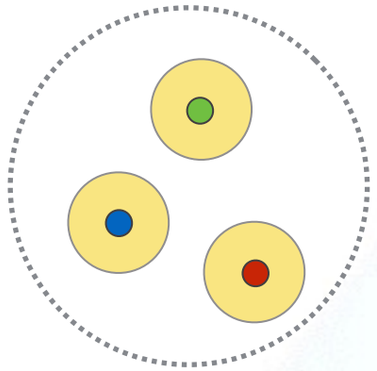
BROOKHAVEN NATIONAL LABORATORY

Where are the gluons?

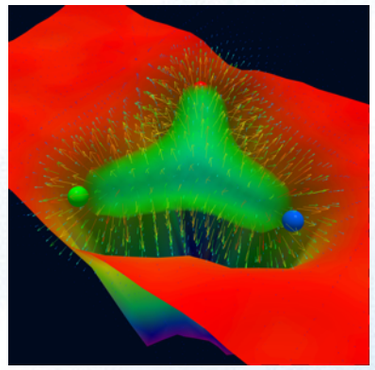
- Bag model:
  - Field energy distribution is wider than the distribution of fast moving light quarks



- Constituent quark model:
  - Gluons and sea quarks “hide” inside massive quarks
  - Sea parton distribution similar to valence quark distribution

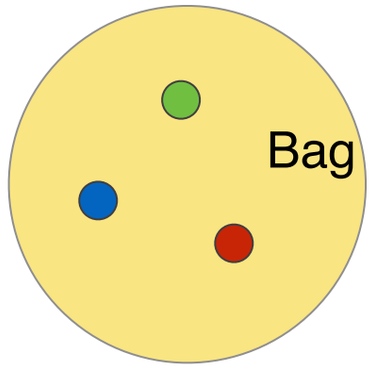


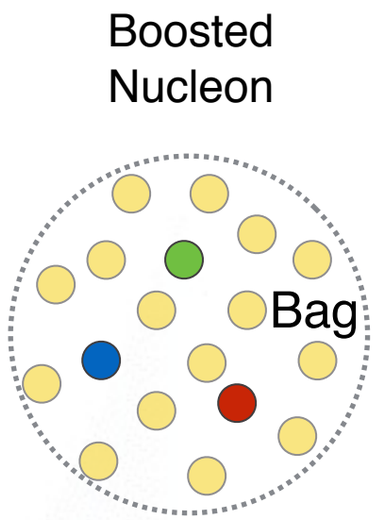
- Lattice gauge theory:
  - (with slow moving quarks)
  - gluons are more concentrated than quarks



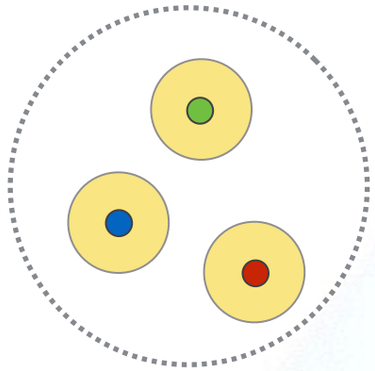
Where are the gluons?

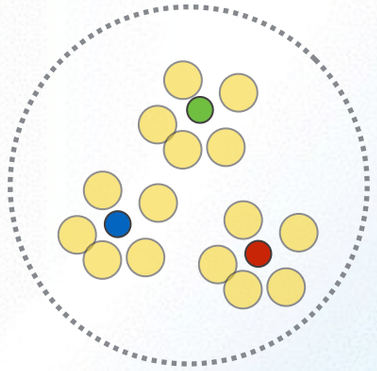
- Bag model:
  - Field energy distribution is wider than the distribution of fast moving light quarks



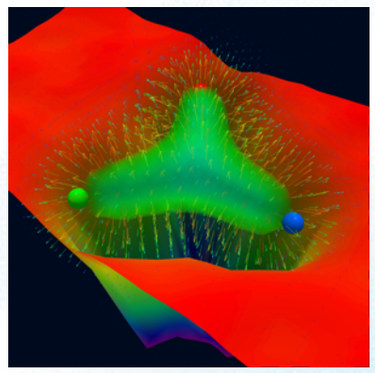


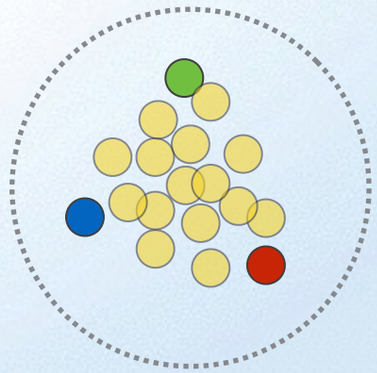
- Constituent quark model:
  - Gluons and sea quarks “hide” inside massive quarks
  - Sea parton distribution similar to valence quark distribution





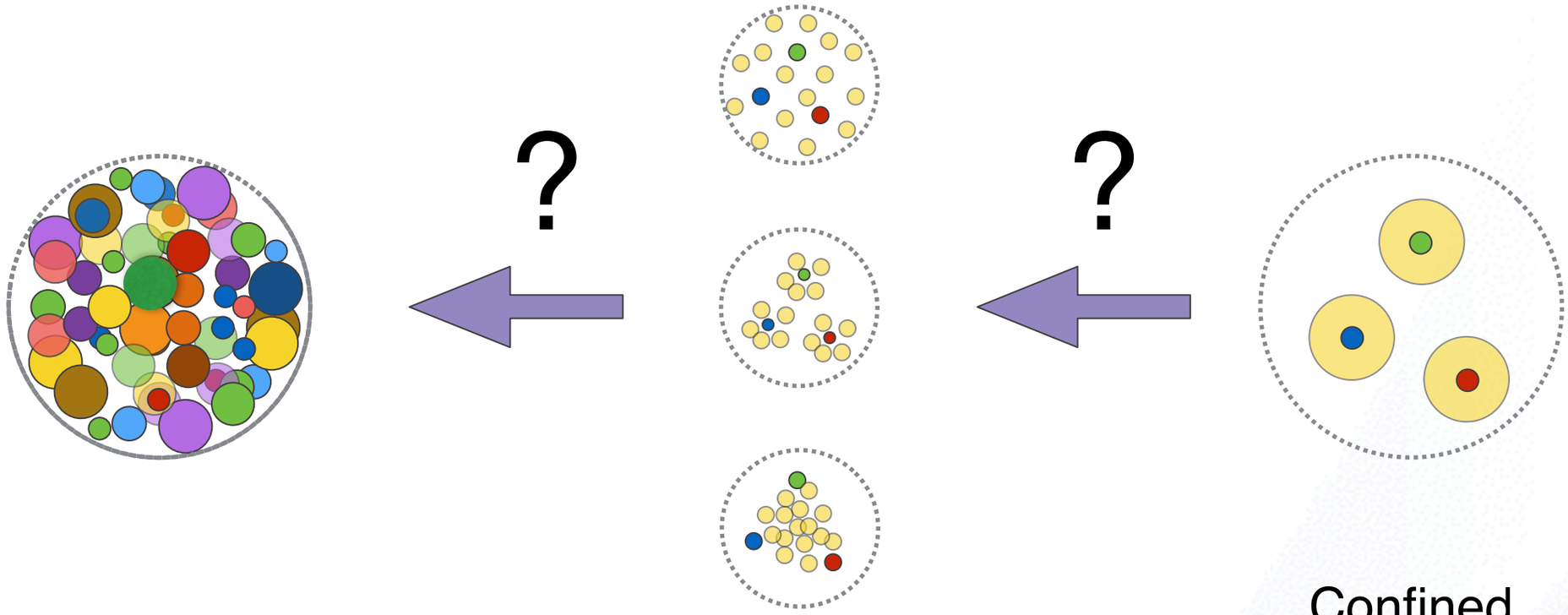
- Lattice gauge theory:
  - (with slow moving quarks)
  - gluons are more concentrated than quarks





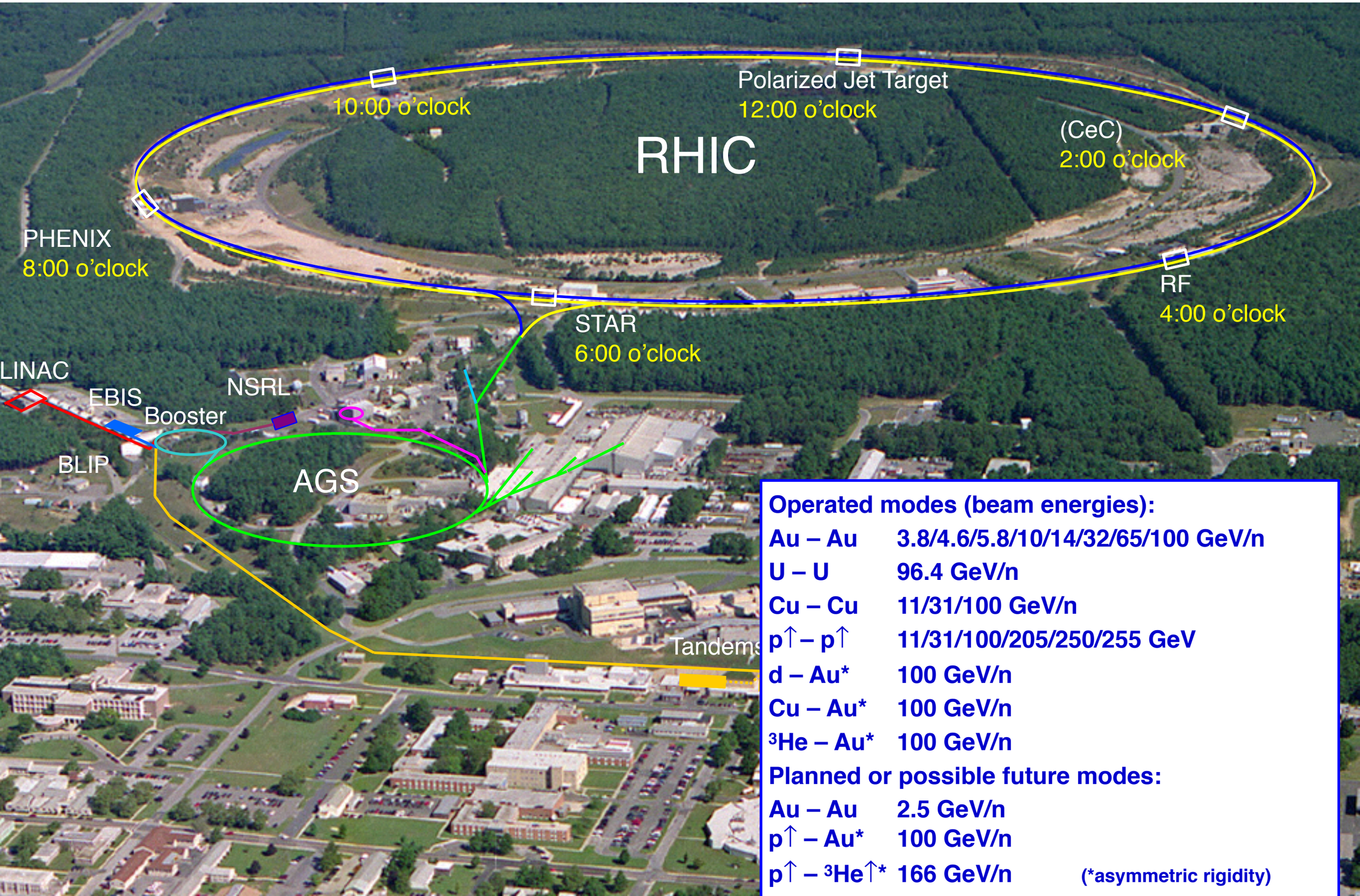
Partons at Q^2 ~ few GeV^2

Partons at Q^2 ~ few GeV^2



Intermezzo: RHIC

RHIC – a High Luminosity Proton & Nucleus Collider



Operated modes (beam energies):

Au – Au	**3.8/4.6/5.8/10/14/32/65/100 GeV/n**
U – U	**96.4 GeV/n**
Cu – Cu	**11/31/100 GeV/n**
$p^{\uparrow} - p^{\uparrow}$	**11/31/100/205/250/255 GeV**
d – Au*	**100 GeV/n**
Cu – Au*	**100 GeV/n**
^{3}He – Au*	**100 GeV/n**

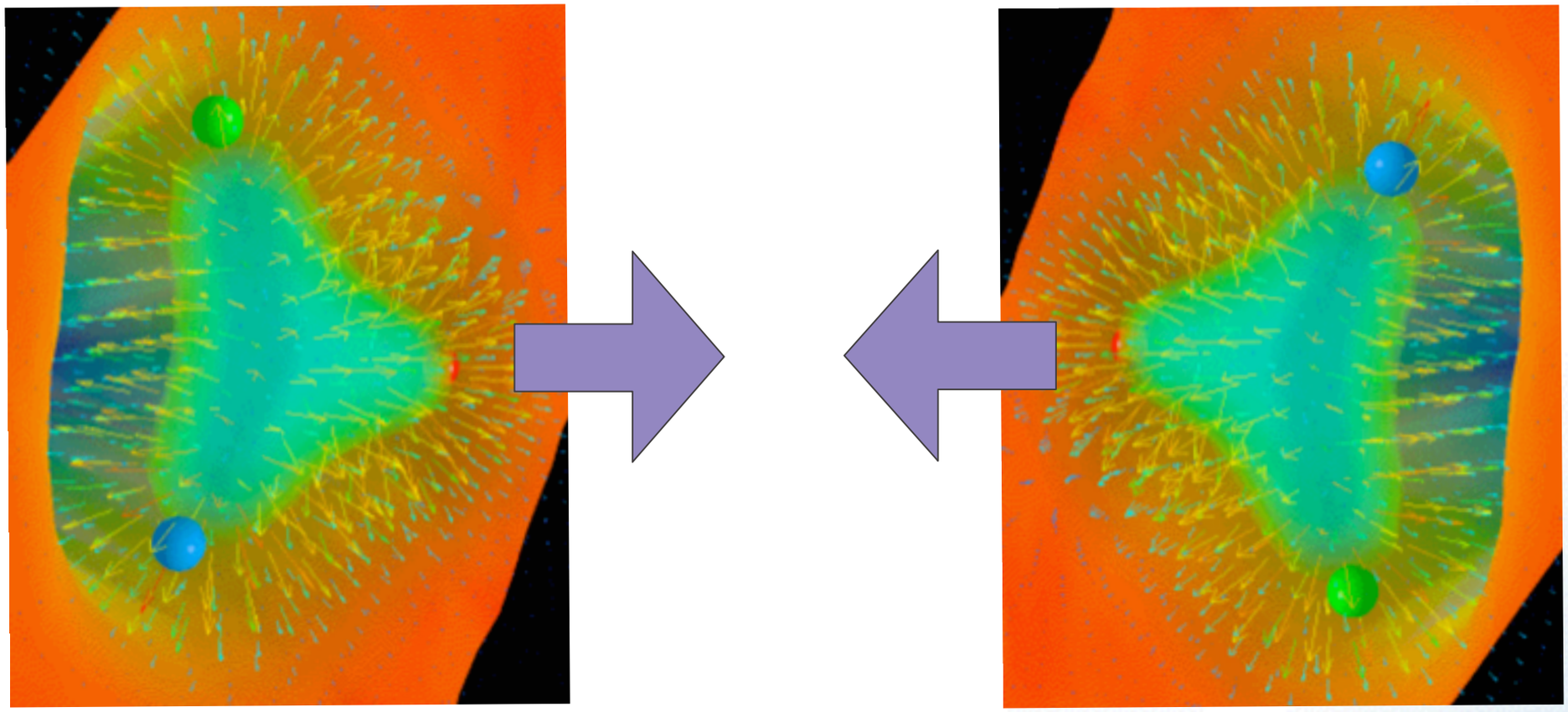
Planned or possible future modes:

Au – Au	**2.5 GeV/n**
$p^{\uparrow}$ – Au*	**100 GeV/n**
$p^{\uparrow} - {}^3He^{\uparrow}$*	**166 GeV/n**

(*asymmetric rigidity)

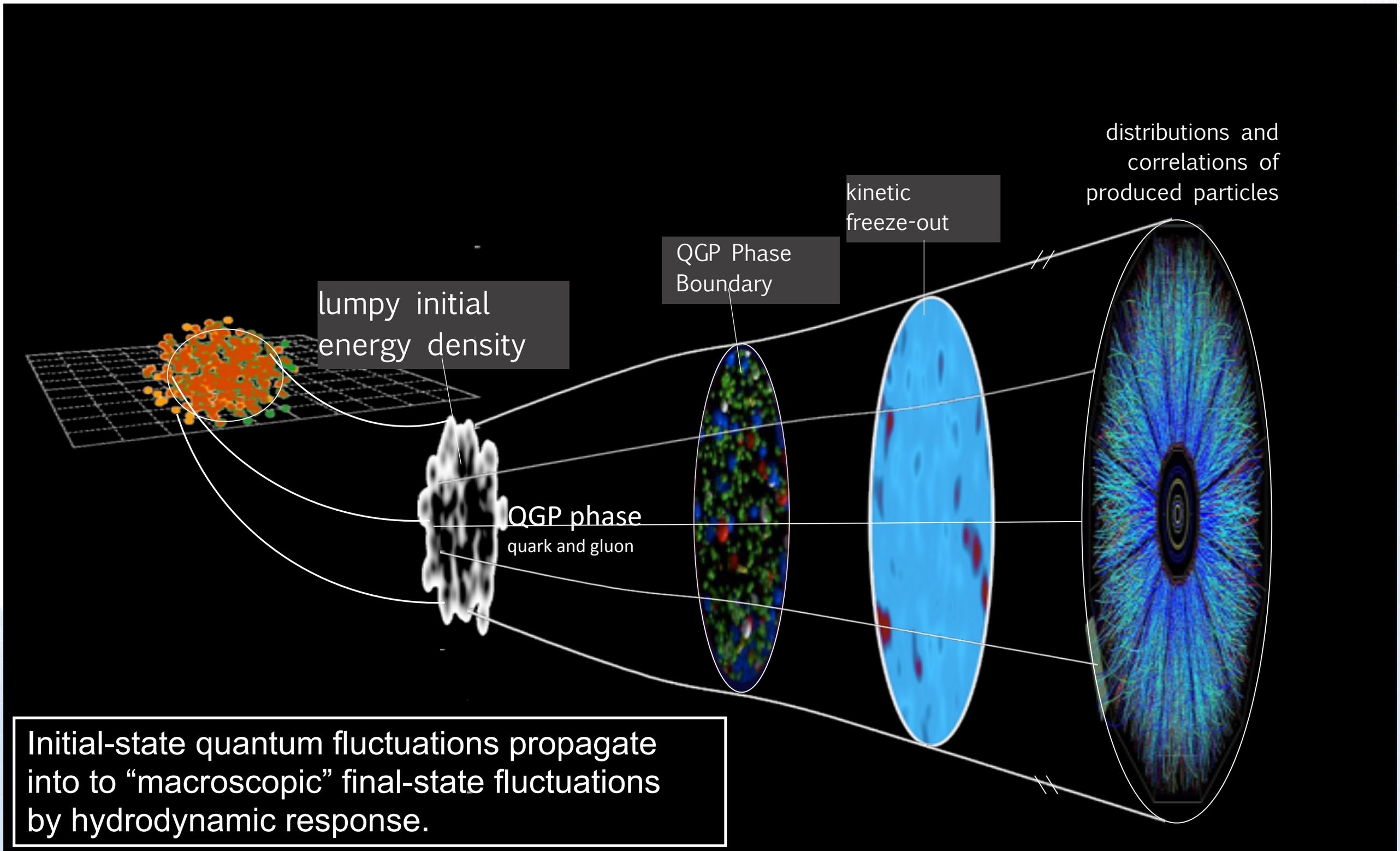
Melting the QCD vacuum

What RHIC does:



RHIC collides many nucleons (as atomic nuclei) and thereby liberates the gluons into a highly excited state (“glasma”) that thermalizes into a quark-gluon plasma.

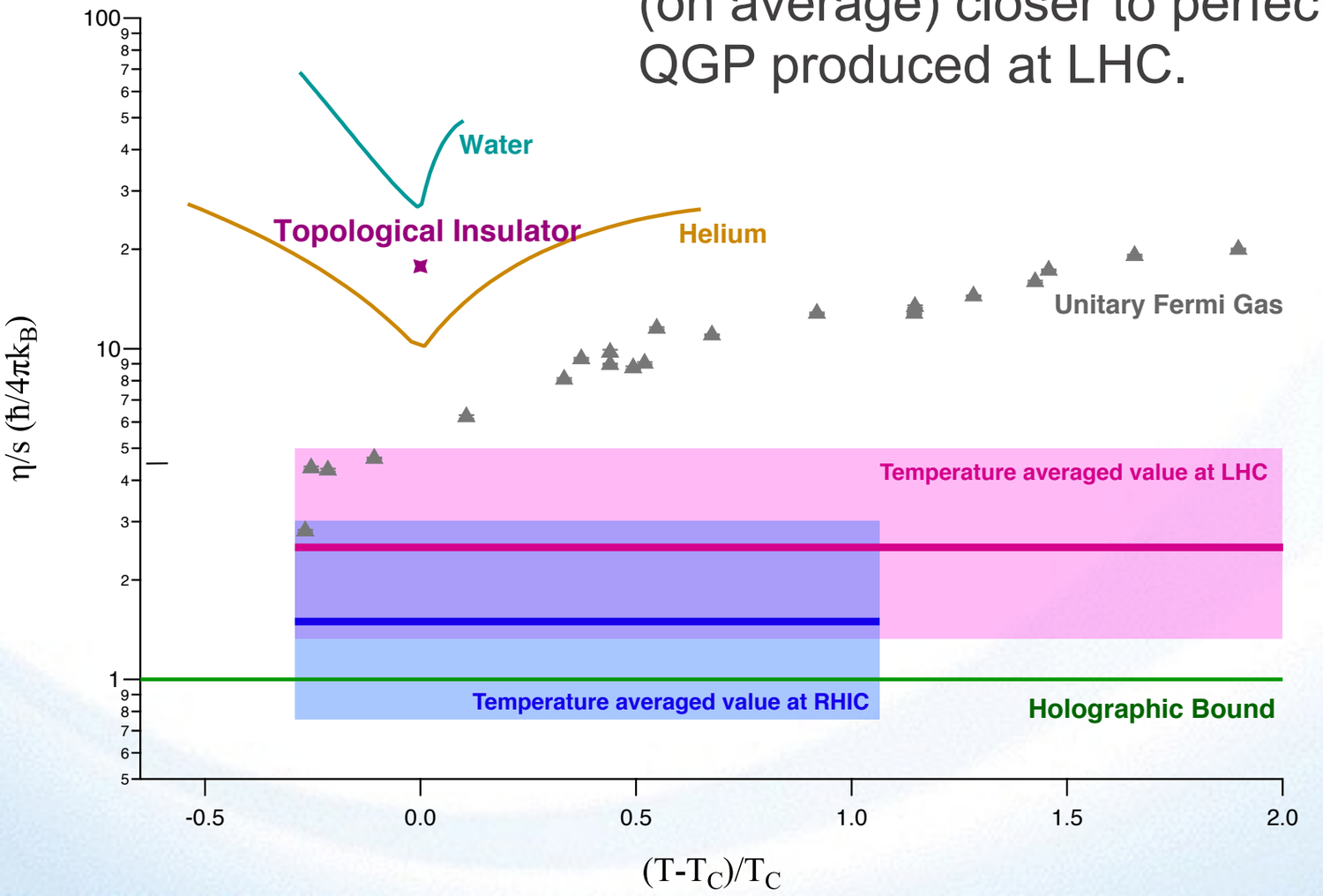
The “Little Bang” at RHIC



Initial-state quantum fluctuations propagate into to “macroscopic” final-state fluctuations by hydrodynamic response.

Hot glue is a “perfect” fluid

- Hot matter produced in collisions at RHIC/LHC is a **liquid** quark-gluon plasma (QGP). The plasma is made up of individually flowing gluons and quarks, not quarks bound into baryons and mesons.
- The QGP is a strongly coupled nearly “**perfect**” liquid (η/s near the quantum limit 1/4π). RHIC’s cooler QGP is (on average) closer to perfection than the 40% hotter QGP produced at LHC.



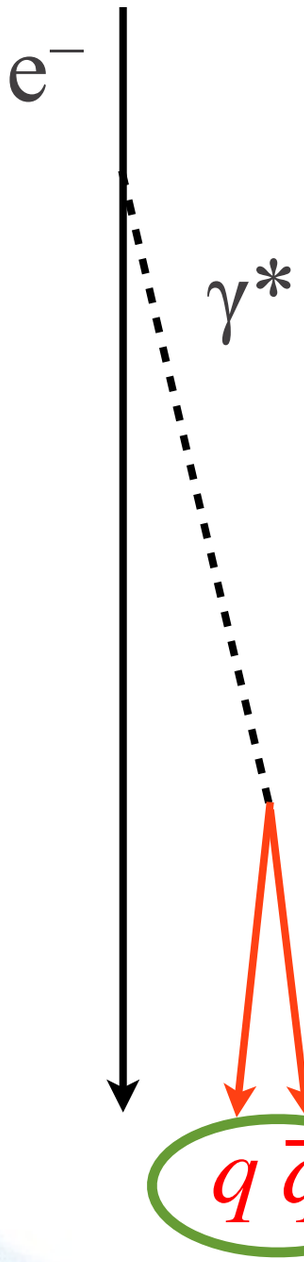
From nuclei to QGP - How?

Is the relevant component of the nuclear wave function that turns into a quark-gluon plasma when nuclei collide a weakly coupled color glass condensate?
Or is it generated by the decoherence of strongly coupled gluon fields surrounding colliding valence quarks?
Or is something more akin to the 4-D shadow of a 5-D gravitational shock wave?

The Electron-Ion Collider:

A Microscope for Gluons

EIC: A color dipole microscope



Color dipole "sees" gluons

Free color charges (quarks, gluons) do not exist, but color dipoles do! Virtual photons are a good source.

Two resolution scales:

- momentum k (longitudinal)
- virtuality Q (transverse)

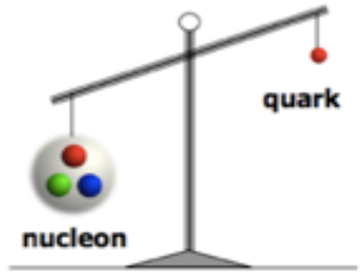
⇒ More powerful than an optical microscope!

HERA was the 1st generation color dipole microscope.

Limited intensity and no polarization.

The EIC will be the 2nd generation color dipole microscope!

Proton mass and spin



m_q ~ 10 MeV

m_N ~ 1000 MeV

- **Proton mass puzzle:**

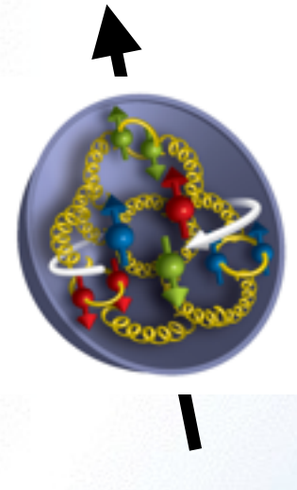
  Quarks carry ~1% of the proton's mass

  How does glue dynamics generate the energy for the nucleon mass?

- **Proton spin puzzle:**

  Quarks carry only ~30% of the proton's spin

  How does quark and gluon dynamics generate the rest of the proton's spin?



- **3D structure of nucleon:**

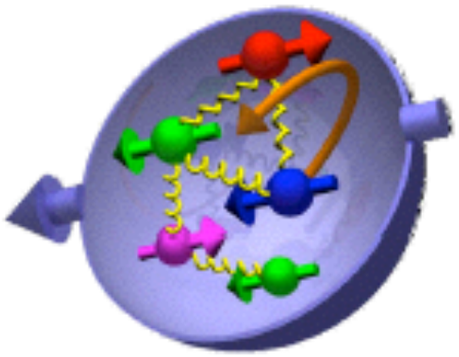
Color Confinement — **Asymptotic freedom**

200 MeV (1 fm) — 2 GeV (1/10) fm — Q (GeV) Probing momentum

How does the glue bind quarks and itself into a proton and nuclei?

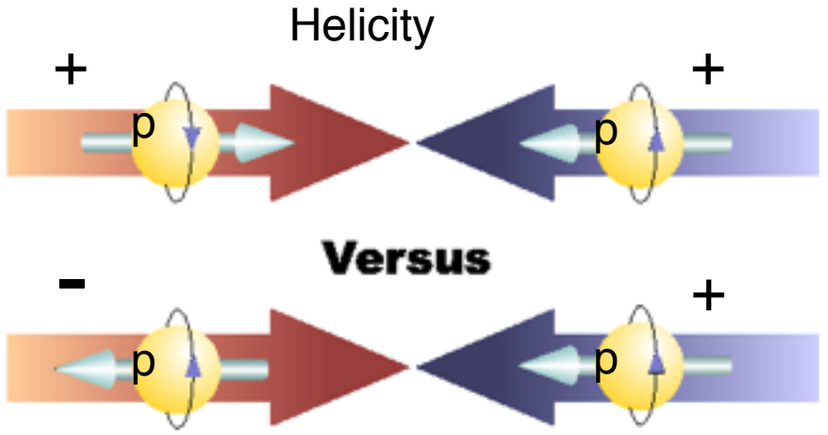
Can we scan the nucleon to reveal its 3D structure?

Where is the proton spin?

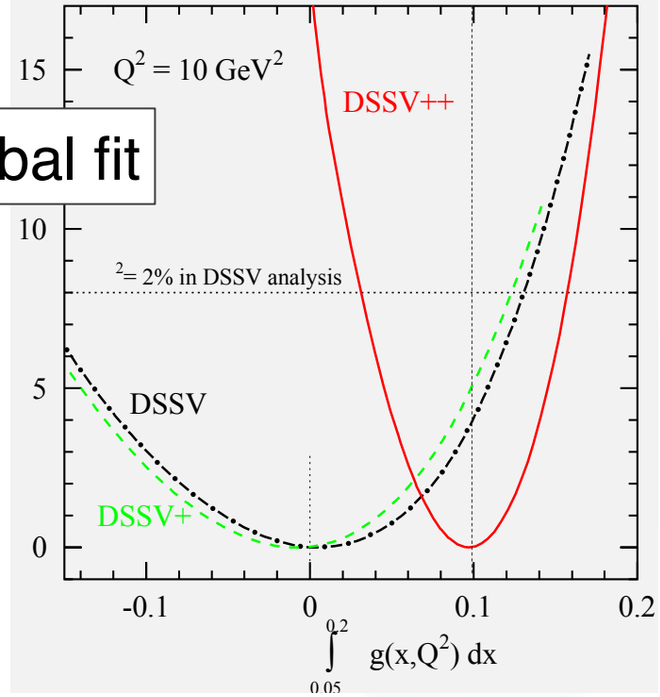


$$S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

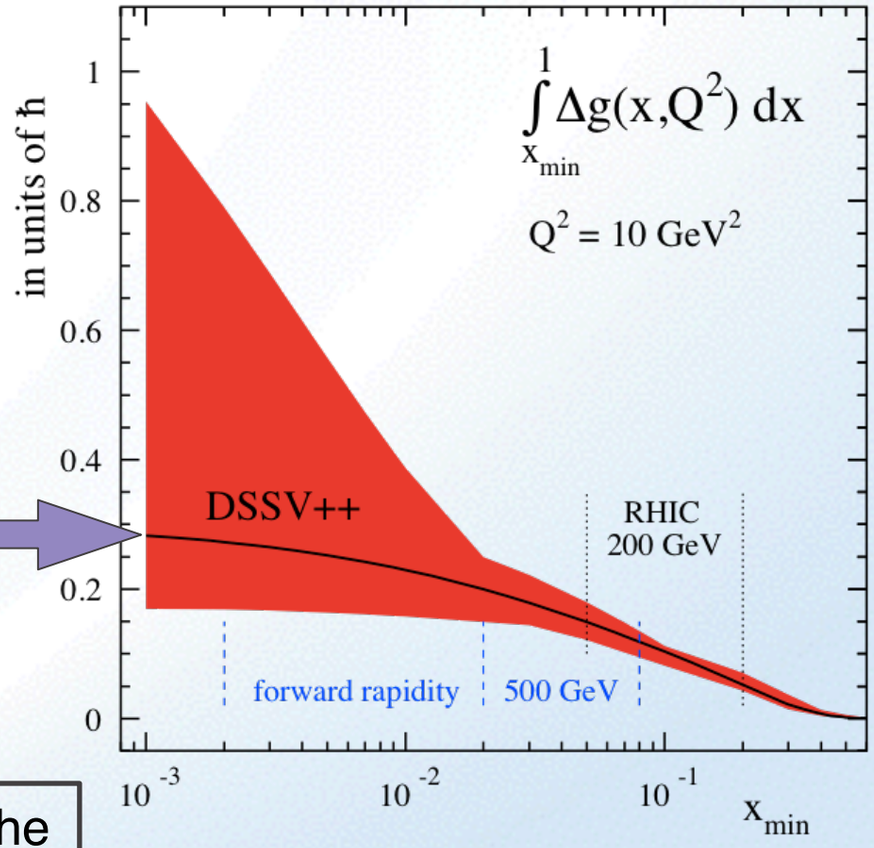
$$\Delta G = \int_0^1 \Delta g(x)\,dx$$



QCD global fit



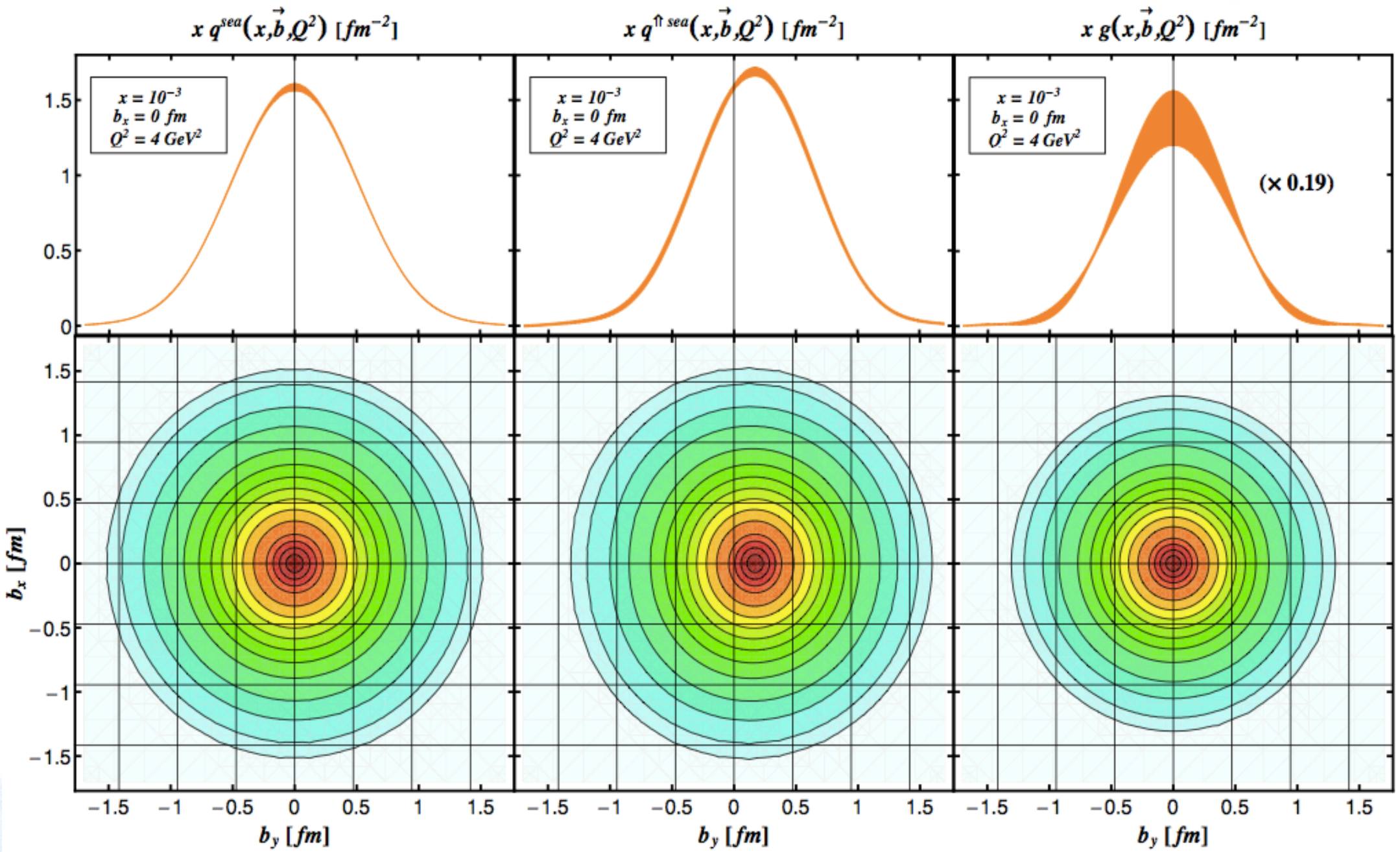
$$\int_{0.05}^{0.2} \Delta g(x)\,dx = 0.1 \pm^{0.06}_{0.07}$$



~60% of the proton spin?

Imaging quarks and gluons

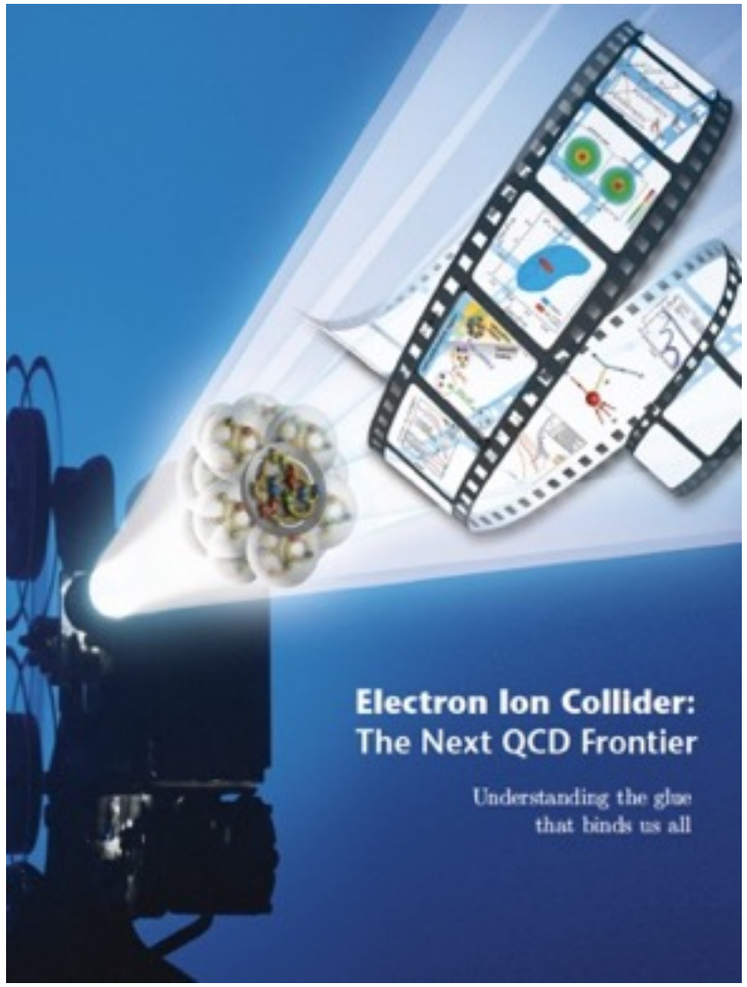
using Generalized Parton Distributions (GPD's):



eRHIC:

EIC @ BNL

EIC - Why now?



EIC White Paper
(arXiv:1212.1701)
to be updated soon

Why now?

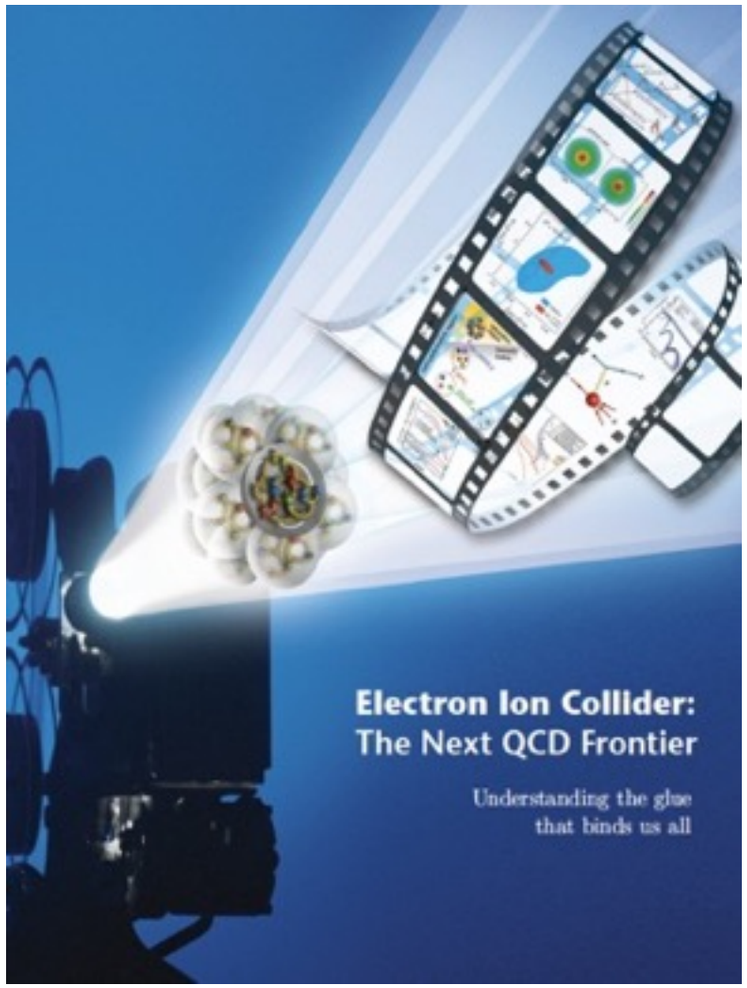
A set of **compelling physics questions** has been formulated.

A set of **measurements** has been identified that can **provide answers** to many of the open questions about the gluon structure of the proton and of nuclei.

A **powerful formalism** has been developed over the past decade that connects measurable observables to rigorously defined properties of the QCD structure of nucleons and nuclei.

Accelerator technology has reached a state where a capable EIC can be constructed at an affordable cost.

EIC - Why now?



Why now?

A set of **compelling physics questions** has been formulated.

A set of **measurements** has been identified that can **provide answers** to many of the open questions about the gluon structure of the proton and of nuclei.

A **powerful formalism** has been developed over the past decade that connects measurable observables to rigorously defined properties of the QCD structure of nucleons and nuclei.

Accelerator technology has reached a state where a capable EIC can be constructed at an affordable cost.

EIC White Paper
(arXiv:1212.1701)
to be updated soon

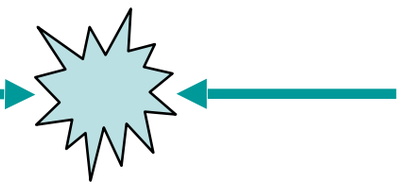
Nuclear Science needs an EIC.
The U.S. should lead the way.

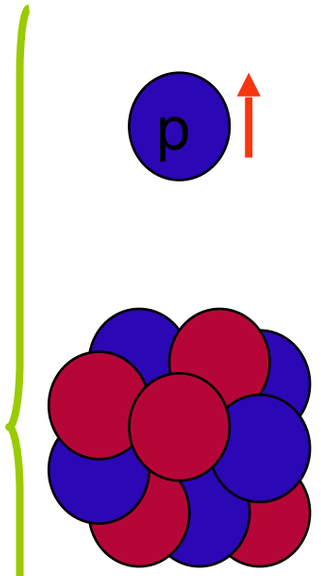
eRHIC: Electron Ion Collider at BNL

Add an electron accelerator to the existing $2.5B RHIC including existing RHIC tunnel and cryo facility

Luminosity:
$10^{33} – 10^{34}$ cm^{-2} s^{-1}

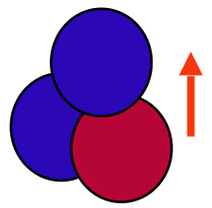
80% polarized electrons:
6.6 – 21.2 GeV





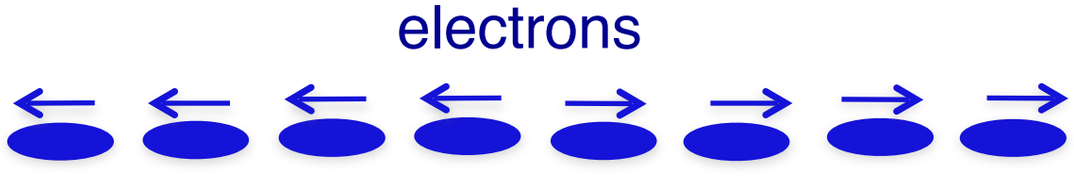
70% polarized protons
25 - 250 (275*) GeV

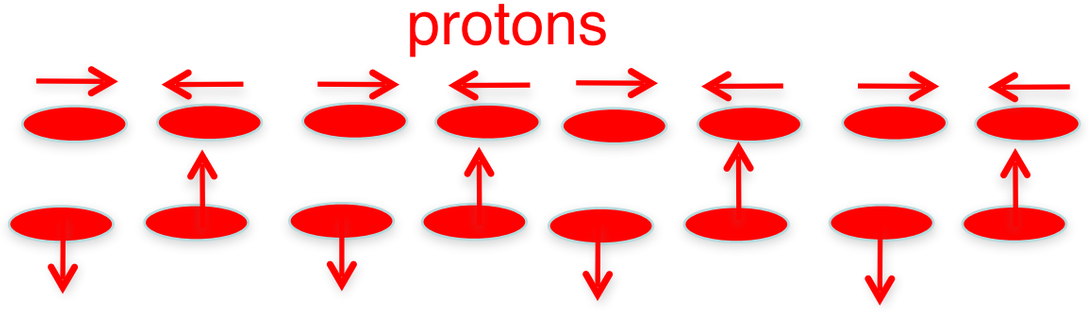
Light ions (d, Si, Cu)
Heavy ions (Au, U)
10 - 100 (110*) GeV/u



Pol. light ions (He-3)
17 - 167 (184*) GeV/u

- Center-of-mass energy range: 30 – 145 GeV
- Full electron polarization at all energies
  Full proton and He-3 polarization with six Siberian snakes
- Any polarization direction in electron-hadron collisions:



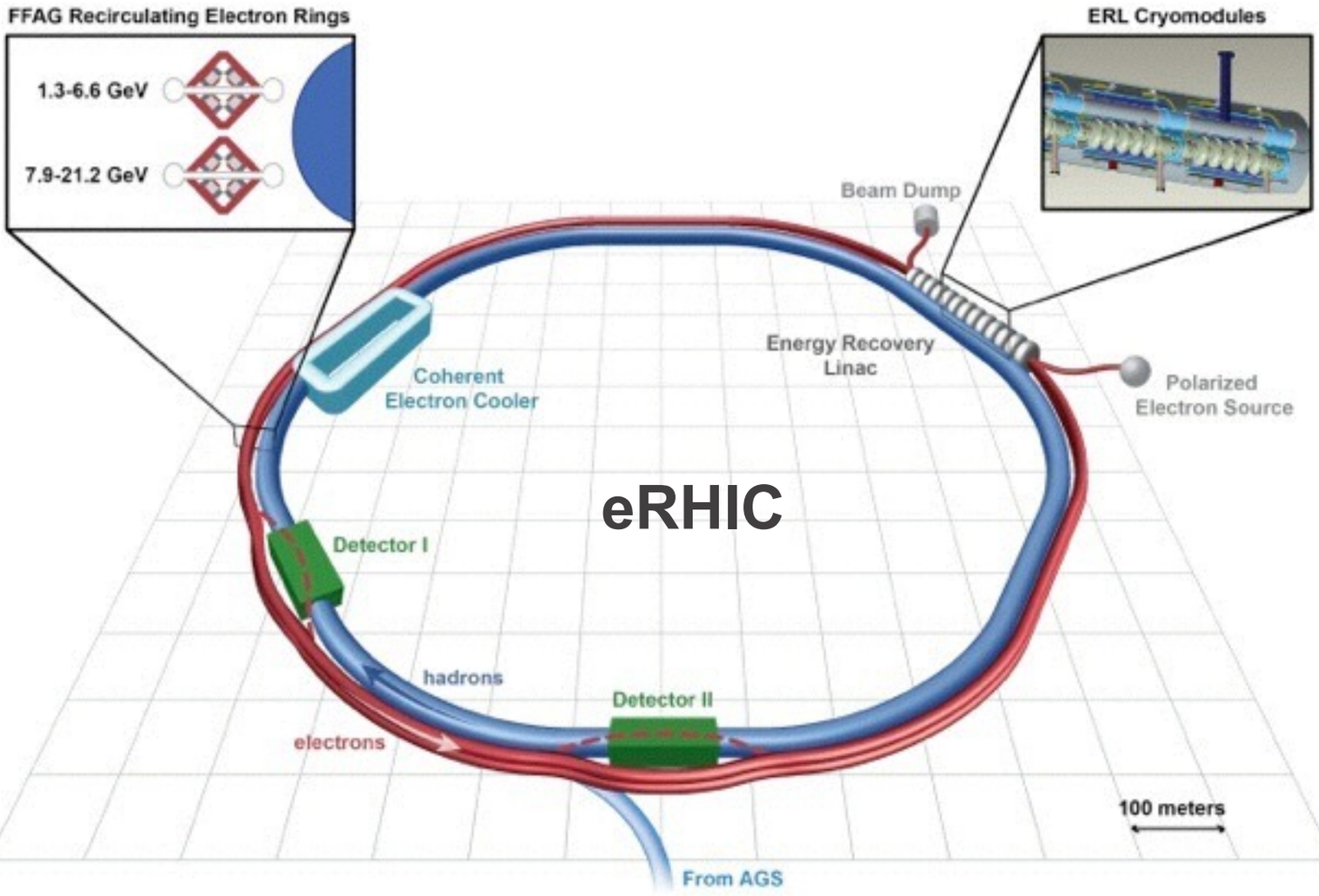


* It is possible to increase RHIC ring energy by 10%

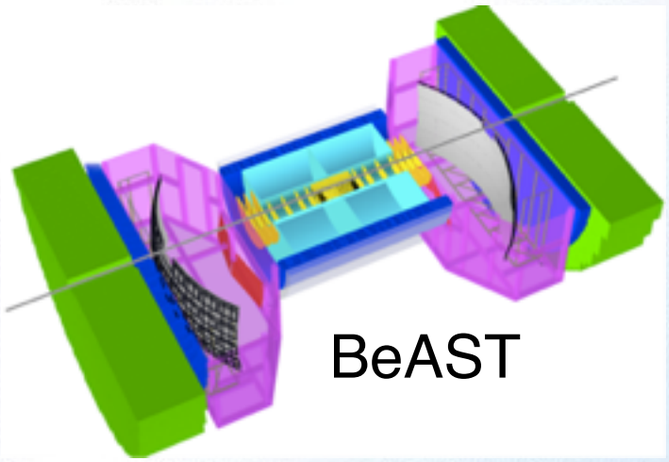
eRHIC Design

eRHIC ERL + FFAG ring design @ $10^{33}/cm^2s$

21.2 GeV e^- + 255 GeV p or 100 GeV/u Au.



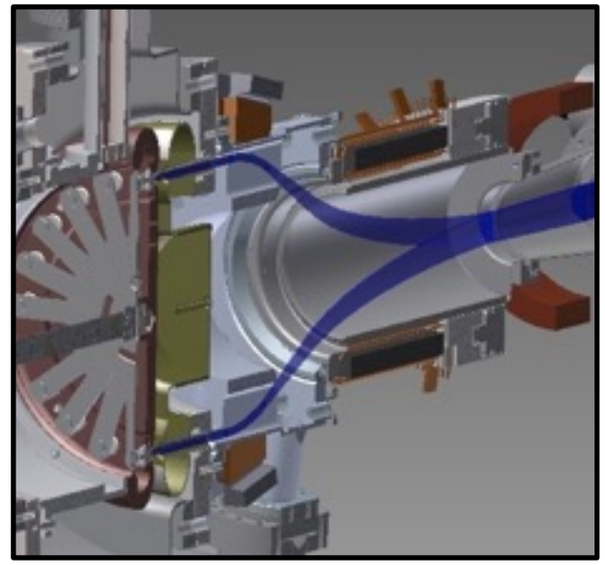
Detector Options

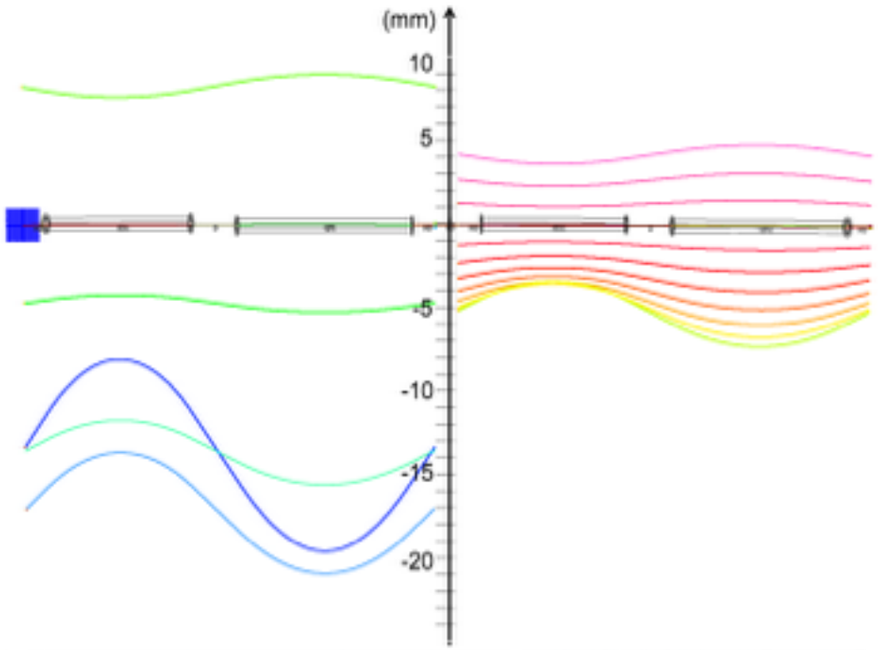


When completed, eRHIC will be the most advanced and energy efficient accelerator in the world

Innovations and challenges of eRHIC

- High intensity (50mA) polarized electron source using multi-cathode gun (“Gatling Gun”)
- Energy Recovery Linac with 98% recovery efficiency (energy loss from synchrotron radiation)
- Up to 16 re-circulations of the electron beam through the same 1.32 GeV Linac
- Novel FFAG lattice allows 16 beam re-circulations using only two beam transport rings
- Permanent magnet technology is used for the FFAG beamline magnets eliminating the need for power supplies, power cables and cooling.
- Strong cooling of hadron beams gives high luminosity while minimizing electron beam current and synchrotron radiation loss.





EIC Recommendation

EIC Recommendation from the QCD Town Meeting Sept. 2014

A high luminosity, high-energy polarized Electron Ion Collider (EIC) is the highest priority of the U.S. QCD community for new construction.

The EIC will, for the first time, image the gluons in the proton and nuclei, resolve the unknown aspects the proton's internal structure including the origins of its binding, mass and spin, and explore a new QCD frontier of ultradense color fields in nuclei at high energy. These advances are made possible by the EIC's unique capability to collide polarized electrons with polarized protons and with heavy nuclei at high energy and unprecedented luminosity. EIC will be absolutely essential to maintain U.S. leadership in fundamental nuclear physics research in the coming decades.