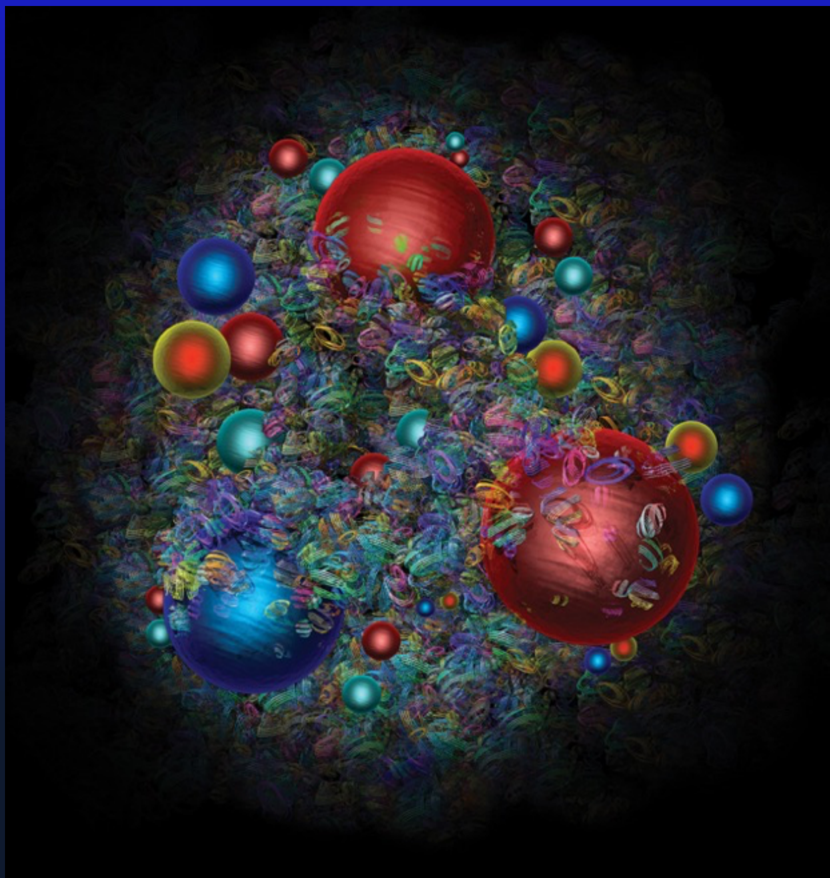
The Electron-Ion Collider:
the ultimate electron microscope



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東京大学
May 29, 2024

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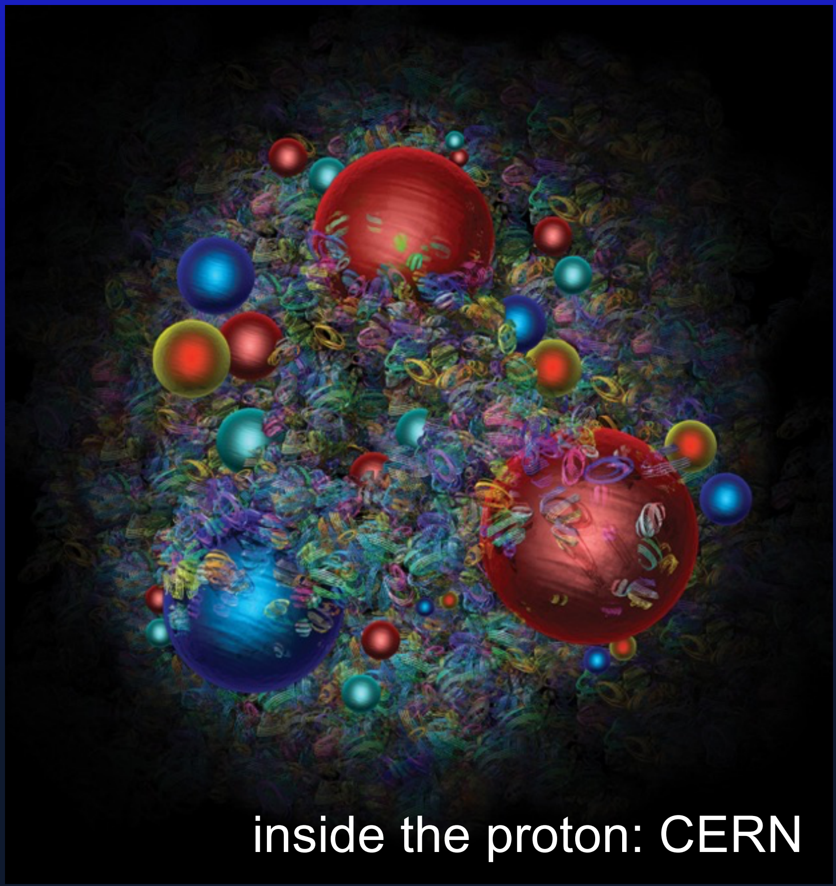

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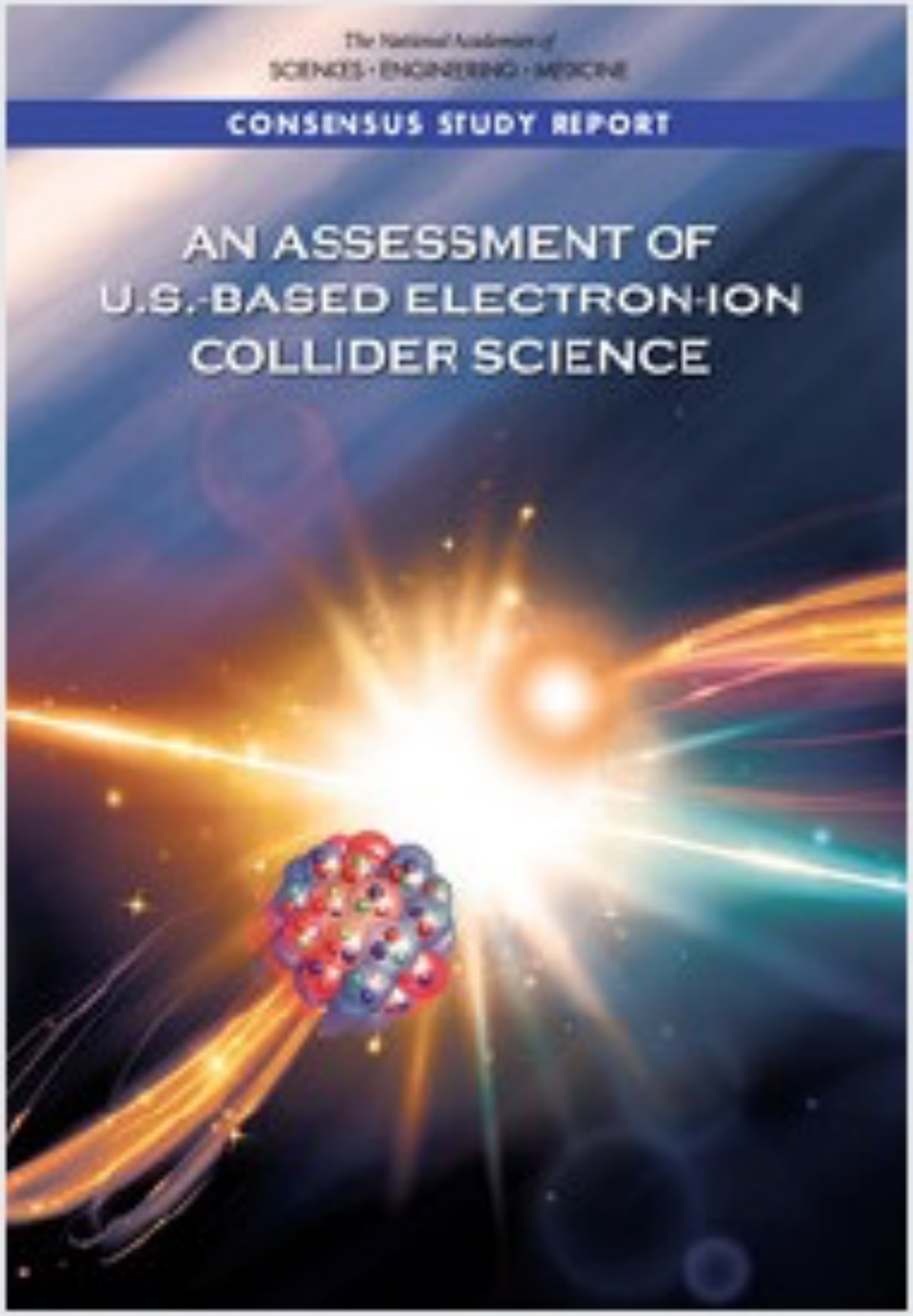
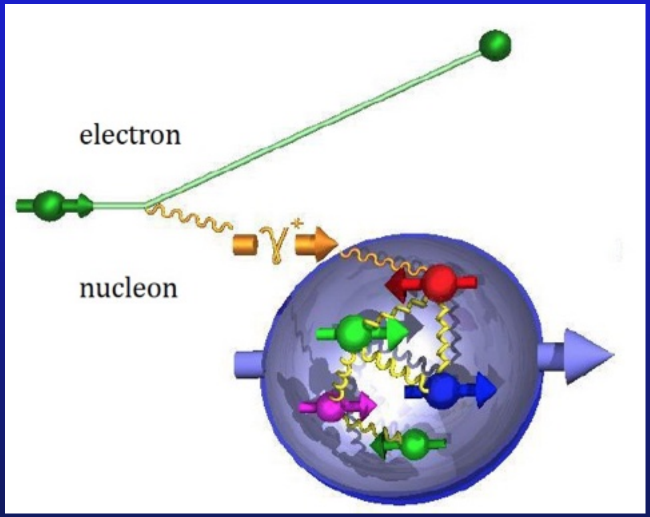


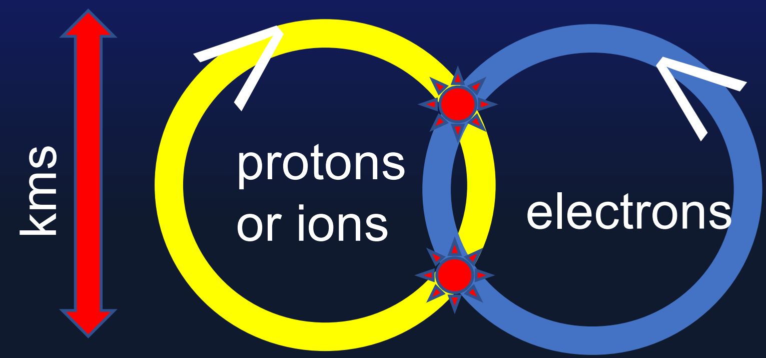
National Academy of Sciences – National Research Council report, July 2018, on the science of an EIC

Download pdf from
https://www.nap.edu/catalog/25171

The Electron-Ion Collider

A very big accelerator -- colliding beams of electrons with beams of protons or heavier ions (atomic nuclei).
A giant electron microscope for peering at the quarks and gluons deep inside the nucleon and atomic nuclei. QCD machine.





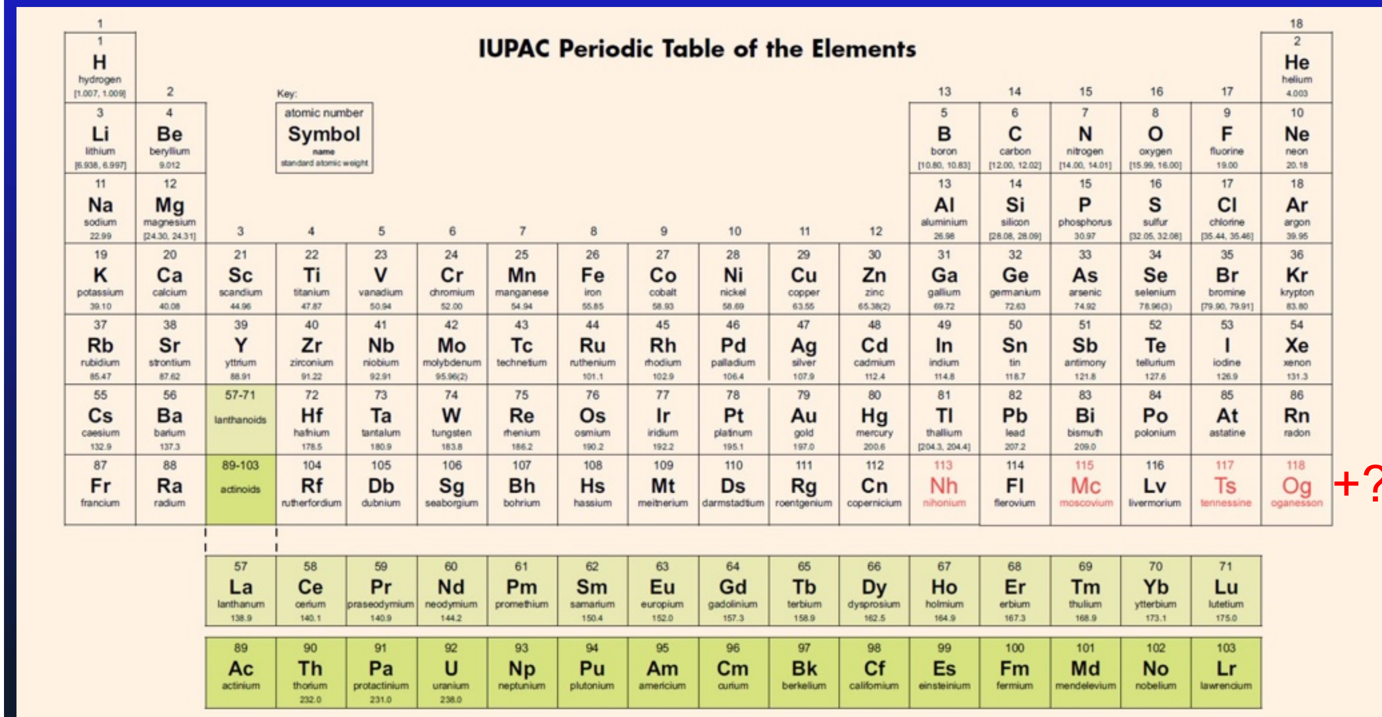
Electron microscope Invented 1931

ca. 1940

Electron-ion center of mass energy:
$\sqrt{s}$ ~ 28~140 GeV.
High luminosity (event rate) and spin polarized beams!
Proton mass ~ 1 GeV

Nuclear physics far from being a solved problem

Atomic nuclei: building blocks of the everyday world:



The periodic table of chemical elements is over 150 years old.

Are there further elements out there? Any of them stable?

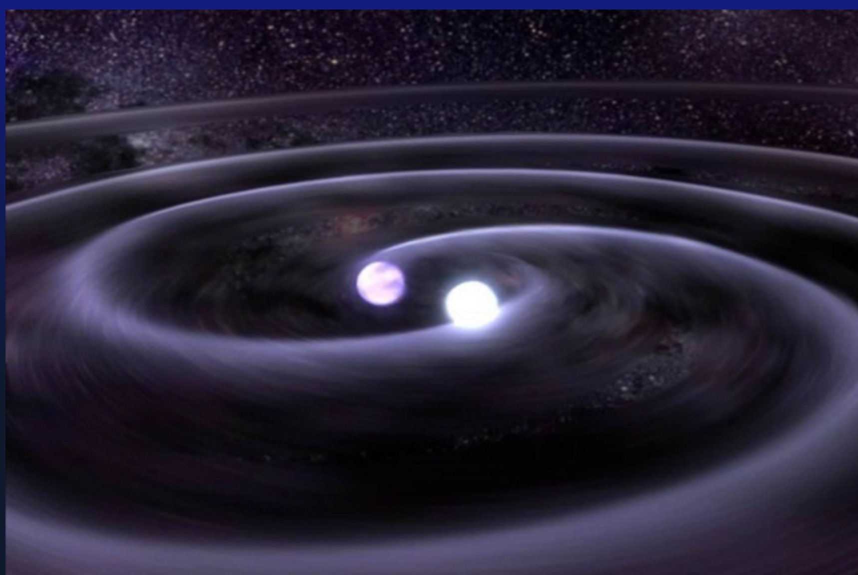
How many isotopes does each element have?

Answers from rare isotope accelerators (e.g., RIBF at RIKEN and FRIB at MSU) studying nuclei far from stability.

F = facility, RIB = rare isotope beam

RIBF

How to make the heavier elements? Answers, remarkably, from multimessenger studies of binary neutron star mergers:
Merger GW170817 observed on 17 Aug. 2017 by LIGO and Virgo (gravitational radiation), FERMI (gamma ray telescope)
+ some 70 other electromagnetic observatories.



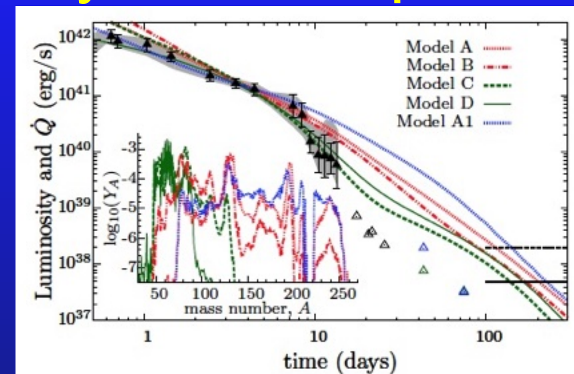
Two neutron stars merging, emitting gravitational radiation and. post-merger, forming:

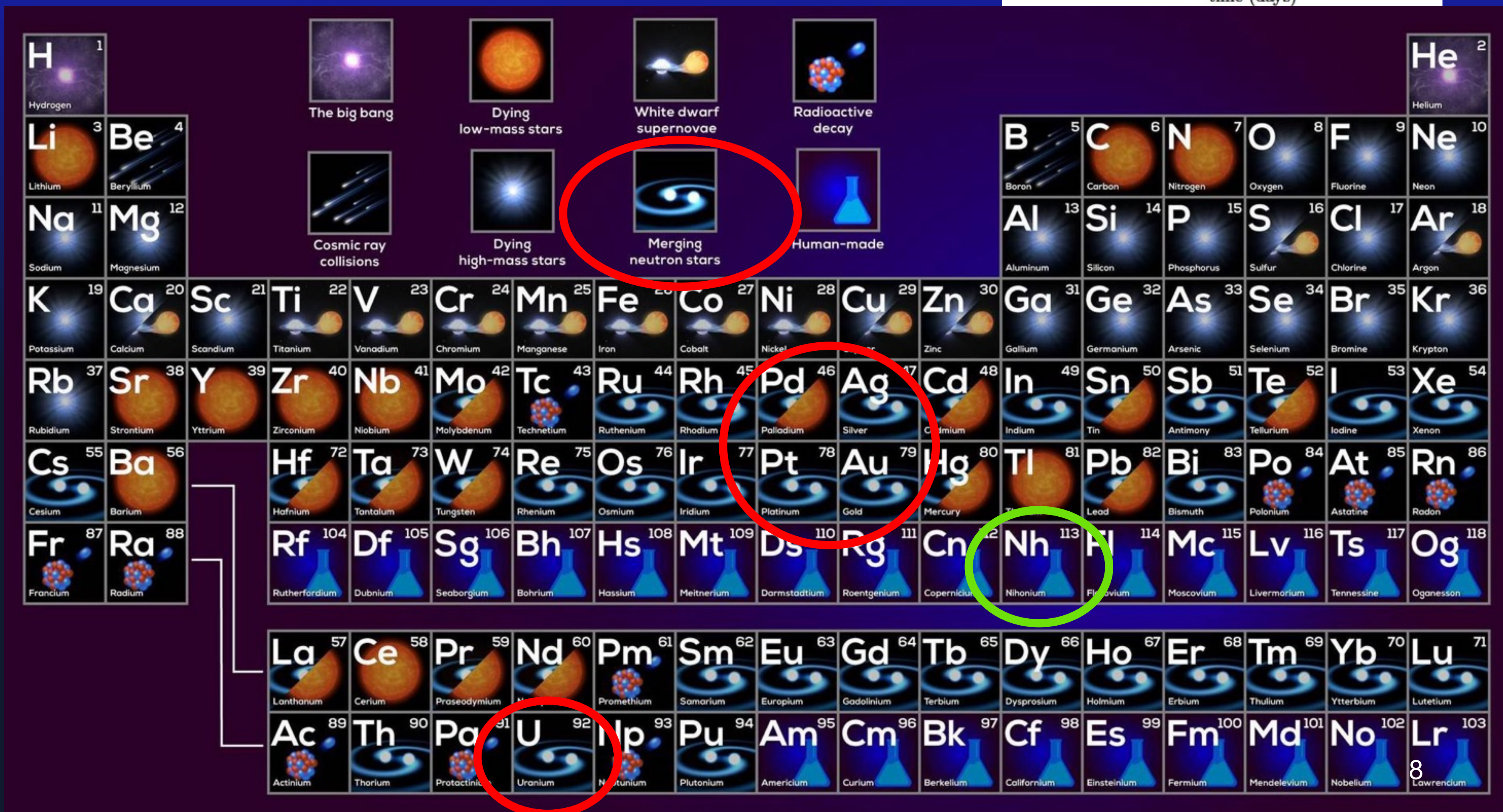
Kilonova: neutron-rich site of r-process

Binary neutron star mergers likely site of heavy element production

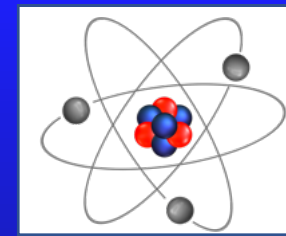
r-process in *kilonova* =>
earth-scale masses of
Au, Ag, Pt, U... and Sr

Kilonova
N= 50, 82, 126



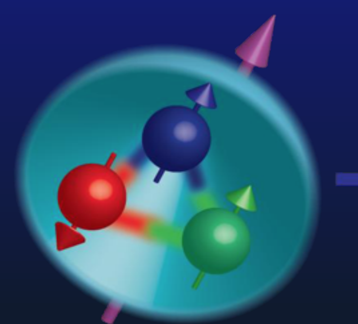


Atoms are made of electrons and nuclei.
Similarly neutrons, protons, and nuclei are made of quarks and gluons. But how? How to explain nucleon masses, spin, magnetic moments, etc. in terms of quarks and gluons?



Quarks = fractionally charged spin-1/2 fermions, baryon no. = 1/3, with internal SU(3) color degree of freedom.

Flavor	Charge/|e|	Mass(MeV)
u	2/3	~2
d	-1/3	~5
s	-1/3	~ 94
c	2/3	~1280
b	-1/3	~4200
t	2/3	~175,000

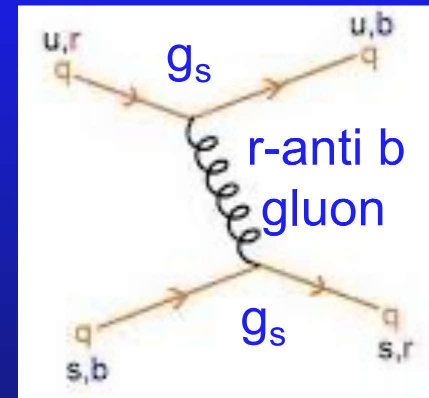


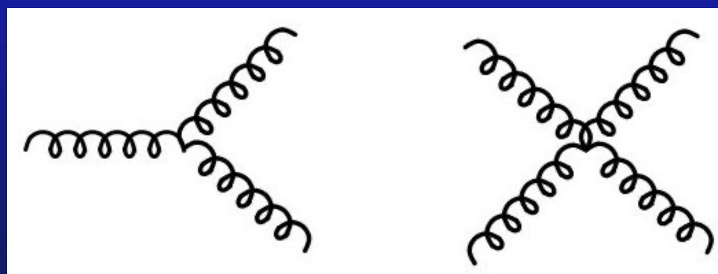
proton = u + u + d
neutron = u + d + d
$\pi^+ = u + \bar{d}$, etc.

Quark matter (baryonic) in the early universe at t < 1 microsec (T > 100 MeV), and in the deep interiors of heavier neutron stars.

Strong interactions – quantum chromodynamics

Quarks interact by exchanging gluons – massless vector bosons (like photon) with spin 1, and coming in 8 colors. Gluons also interact with each other!!

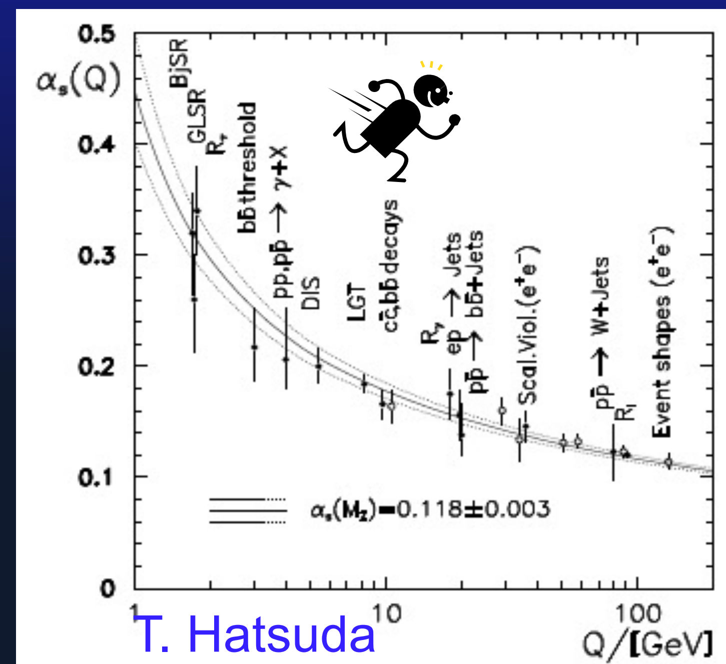




QCD

$$\alpha_s(\mu) = \frac{g_s^2}{4\pi} = \frac{6\pi}{(33-2N_f)\ln(\mu/\Lambda_{QCD})}$$

μ = energy scale $\qquad \Lambda_{QCD}$ ~ 340 MeV



Running coupling constant

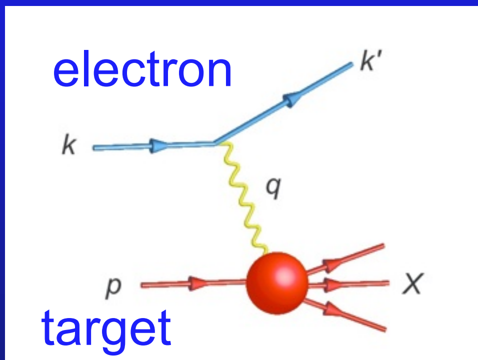
Asymptotic freedom as $\mu \to \infty$

(Even at Grand Unified (GUT) scale, 10^{15} GeV, g_s is not small: ~½; cf. electrodynamics:

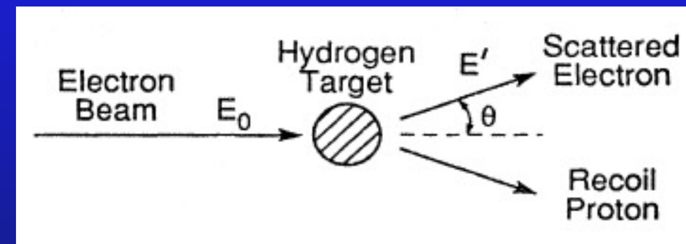
$e^2/4\pi = 1/137 \Rightarrow e \sim 1/3$)

Electron scattering on nucleons and nuclei

Electron scattering on nucleons and nuclei: origins



Electrons (without internal structure) are precise probe of the complex structure of nucleons and nuclei.



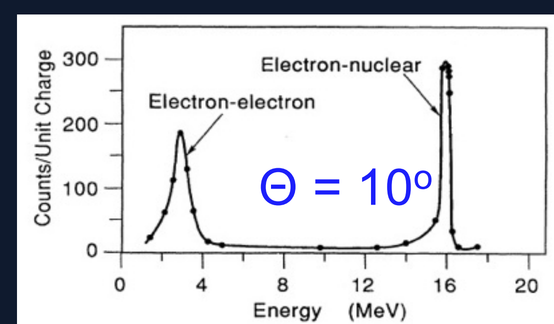
First scattering of electrons on nuclei, Illinois Betatron 1951

Al Hanson

Ernie Lyman

and Merrill B. Scott

15.7 MeV electron beam on Be and Au foils



Donald Kerst, U of I, with the Betatron, ca. 1941

First scattering of electrons on protons and alpha particles

R. W. McAllister and Robert Hofstadter, 1956, with 187 MeV electrons at Stanford High Energy Physics Lab (HEPL) on H_2 and He gaseous targets, and then on polyacetylene (CH_2).

Found first hint of internal structure of the proton from the angular distribution:

proton radius $r_{proton} \sim 0.7$ fm (1fm = 10^{-13}cm)

But is the inside of the proton a continuous "pudding" or are its constituents point particles?

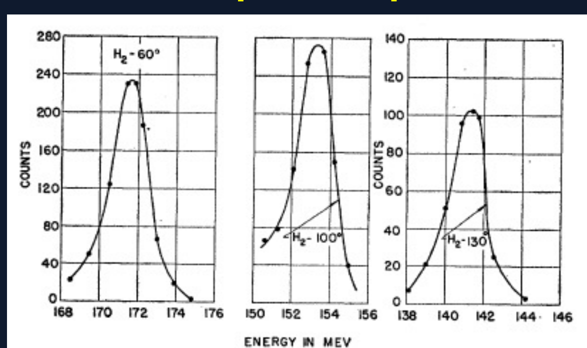
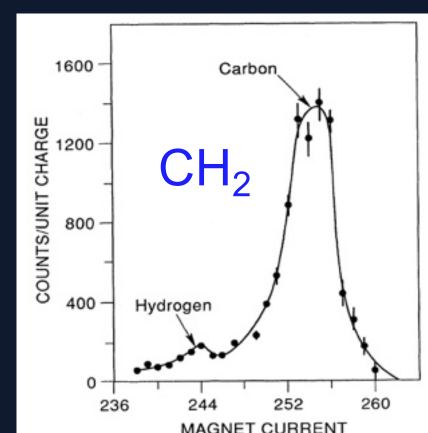
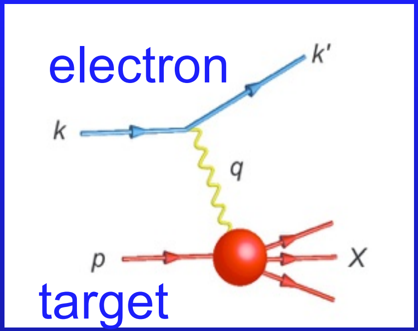


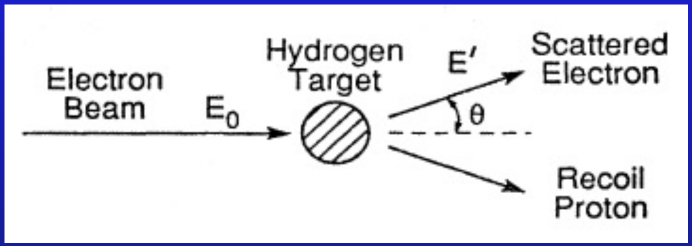
FIG. 3. Typical elastic profiles obtained with hydrogen gas at 185 Mev.

Elastic scattering on H_2 at various Θ





Kinematic variables in electron scattering from nucleons and nuclei



Electron scattering angle: θ

Electron energy transfer in lab: $\nu = E_e - E_e'$

3-momentum transfer from electron in lab: **q**

4-momentum transfer squared: $Q^2 = \mathbf{q}^2 - \nu^2$
Larger Q^2 = higher (transverse) resolution

Elastic scattering on target of mass m:
Energy conservation $(m^2 + q^2)^{1/2} = m + \nu$ => $\nu = Q^2/2m$

Bjorken scaling variable: $x = Q^2/(2m_{proton}\,\nu)$
x is like the "shutter speed"

The variables Q^2 and x define the landscape of electron scattering

Discovery of quarks 1967-73

Friedman, Kendall, and Taylor do deep-inelastic scattering (DIS) destroying proton target – at the Stanford Linear Accelerator Center (SLAC) 2 mile long, 20 GeV electron accelerator.

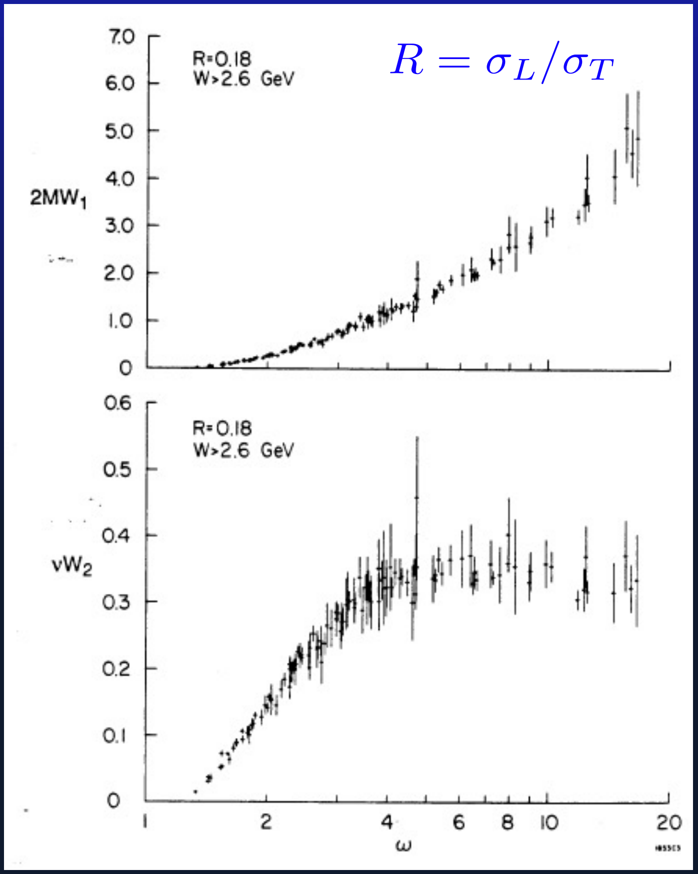
Measure electron angular cross section:

$$\sigma(E,E',\theta)=\frac{4e^4E'^2}{Q^4}\left\{W_2(\nu,Q^2)\cos^2\frac{\theta}{2}+2W_1(\nu,Q^2)\sin^2\frac{\theta}{2}\right\}$$

For scattering from point particles inside proton, W_1 and νW_2 depend only on Bjorken scaling variable

$$x=\frac{Q^2}{2m_{proton}\nu}$$

Observe dependence on x only; shows that proton is made of point particles



Bjorken scaling indicating quark structure: ω = 1/x (W = mass of recoiling target)

Proposal of quarks as mathematical model 1964

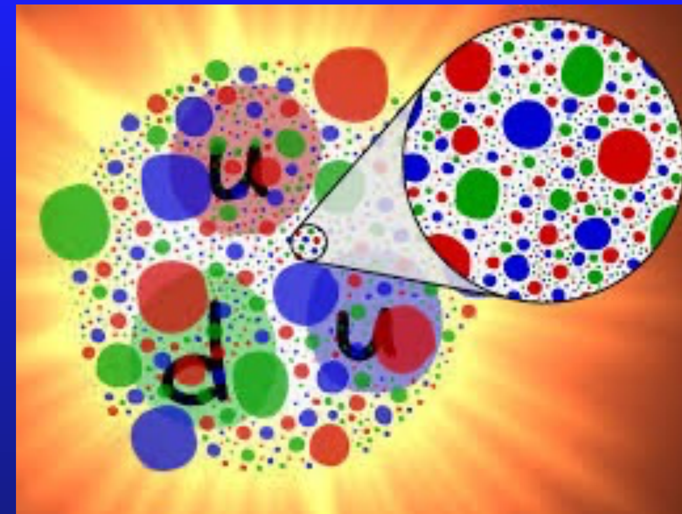
Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Ordinary matter near the earth's surface would be contaminated by stable quarks as a result of high energy cosmic ray events throughout the earth's history, but the contamination is estimated to be so small that it would never have been detected. A search for stable quarks of charge $-\frac{1}{3}$ or $+\frac{2}{3}$ and/or stable di-quarks of charge $-\frac{2}{3}$ or $+\frac{1}{3}$ or $+\frac{4}{3}$ at the highest energy accelerators would help to reassure us of the non-existence of real quarks.

Parton model (Feynman, 1969)



building on J.D. Bjorken:

Understand electron scattering in terms of *partons* -- quasiparticles

Given parton carries momentum p (in beam direction) -- $\nu = E_{el} - E'_{el}$
a fraction x of the total target proton momentum p_{proton} . Same x

$$\frac{p_{parton}}{p_{proton}} = x = \frac{Q^2}{2m_{proton}\nu}$$

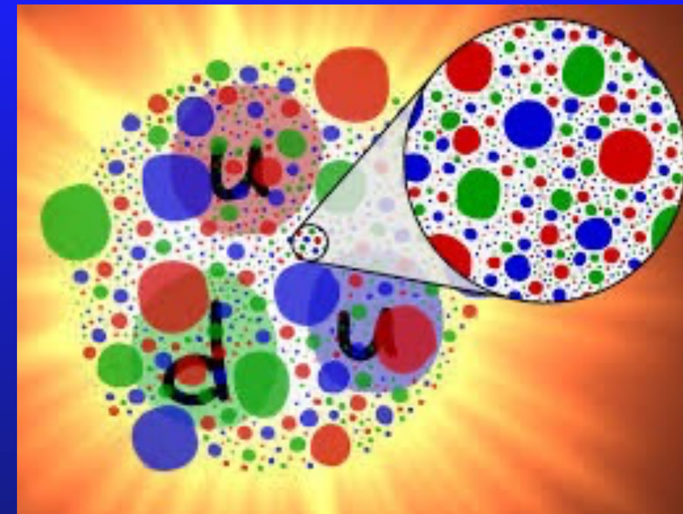
energy conservation in scattering on parton $\nu = \frac{Q^2}{2m_{parton}}$

$$m_{parton} = x\, m_{proton}$$

Measure x in "infinite momentum" frame, i.e., with the proton moving at (nearly) the speed of light.

--Point partons identified with quarks, antiquark, and gluons -- all governed by QCD, with asymptotic freedom: Bjorken and Paschos
--Quarks are physical, not merely a tool: Brodsky and Farrar

Parton model (Feynman, 1969)



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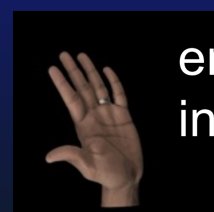

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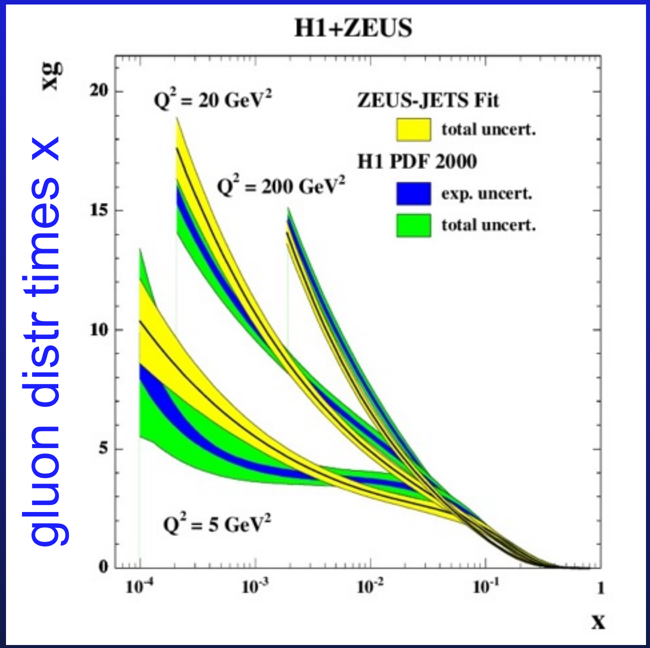
1991-2007 e scattering at HERA
(Hadron-Electron Ring Accelerator, Hamburg)

High-energy collisions of 27.5 GeV electron and positron beams (polarizable) with 920 GeV proton beams (unpolarized). No nuclear beams

HERMES (spin) fixed-target experiment.

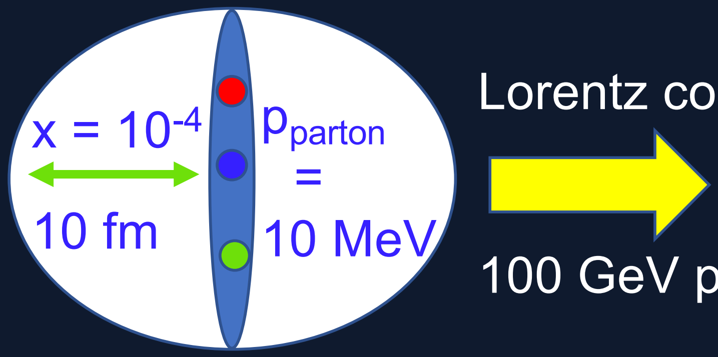
HERA => great abundance of very low momentum (x<<1) gluons within nucleon.



How can electrons probe electrically neutral gluons?

$g \to q + \bar{q}$ causing an effective electric dipole moment

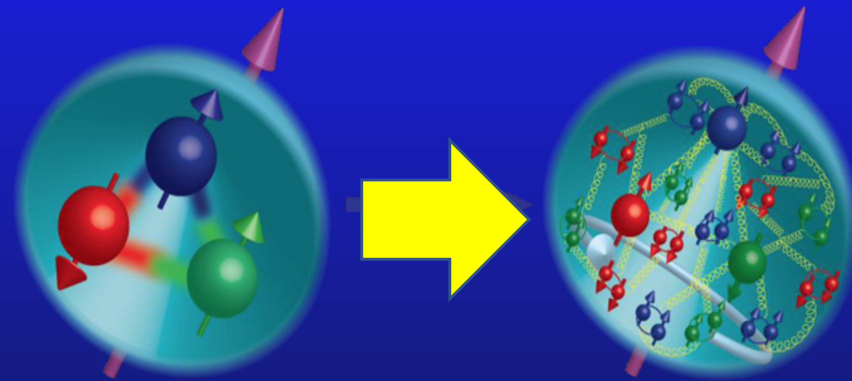
View proton in frame in which proton is "slower" than ∞ momentum.
Heisenberg => low x "wee" partons stick out.



Physics with an electron-ion collider

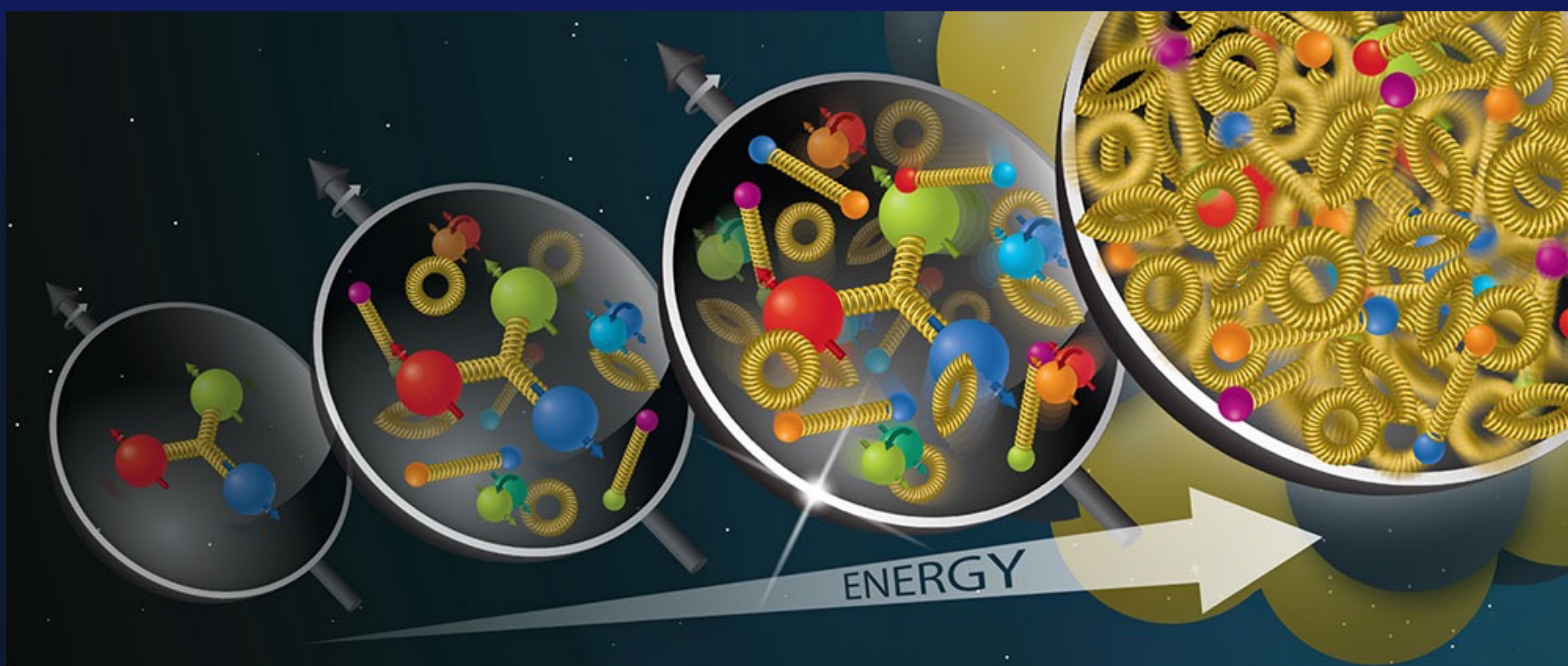
Physics goals of an EIC

Our picture of the nucleon has evolved considerably from the first simple picture as a “bag” of three valence quarks.
Have sea of quark-antiquark pairs (u, d, s) as well as cloud of gluons, all interacting!



1970s cartoon Now

Z-E Meziani



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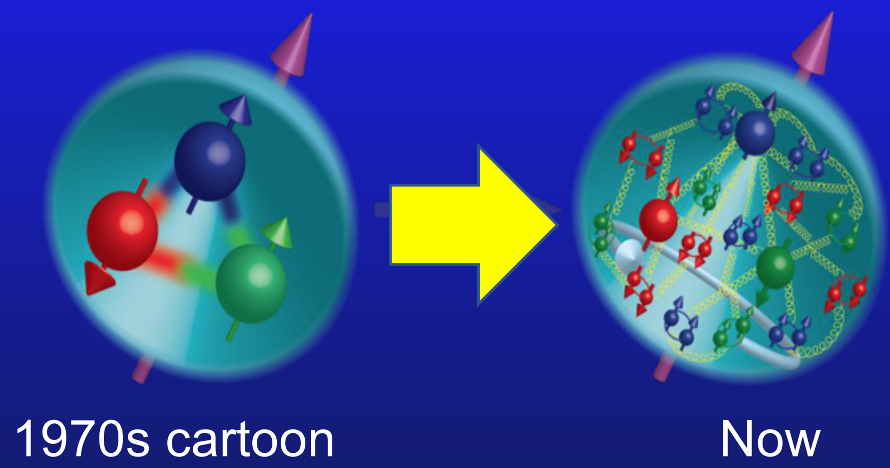

Z-E Meziani

Where are all the quarks and gluons -- in space and in momentum space? What is the many-body physics of all these interacting degrees of freedom.

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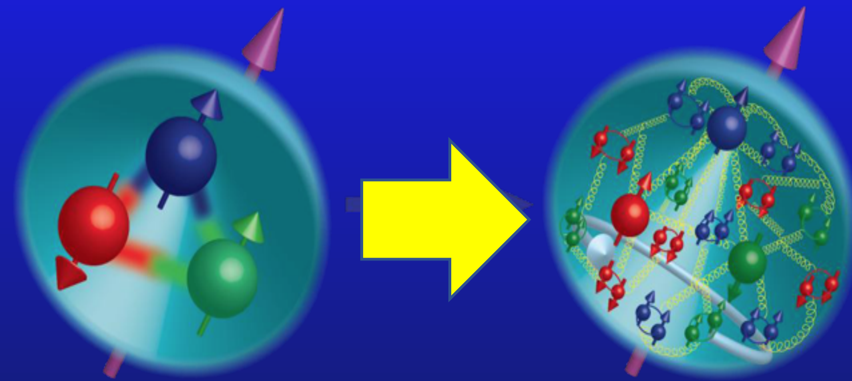

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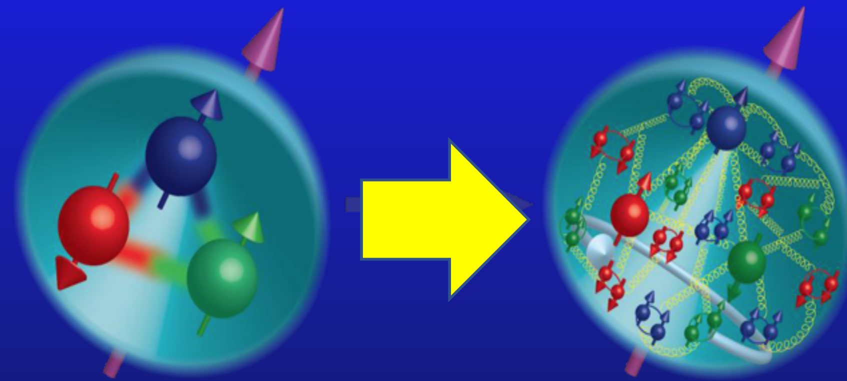

1970s cartoon Now

Z-E Meziani

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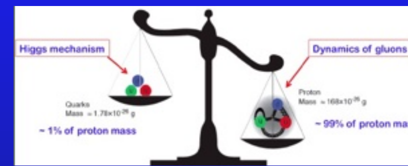
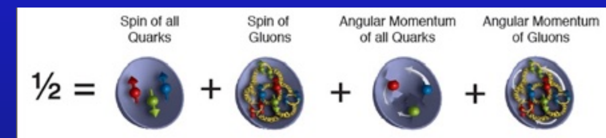
Sketch of worm vs. modern electron microscope picture (deep ocean worm)

Basic science questions for an EIC

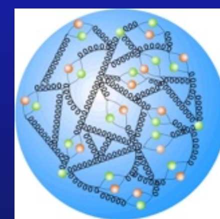
How does the nucleon get its mass?



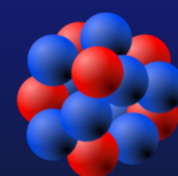
How does the spin of the nucleon arise from its elementary quark and gluon constituents?



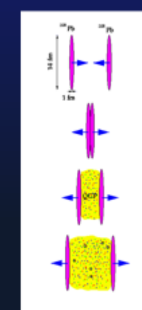
What are the emergent properties of dense systems of gluons?



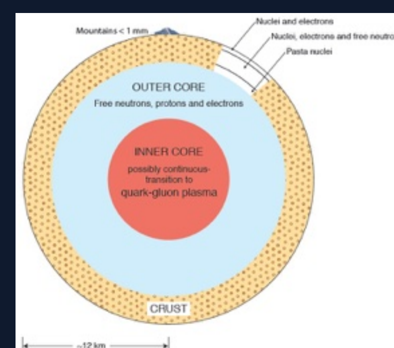
What is the internal structure of nuclei? How do nuclei differ from being a simple collection of nucleons?



What is the "initial state" in ultrarelativistic heavy-ion collisions?



How does dense matter crossover from nucleonic degrees of freedom to quark degrees of freedom at higher density – application to neutron stars

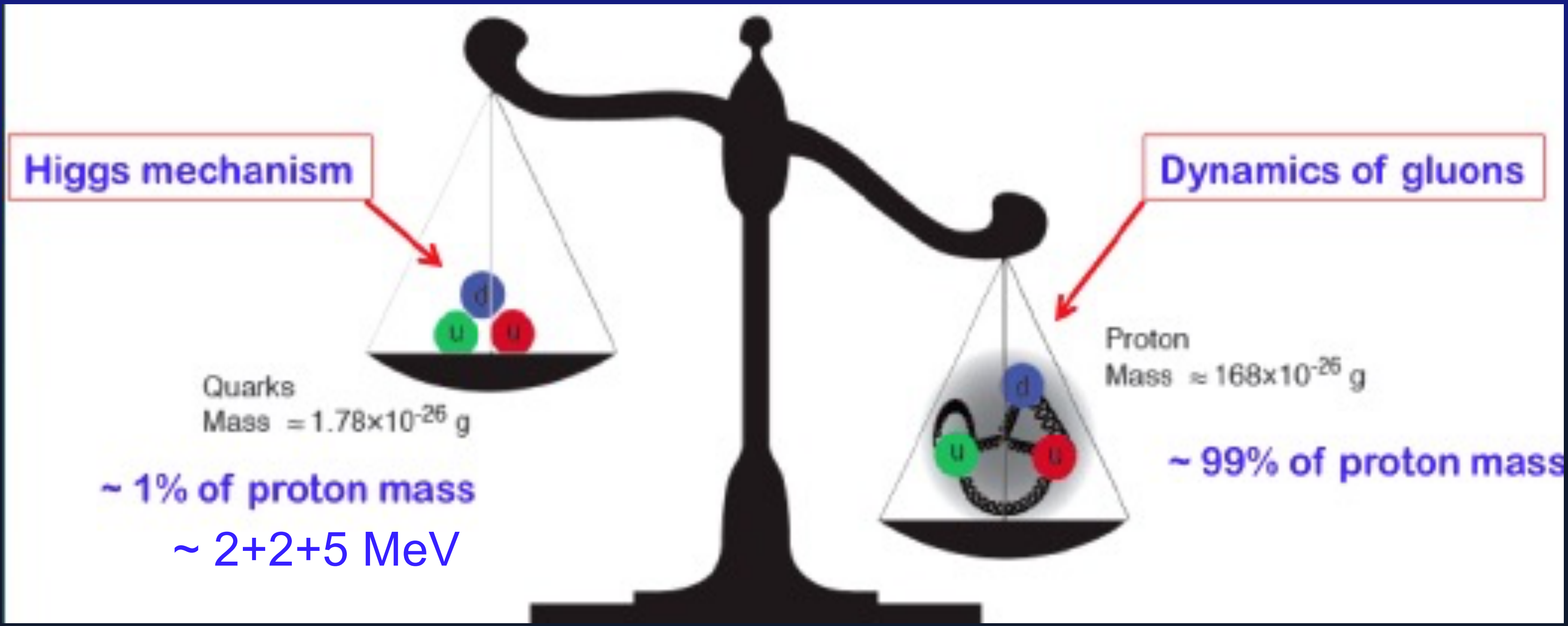


Signals of beyond-the-standard-model physics? Effects of new particles and forces?

How does a nucleon get mass?

m_{proton} = 938 MeV is almost 100 times greater than the masses of its valence quarks (u+u+d ~ 2+2+5 MeV).

Cannot be understood in terms of the Higgs mechanism!!
Higgs => I should weigh ~ 750 gm

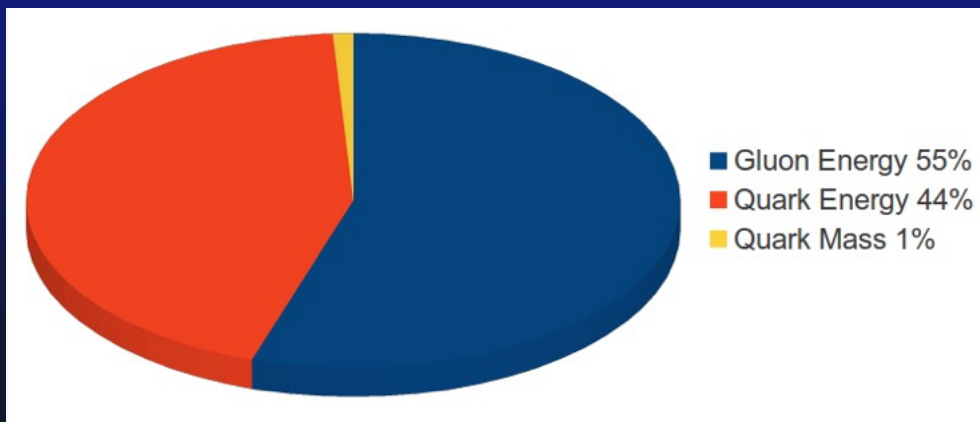


In atoms, mass = total mass of constituents minus binding energy (energy released in chemical reactions) < mass of constituents.
In nucleons, mass >> total mass of constituents.

Zero point energy => mass of the nucleon

Naively, the mass of the nucleon arises from all quark, anti-quark and gluon kinetic energies – from the uncertainly principle when localizing excitations within the nucleon (radius, r_p).

$\Delta E \sim \hbar c / r_p$ per quark or gluon.



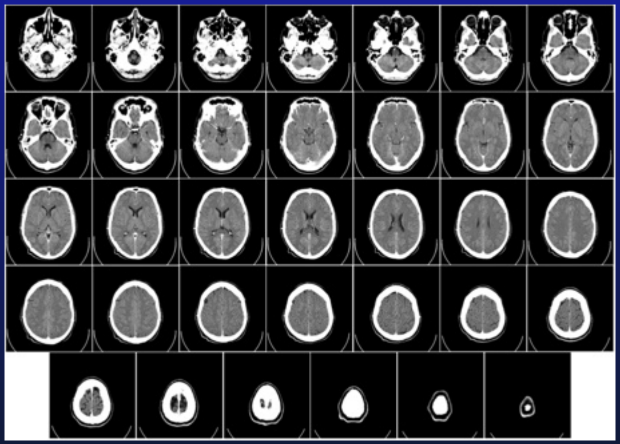
Energy distribution within nucleon

How are these components distributed (in space and momentum) in the nucleon?

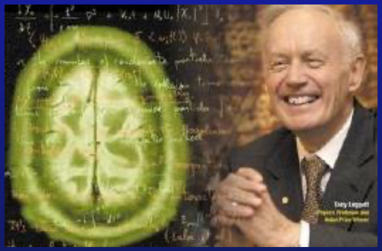
And how do nuclei differ from being a simple collection of nucleons – changes of quark and gluon distributions in nuclei?

Tomography

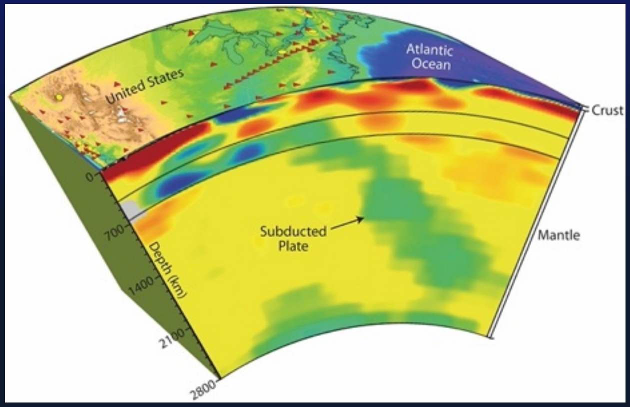
Determine internal structure of nucleon by measuring its momentum distributions ($\vec{k}_\perp$) transverse to the beam at varying x.
(Requires large luminosity.)



Computer assisted tomography of brain



A.J. Leggett

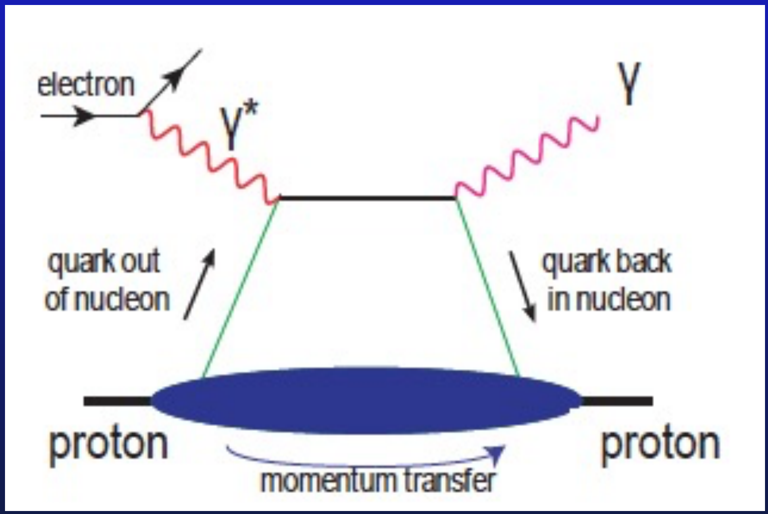


Seismic tomography, slices at varying depth; earthquakes as probes

Measure dependence of cross section on momentum transfer from electron to target => information about transverse position and momentum of struck quarks and gluons.

Measuring quark and gluon transverse momentum distributions

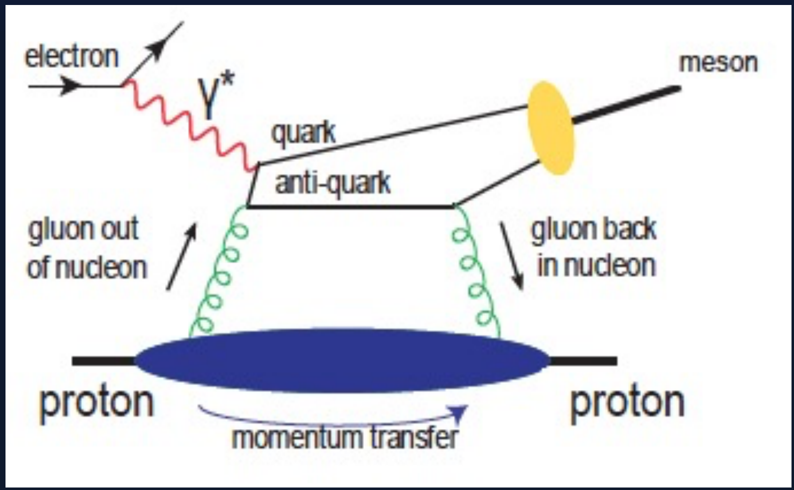
Real photon production γ:
Deeply virtual Compton scattering
sensitive to transverse position
of quarks.



Real meson production:
gives info on gluon distribution.

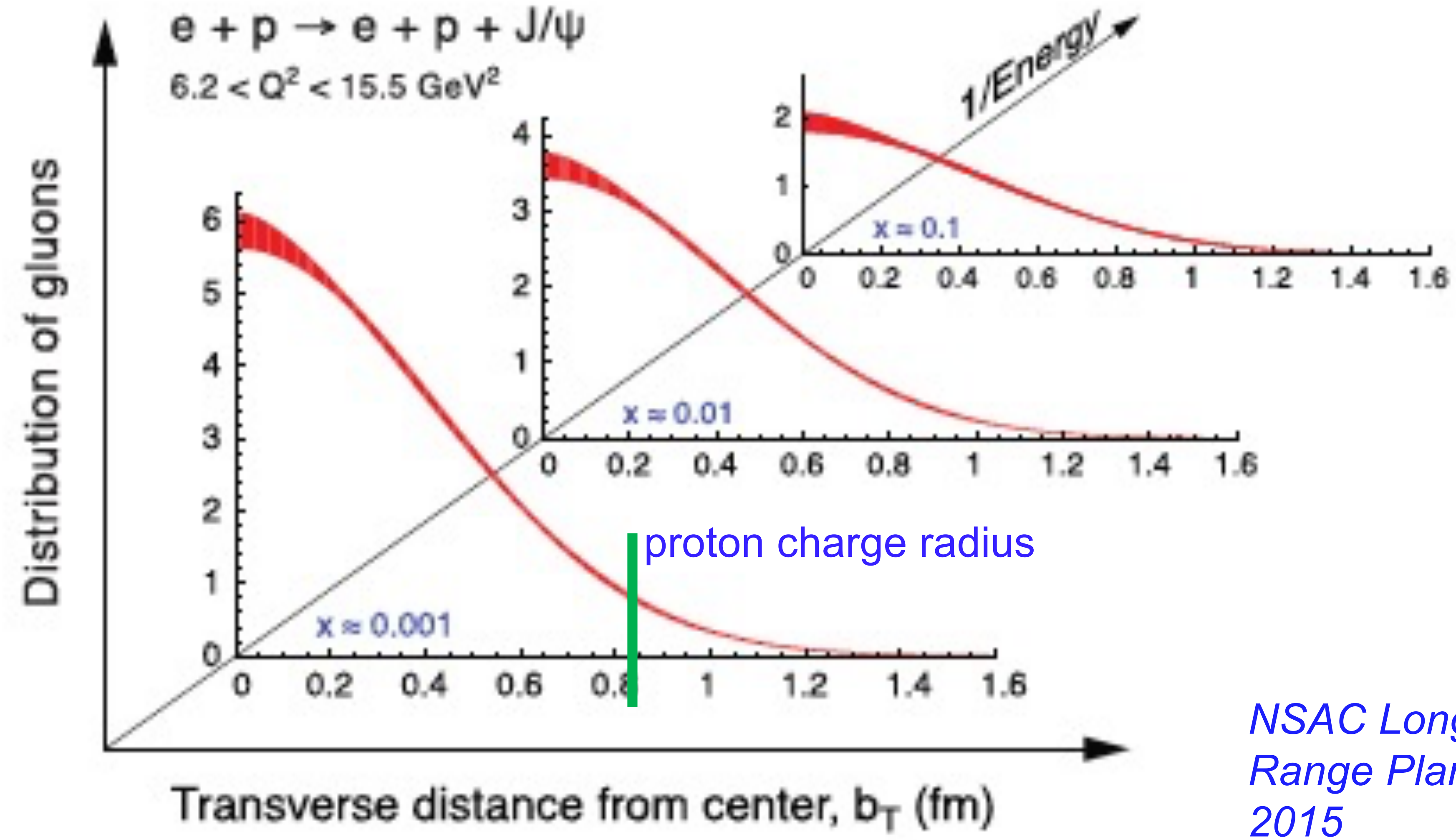
Ex., Heavy mesons J/ψ or Upsilon (Υ):

$$\gamma^* \to \bar{b}b \to \Upsilon$$



Expected transverse gluon distributions in space

Slices vs. transverse position b_T at various x

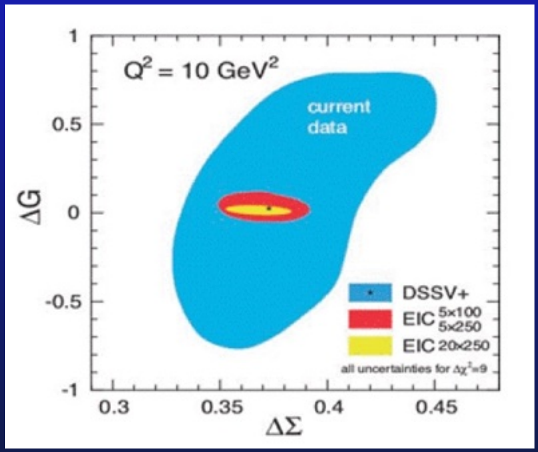


NSAC Long Range Plan 2015

How do the quarks and gluons give the proton its spin?

Proton spin is the basis of nuclear magnetic resonance (MRI) imaging.

Spin crisis:



Current estimate of contributions to spin (in units of ħ/2):

Quarks ΔΣ ~ 30-40%

Gluons ΔG ~ -70 to + 70% ?? (RHIC pp)

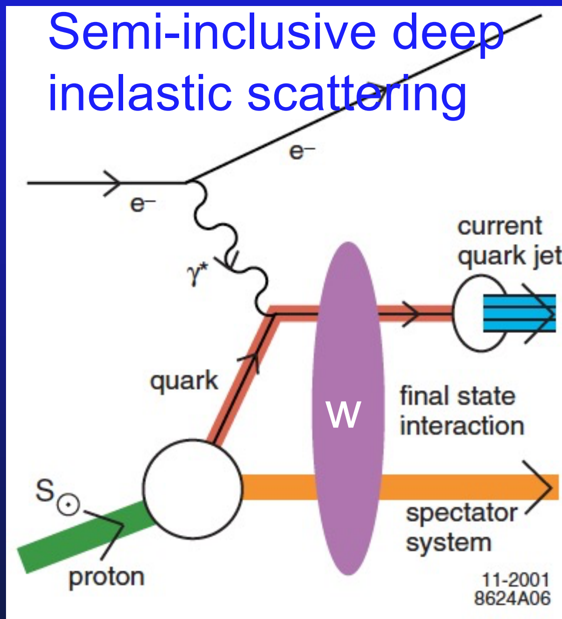
Orbital motion ?? (JLab - 12GeV)

Extract orbital contributions from transverse motion measured by spatial and momentum distributions of components in deep inelastic scattering -- tomography.

Extract gluon contributions from transfer of gluon polarization to q-bar q pair, probed by polarized electrons.

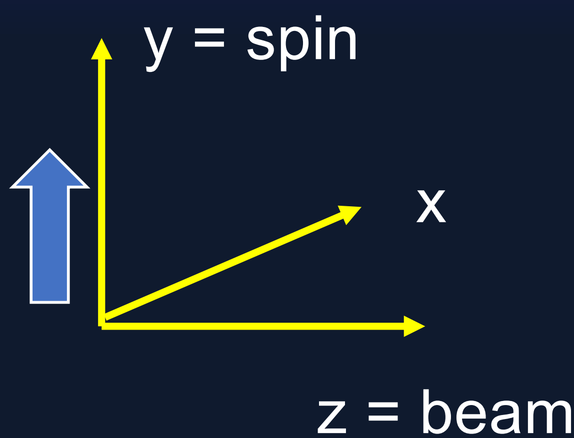
Polarized beams (> 70%) in EIC critical !

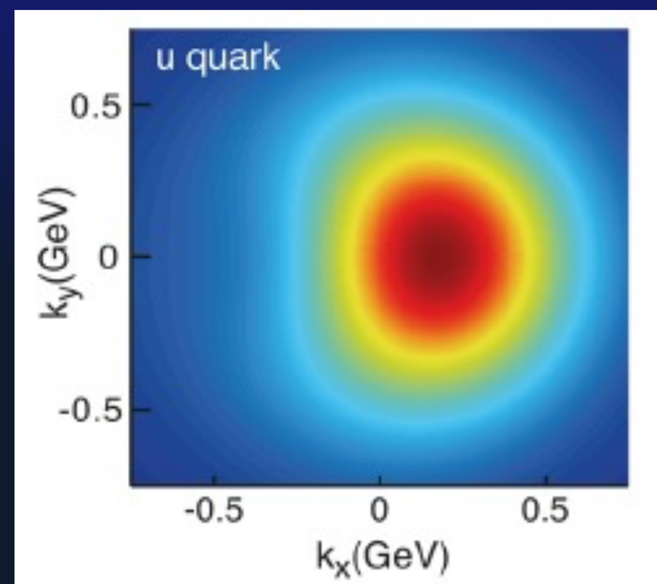
Detecting quark orbital contributions to proton spin



Proton spinning (along y) with orbital motion as well leads to asymmetry of quark distributions in x direction.

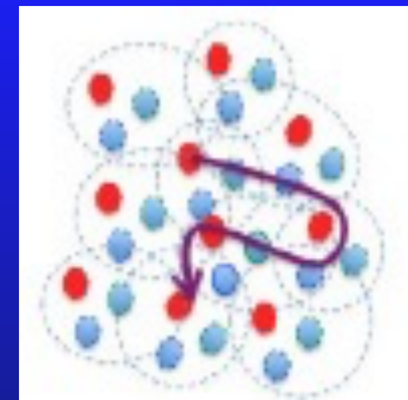
Beam along z.





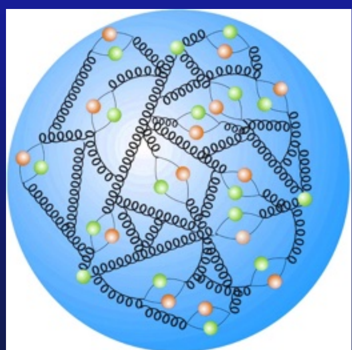
Representative asymmetry of up-quark distribution for x = 0.1

Gluon physics



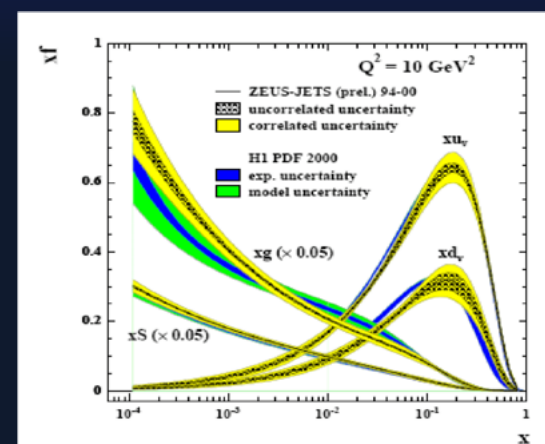
Gluons in nucleons and nuclei (as well as other hadrons) are like dark matter in the universe– unseen but crucial in holding matter together.

DESY



"The most precise picture of the proton"

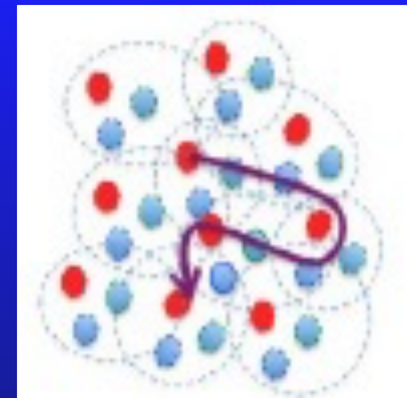
Nucleons and nuclei are in fact complex interacting many-body systems – not simply bags of free quarks and free gluons. Ex., nuclei exhibit composite fermions– the nucleons. Confinement!



HERA => huge numbers of low momentum gluons in the nucleon -- at low x ($<10^{-4}$).
Low momentum sector ("wee') partons dominated by strongly interacting gluons!. The gluon field is highly non-linear!

A new many-body system! New emergent phenomena?

Gluon physics



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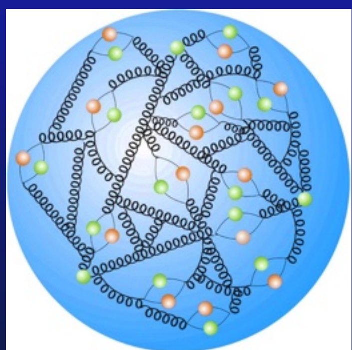

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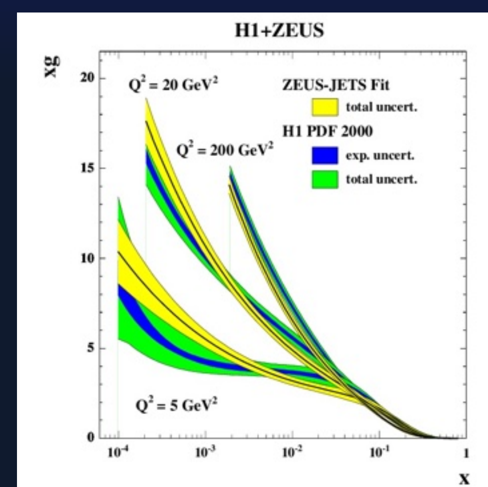

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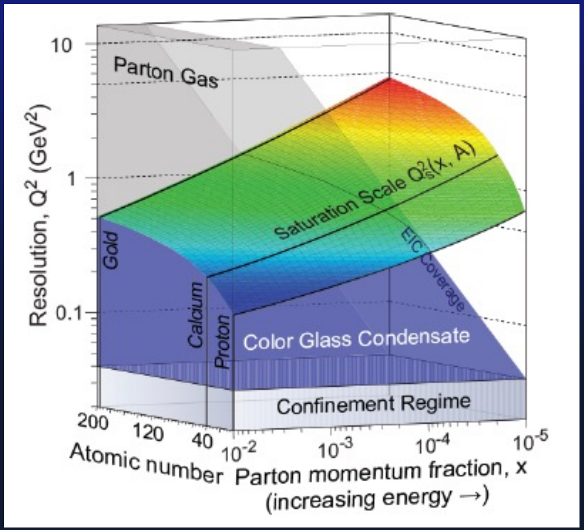
A new many-body system! New emergent phenomena?

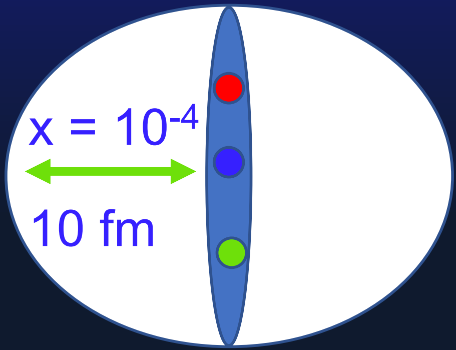
Gluon self-interactions become important at small x where there are many many gluons

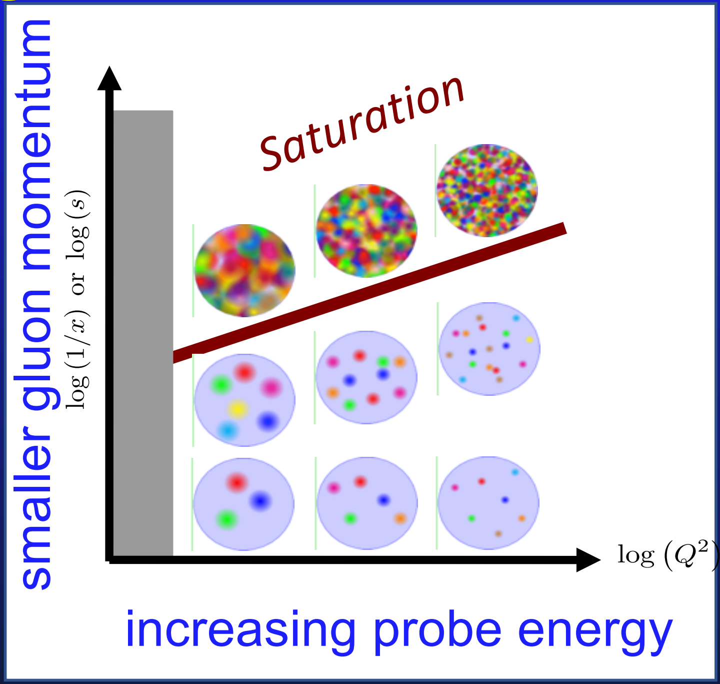
Scale of saturated gluonic matter: Q_s

At HERA (318 GeV c.m.) $Q_s^2 \sim 1$ GeV^2

At EIC ~ 1-few GeV^2, growing with A.







Lorentz contracted
100 GeV proton

First approximation, dense cloud of gluons forms a Bose condensate – "color glass condensate."

Excitations of saturated gluonic matter? Topology?

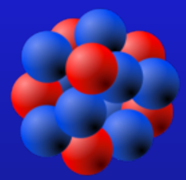
Evidence of non-linearity from STAR at RHIC: PRL 129, 092501 (2022)

Connections with nuclear physics elsewhere

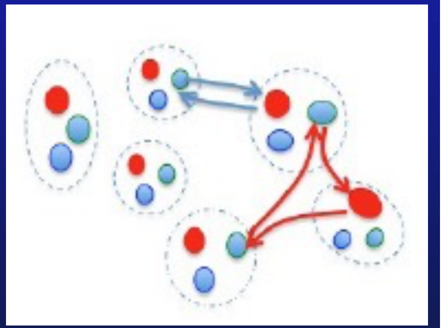
structure of the nucleon,
heavy ion
&
neutron star physics

What role do quarks play within laboratory nuclei?

How does the picture of individual non-overlapping nucleons within familiar nuclei break down?



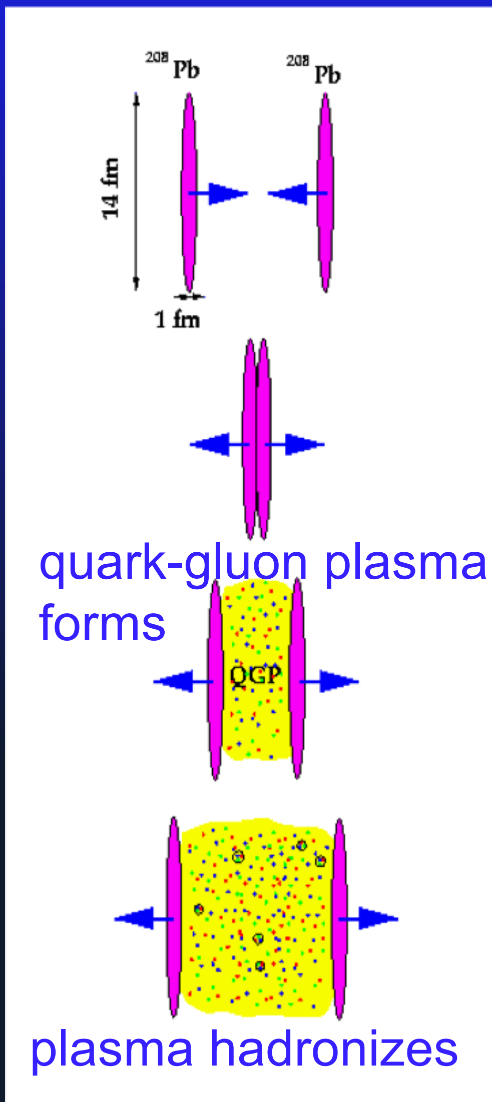
Standard picture is in terms of nucleonic degrees of freedom interacting via forces. More microscopically have quark exchanges, leading to correlations among nucleons. How do nuclei differ from being a simple collection of nucleons?



Where are all the quarks and gluons -- in space and in momentum space? What is the many-body physics of all these interacting degrees of freedom?

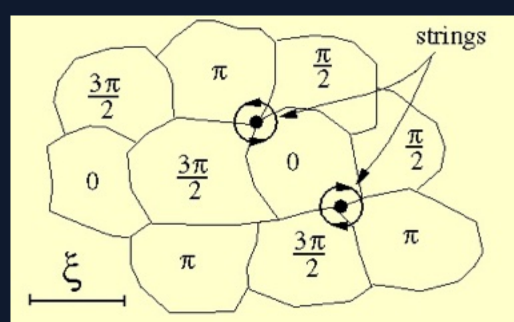
EIC should lead to new perspectives on the nuclear science being studied at other facilities, e.g., FRIB, and JPARC

Connections to heavy ion collisions:

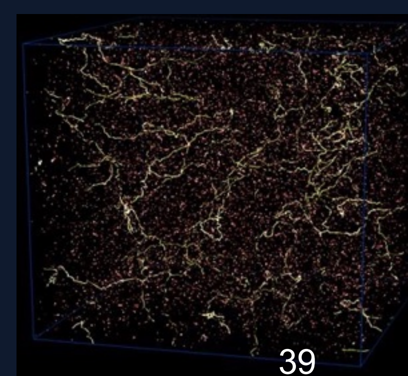


Saturated gluonic matter reachable at a sufficiently energetic EIC. Describes “initial state” in ultrarelativistic heavy ion collisions. Bose-condensed gluonic matter (color-glass condensate, ...). Condensate is metastable, decaying into quark-gluon plasma.

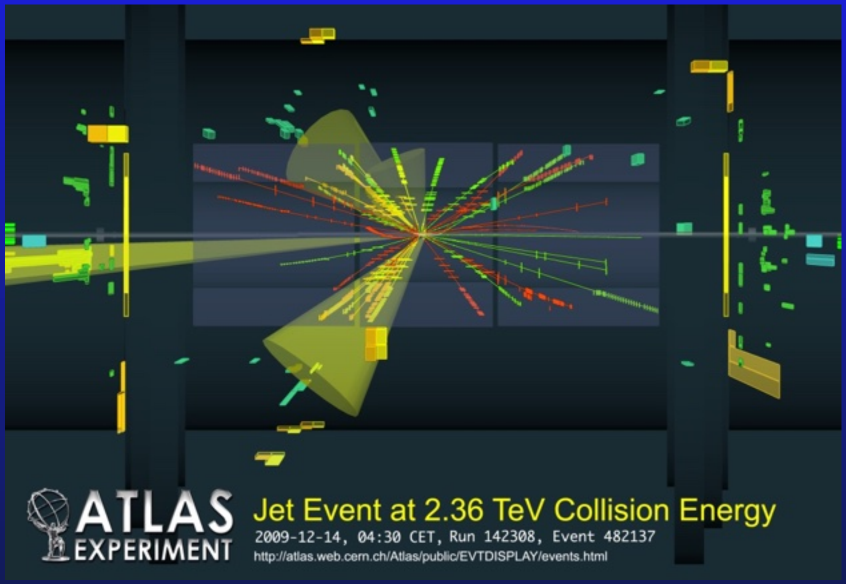
As in the early universe, expect topological defects, e.g., handedness asymmetry of produced q $\bar{q}$ pairs (chiral magnetic effect) related to the structure of the color field in saturated gluonic matter.

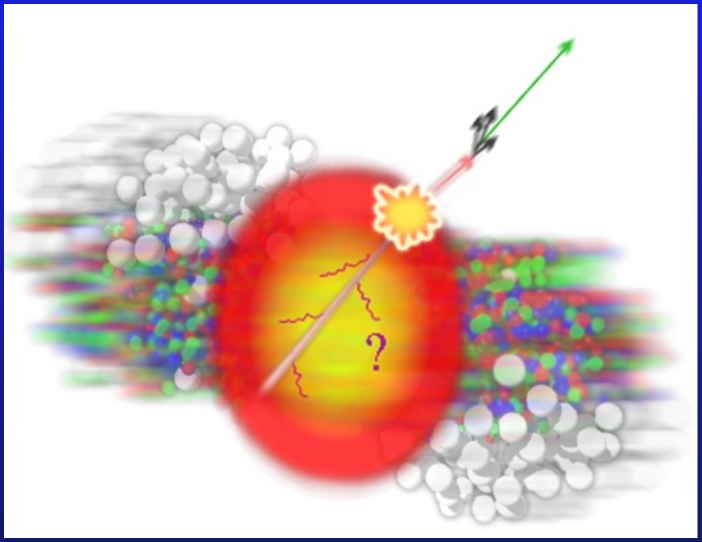


cosmic strings

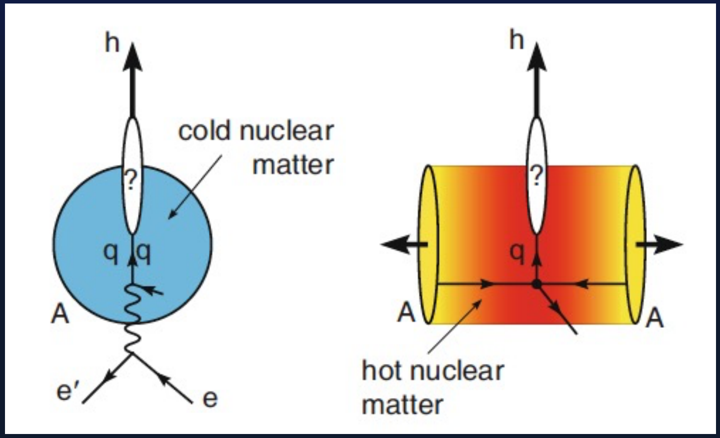


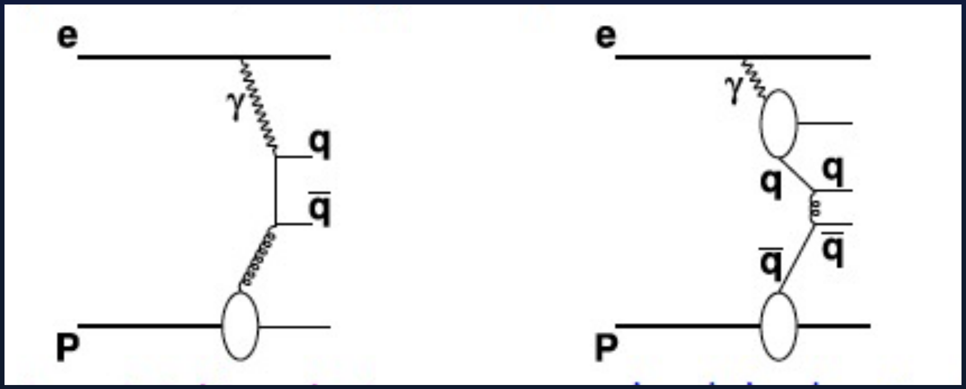
Particle jets in electron-ion and ion-ion collisions





asymmetric jet in AA collision

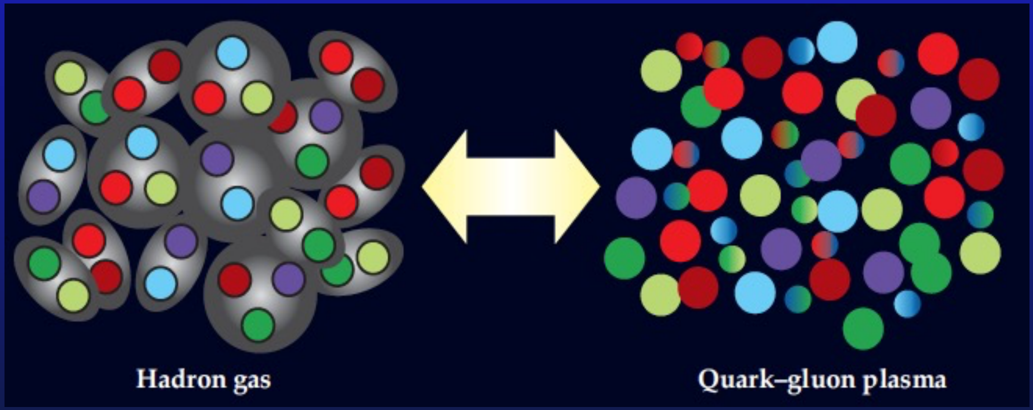


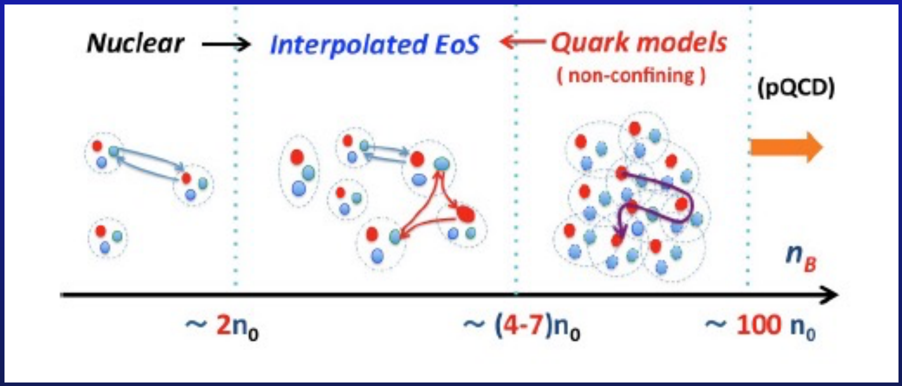


Jets probe quark and gluon distributions

Dense matter and neutron stars:

Study transition from cold nuclear matter to quark matter – vital for neutron stars.   What is energy density vs. baryon density?

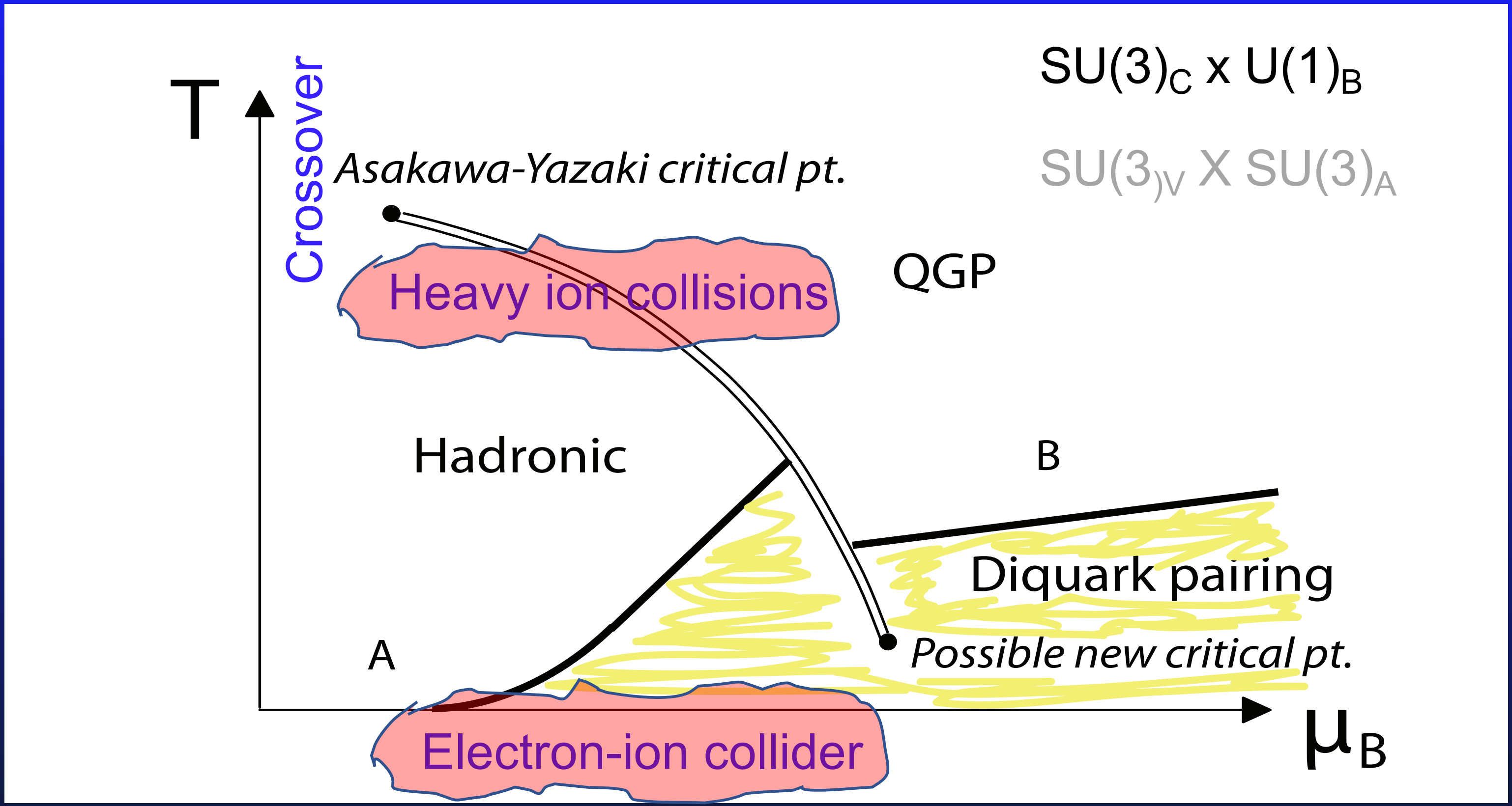




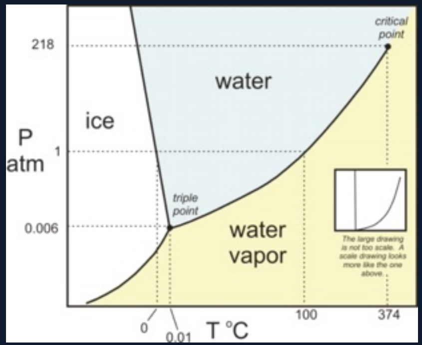
Expect "smooth" transition from nucleons to quarks

Gluon (and quark) distributions in nuclei at finer and finer scales should shed light on transition from nucleonic to quark degrees of freedom as density of matter increases.

(Can mapping of energy-momentum tensor (stress-energy tensor) in eA collisions reveal pressure vs. baryon density in dense matter?)



Critical points similar to those in liquid-gas phase diagram (H_2O). Neither critical point required!!

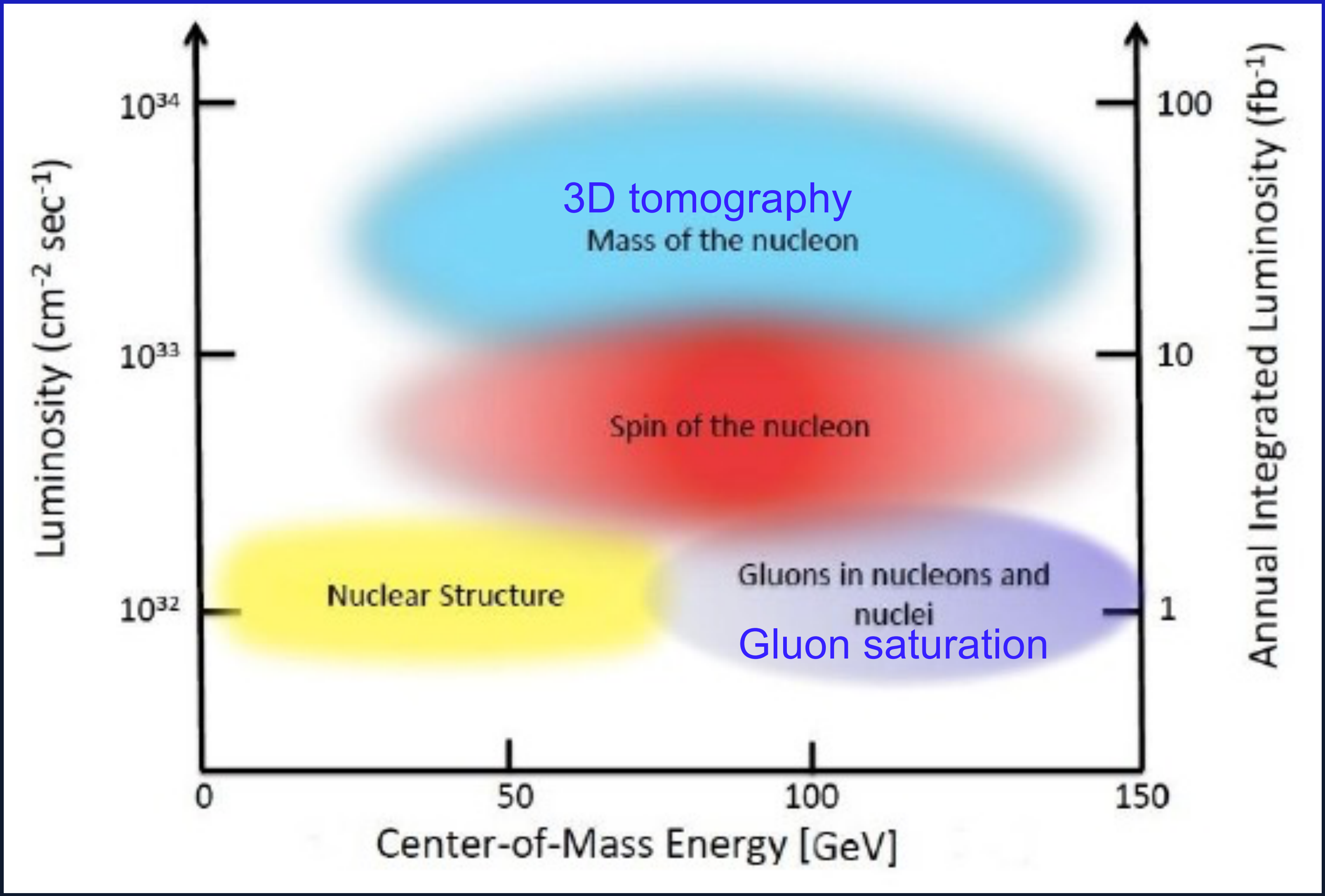


Can go continuously from A to B around the upper critical point. Liquid-gas phase transition.

In lower shaded region have BCS pairing of nucleons, of quarks, and possibly other states (meson condensates). Different symmetry structure than at higher T.

The accelerator

(electron-proton) c.m. energy - luminosity landscape



(Luminosity measures the rate of collisions: $L\sigma$ = event rate)

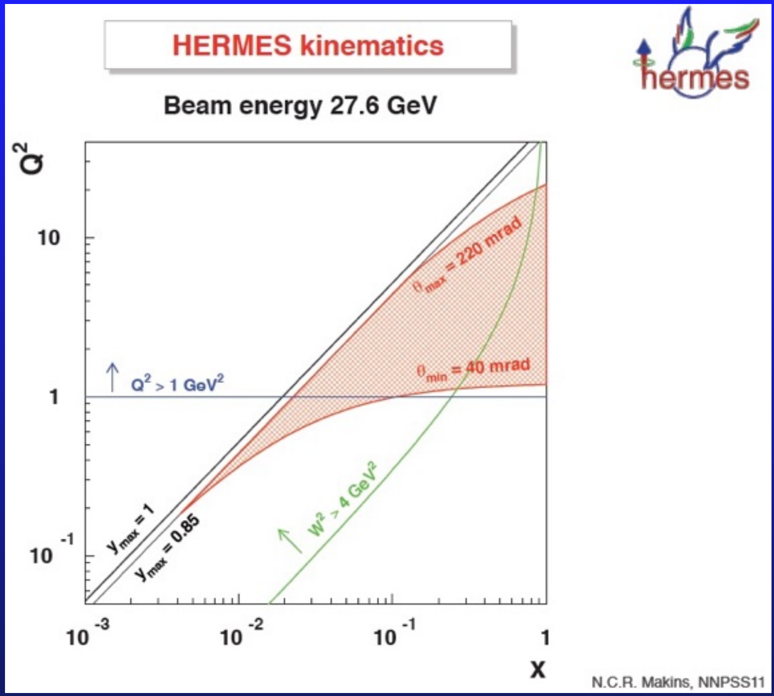
Kinematic range

$Q^2 = x(1 - E_{e'}/E_e)s \leqq x\,s$

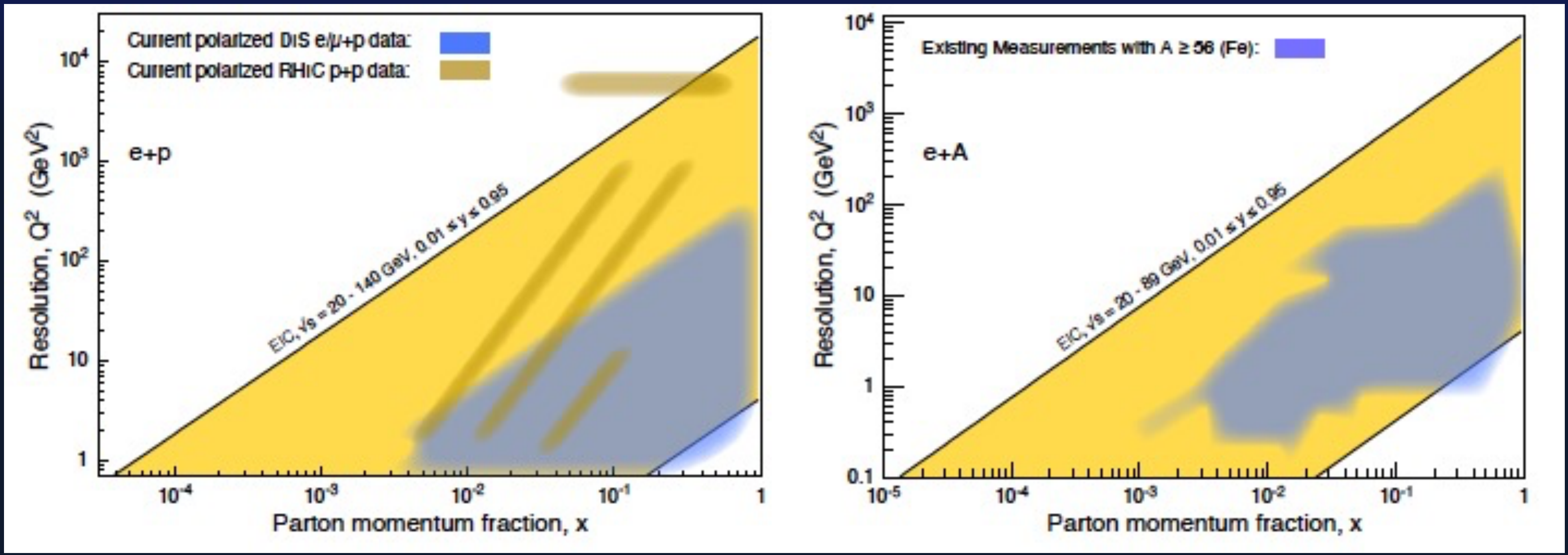
$\sqrt{s}$ = center of mass collision energy

$x \gtrsim 10^{-4}$ for $Q^2 \sim 1$ GeV^2, $\sqrt{s} \sim 100$ GeV

($Q^2 \sim 1$ GeV^2 lower limit for inelastic scattering)

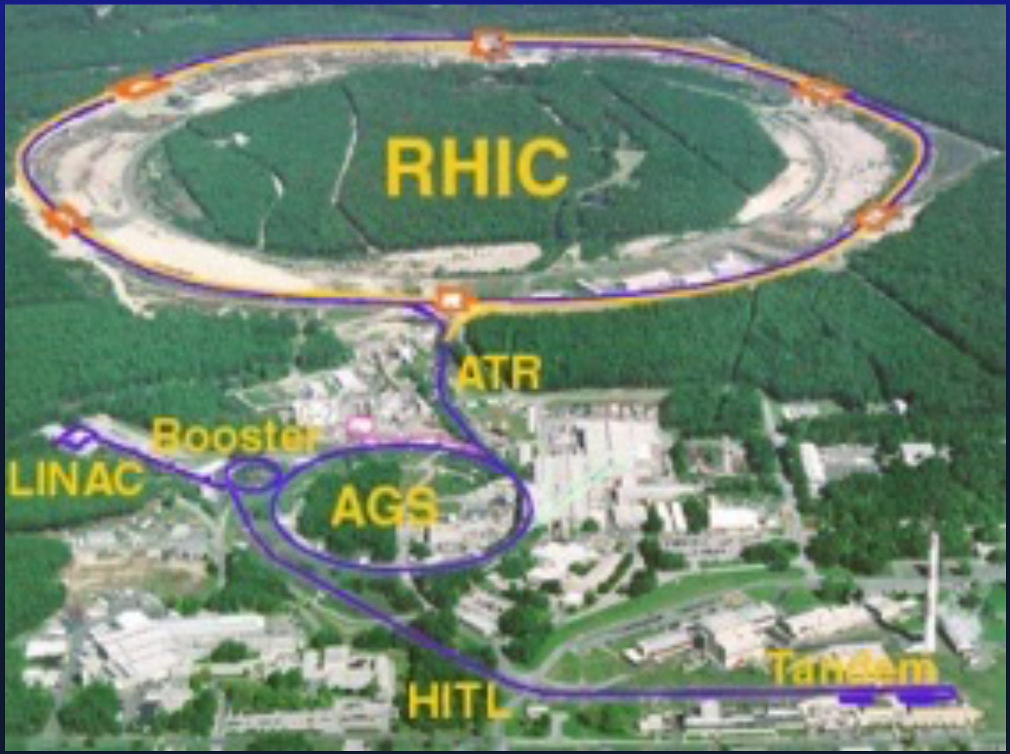


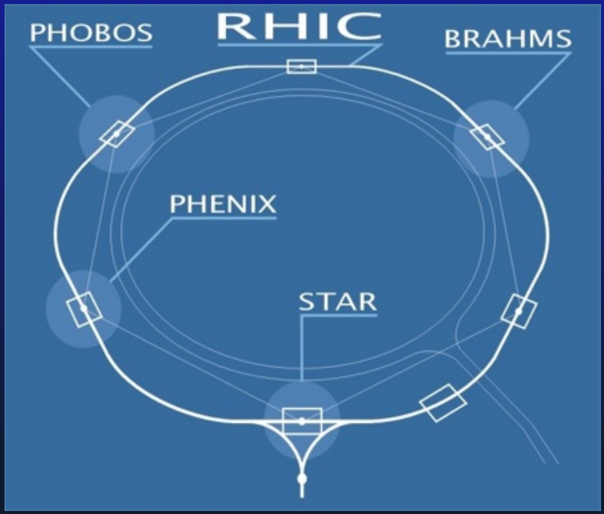
To reach small x region requires large beam energy



Relativistic Heavy Ion Collider (Brookhaven) since 2000 now becoming the EIC (joint project with Jefferson Lab)

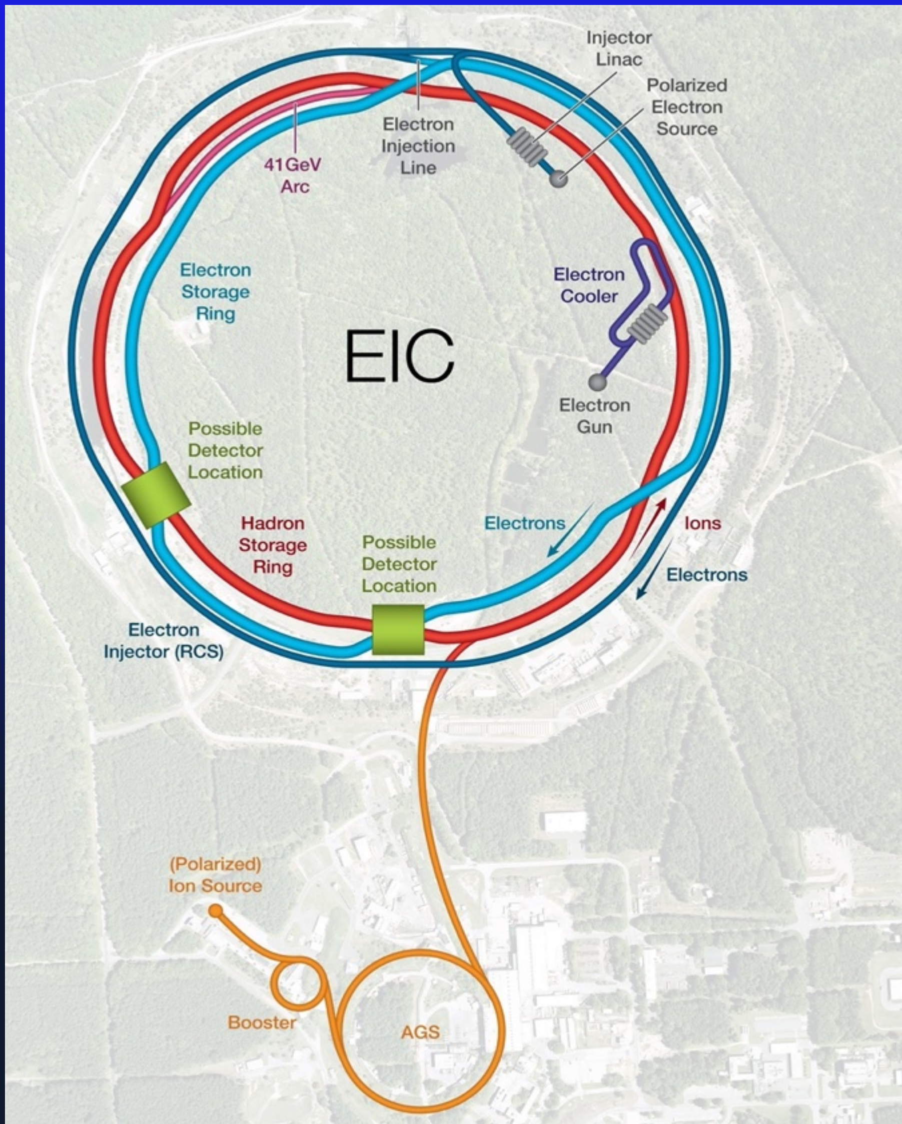
RHIC: Colliding heavy ion beams 100 GeV/A
Colliding polarized proton beams ~255 + 255 GeV





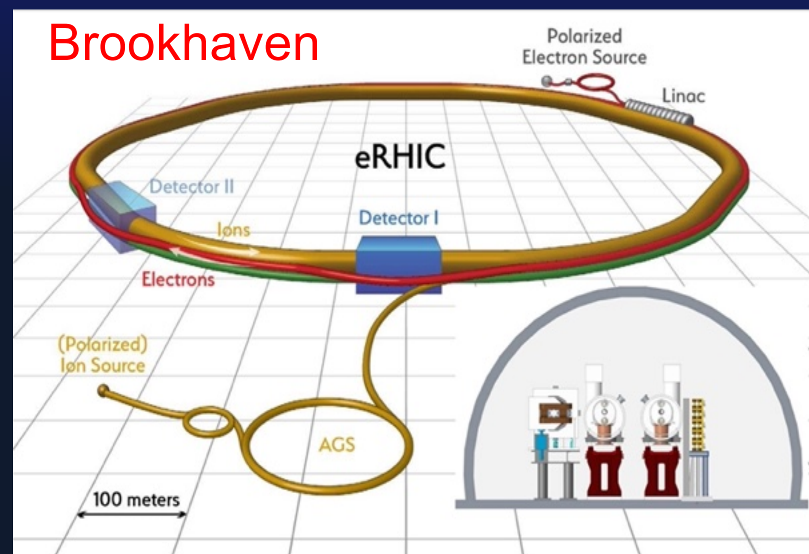
Au(197×100GeV)+Au(197×100GeV)

Brookhaven eRHIC

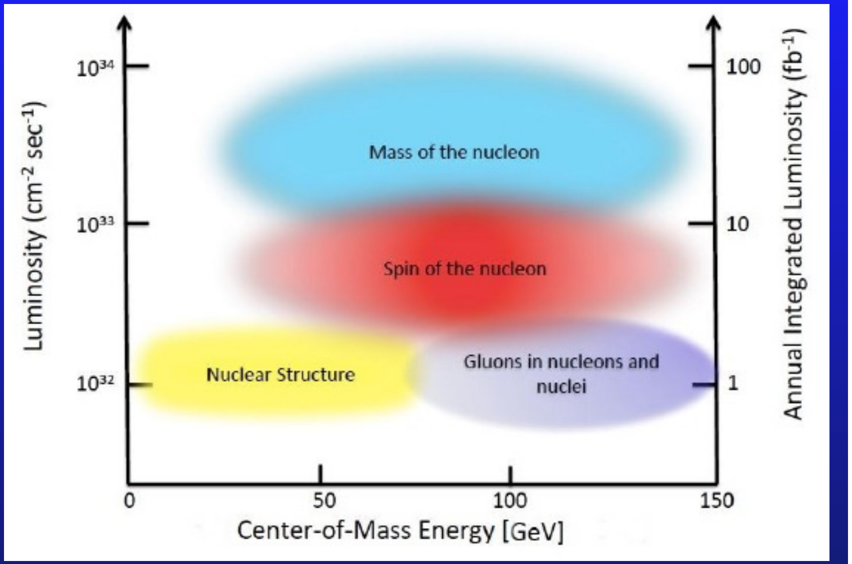


Add 5-18 GeV electron storage ring in present RHIC tunnel. Collide e with p to 275 GeV (vs 255 GeV now) and ions to 100 GeV/A in one RHIC ring.

$\sqrt{s} \simeq 2\sqrt{E_e E_p}$ = 75-140 GeV



Accelerator requirements



To map quarks and gluons -- from nuclei (quark-gluon gas) to saturated gluonic matter – designing for variable c.m. energy range from ~28 to ~120 GeV, upgradeable to 140 GeV.

Reach x down to 10^{-4}

Need ion beams from p to heavy stable nuclei: A = 1 - 208

3D imaging of gluon and sea quark distributions in nucleons and nuclei requires high luminosity:

L up to 10^{34} /cm^2 sec. (~ 10^2 -10^3 X HERA, and LHC at 2 X 10^{34})

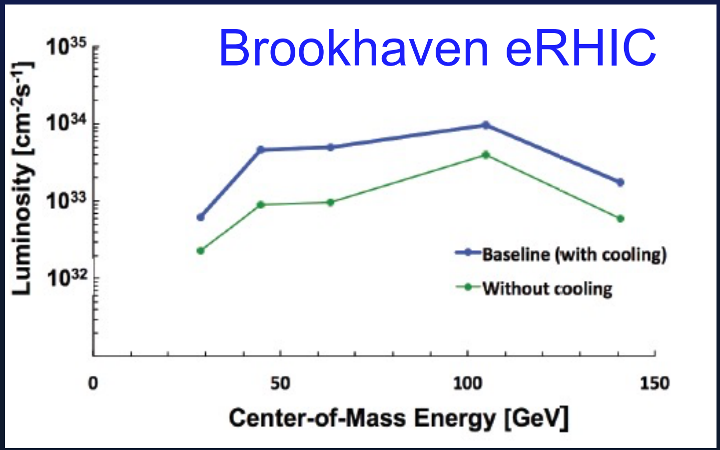
To study correlations of gluon and sea quark distributions with spin, need polarized e-, p, (and light-ion beams) each above 70%.

Two intersection regions (IP6 and IP8): allow for two detectors

Accelerator challenges

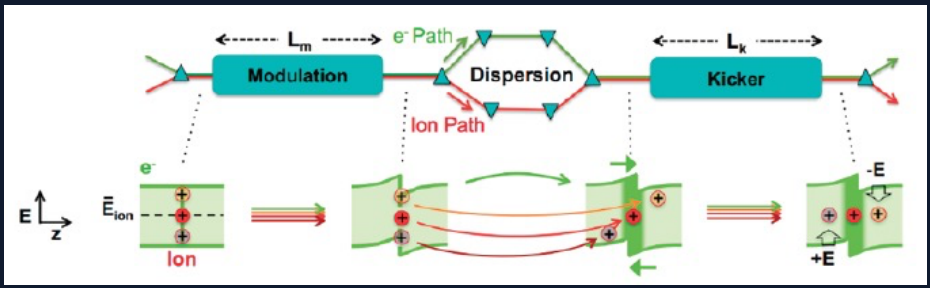
EIC accelerator requirements beyond current technology.
(only large scale accelerator project in the U.S.!)

1) High energy, spin-polarized beams colliding with high luminosity.
Polarized beams in a collider achieved only at
--HERA (polarized e^- or e^+ on unpolarized p) and at the
--Relativistic Heavy Ion Collider (RHIC - pp) with both proton beams polarized



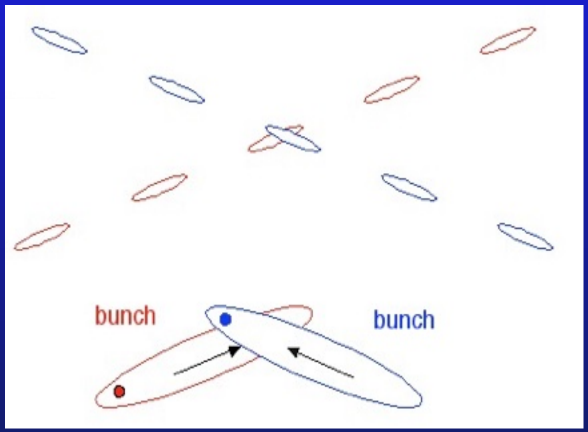
luminosity increase at eRHIC with hadron cooling

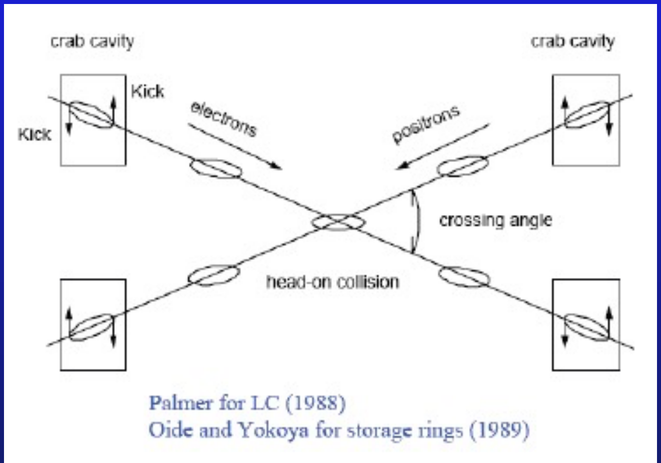
2) Require strong hadron beam cooling (focusing) to achieve high luminosity



e.g., Coherent Electron Cooling: kick slow hadrons forward, fast ones backward

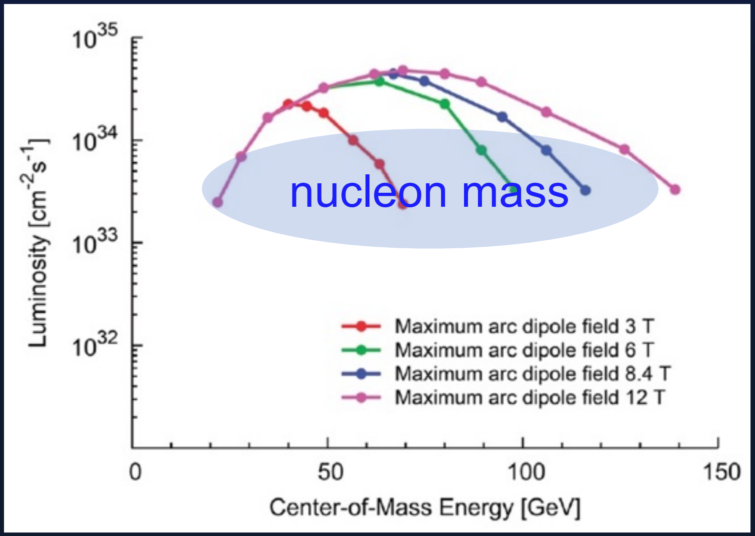
3) Intersection region design: Crab crossings
(beam walking sideways) to maximize collisions





Instead of bunches crossing at an angle, turn them parallel when they collide parallel.   At KEK-B (e^+e^-), but never used in hadron beams.

4) Magnet technology

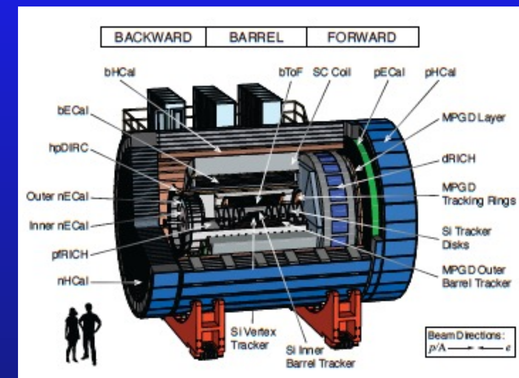


luminosity and cm e-p energy vs magnetic fields. Red curve ~ 10 GeV e +100 GeV p

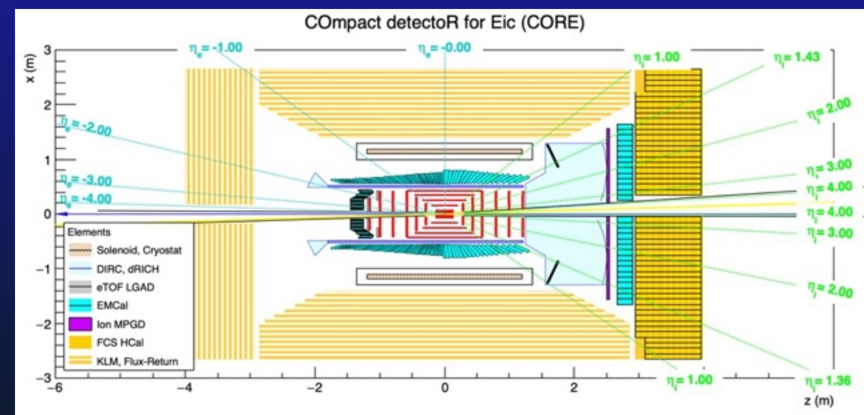
Detectors

Three proposed detectors at IP6:
Possibly a second detector in the future

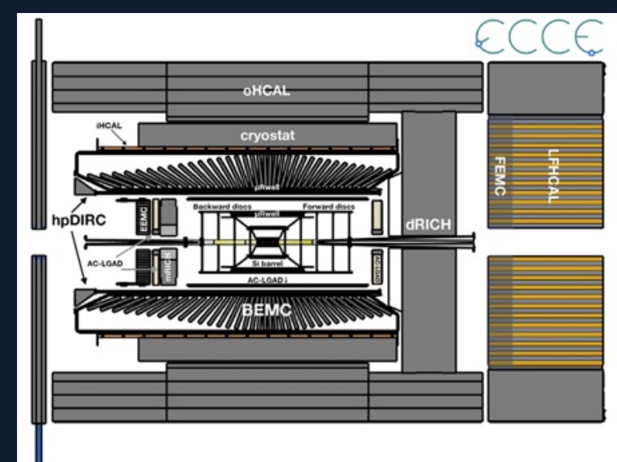
ATHENA (A Totally Hermetic Electron Nucleus Apparatus) *J. Adam et al. J. Instrument. 17, P10019 (2022)*



CORE - a COmpact detectoR for the EIC (arXiv:2209.00496)

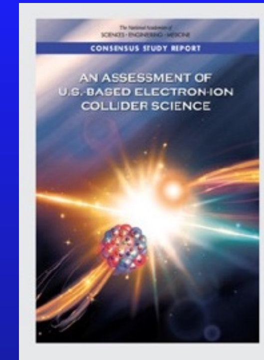


ECCE - EIC Comprehensive Chromodynamics Experiment (arXiv:2209.02580)



EPIC (Electron Proton/Ion Collisions)
collaboration finalizing detector design.
Second detector working group formed

Timeline of EIC

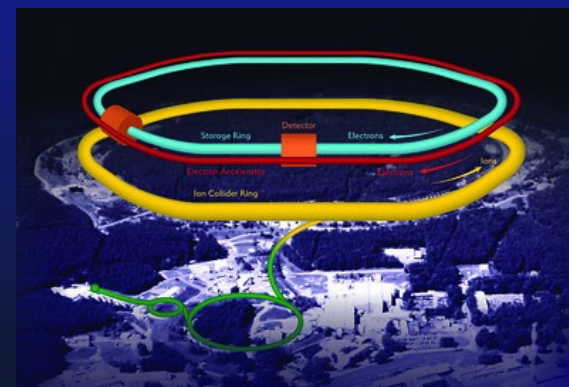


Summer 2018: National Academy of Sciences report issued

Sept 2019: EIC enters U.S. budget

Dec. 19. 2019:   Department of Energy first approval (CD-0)

Jan. 9, 2020: Site selection -- Brookhaven



June 2021: Preliminary plan approved (CD-1)

April 2024: CD-3A approved.
"Construction procurement"

April 2025   Approval of final plan (CD-2/3)
(RHIC shutdown June 2025)

Early 2030's: Beams!!
(CD-4)

Department of Energy (DOE) approval steps

PROJECT ACQUISITION PROCESS AND CRITICAL DECISIONS					
Project Planning Phase		Project Execution Phase			Mission
Preconceptual Planning	Conceptual Design	Preliminary Design	Final Design	Construction	Operations
CD-0 Approve Mission Need	CD-1 Approve Preliminary Baseline Range	CD-2 Approve Performance Baseline	CD-3 Approve Start of Construction	CD-4 Approve Start of Operations or Project Closeout	

どうもありがとう

[redacted]