The Electron-Ion Collider

Lecture 2

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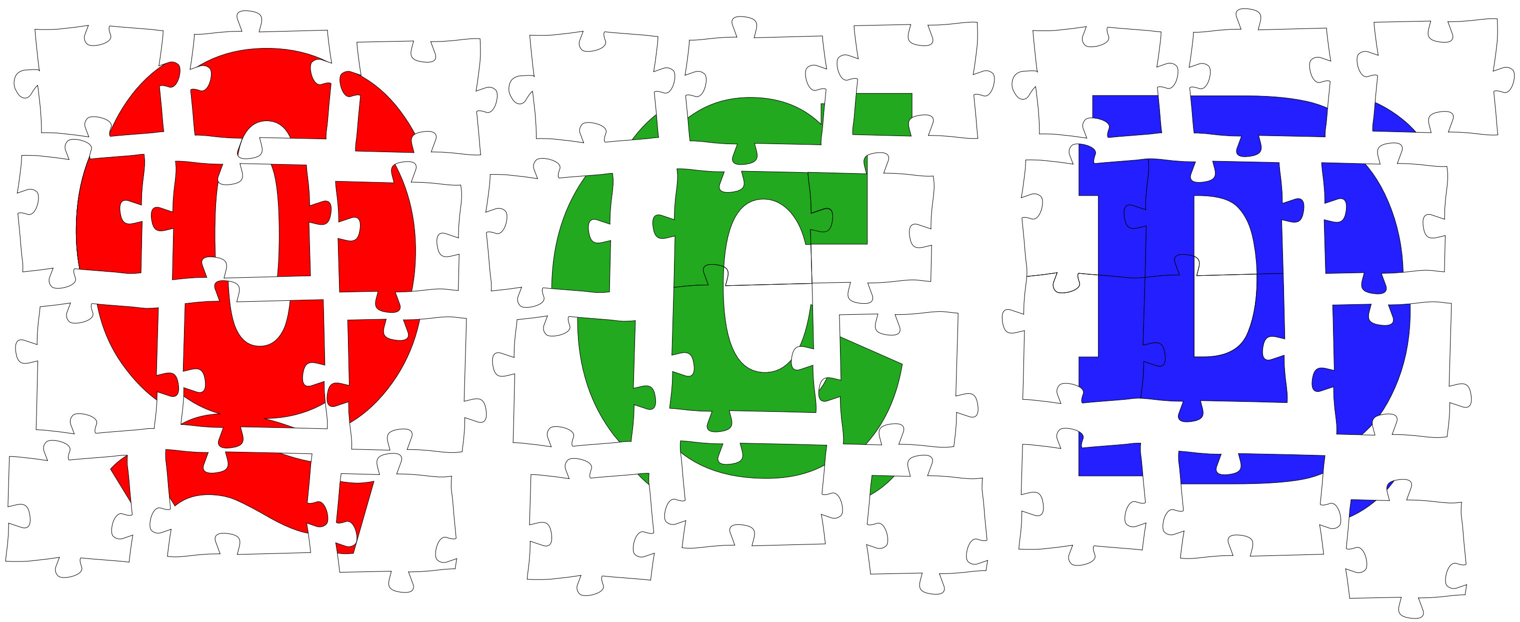
Yale BROOKHAVEN NATIONAL LABORATORY

Outline (Lecture 1)

4. The Frontiers of Our Ignorance
   4.1. Mass
   4.2. Cross-Sections
   4.3. Saturation
   4.4. Spin Puzzle
   4.5. Imaging
   4.6. Fragmentation
5. Landscape of QCD
6. Big question and what we need to answer them
7. Realization of an EIC
8. Closing comments and further reading

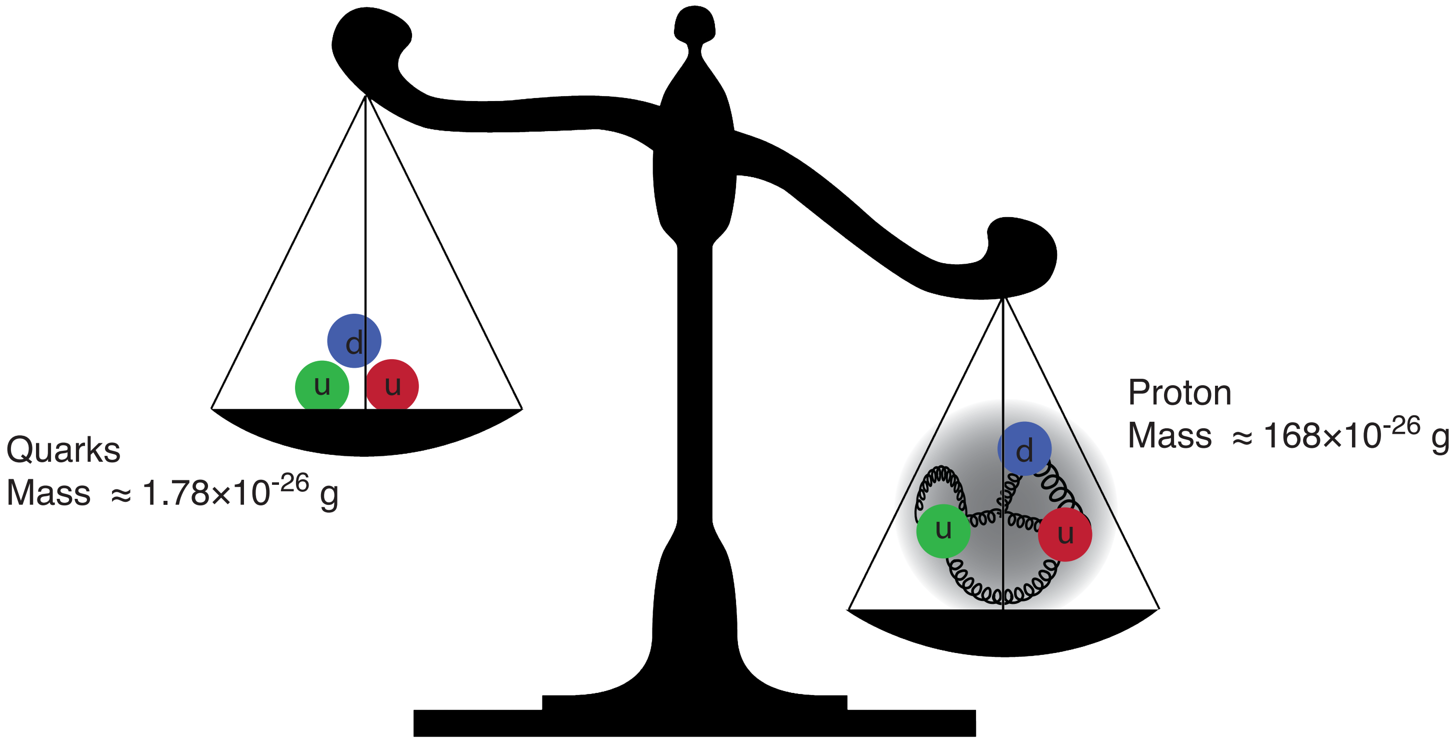
4. The Frontiers of Our Ignorance



... that motivate an Electron-Ion Collider

The Mass Puzzle

The Higgs is responsible for quark masses
~ 2% of the proton mass.



Gluons are massless…yet their dynamics are responsible for (nearly all) the mass of visible matter. We do not know how?

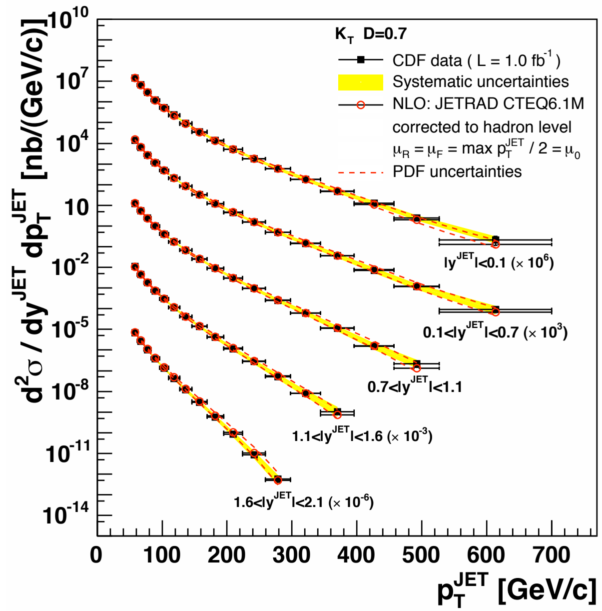
Scattering in the Strong Interactions

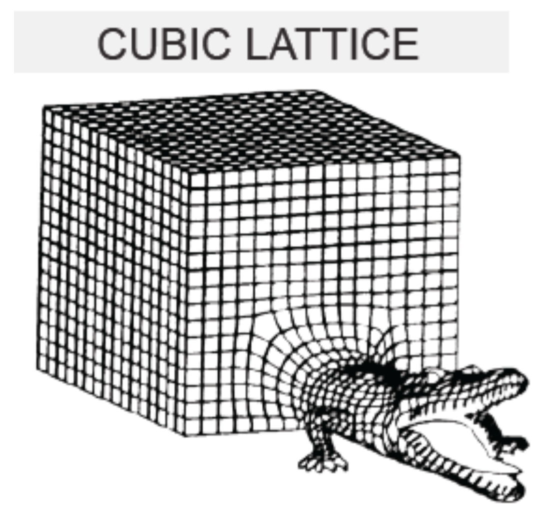
Perturbative QCD:

- Describes only a small part of the total cross-section

Lattice QCD:

- First principles treatment of static properties of QCD: masses, moments, thermodynamics
- Very challenging for dynamical processes and very limited utility in describing scattering



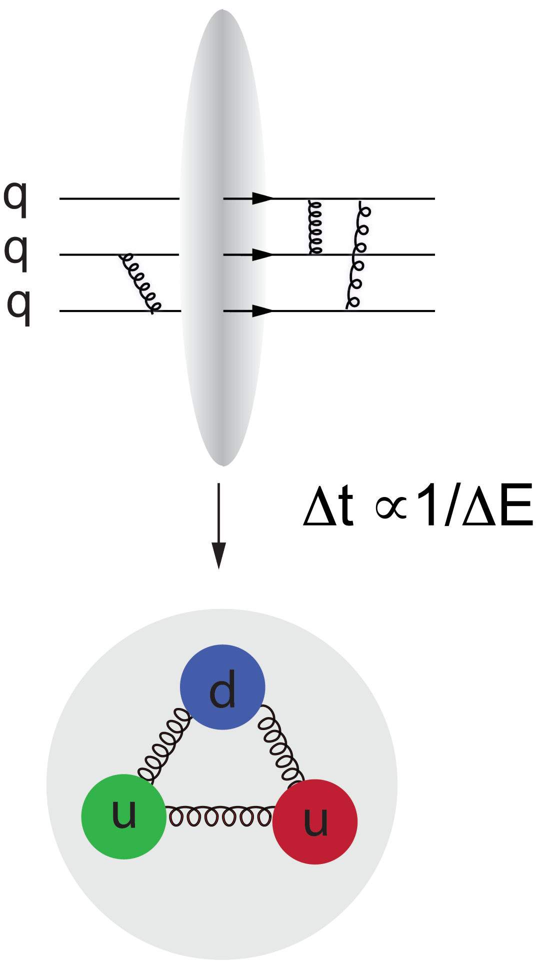


Instead ⇒ Effective theories:

- How do quark and gluon degrees organize themselves to describe the bulk of the cross-section?

A Look Inside the Boosted Proton

(1)



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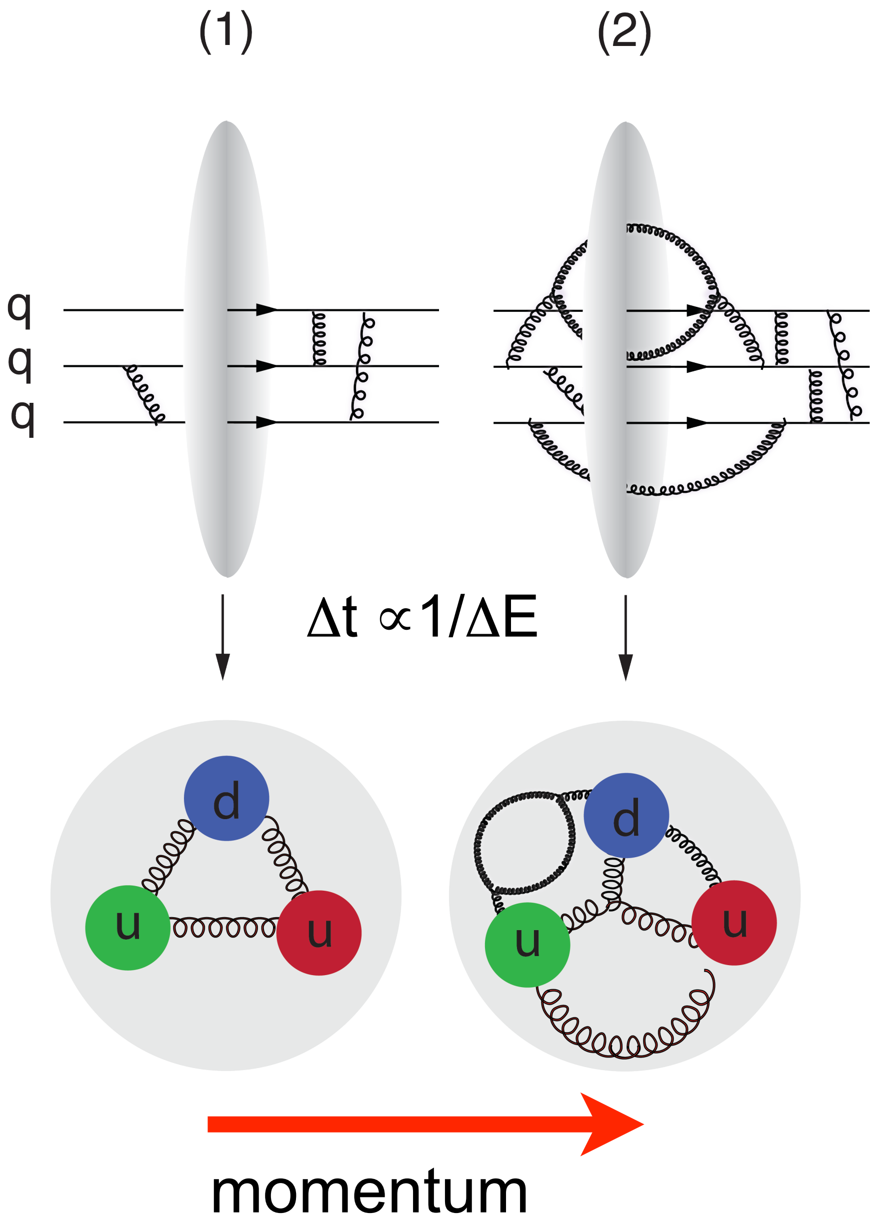

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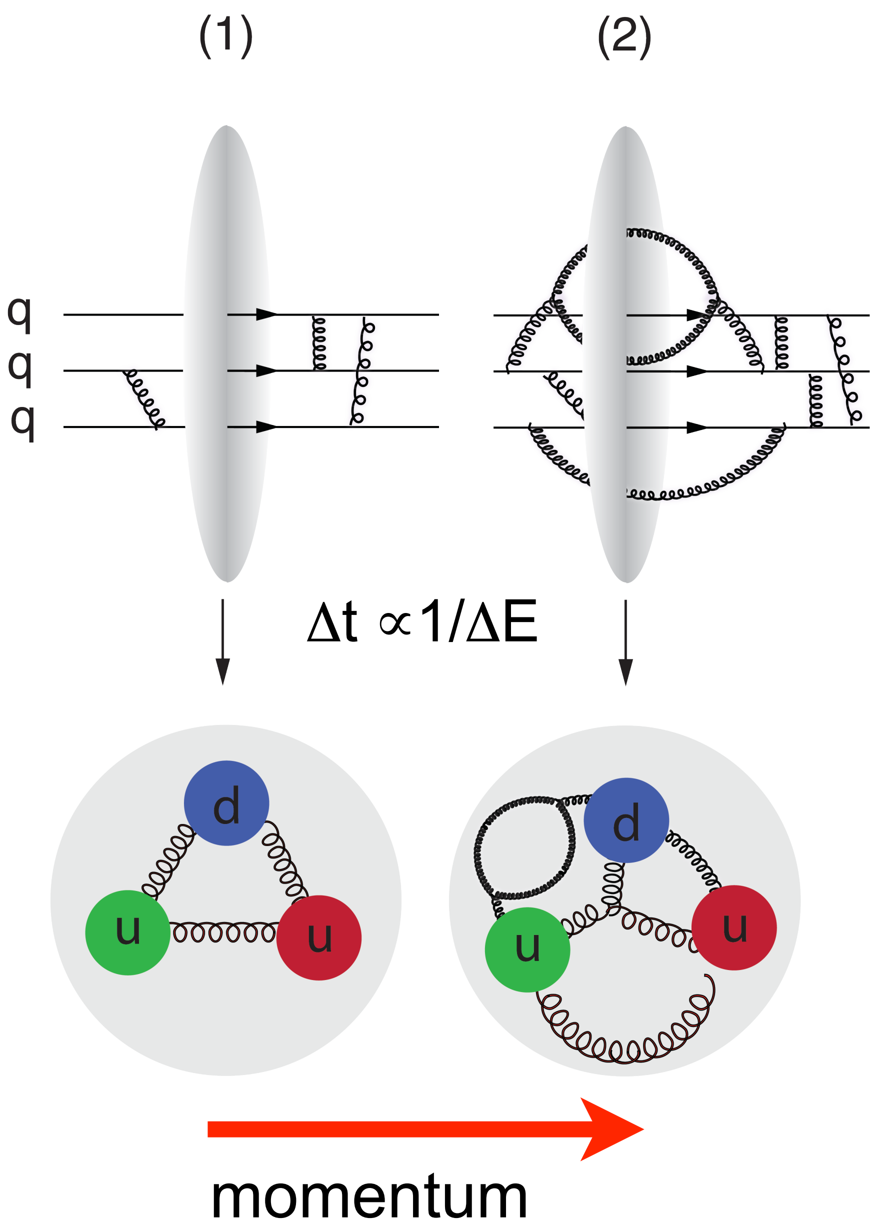

In QCD, the proton is made up of quanta that fluctuate in and out of existence

- Boosted proton:
  - Fluctuations time dilated on strong interaction time scales
  - Long lived gluons can radiate further small x gluons…
  - Explosion of gluon density

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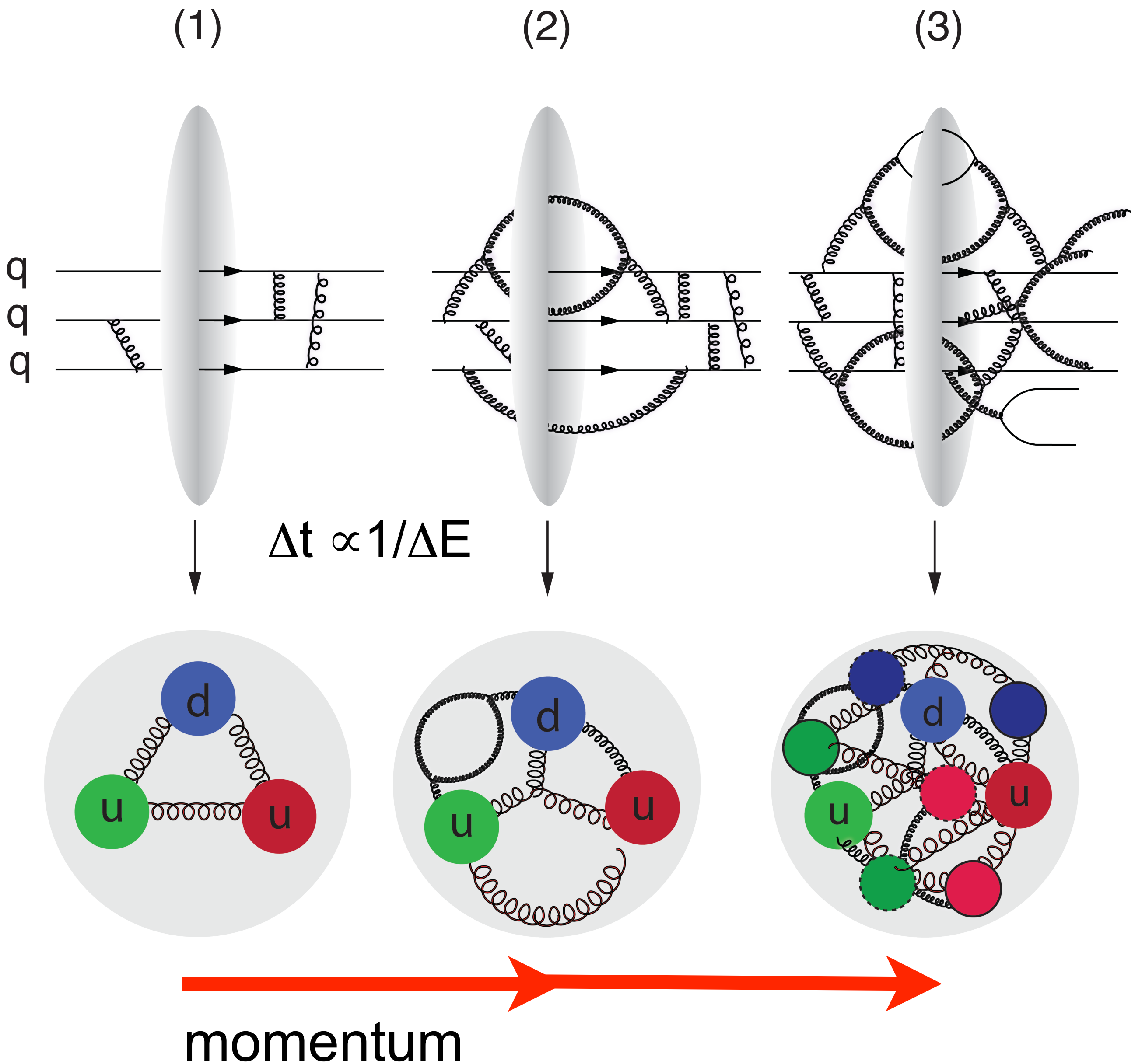

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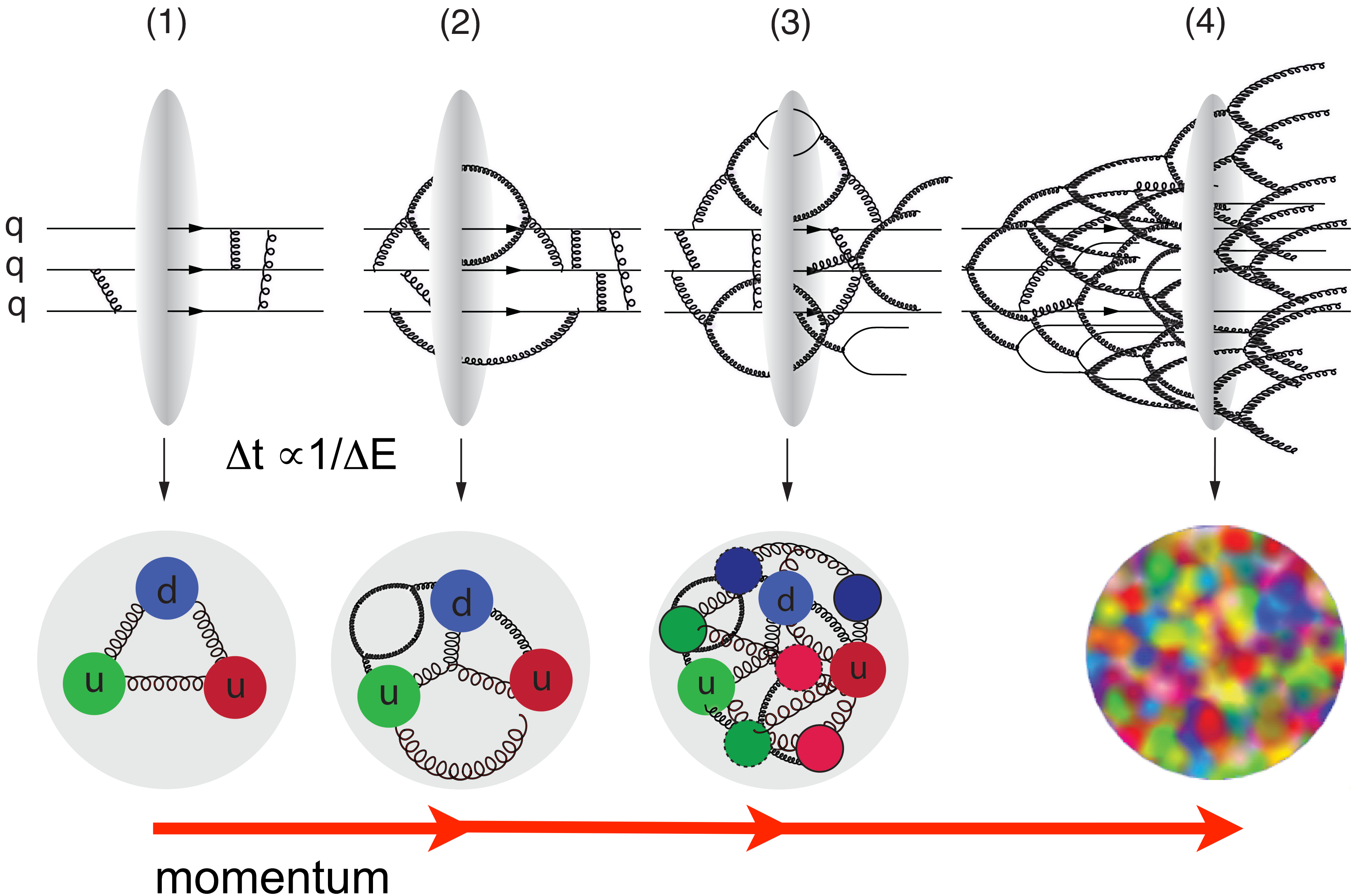

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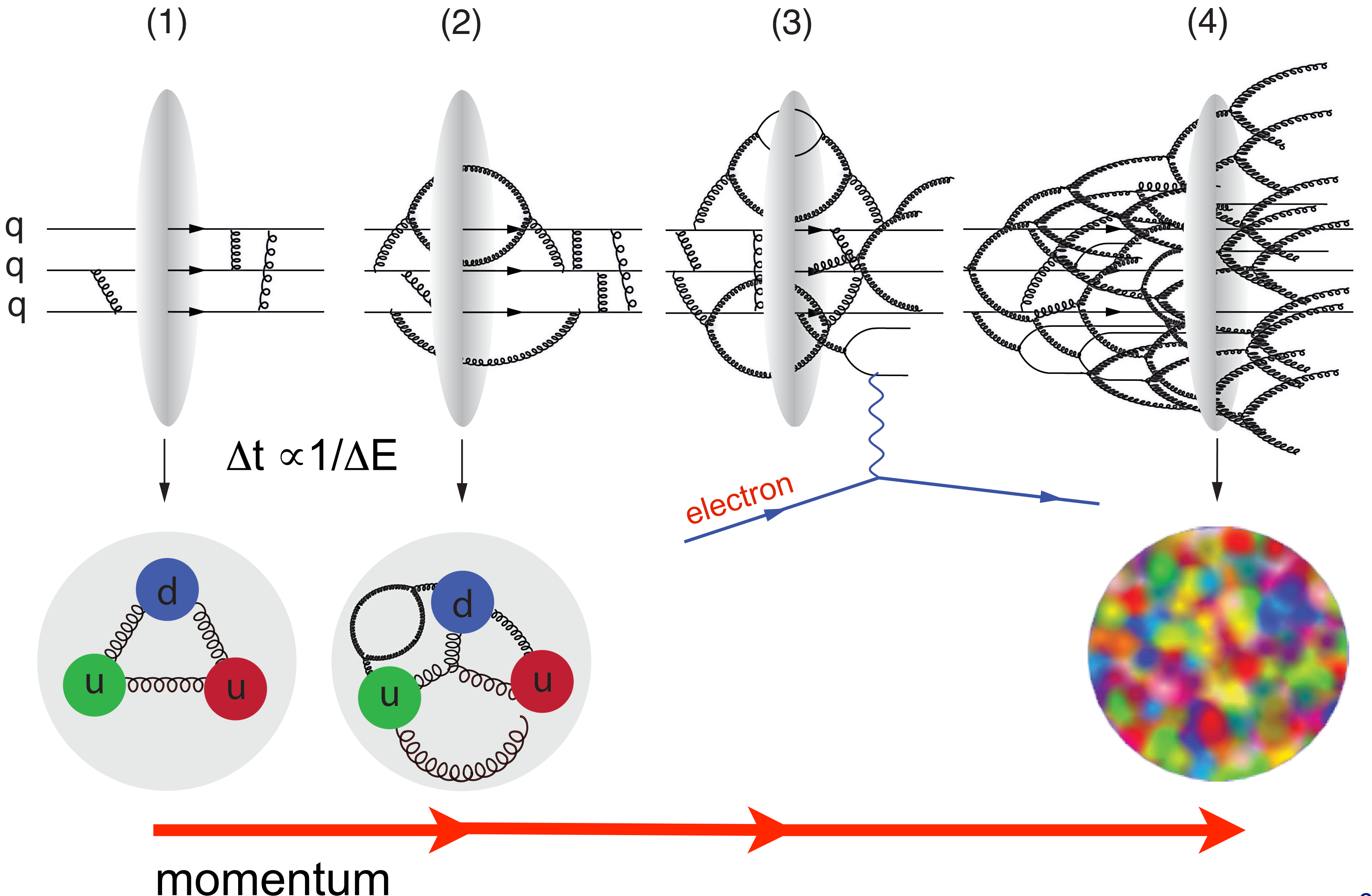


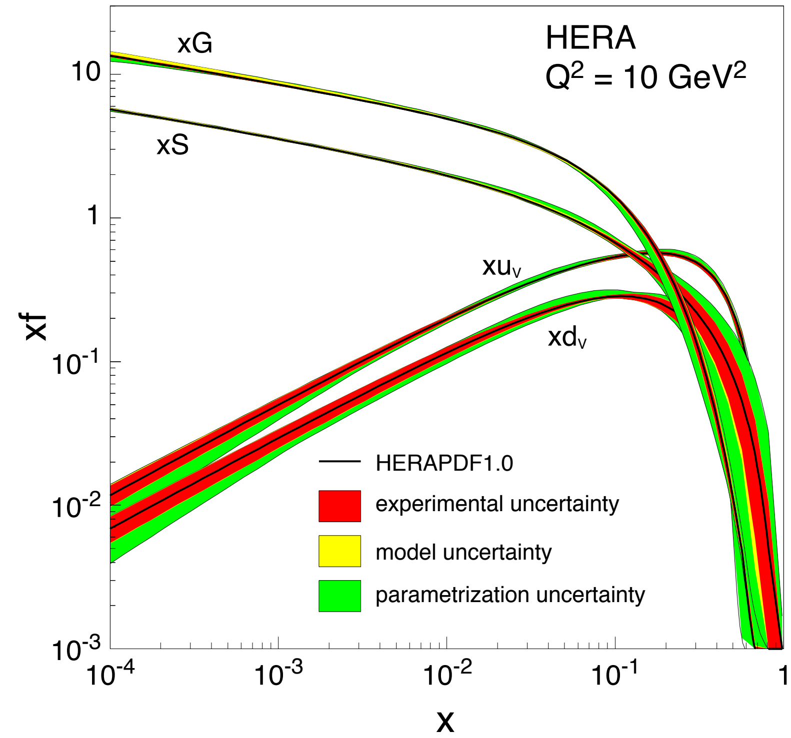
A Look Inside the Boosted Proton

momentum

Issues with our Current Understanding

Linear DGLAP Evolution Scheme

- built in high energy "catastrophe"
- G rapid rise violates unitary bound



Linear BFKL Evolution Scheme

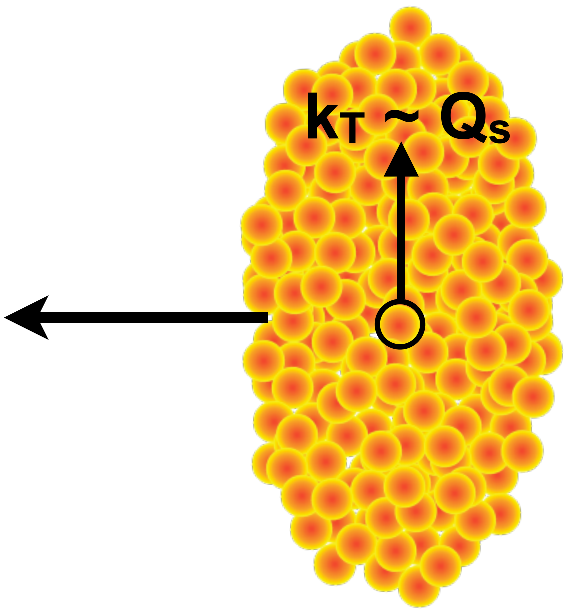
- Density along with σ grows as a power of energy
- Can densities & σ rise forever?
- Black disk limit: $\sigma_{total} \leq 2\pi R^2$

Something's wrong:
Gluon density is growing too fast
⇒ Must saturate (gluons recombine)

What's the underlying dynamics? Need New Approach

Gluon Saturation

In transverse plane: nucleus/ nucleon densely packed with gluons



McLerran-Venugopalan Model:

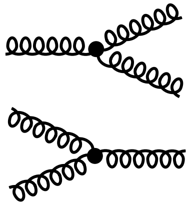
- Weak coupling description of the wave function
- Gluon field $A_\mu \sim 1/g \Rightarrow$ gluon fields are strong classical fields!
- Most gluons $k_T \sim Q_S$

New Approach: Non-Linear Evolution:

- At very high energy: recombination compensates gluon splitting
- Cross sections reach unitarity limit ⇒ saturation
- Needs new evolution equations (JIMWLK/BK)
- Saturation regime characterized by $Q_s(x,A)$

BFKL:

BK adds:



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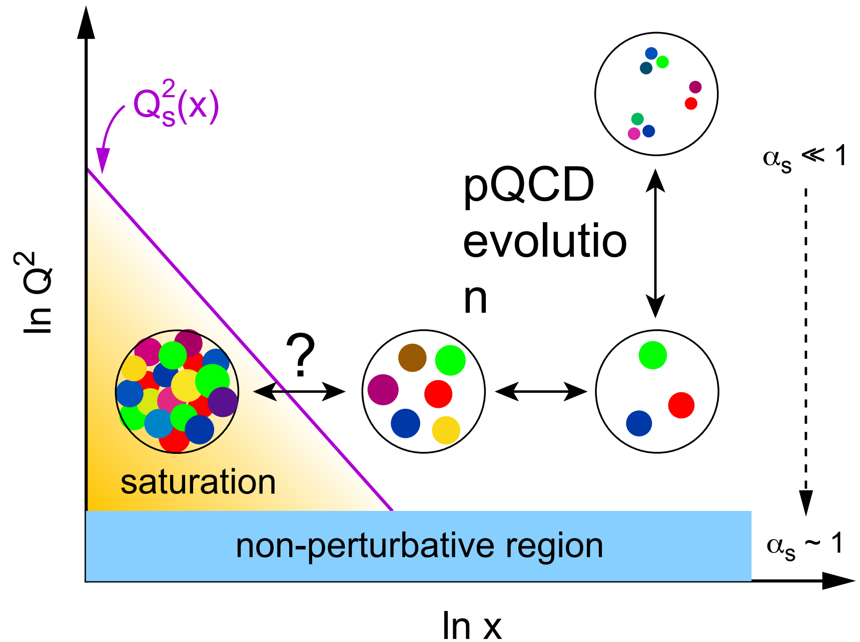

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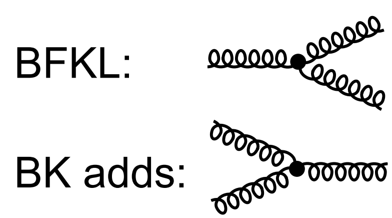
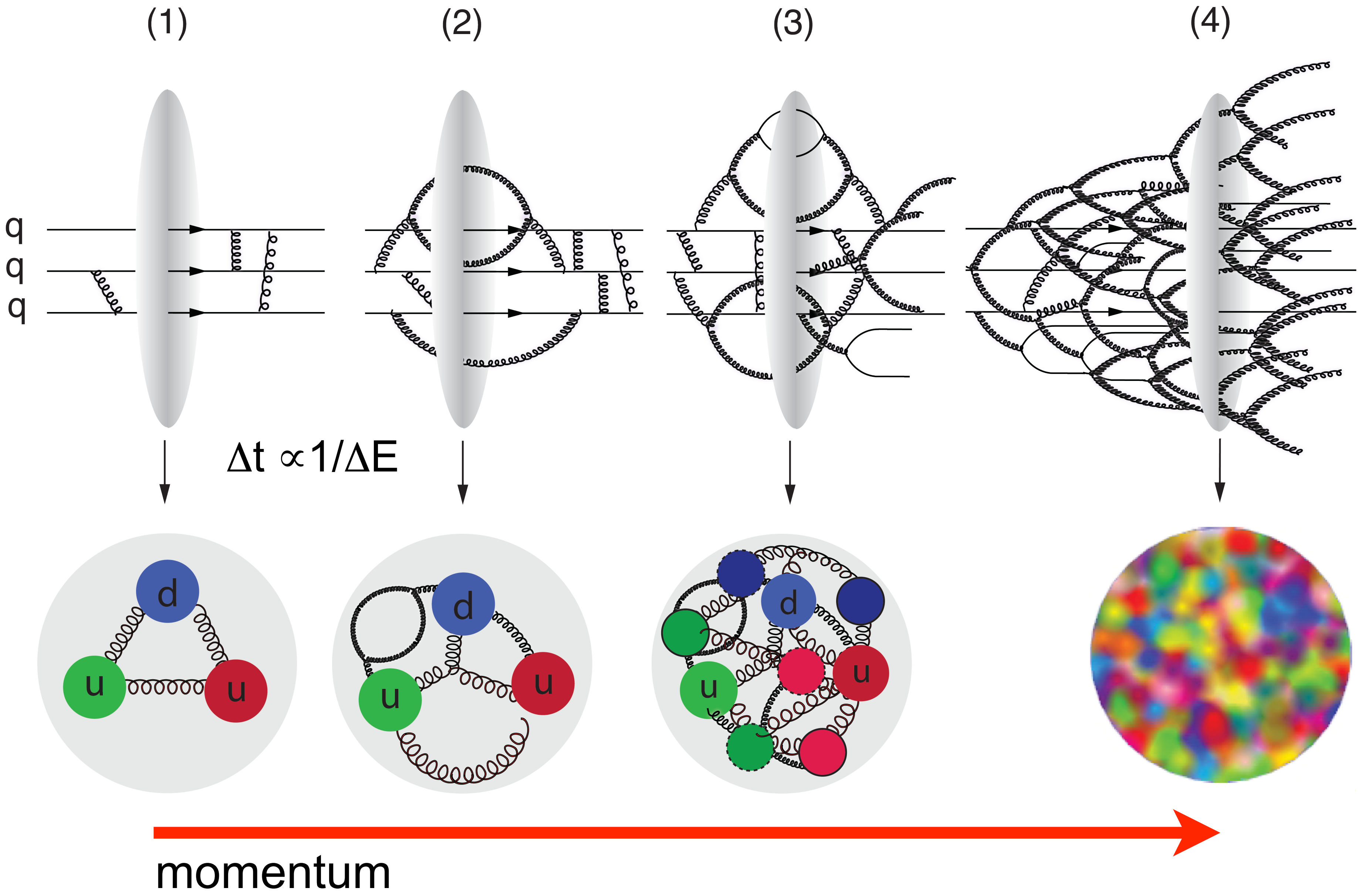


Color Glass Condensate (CGC)

- The saturated regime is called a Color Glass Condensate
  - "Color" in the name refers to the color charge of quarks and gluons
  - “Glass” is borrowed from the term for silica and other materials that are disordered and act like solids on short time scales but liquids on long time scales. In the CGC the gluons themselves are disordered and do not change their positions rapidly because of time dilation.
  - "Condensate" means that the gluons have a very high density (there is some speculation if the CGC is a BEC)
- The effective theory that describes the CGC is also called the CGC (just to confuse you)
- The CGC evolution equation is called JIMWLK and it’s mean field equivalent BK (replacing BFKL)

A Look Inside the “Saturated” Proton



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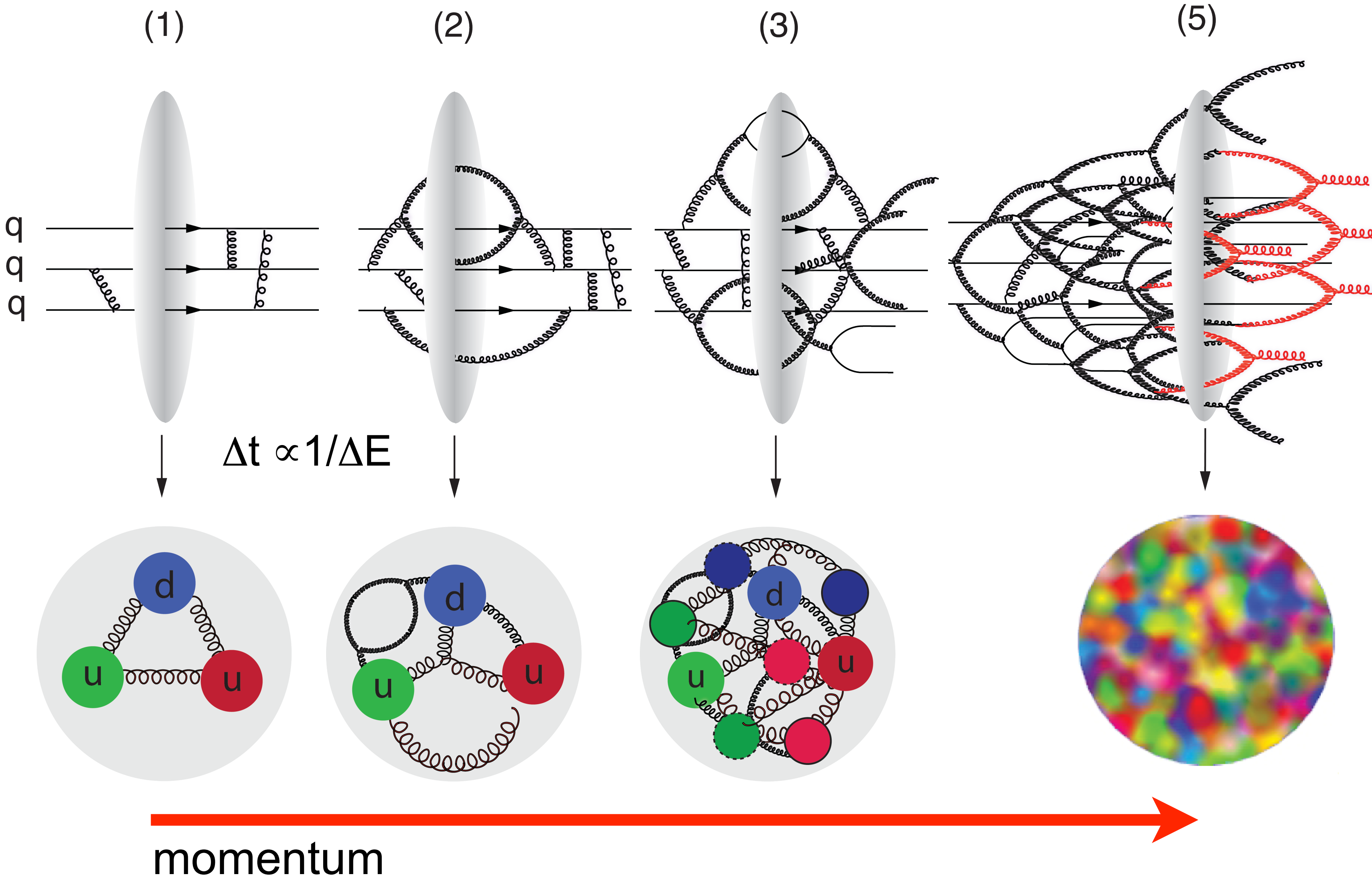

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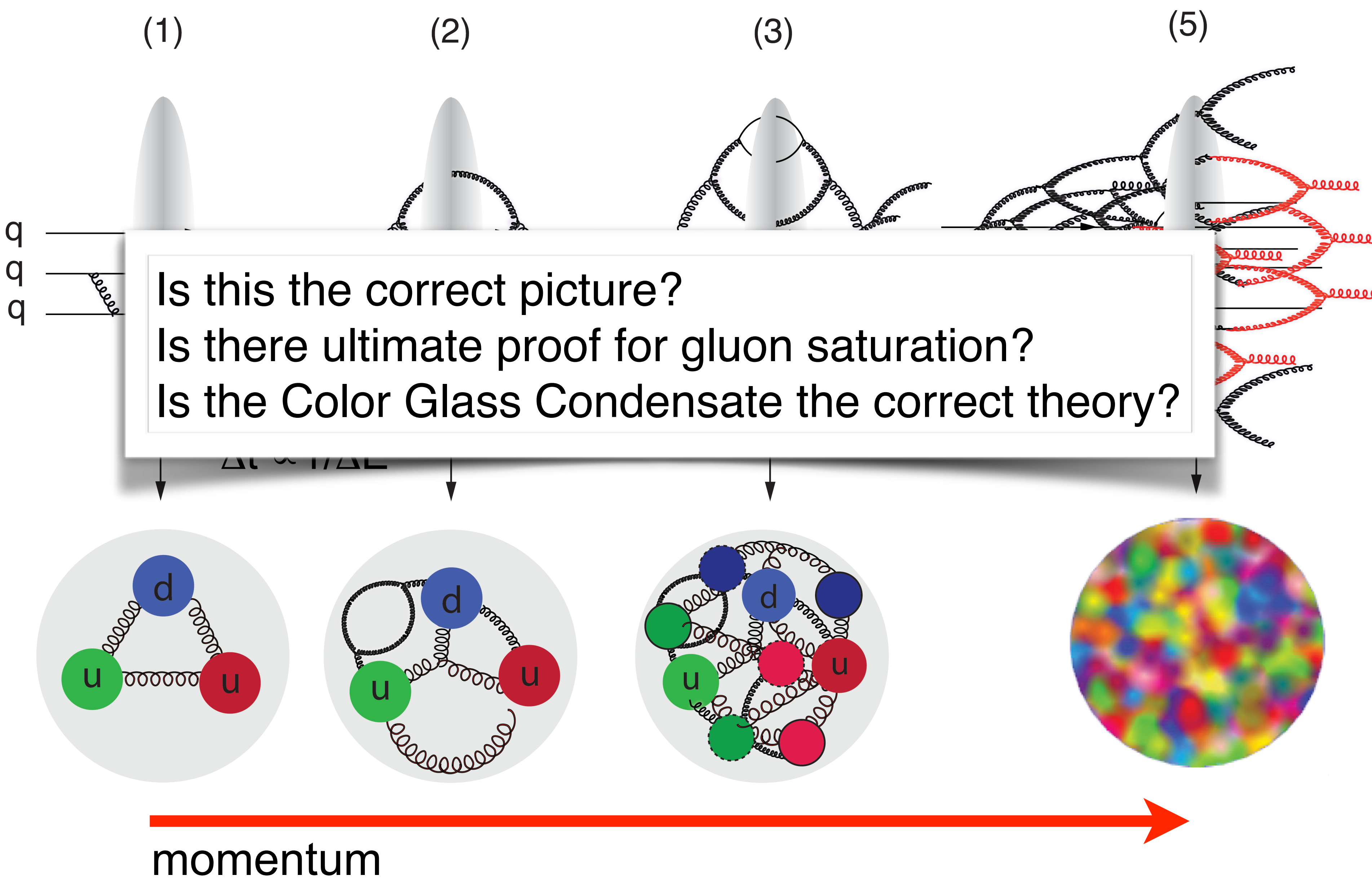
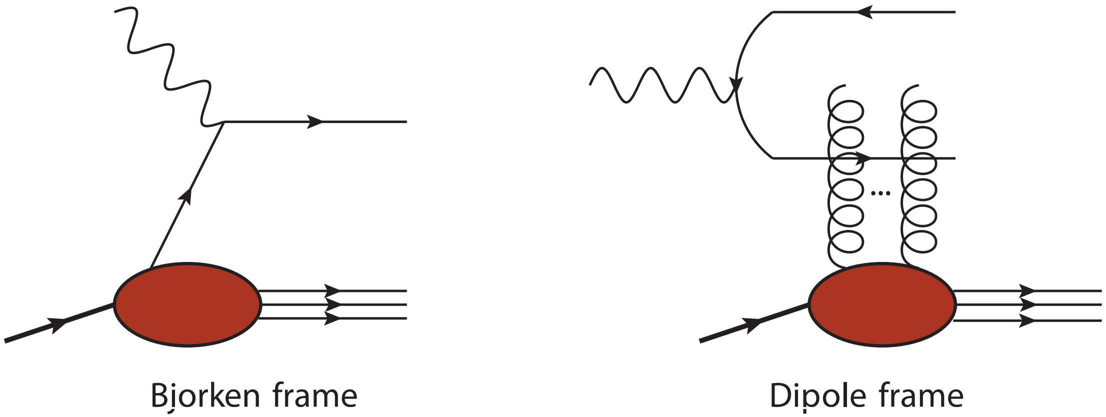
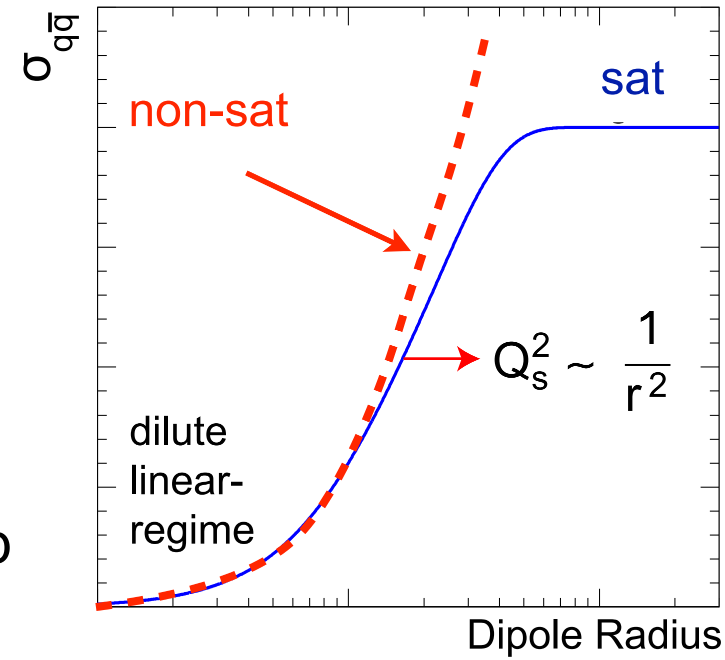


Is this the correct picture?
Is there ultimate proof for gluon saturation?
Is the Color Glass Condensate the correct theory?

N.B.: Important Dual Description of DIS





- Bjorken frame: Partonic picture of a hadron is manifest. Saturation shows up as a limit on the occupation number of quarks and gluons.

- Dipole frame: Partonic picture is no longer manifest. Saturation appears as the unitarity limit (black disk) for scattering. Convenient to resum the multiple gluon interactions.

Dipole frame commonly used to describe diffractive processes
[A. Mueller, 01; Parton Saturation-An Overview]

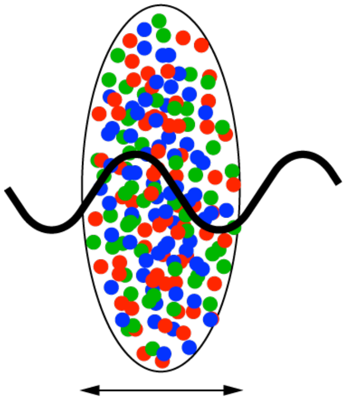
Nuclear Oomph

Scattering of electrons off nuclei:

Probes interact over distances $L \sim (2m_N x)^{-1}$

For $L > 2\,R_A \sim A^{1/3}$ probe cannot distinguish between nucleons in front or back of nucleon

Probe interacts ***coherently*** with all nucleons

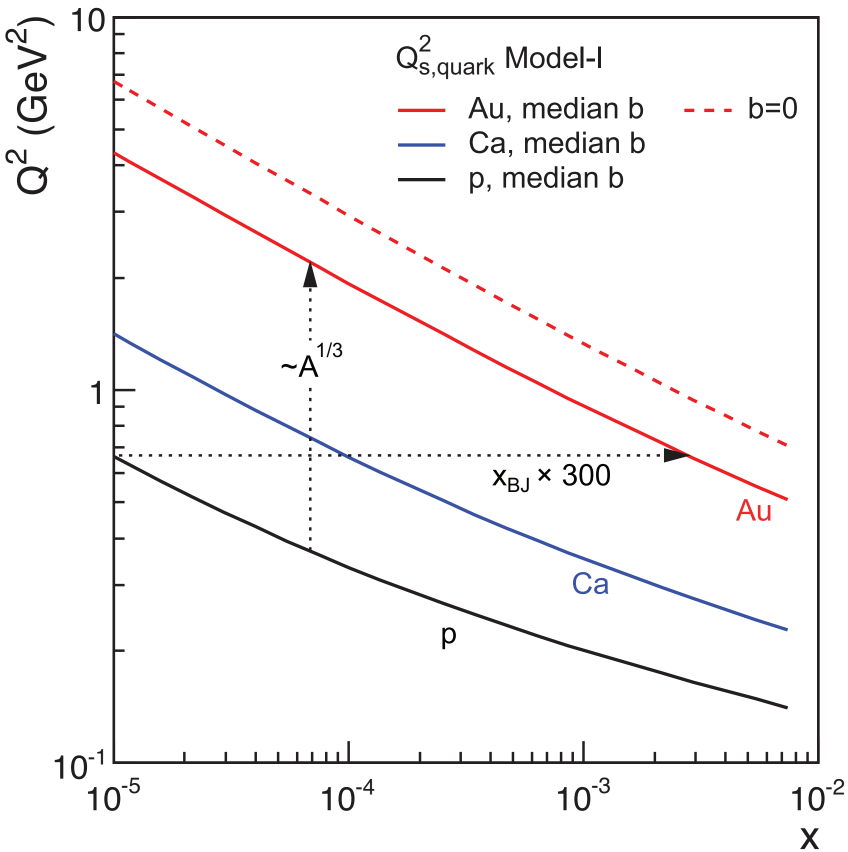


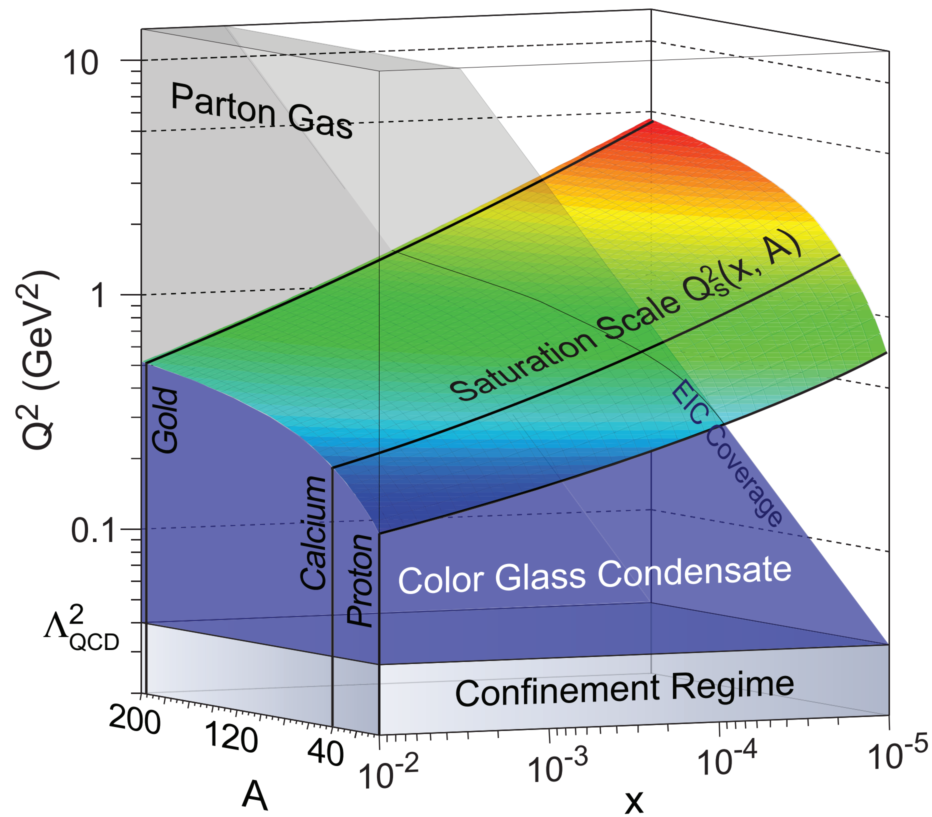
$$Q_s^2 \sim \frac{\alpha_s\, xG(x,Q_s^2)}{\pi R_A^2} \qquad \text{HERA}: \; xG \sim \frac{1}{x^{0.3}} \qquad \text{A dependence}: \; xG_A \sim A$$

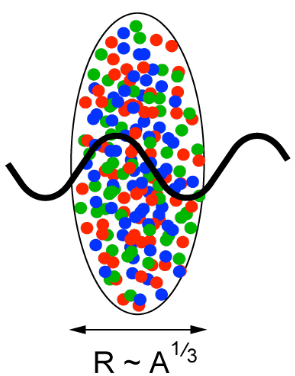
"Expected"
Nuclear Enhancement Factor
(Pocket Formula):

$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

Enhancement of Saturation Scale







$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

Enhancement of Q_S with A:

saturation regime reached at significantly lower energy in nuclei (and lower cost)

Some Interesting Ideas

- Conjecture I:
  - at very low-x all hadrons $Q_S(x)$ becomes equal for nucleons, nuclei, mesons, baryons …
  - maybe even for photons (more later)
  - truly **universal** regime

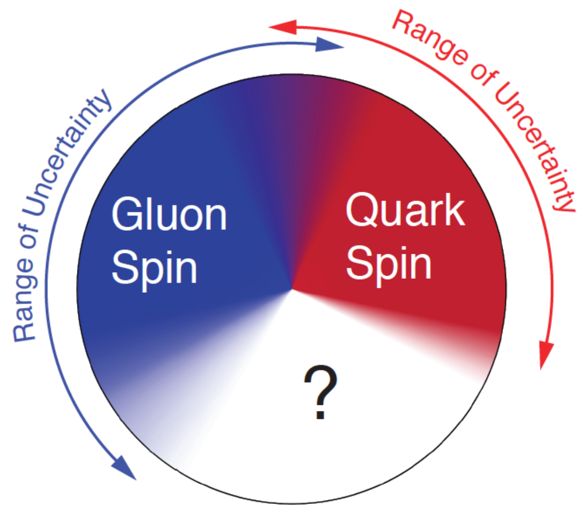
- Conjecture II:
  - as $Q_s(x)$ grows towards small-x, Q_s becomes the largest scale, hence $\alpha_s(Q^2) \rightarrow \alpha_s(Q_s^2)$
  - end of the line for α_s (as long as $Q < Q_s$) ?

Physics at extreme low-x appears to be a wonderland. Experimentally we might not get there in our life time.

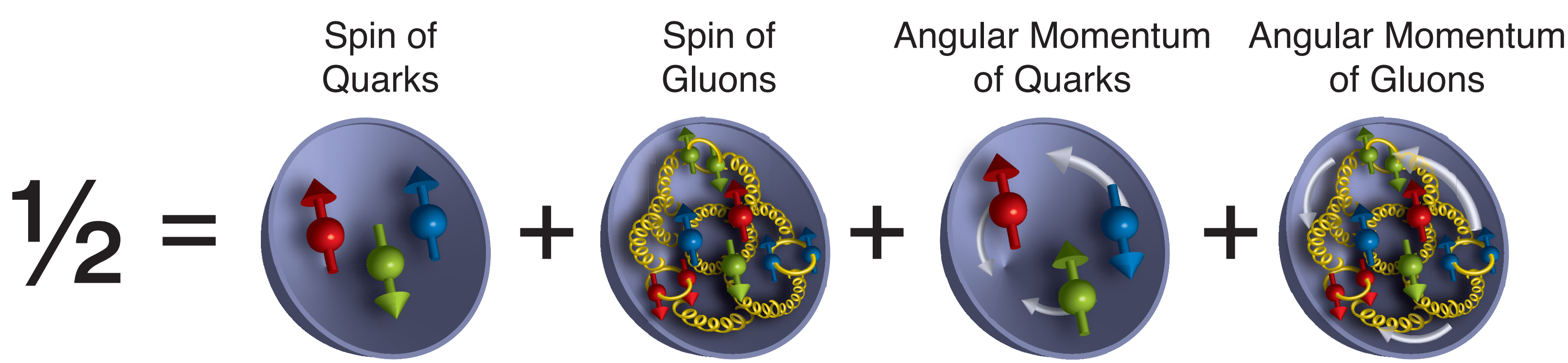
Key Topic in ep: Proton Spin Puzzle

What are the appropriate degrees of freedom in QCD that would explain "spin" of a proton?

- After 20 years effort
  - Quarks (valence and sea): ~30% of proton spin in limited range
  - Gluons (latest RHIC data): ~20% of proton spin in limited range
  - Where is the rest?



It is more than the number ½! It is the interplay between the intrinsic properties and interactions of quarks and gluons



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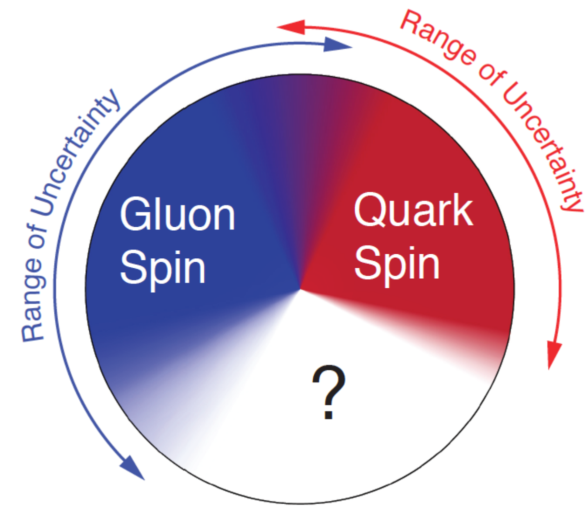

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Jaffe-Manohar sum rule:

$$\frac{1}{2} = \frac{1}{2}\int_0^1 \mathrm{d}x \Delta\Sigma(x, Q^2) + \int_0^1 \mathrm{d}x \Delta g(x, Q^2) + \sum_q L_q + L_g$$

What Does a Proton Look Like?

- In transverse momentum?
- In transverse space?
- How are these distributions correlated with overall nucleon properties, such as spin direction?

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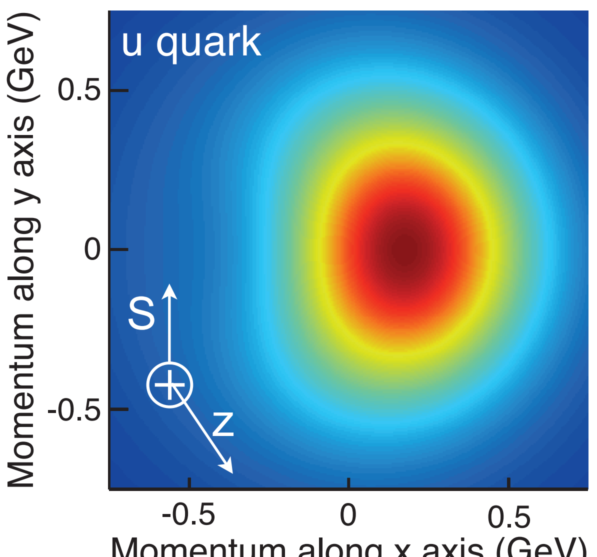
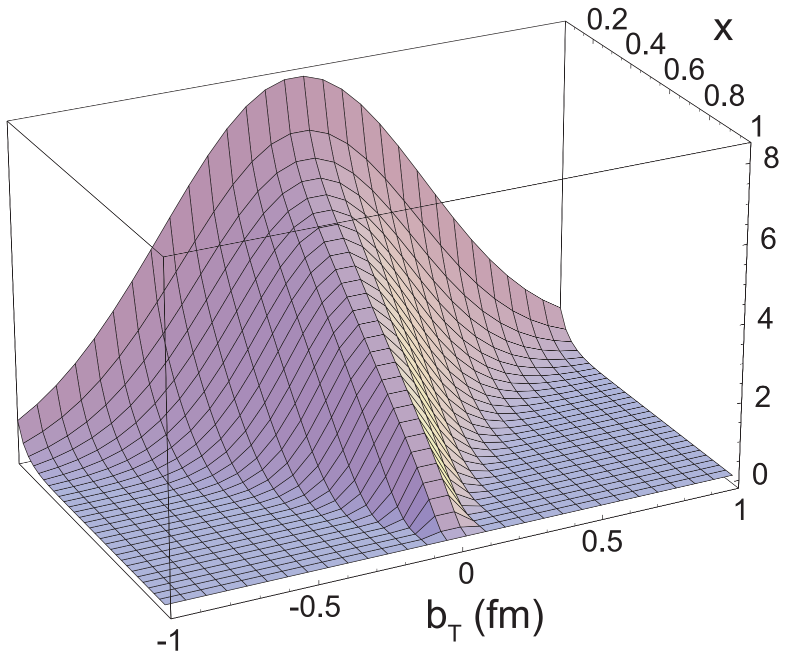
3D Imaging with EIC

What Does a Proton Look Like?

- **Transverse Momentum Distributions (TMDs):**
  - 2D+1 picture in momentum space (k_T)



- **Generalized Parton Distributions (GPDs):**
  - 2D+1 picture in coordinate space (b_T)

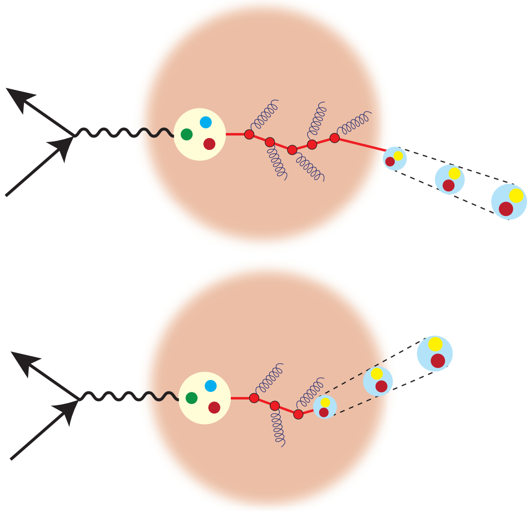


Fragmentation

Color propagation and neutralization

- Fundamental QCD Processes:
  - Partonic elastic scattering
  - In Nucleus: Gluon bremsstrahlung in vacuum and in medium (E-loss)
  - Color neutralization
  - Hadron formation

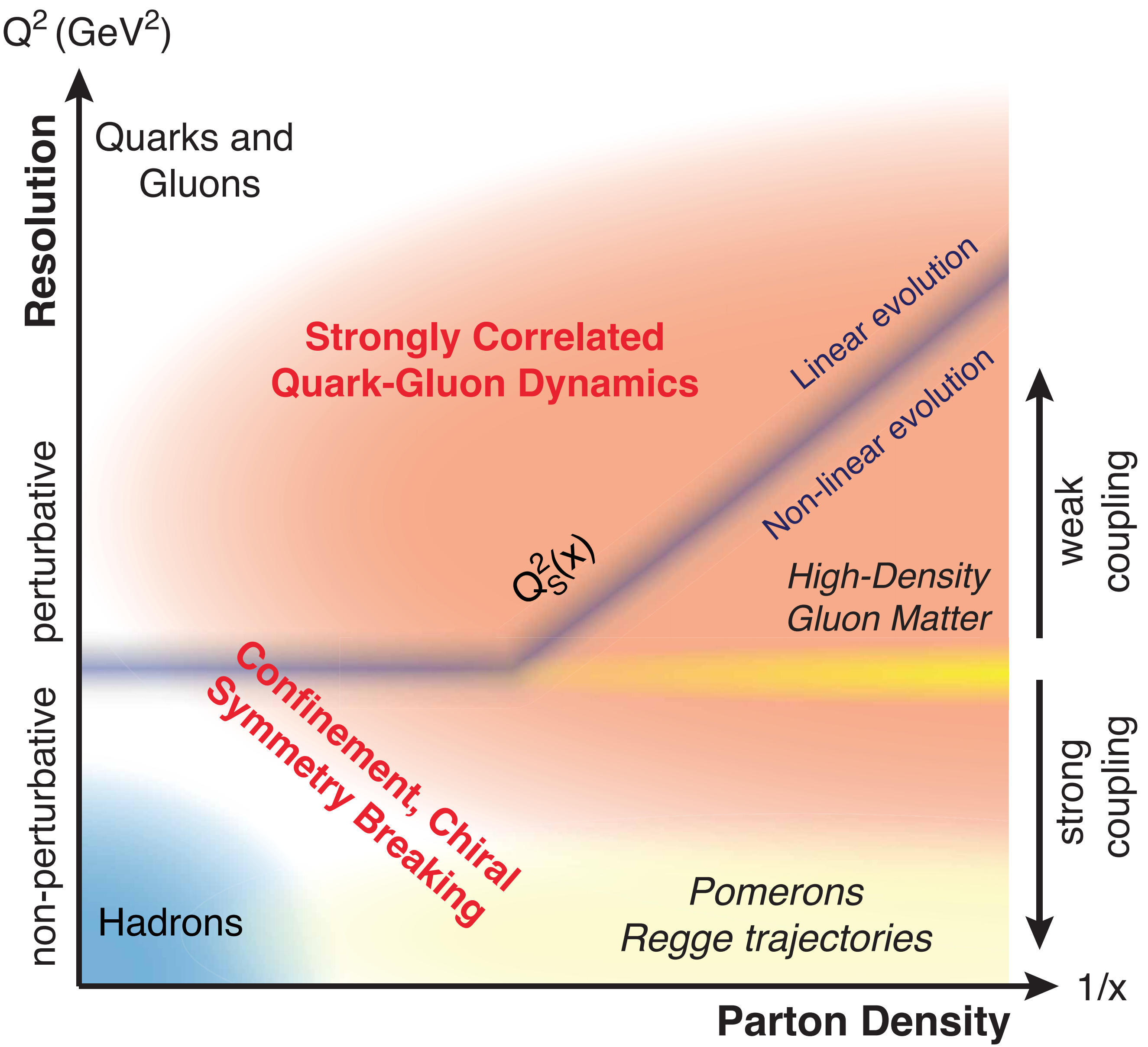
} dynamic confinement



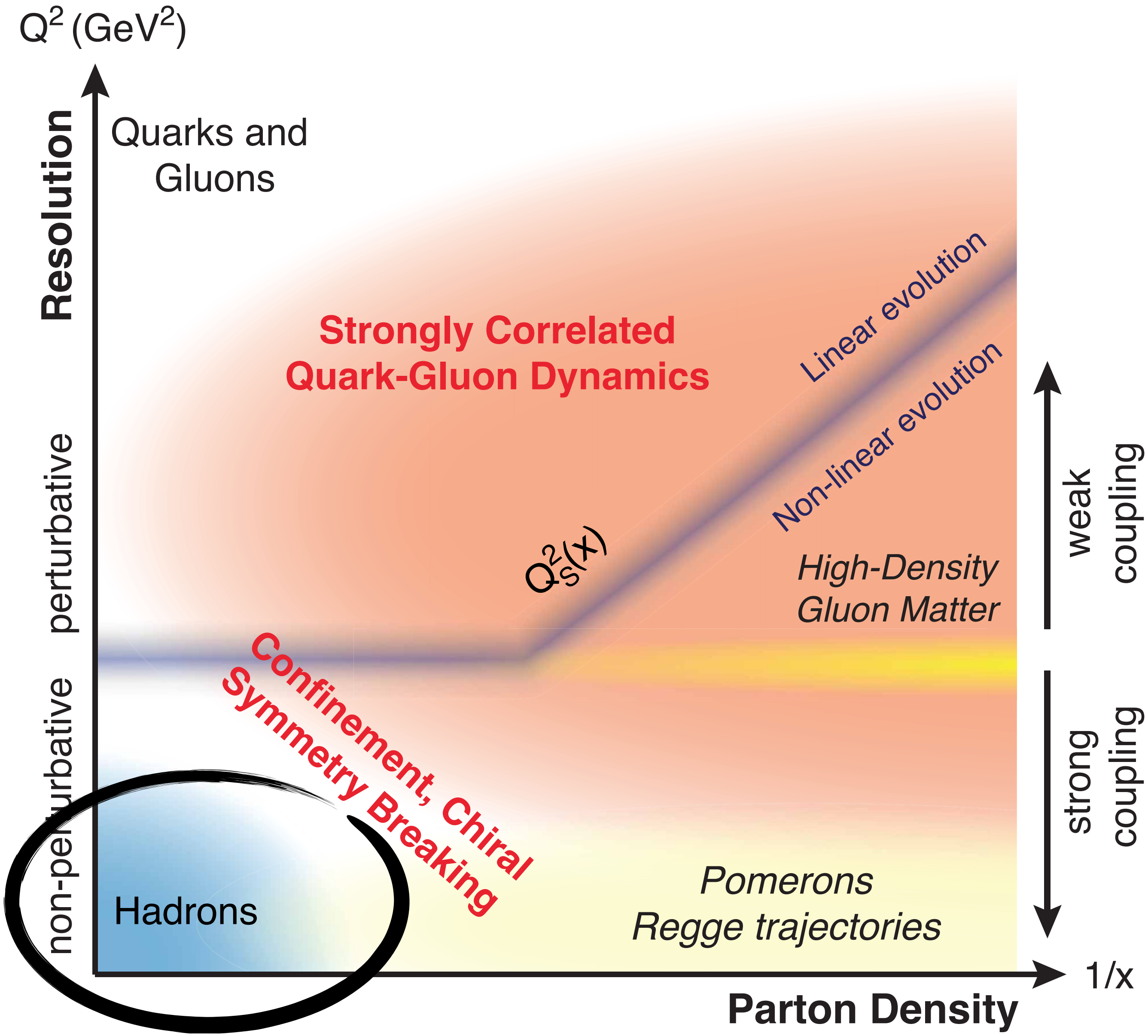
- Process not understood from first principles (QCD)
- Parametrization: Fragmentation Functions
- Nuclei as space-time analyzer allows to dissect process

5. Landscape of QCD

Landscape of QCD

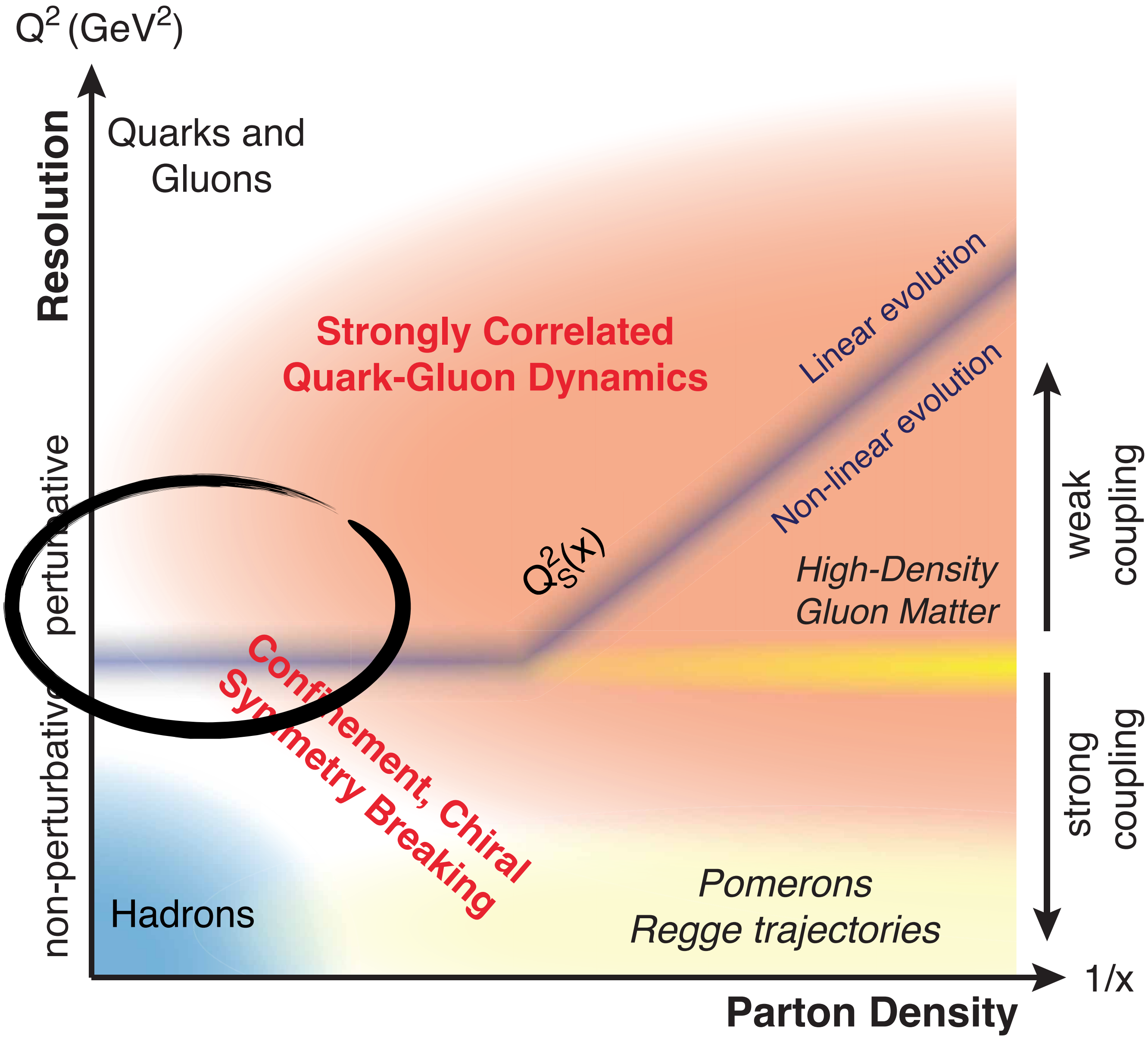


Landscape of QCD



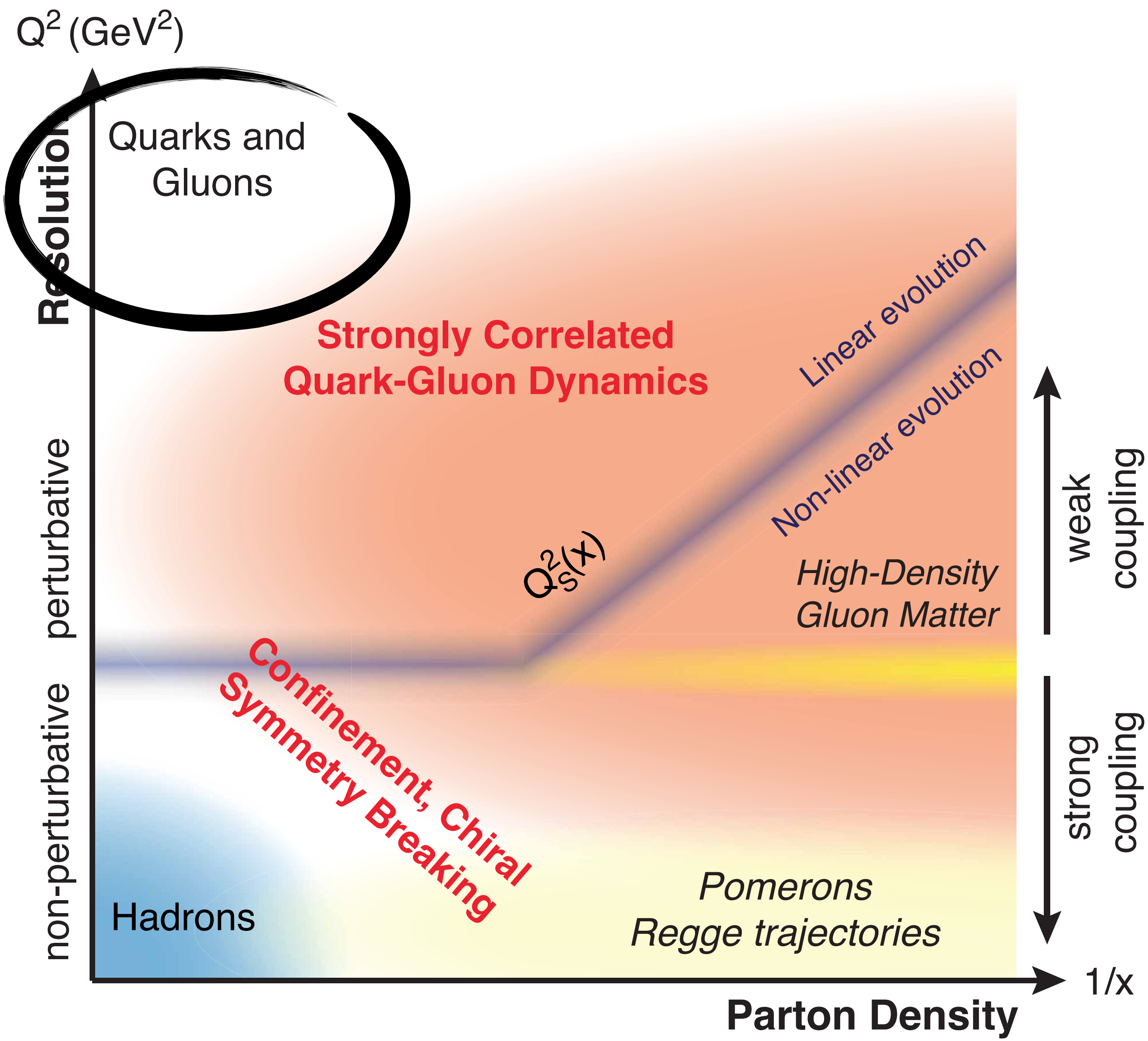
QCD coupling is large, the fields are nonlinear, and the physics is nonperturbative.

Landscape of QCD



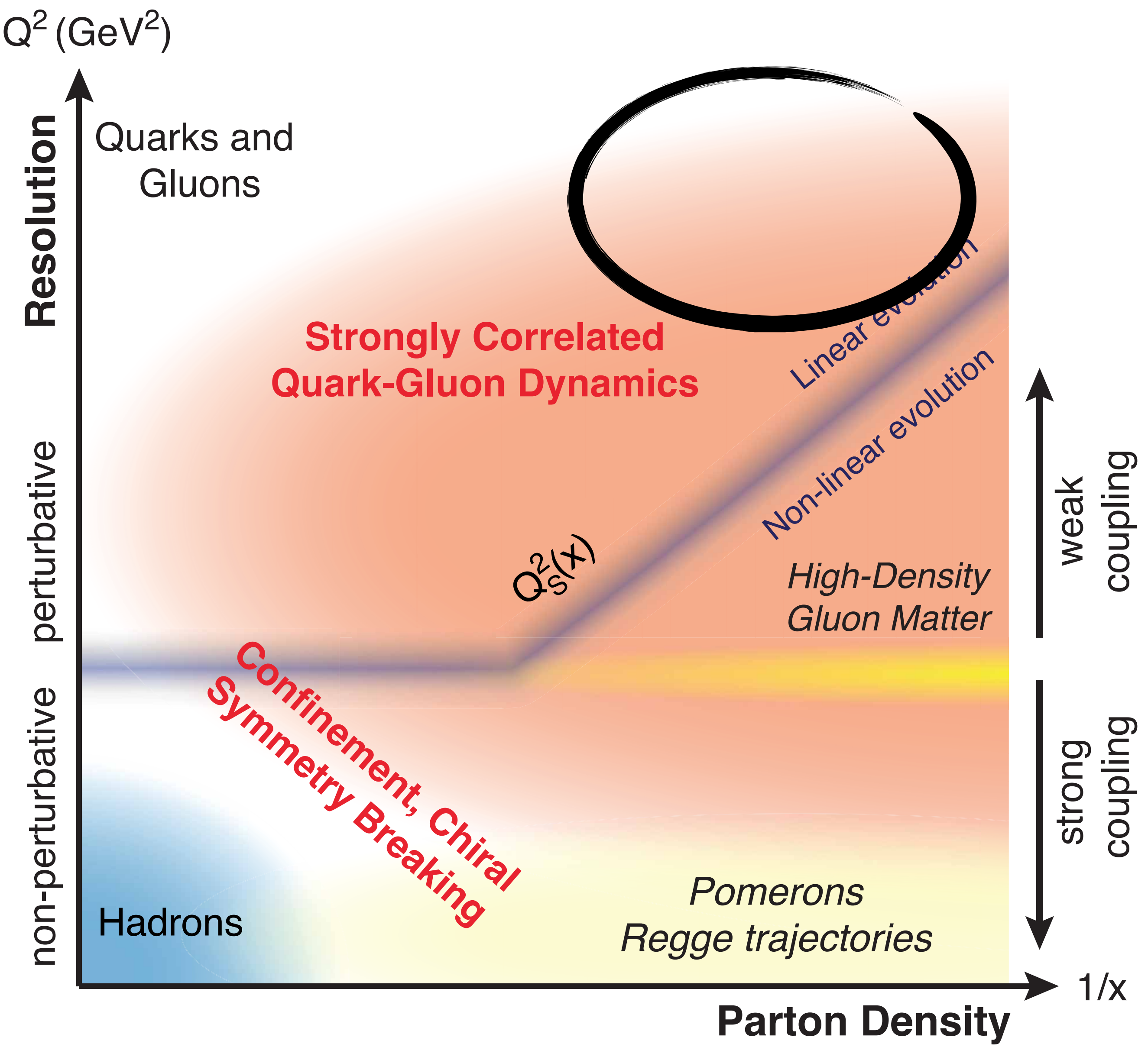
What the degrees of freedom describing this transition region are, is not understood

Landscape of QCD



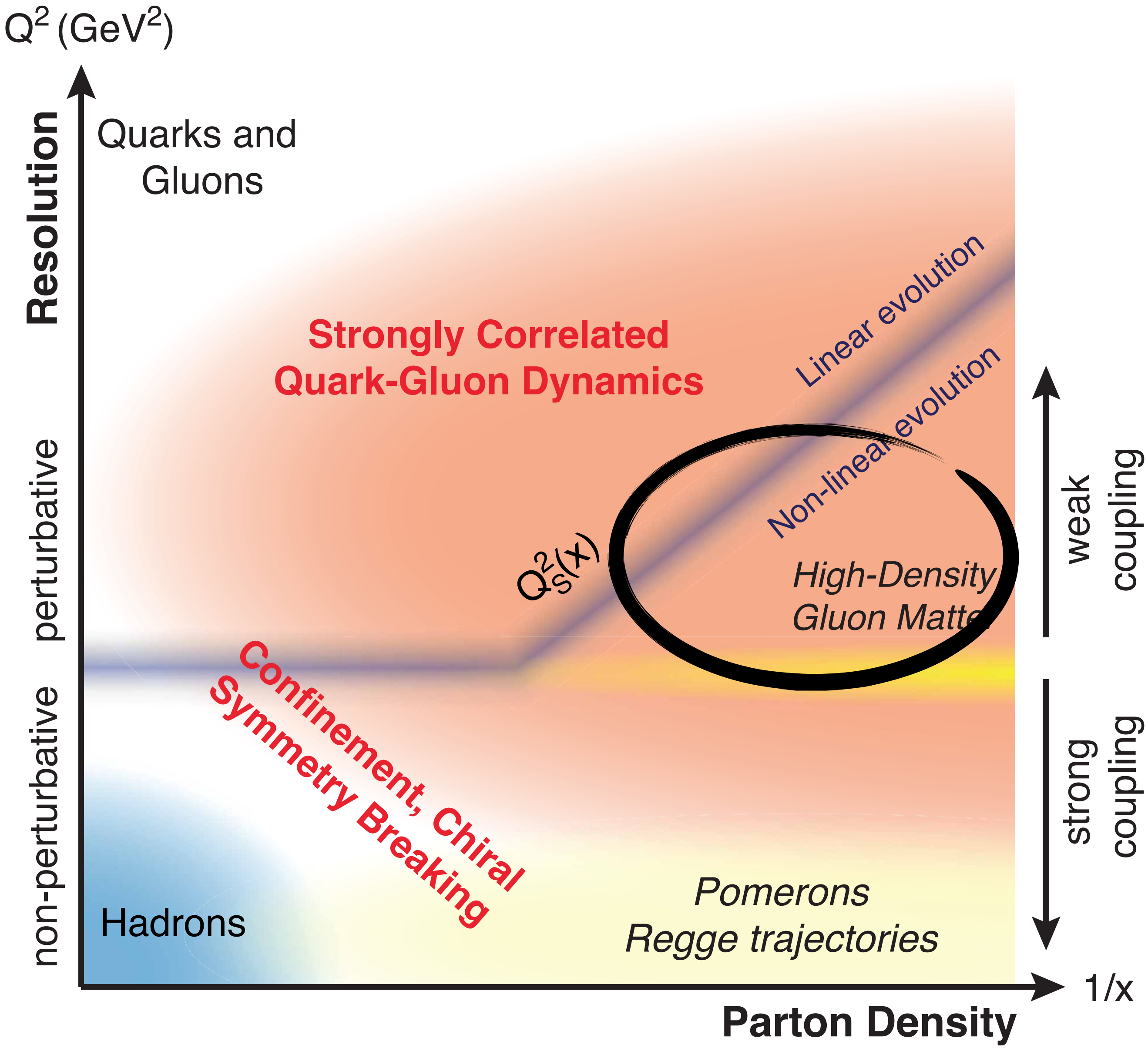
The coupling becomes weak due to asymptotic freedom, and perturbative QCD describes well the interactions of quarks and gluons.

Landscape of QCD



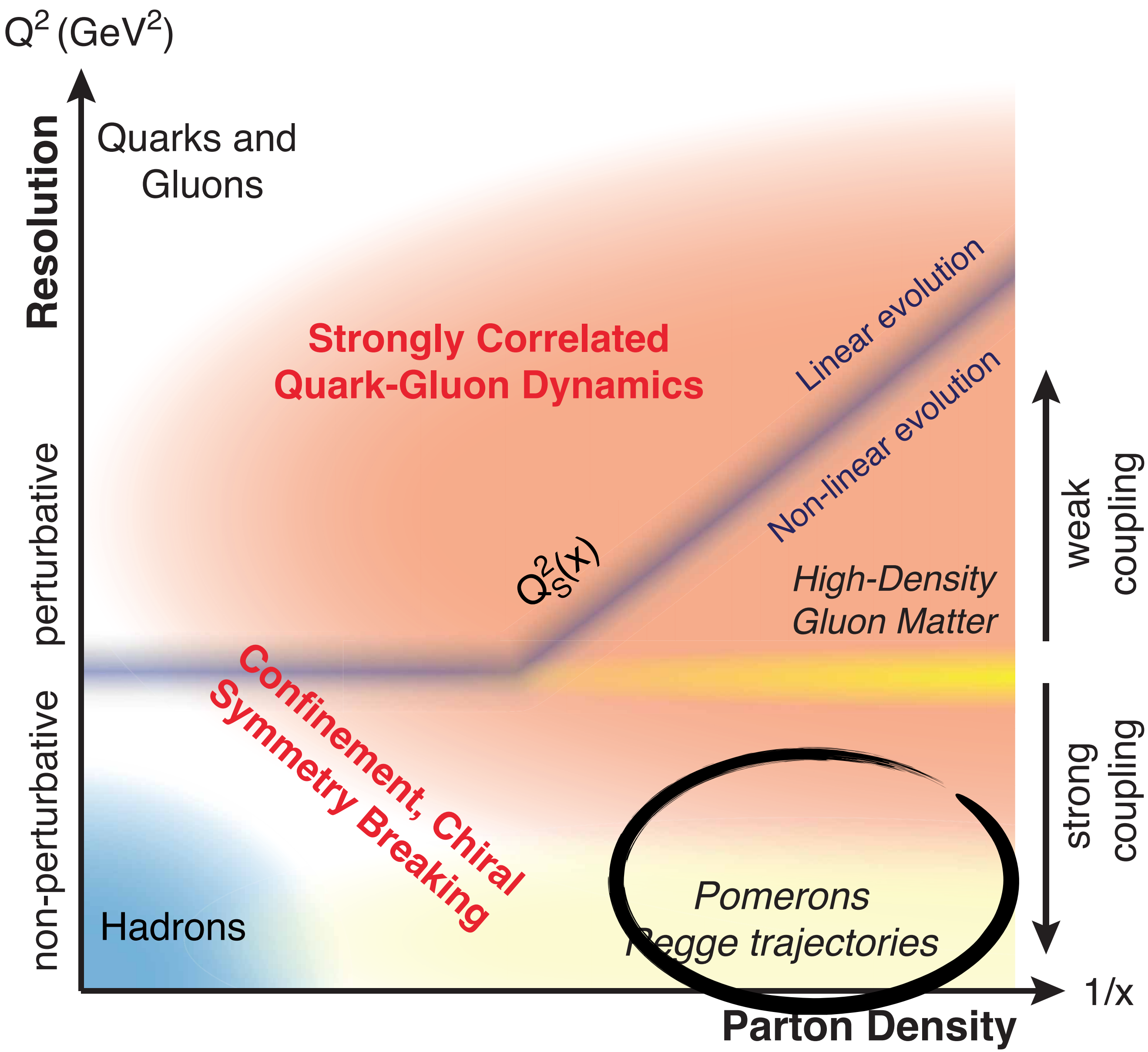
At large Q^2, as one moves towards higher parton density, many-body correlations between quarks and gluons become increasingly important.

Landscape of QCD



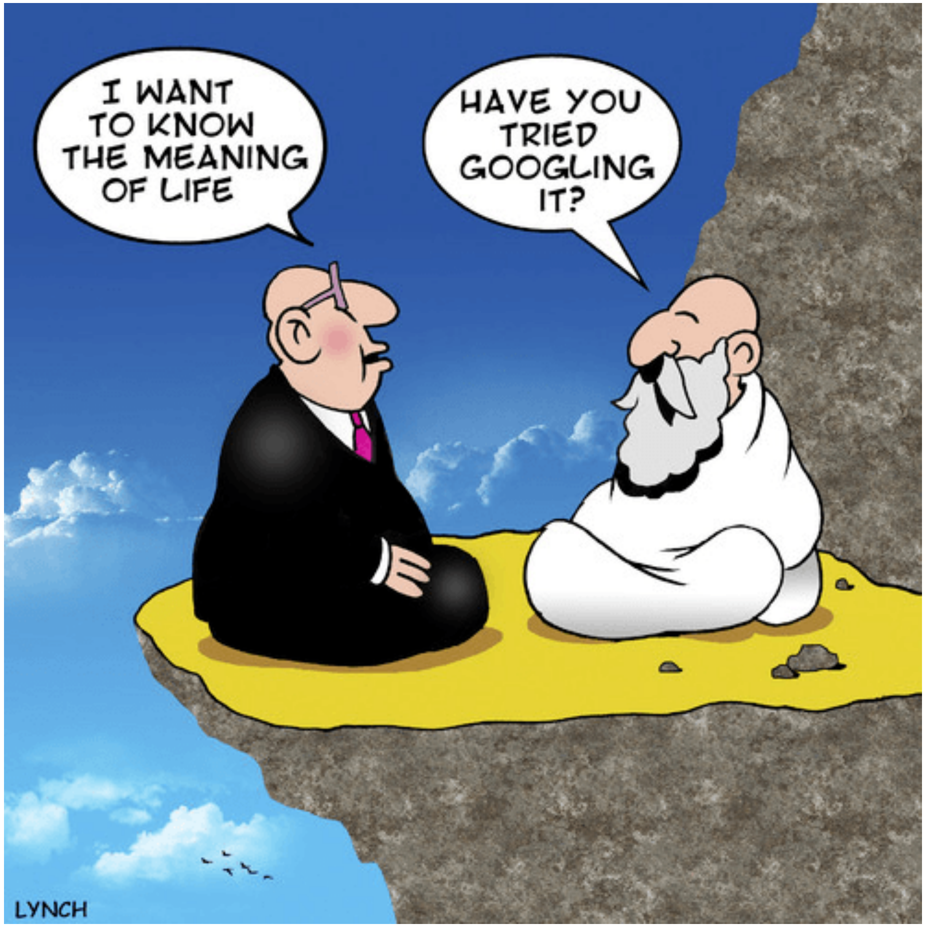
The feature of weak coupling is key because it allows, for the first time, systematic computations of the manybody dynamics of quarks and gluons in an intrinsically nonlinear regime of QCD.

Landscape of QCD



Total cross-sections in high energy scattering are dominated by the physics of small x and low Q^2. The least understood region

6. Big Question and what we need to answer them



The Essential Mystery

There is an elegance and simplicity to nature's strongest force we do not understand

- (Nearly) all visible matter is made up of quarks and gluons
- But quarks and gluons are not visible
- All strongly interacting matter, their properties and dynamics are an *emergent* consequence of many-body quark-gluon dynamics.

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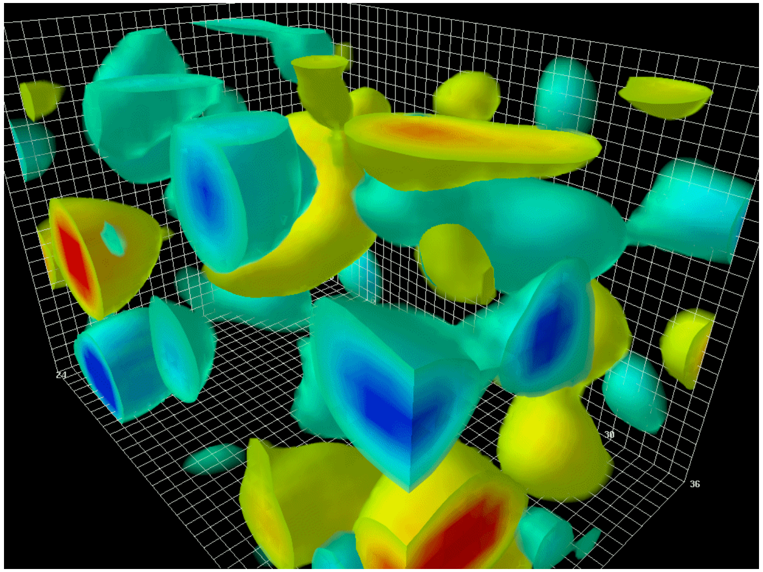
Understanding the origins of matter demands we develop a deep and varied knowledge of this emergent dynamics



Driving Fundamental Questions in e+p

Proton serves as:

- How do quark and gluon dynamics generate the proton spin?
- What is the role of the orbital motion of sea quarks and gluons in building up the nucleon spin?
- How are the sea quarks and gluons distributed in space and transverse momentum inside the nucleon?
- How are these distributions correlated with overall nucleon properties, such as spin direction?

} **Object of Interest**

Driving Fundamental Questions in e+A

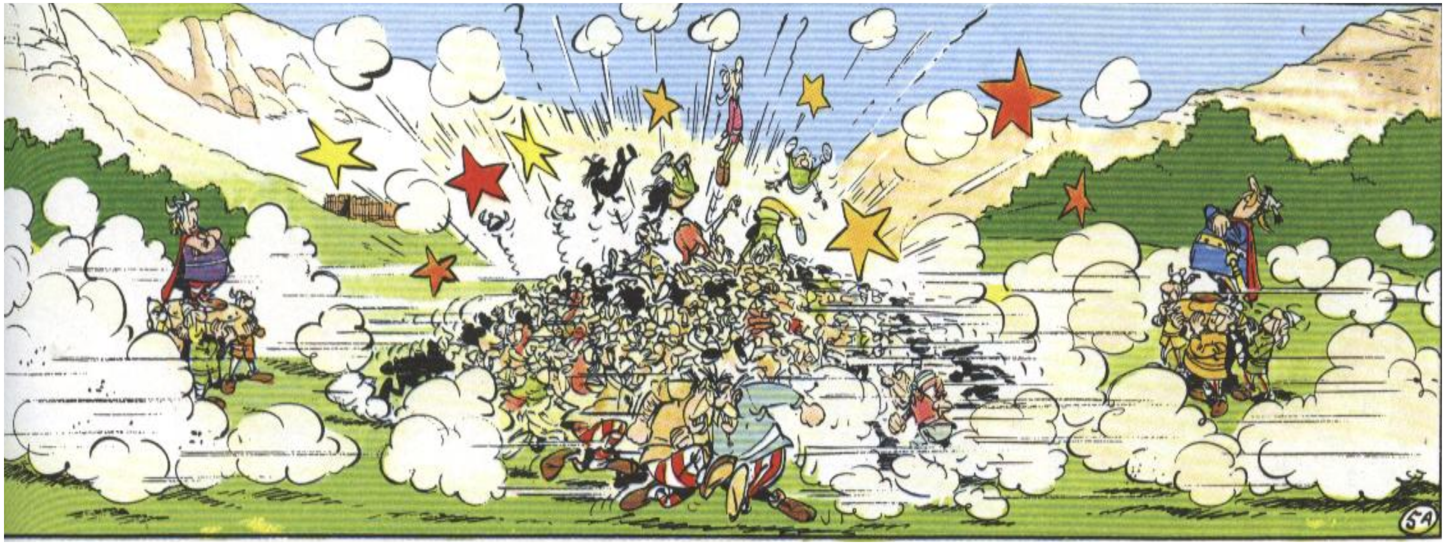
Nucleus serves as:

- What is the fundamental quark-gluon structure of atomic nuclei? — **Object of Interest**
- Can we experimentally find and explore a novel universal regime of strongly correlated QCD dynamics?
- What is the role of saturated strong gluon fields, and what are the degrees of freedom in this strongly interacting regime? — **Amplifier**
- Can the nuclear color filter provide novel insight into propagation, attenuation and hadronization of colored probes? — **Analyzer**

Requirements: What is Needed?

- Access to wide range in x and Q^2
  - ➡ Large center-of-mass energy ($\sqrt{s}$) range
- Access to spin structure of nucleons and nuclei
- Access to 3D spatial and momentum structure of nucleon
  - ➡ Polarized electron and hadron beams
- Accessing the highest gluon densities ($Q_S^2 \sim A^{1/3}$)
  - ➡ Nuclear beams, the heavier the better (up to U)
- Essential for mapping 3D structure of nucleons and nuclei access to rare probes
- Studying observables as a fat of x, Q^2, A, etc.
  - ➡ High luminosity (100x HERA)

7. Realization of an EIC



Reality Check

Designing a dream machine is easy but

- It has to be fundable
- The technology has to be available

Find the parameters that do the job (here EIC White Paper):

- Highly polarized (70%) e- and p beams
- Ion beams from D to U
- Variable center-of-mass energies from $\sqrt{s}$=20-~140 GeV
- High collision luminosity 10^{33-34} $cm^{-2}s^{-1}$ (HERA ~ 10^{31})
- Possibilities of having more than one interaction region

Electron-Ion Collider Initiatives

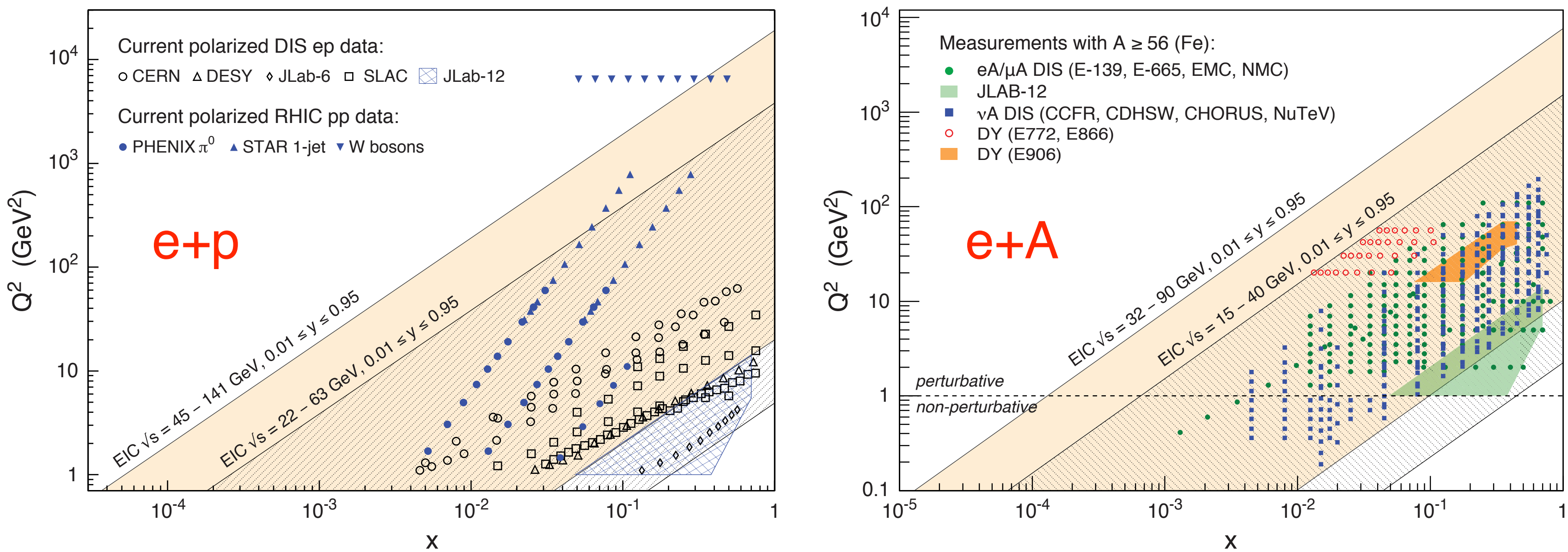
Past — HERA@DESY; Future — LHeC@CERN, HIAF@CAS, ENC@GSI, JLEIC@JLab, eRHIC@BNL

	HERA@DESY	LHeC@CERN	HIAF@CAS	ENC@GSI	JLEIC@JLab	eRHIC@BNL
$\sqrt{s}$ (GeV)	320	800-1300	12-65	14	20-64	32-140
Proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-4}	5×10^{-3}	3×10^{-4}	5×10^{-5}
Ions	p	p … Pb	p … U	p … Ca	p … Pb	p … U
L ($cm^{-2}s^{-1}$)	2×10^{31}	$\sim10^{34}$	$\sim10^{32-35}$	$\sim10^{32}$	$\sim10^{33-35}$	$\sim10^{33-34}$
IRs	2	1	1	1	2+	2+
Year	1992-2007	post ALICE	> 2020	Fair Upgrade	post 12 GeV	post RHIC

High-Energy Physics — HERA@DESY, LHeC@CERN; Nuclear Physics — HIAF@CAS, ENC@GSI, JLEIC@JLab, eRHIC@BNL

- World-wide interest in EIC
- All future collider include e+A in their planning

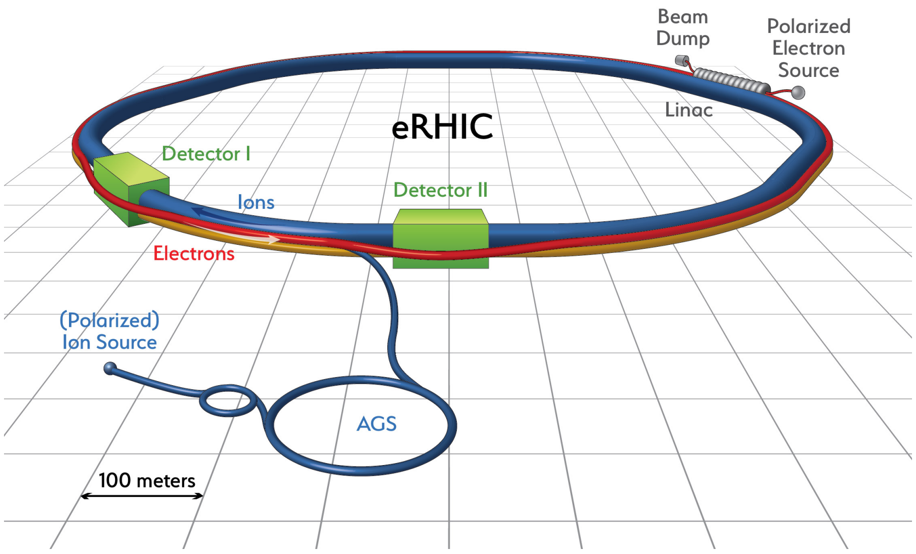
EIC: Kinematic Range

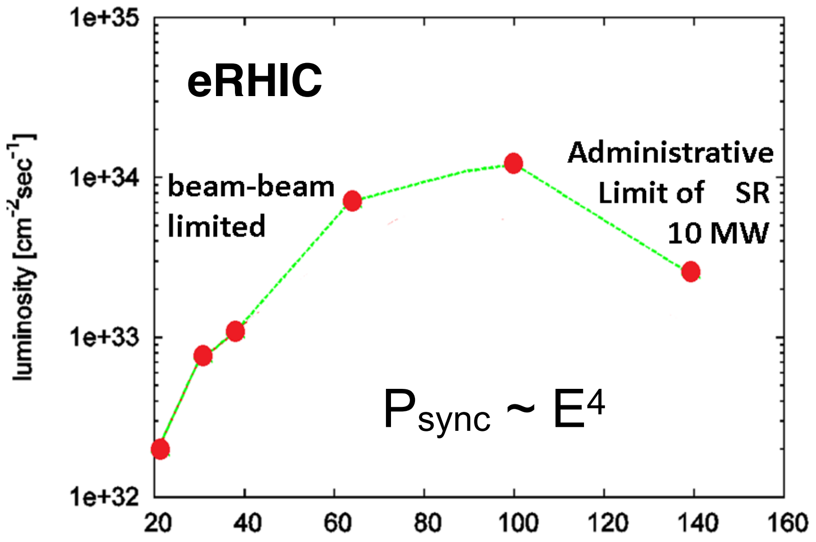


- EIC cannot compete with e+p at HERA (√s = 318 GeV)
- EIC's strength is polarized e↑+p↑ and e+A collisions
- Here the kinematic reach extends substantially compared to past (fixed target) coverage
  - $Q^2 \times 20$, $x/20$ for e+A
  - $Q^2 \times 20$, $x/100$ for polarized e↑+p↑

US Electron Collider: eRHIC Options

- **eRHIC (BNL)**
  - Add e Rings to RHIC facility: Ring-Ring (alt. recirculating Linac-Ring)
  - Electrons up to 18 GeV
  - Protons up to 275 GeV
  - $\sqrt{s}$=30-140 $\sqrt{(Z/A)}$ GeV
  - $L \approx 1\times10^{34}$ $cm^{-2}s^{-1}$ at $\sqrt{s}$=105 GeV
  - 2 IRs

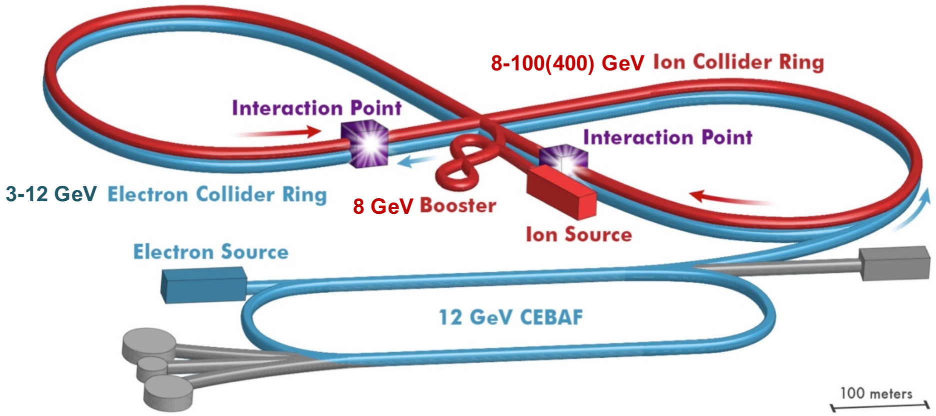


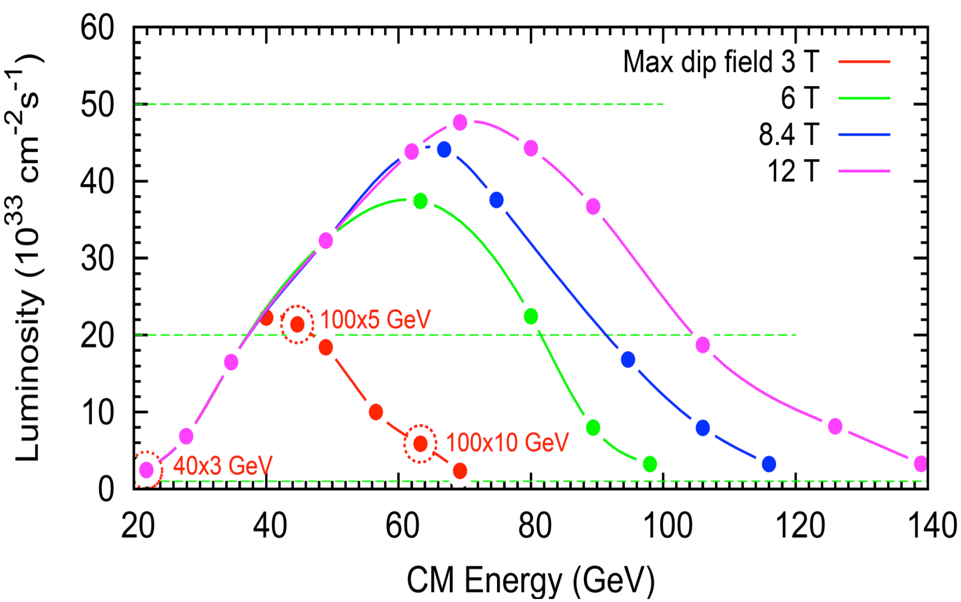


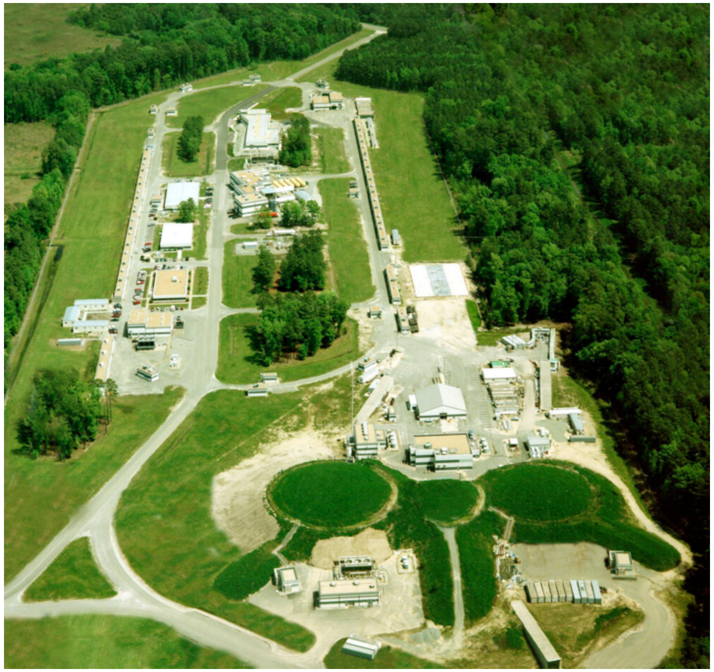
eRHIC: pre-CDR in preparation

US Electron Collider: JLEIC Option

- **JLEIC (JLab)**
  - Figure-8 Ring-Ring Collider, use of CEBAF as injector
  - Electrons 3-10 GeV
  - Protons 20-100 GeV
  - e+A up to √s=40 GeV/u
  - e+p up to √s= 64 GeV
  - L ≈ 2×10^{34} cm^{-2} s^{-1} at √s=45 GeV

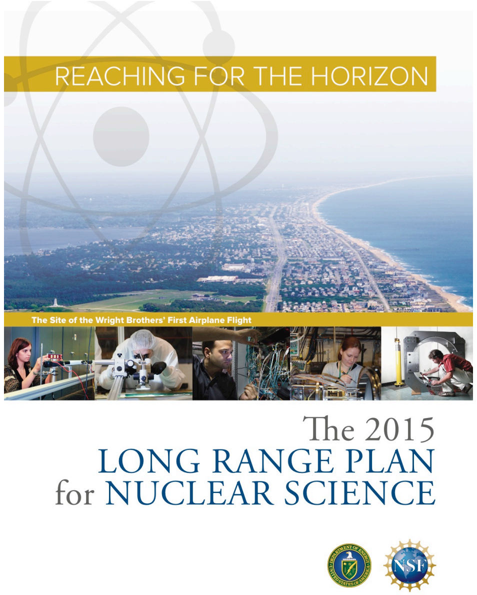






arXiv:1504.07961

Status of US Based EIC?



2015:
US Nuclear Physics Long Range Plan:

"We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB."

2017/18: National Academy Review

U.S.-Based Electron Ion Collider Science Assessment
Release expected this month

Expectations:

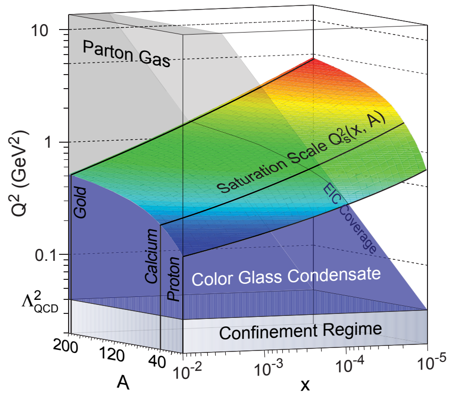
- DOE Critical-Decision-0 (CD-0) in 2018 (Mission Need)
- Site selection before CD-1

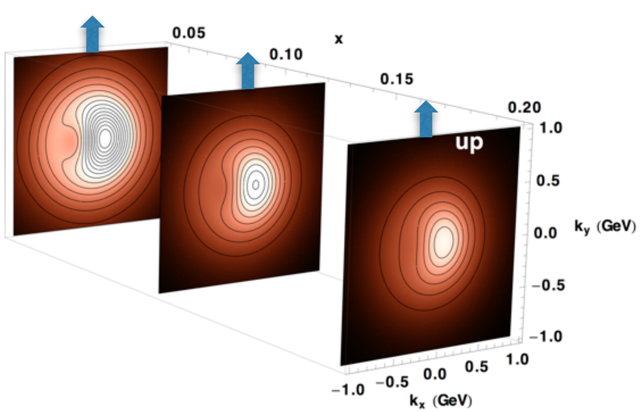
Closing Comments

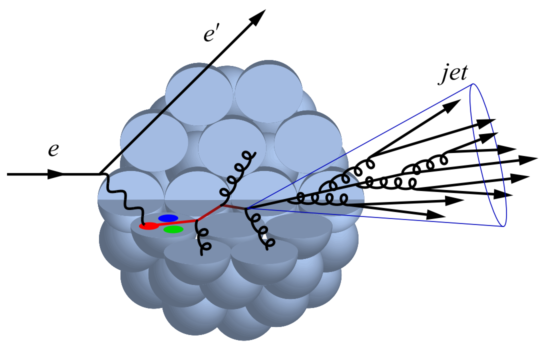
EIC will provide answers to profound questions in QCD

- **ep:** Precision studies of structure functions, TMDs, and GPDs will lead to the most comprehensive picture of the nucleon ever: its flavor, spin, and spatial structure

- **eA:** Unprecedented study of matter in a new regime of QCD. New capabilities open a new frontier to study the saturation region, measure the gluonic structure of nuclei, and investigate color propagation, and fragmentation using the nucleus as analyzer.

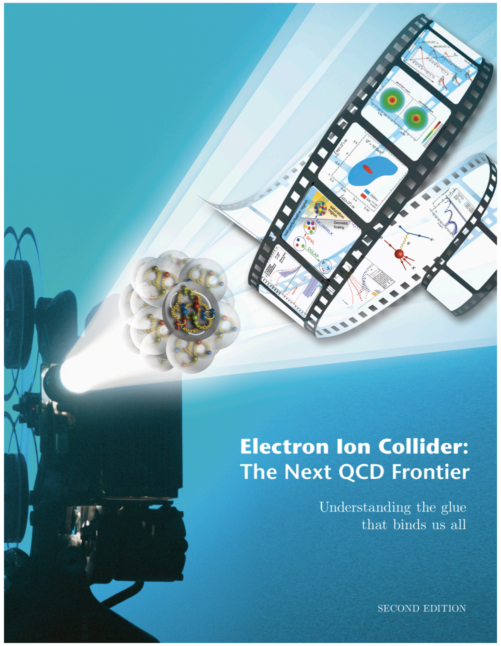






There is precedent for surprises in nature, provided you look

Selected Reading



EIC White Paper:
Electron Ion Collider: The Next QCD Frontier
Eur.Phys.J. A52 (2016) no.9, 268
arXiv:1212.1701

Scientific American (May 2015)
The Glue That Binds Us
by R. Ent, R. Venugopalan, TU


PARTICLE PHYSICS

the glue that binds us

Physicists have known for decades that particles called gluons keep protons and neutrons intact—and thereby hold the universe together. Yet the details of how gluons function remain surprisingly mysterious

By Rolf Ent, Thomas Ullrich and Raju Venugopalan