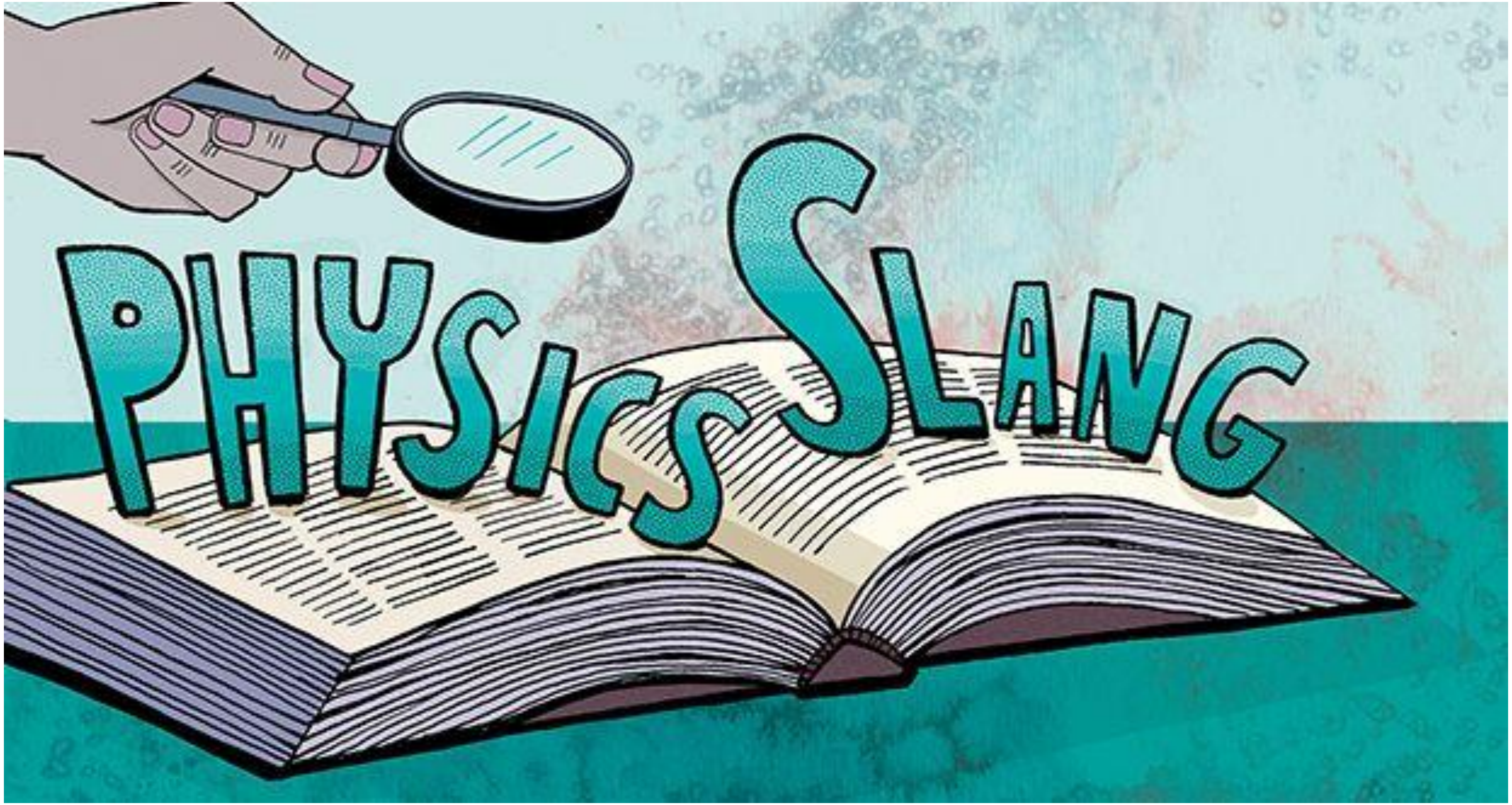
Hadronic Physics:
Research questions and opportunities in the 21st century

Daniel Tapia Takaki

GraSPA summer school

July 21, 2026

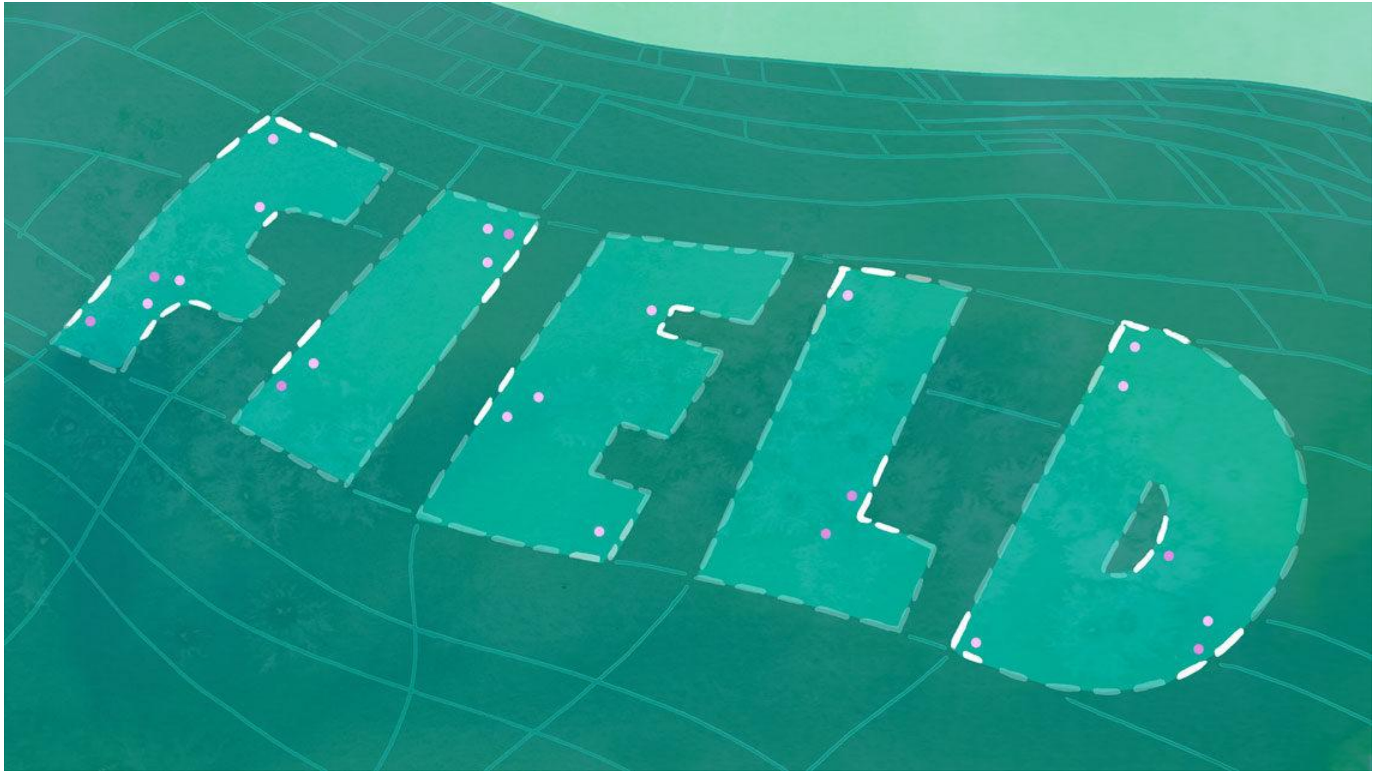
Annecy, France


PHYSICS SLANG

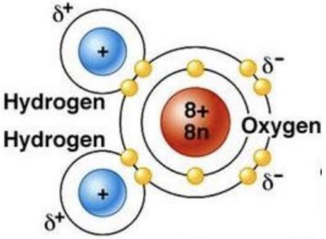
Physics slang

Illustration by Sandbox Studio, Chicago with Corinne Mucha

Physics slang

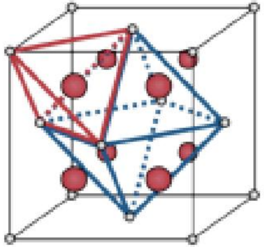

FIELD

Molecule:



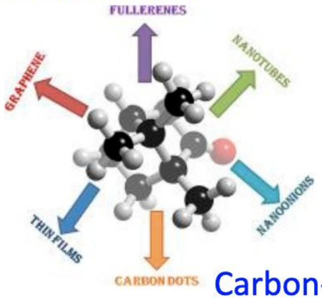
"Water"

Crystal:



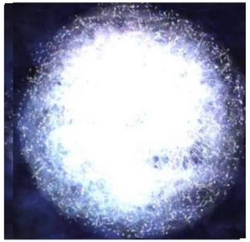
Rare-Earth metal

Nanomaterial:

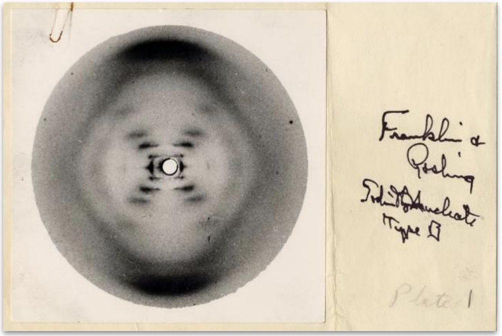


Carbon-based

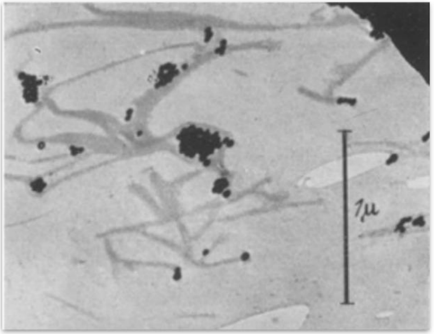
Proton (artistic impression):



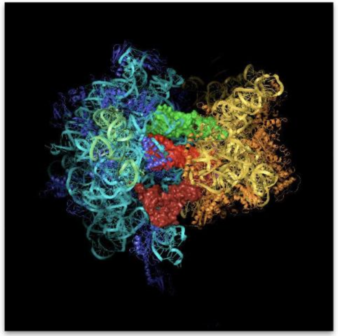
Full of quarks and gluons



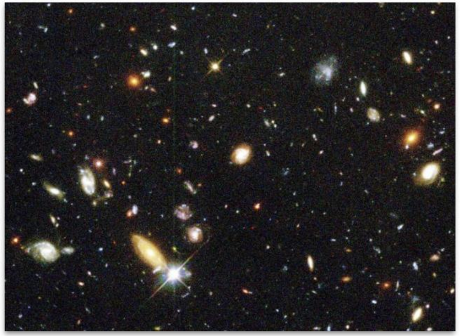
Rosalind Franklin's "Photo 51" (1952) – DNA Double Helix



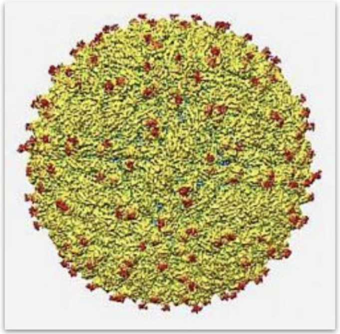
First Electron Microscope Image of a Virus (1939)



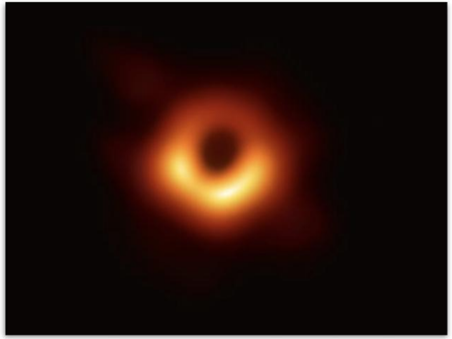
High-resolution Ribosome Structure (2000)



Hubble Deep Field Picture (1995)

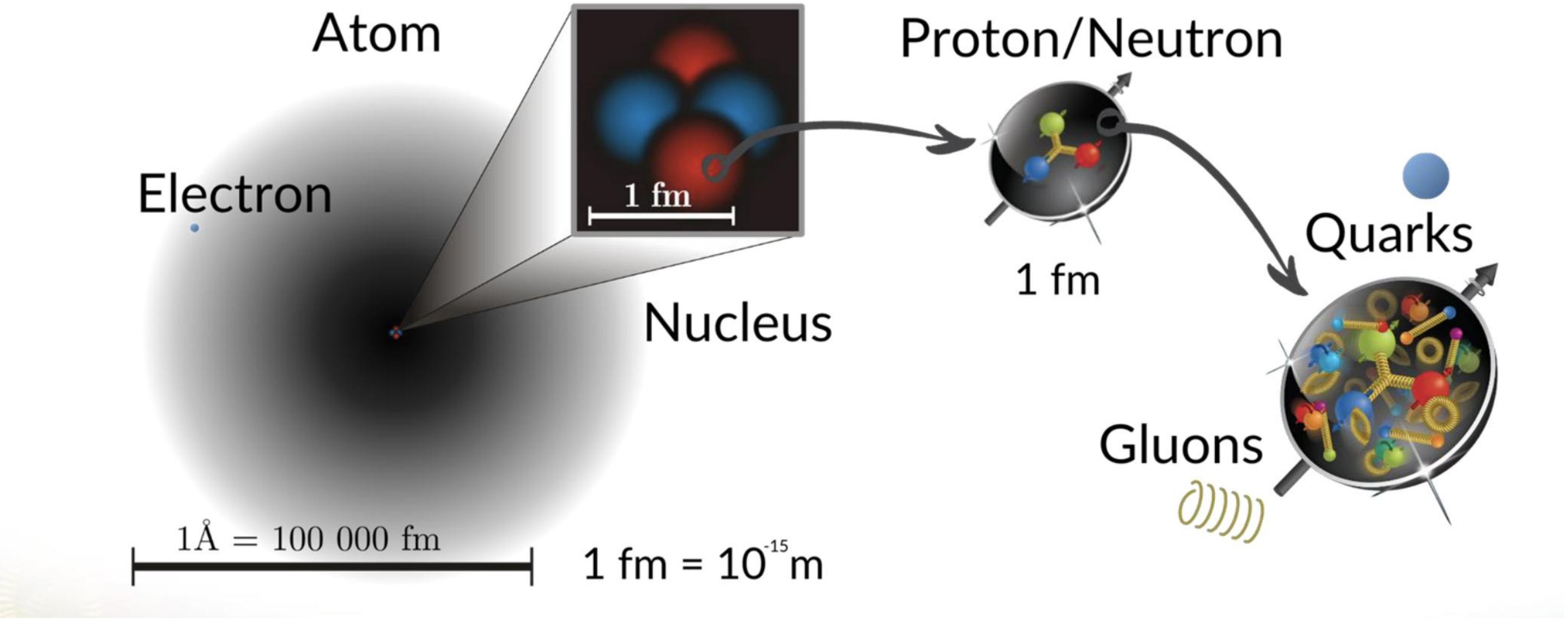


Cryo-EM Image of Zika Virus (2016)



First Image of a Black Hole (2019)

Credit: Maria Zurek



Credit: Maria Zurek

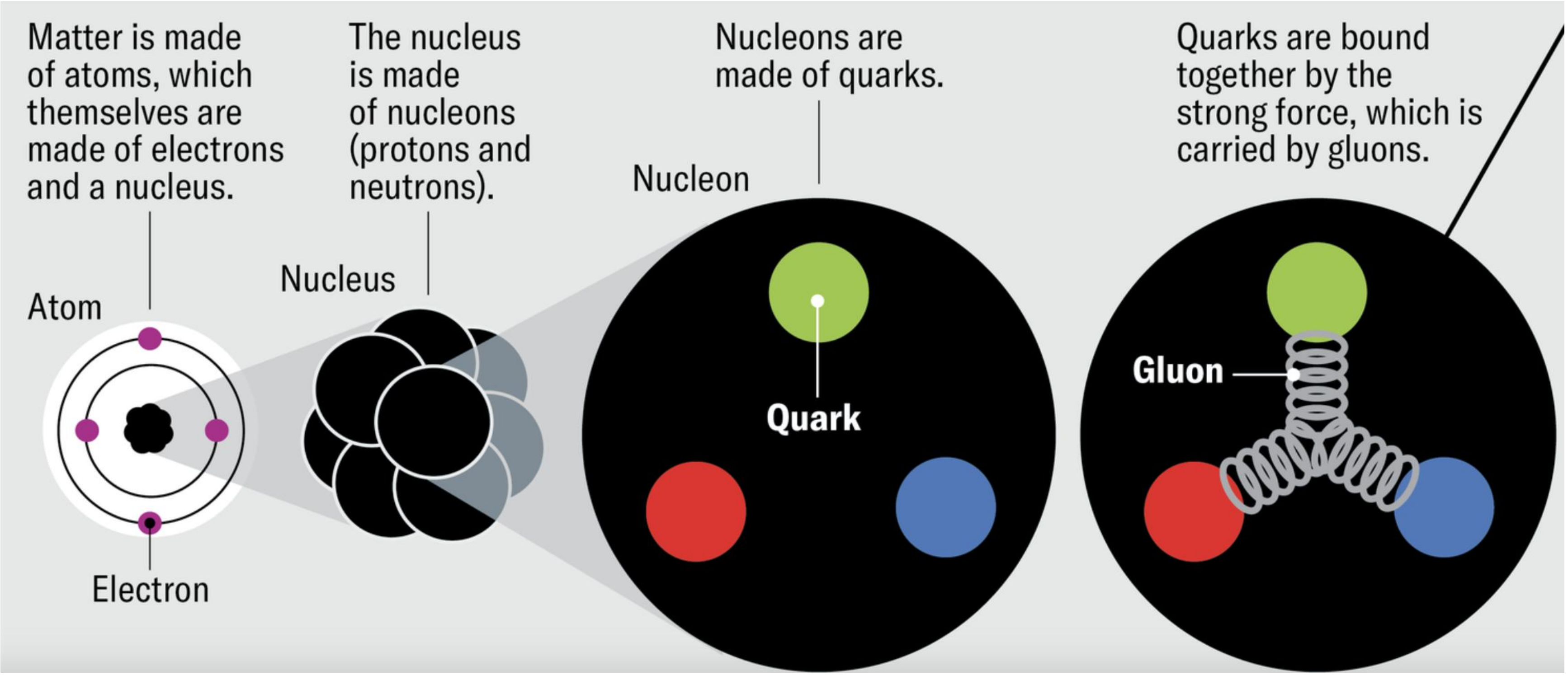
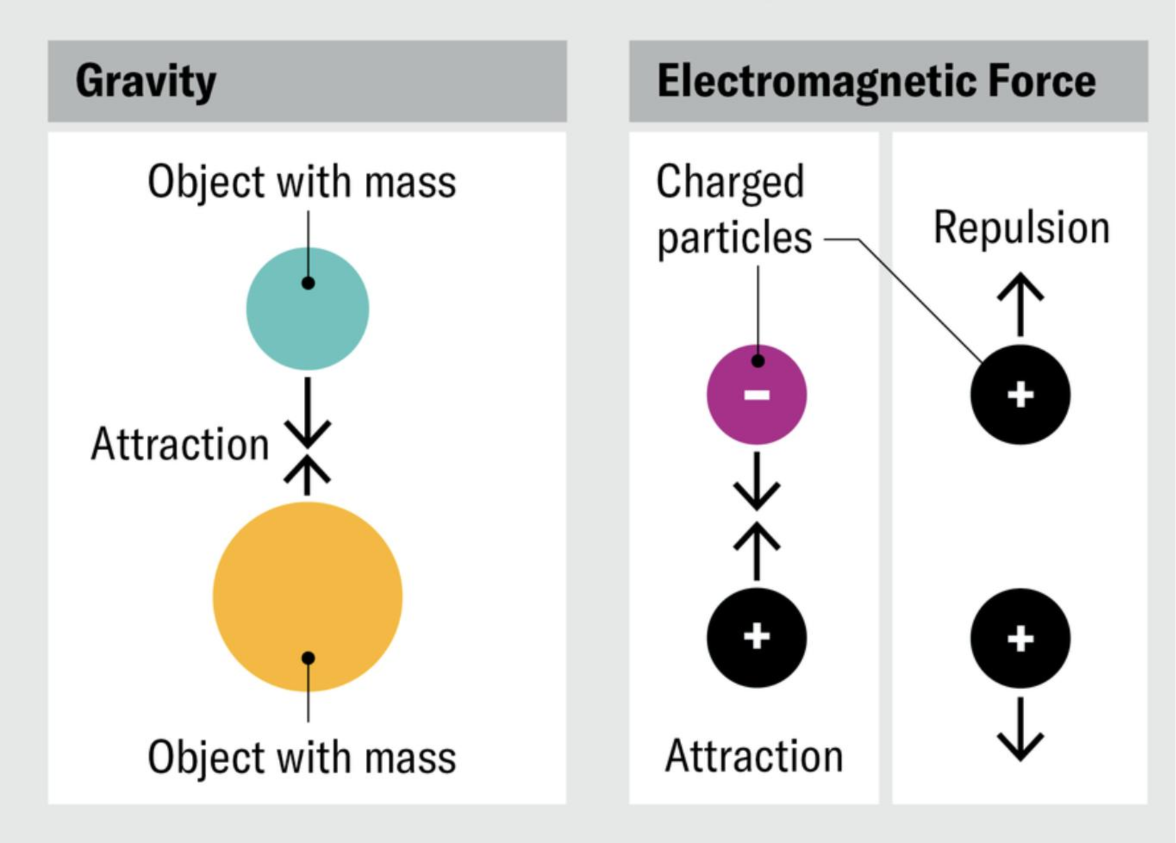
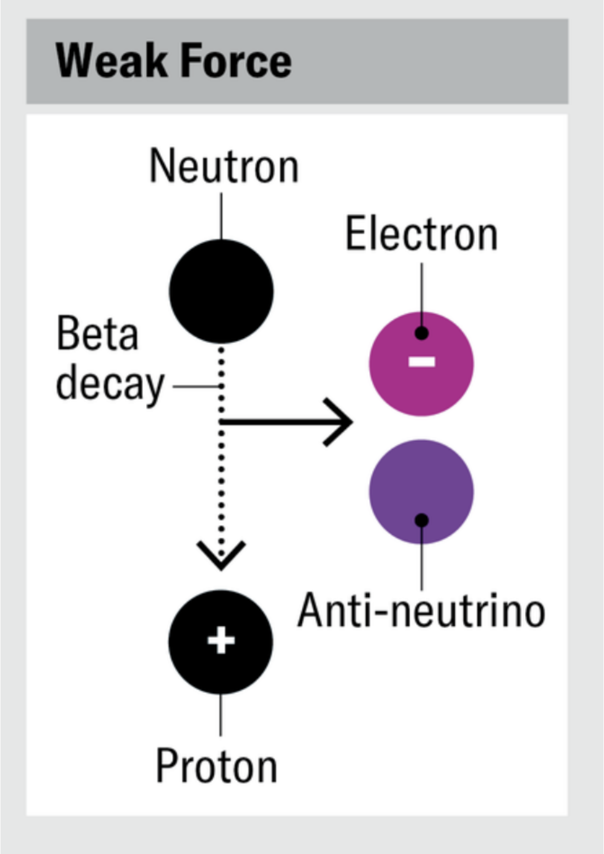


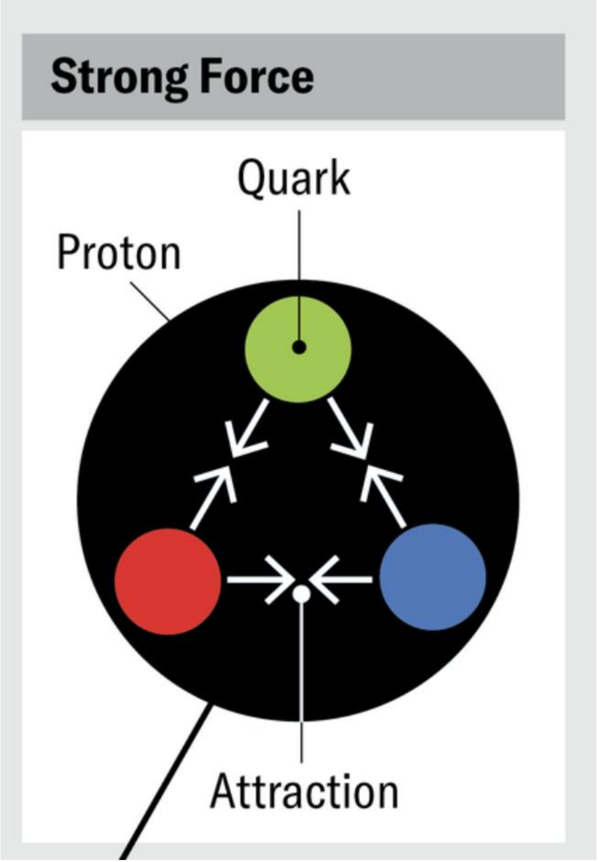
Image: Jen Christiansen

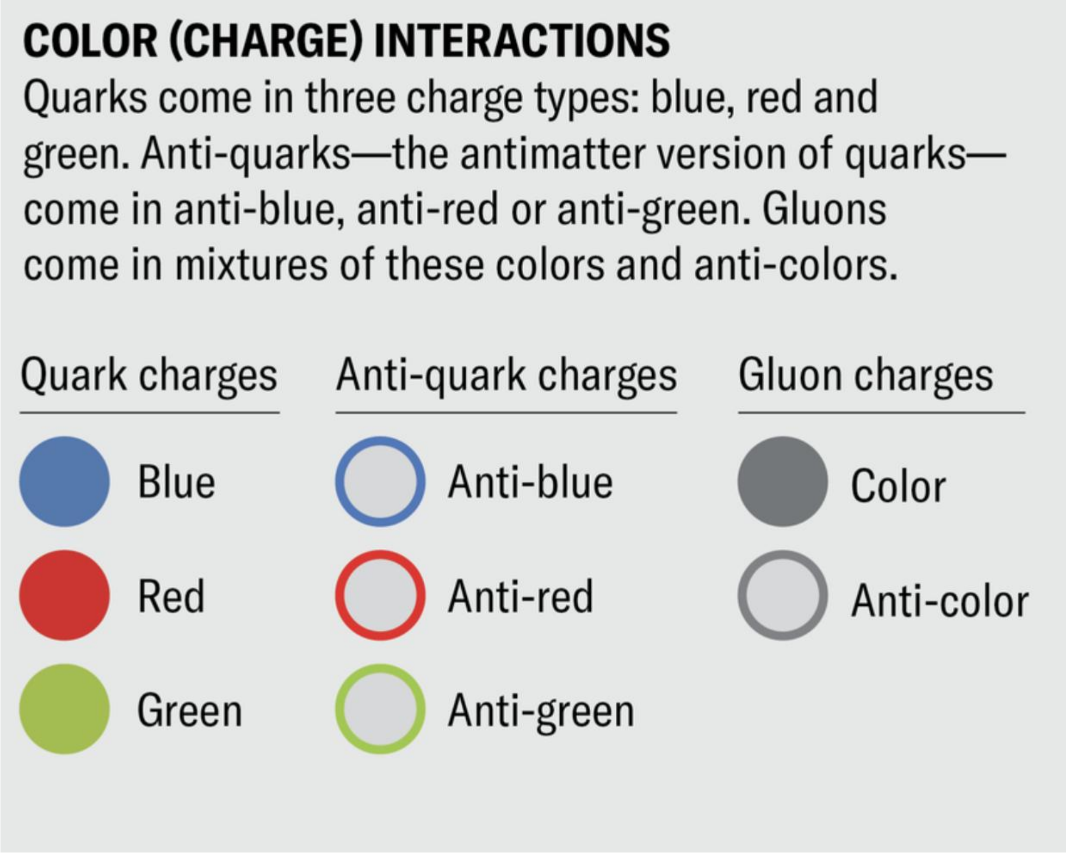
Forces

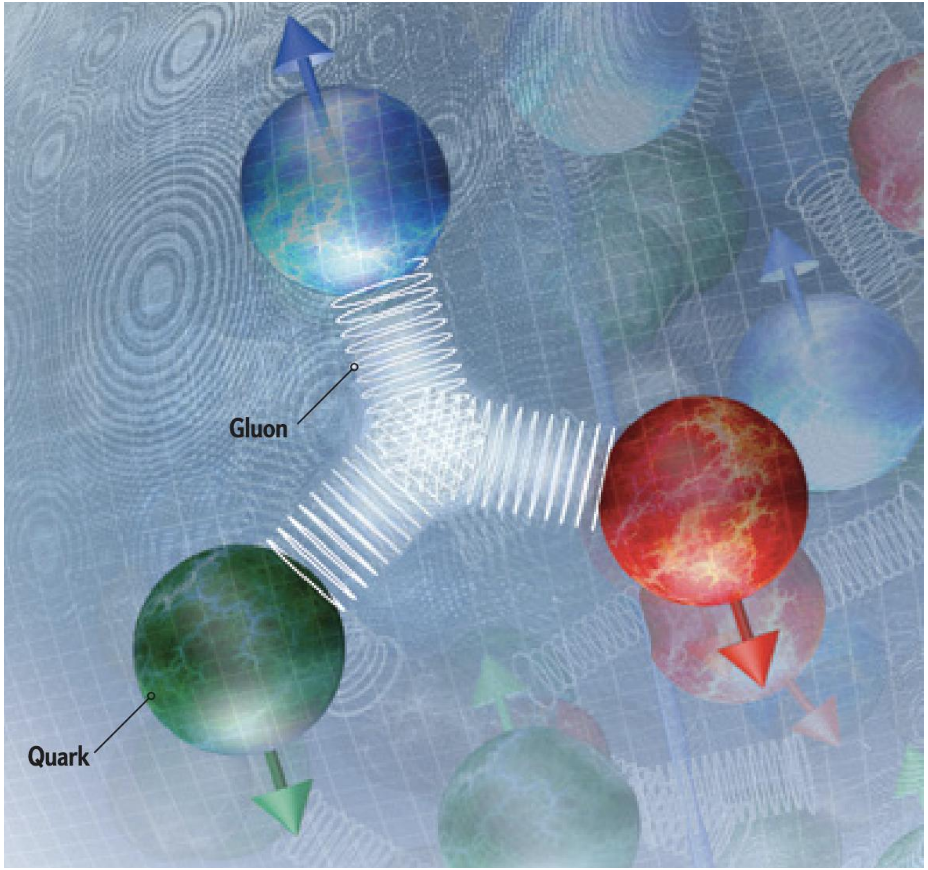


Gravity
Object with mass
Attraction
Object with mass
Electromagnetic Force
Charged particles
Repulsion
Attraction


Weak Force
Neutron
Electron
Beta
decay
Anti-neutrino
Proton


Strong Force
Quark
Proton
Attraction


COLOR (CHARGE) INTERACTIONS
Quarks come in three charge types: blue, red and green. Anti-quarks—the antimatter version of quarks—come in anti-blue, anti-red or anti-green. Gluons come in mixtures of these colors and anti-colors.
Quark charges
Anti-quark charges
Gluon charges
Blue
Anti-blue
Color
Red
Anti-red
Anti-color
Green
Anti-green

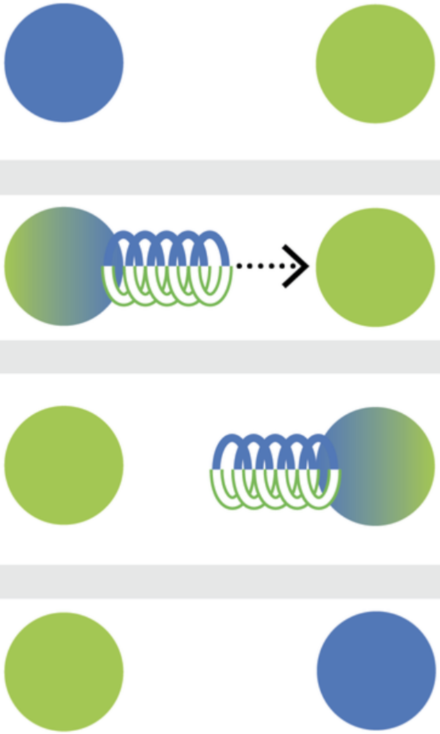

Gluon
Quark

The strong force is the attraction felt by quarks when they share colors via gluons. For example, take a blue quark and a green quark.

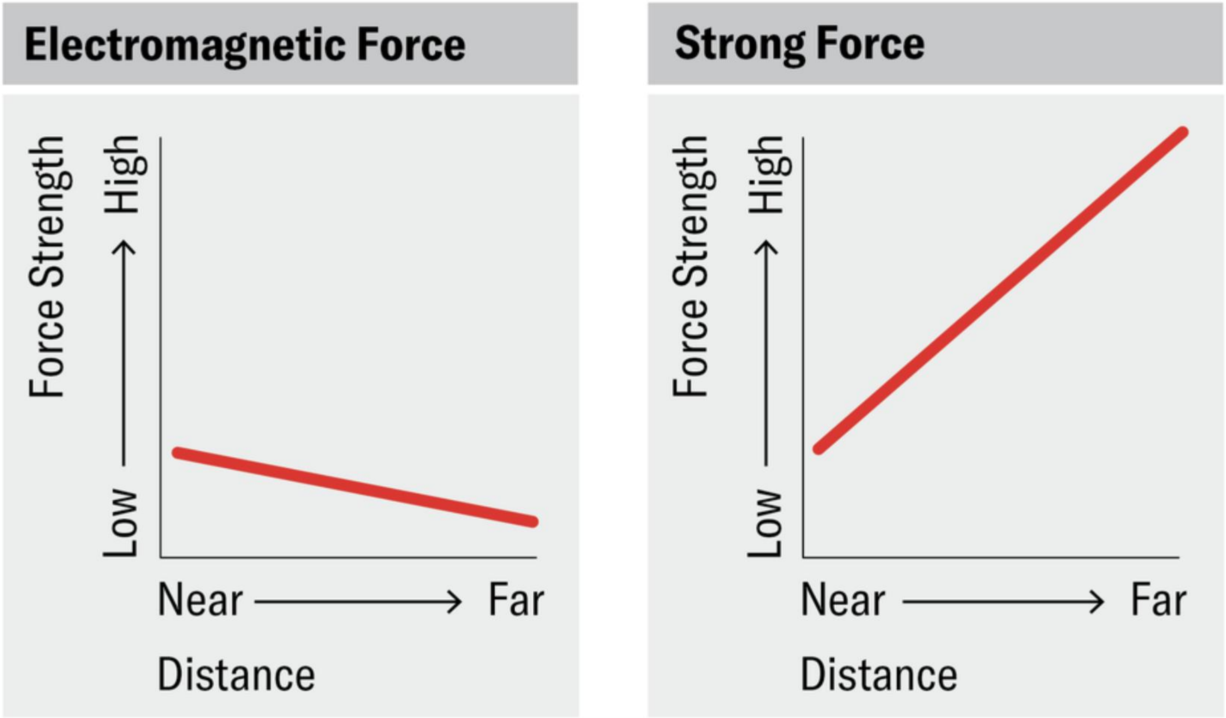
The blue quark emits a gluon that carries blue and anti-green.

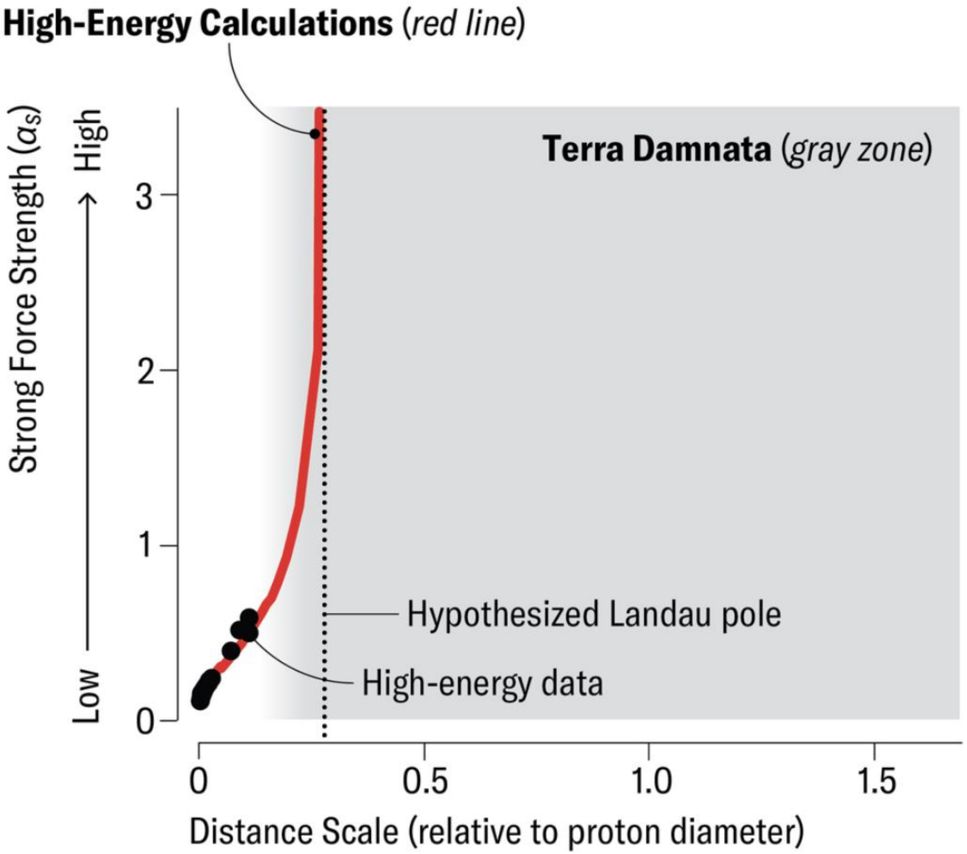
The green quark absorbs the gluon and turns blue. Its green color is annihilated by the anti-green of the gluon.

The process repeats, binding quarks together.

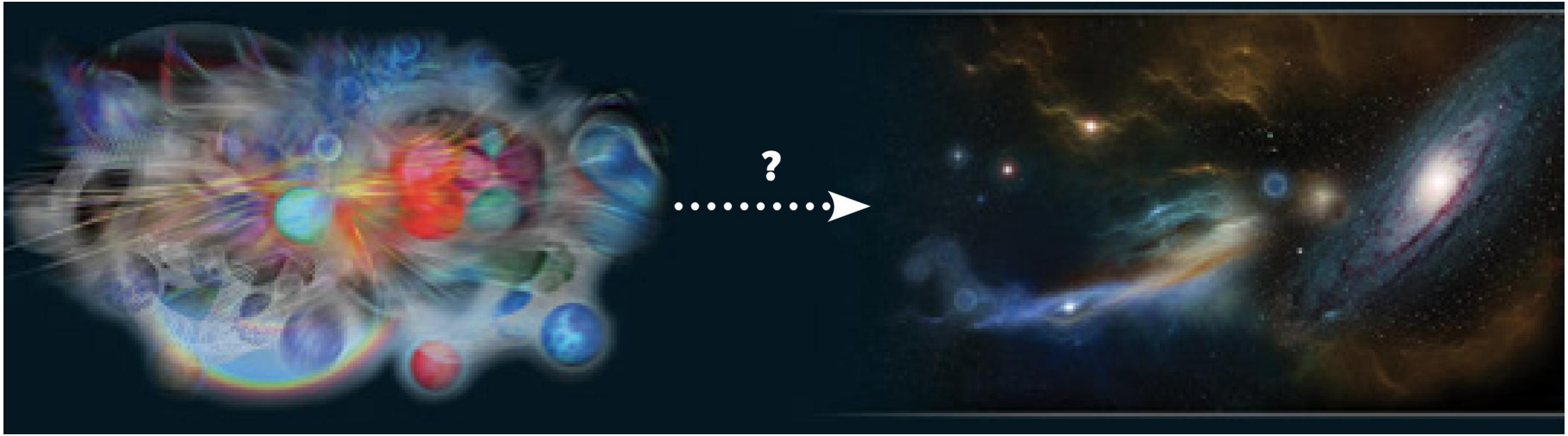


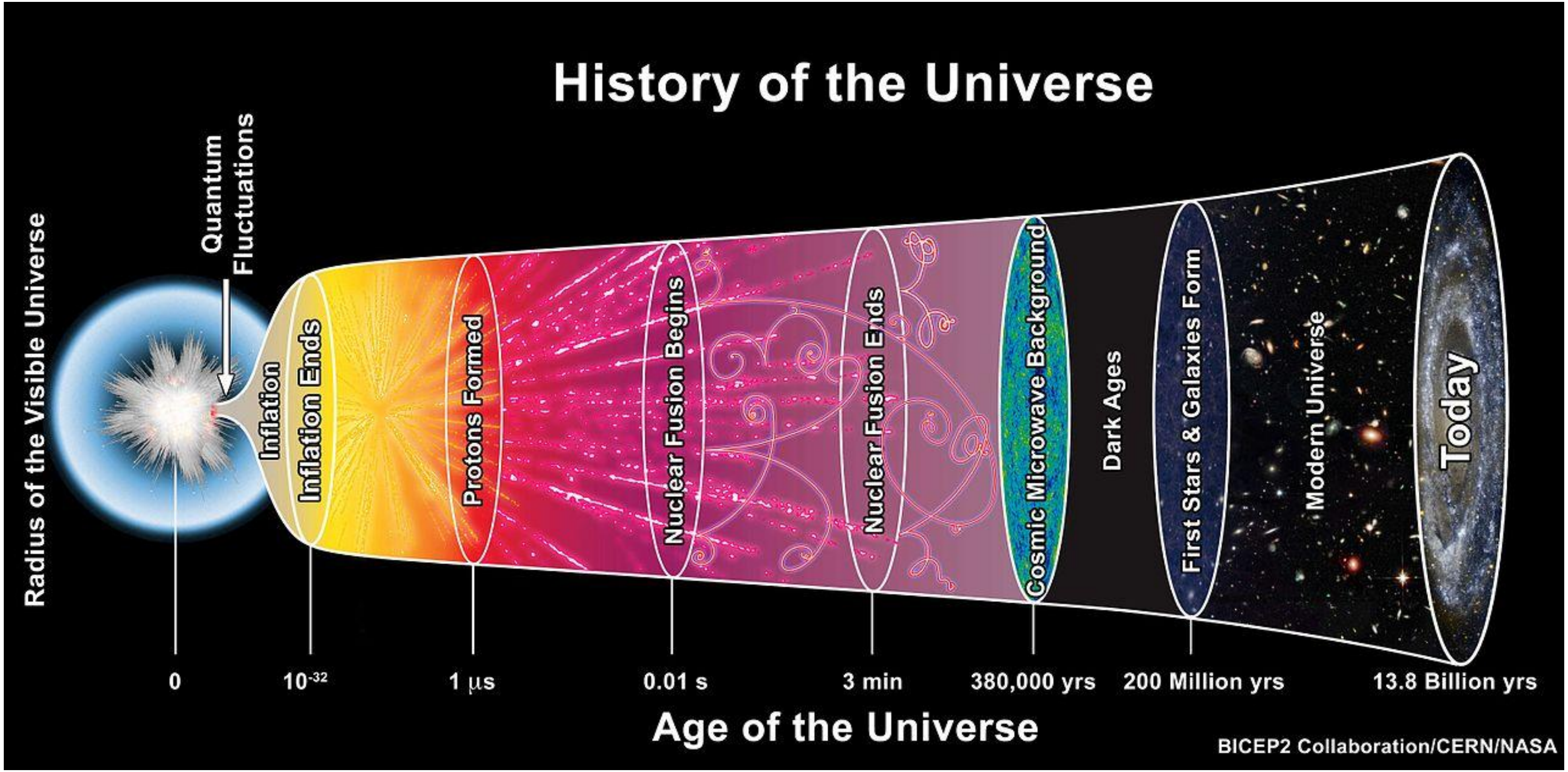
Coupling Strength



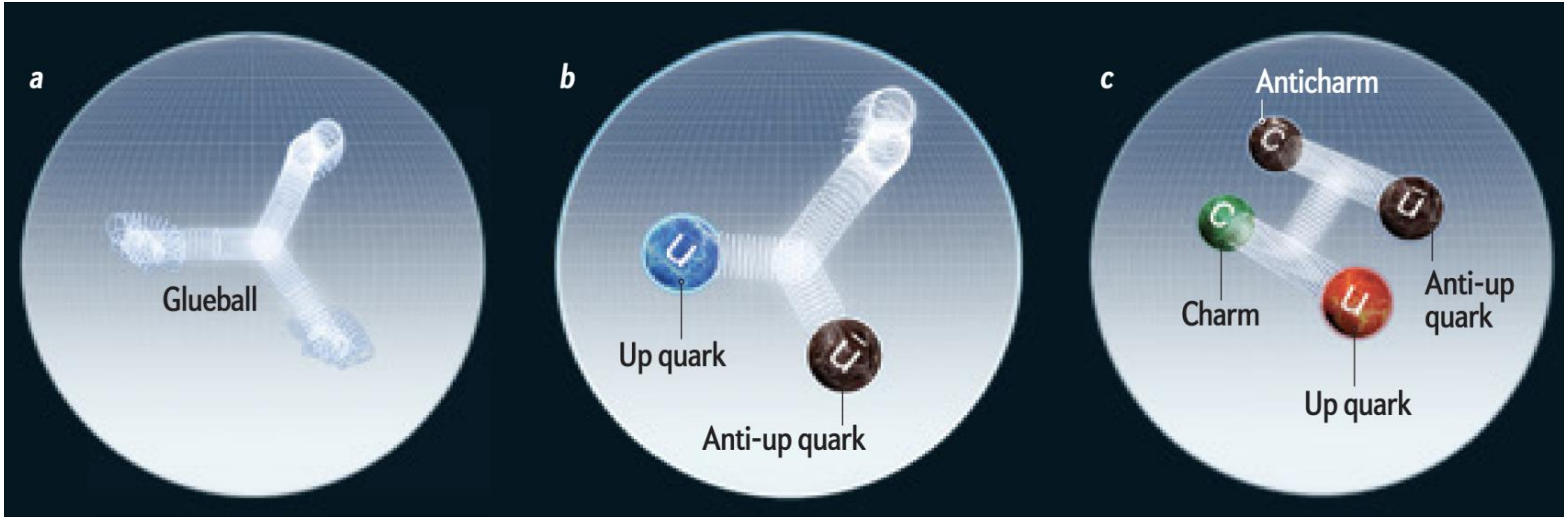


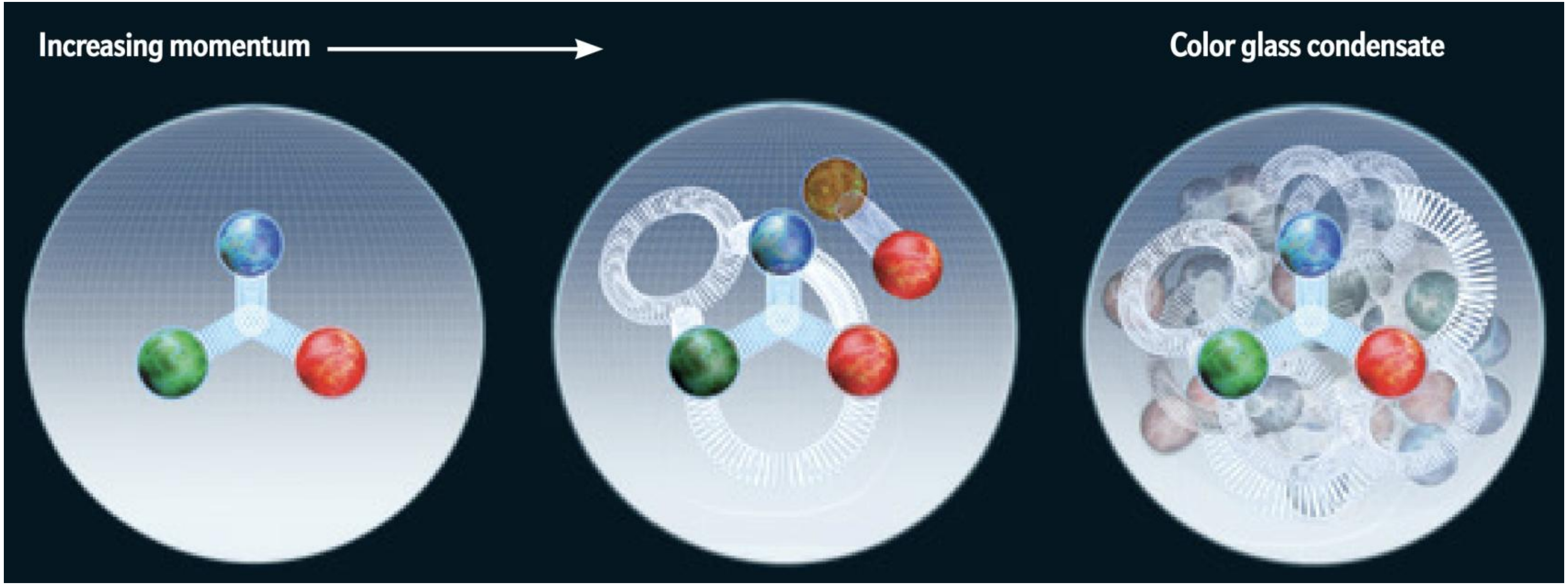
High-Energy Calculations (*red line*)
Terra Damnata (*gray zone*)
Strong Force Strength (α_s)
Low ⟶ High
0
1
2
3
Hypothesized Landau pole
High-energy data
0
0.5
1.0
1.5
Distance Scale (relative to proton diameter)



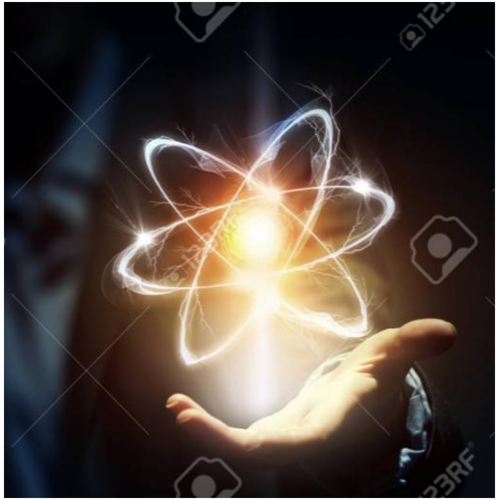


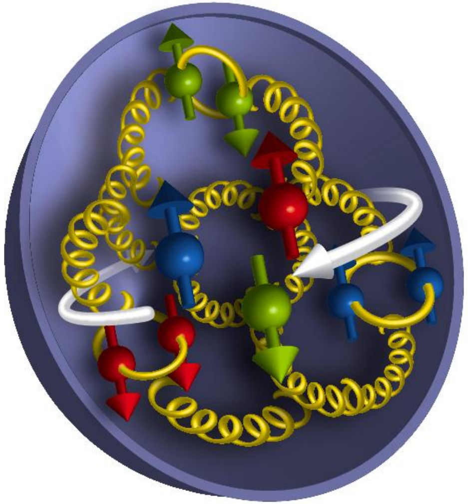
History of the Universe
Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
10^{-32}
1 μs
0.01 s
3 min
380,000 yrs
200 Million yrs
13.8 Billion yrs
Age of the Universe
BICEP2 Collaboration/CERN/NASA


a
Glueball
b
Up quark
Anti-up quark
c
Anticharm
Charm
Anti-up
quark
Up quark


Increasing momentum
Color glass condensate

About 100 years after the discovery of the atom and the proton





We know atomic structure so well, that we *define* “time” using electronic transitions:
Current accuracy
~1 sec in 220 Million years

However, the internal structure of the proton is known to only about 20-30%
~20 minutes in an hour…!

WHY?

Because of the gluons

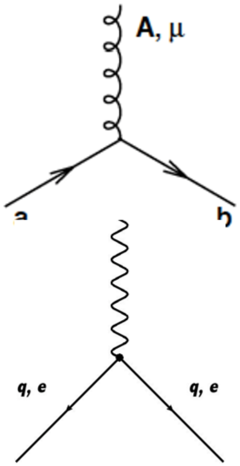
Credit: A. Deshpande

What distinguishes QCD from QED?

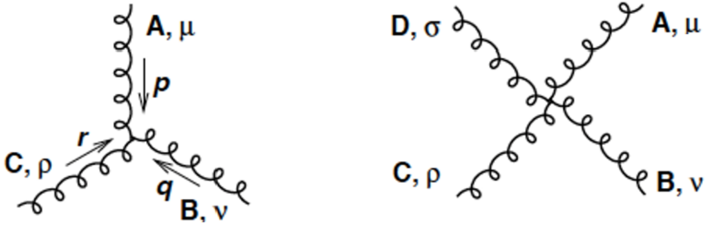
QED is mediated by photons (γ) which are charge-less (and couple to charged particles)

QCD is mediated by gluons (g), also charge-less but *are* colored! → can interact with themselves, and colored quarks

In QCD &
g → γ in QED

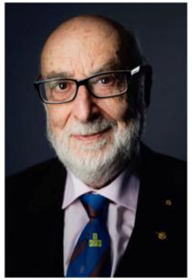


Only in QCD

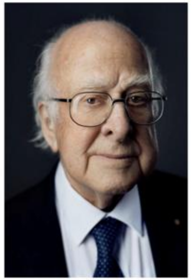


Nonlinear growth in g-g interactions…
Bring richness and complexity to QCD
Experimental guidance always needed

Proton mass puzzle



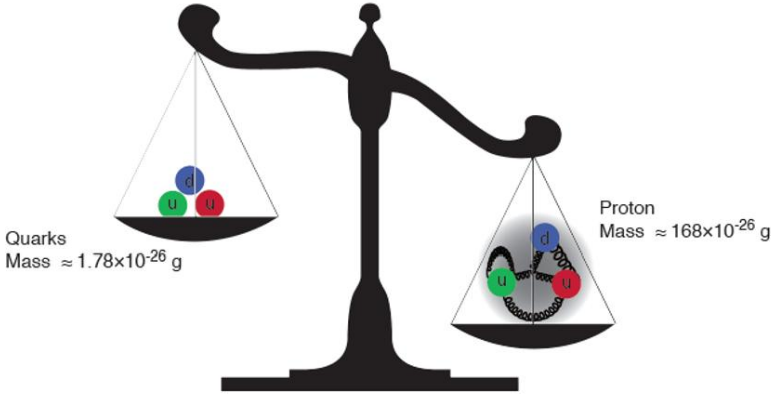
François Englert



Peter W. Higgs

Nobel 2013 With Francois Englert

“Higgs Boson” that gives mass to quarks, electrons,….



Add the masses of the quarks (HIGGS mechanism) together 1.78 x 10^{-26} grams

But the proton’s mass is 168 x 10^{-26} grams

➔ **only 1% of the mass of the protons (neutrons)** ➔ Hence the Universe

➔Where does the rest of the mass come from?

Non-linear Dynamics of QCD has Fundamental Consequences

- Quark (Color) confinement:
  - Unique property of the strong interaction
  - Consequence of nonlinear gluon self-interactions

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  - Confined motion of quarks and gluons – Transverse Momentum Dependent Parton Distributions (TMDs)
  - Confined spatial correlations of quark and gluon distributions -- Generalized Parton Distributions (GPDs)

⇒ Deeply connected to emergence of mass and spin of observed building blocks of nature

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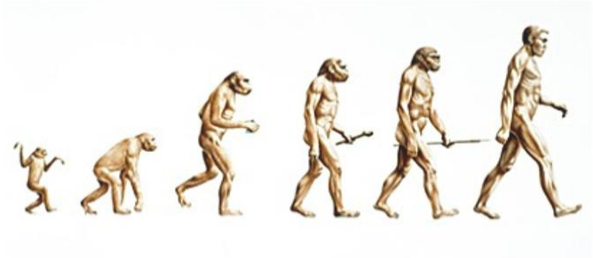
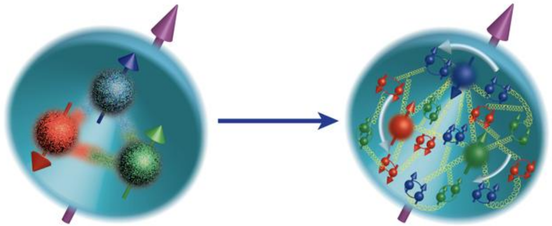
- Ultra-dense color (gluon) fields in all nucleons and nuclei?
  - Runaway growth in gluon number: Is it tamed by existing mechanisms in QCD?
  - Is there a universal many-body structure due to ultra-dense color fields?
  - Happens **in all** hadrons and nuclei? ➔ Universal?

Spin "Crisis" → Spin Puzzle

Discovered by EMC experiment at CERN





25% 25%

$$\frac{1}{2} = [\mathrm{Q}_{\mathrm{spin}} + \mathrm{Q}_{\mathrm{ang.mom.}}] + [\mathrm{G}_{\mathrm{spin}} + \mathrm{G}_{\mathrm{ang.mom.}}]$$

? ?

Transverse motion and finite size of the proton must create the orbital motion

Nuclear Puzzle

Discovered by EMC experiment at CERN

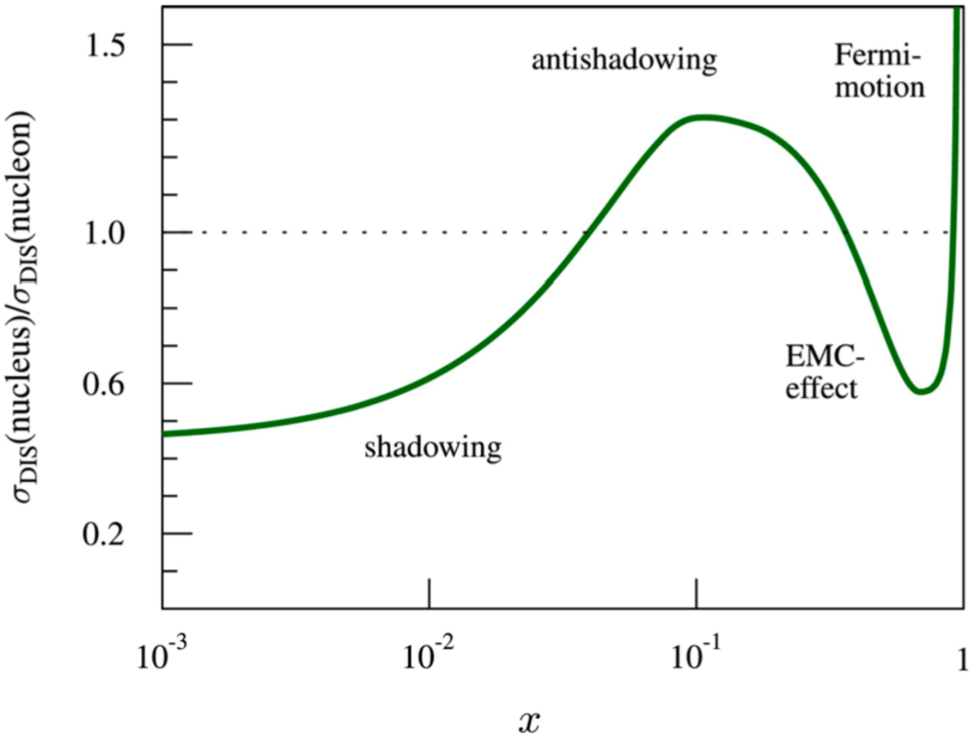
Nuclear EMC effect

Parton distributions are different in protons and nuclei

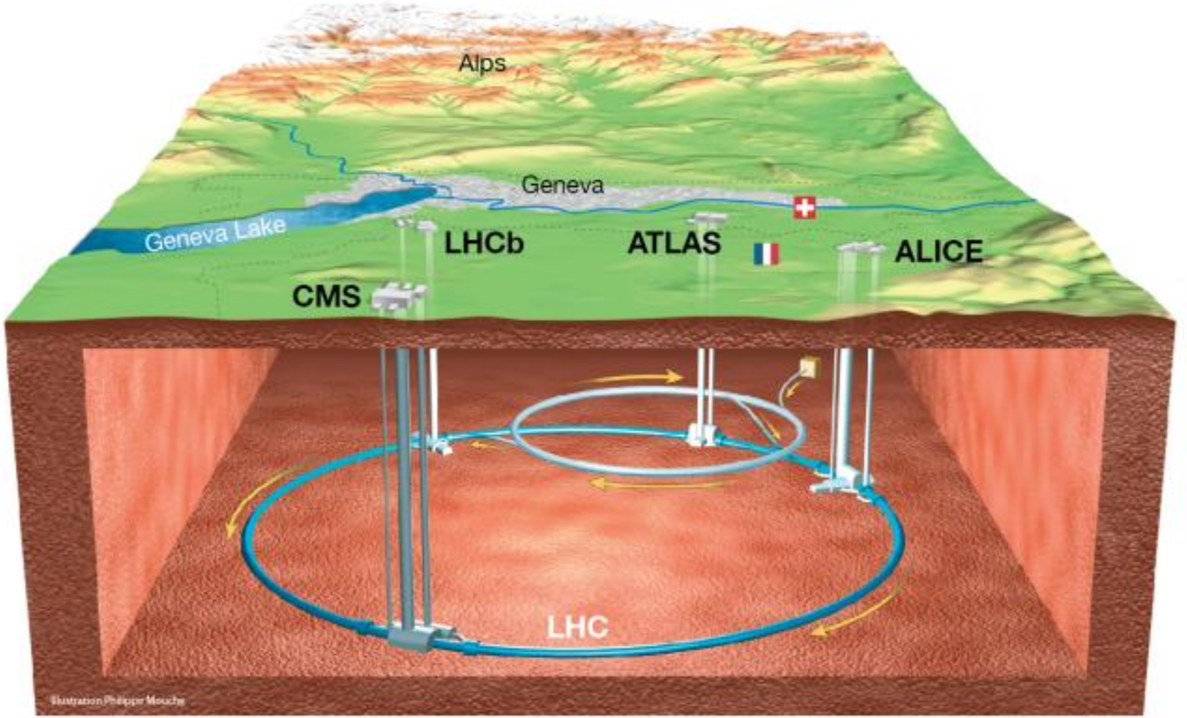
Exactly how do they get modified?

What happens in regions x < 0.001? Not quite known, and not predictable

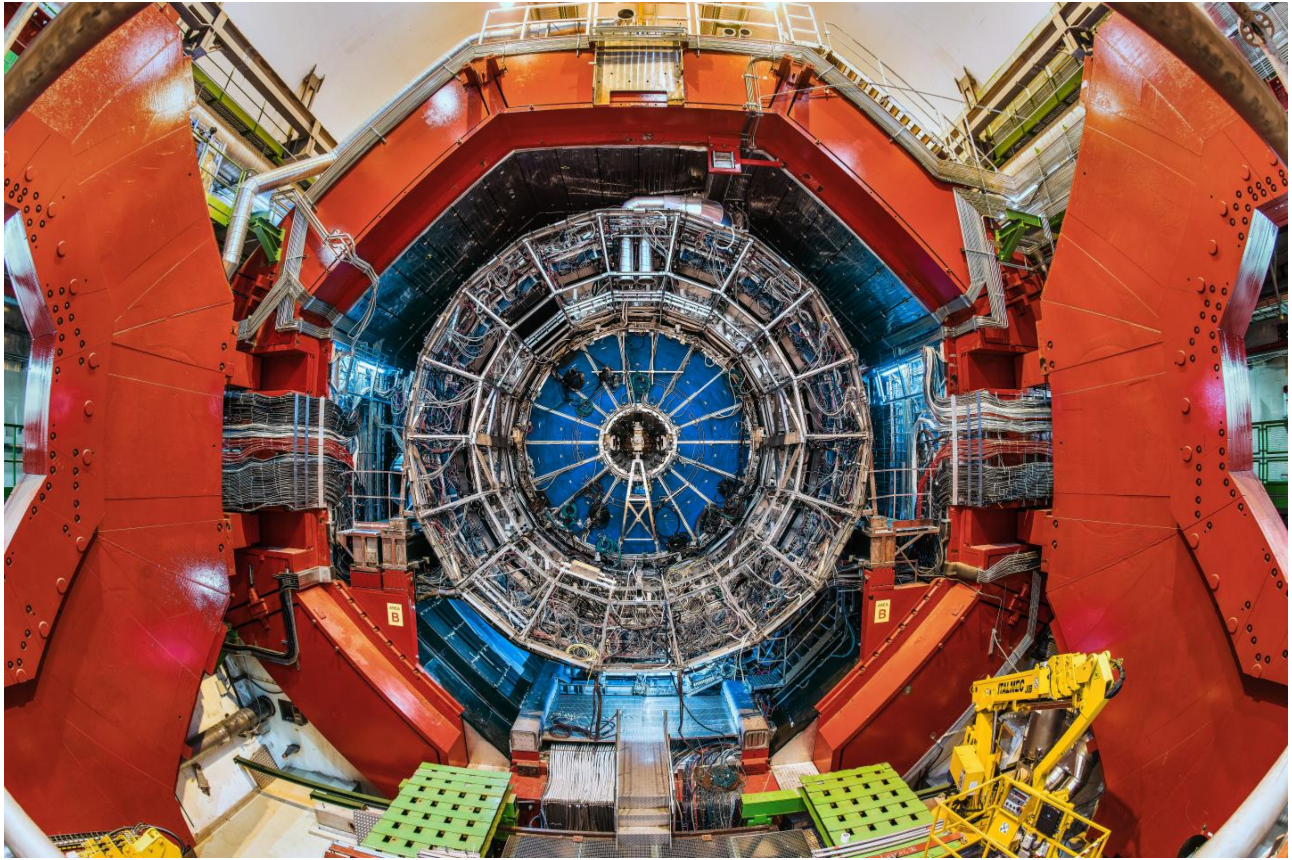
However, low-x dynamics in protons and nuclei is of great interest, need to measure experimentally



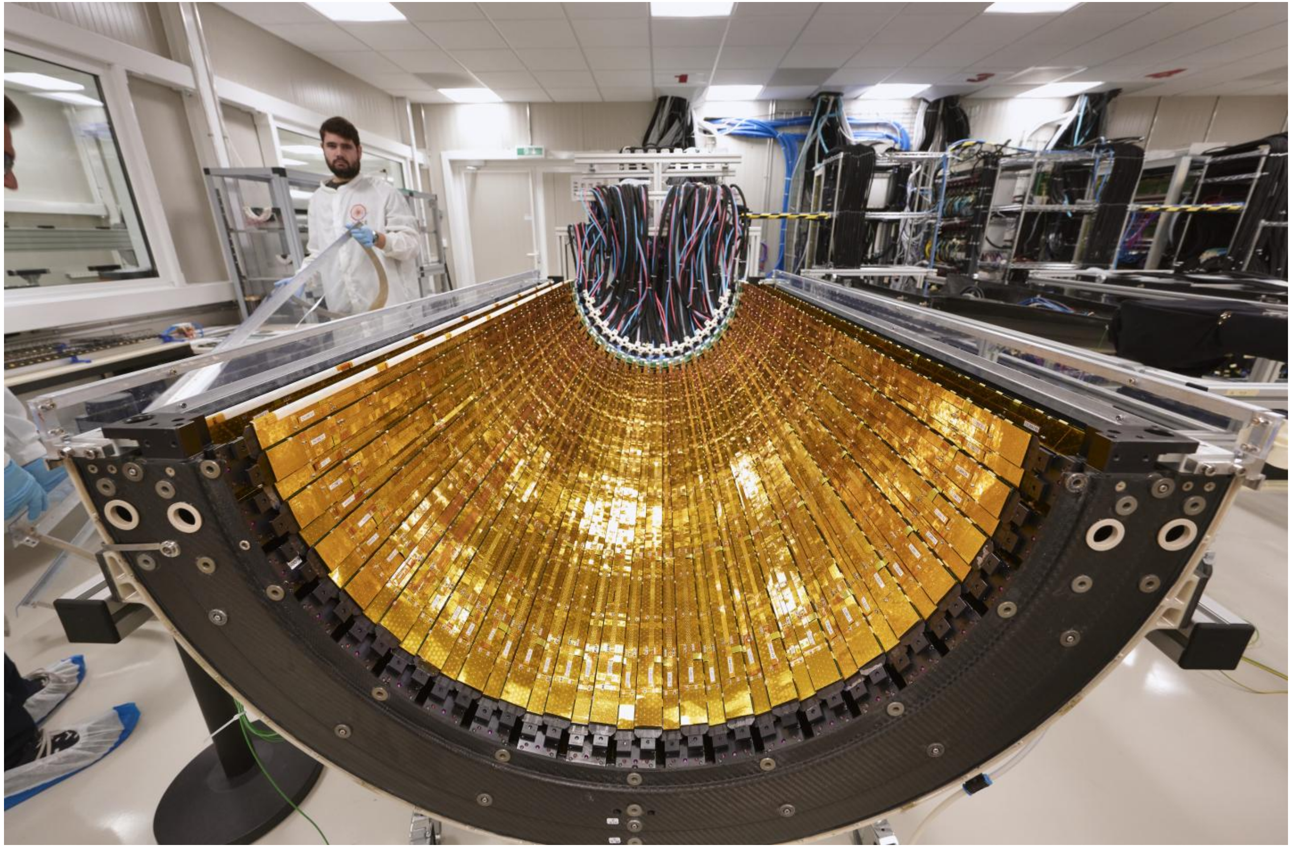
The CERN Large Hadron Collider

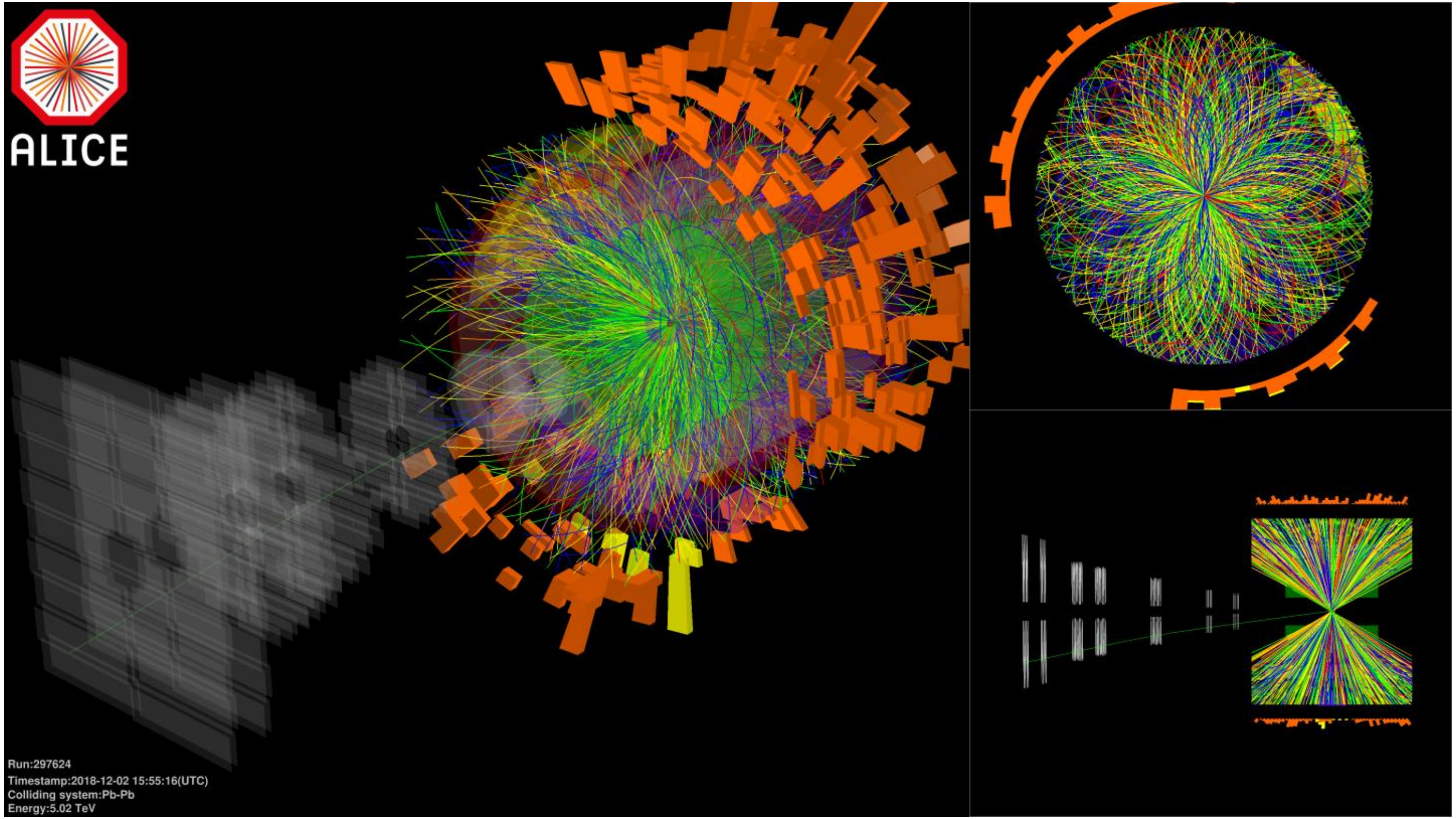

Alps
Geneva
Geneva Lake
LHCb
ATLAS
ALICE
CMS
LHC

The ALICE experiment at the CERN LHC



The ITS Inner Tracking System




ALICE
Run:297624
Timestamp:2018-12-02 15:55:16(UTC)
Colliding system:Pb-Pb
Energy:5.02 TeV

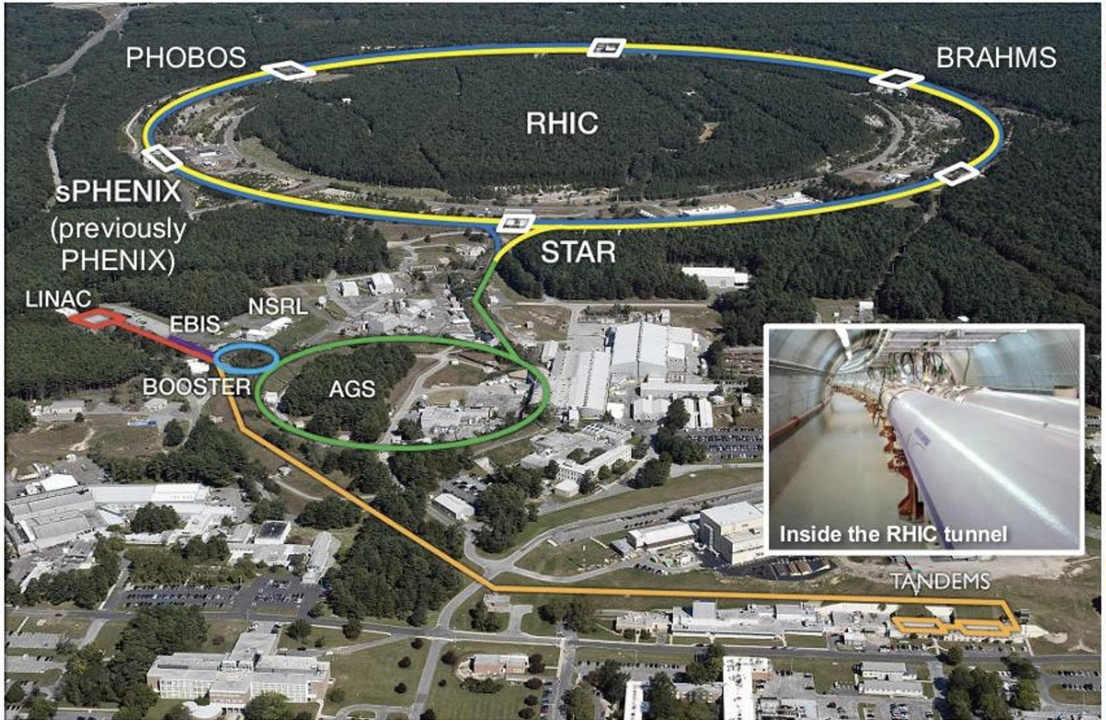
A Large Ion Collider Experiment
ALICE
CERN
ION PHYSICS: STABLE BEAMS
Fill 10330 Energy= 6799 (GeV)
BEAM Instr. BACKGROUND
ALICE CLOCK STATUS
AUTO / BEAM1 (0)
ALICE BACKGROUND
347

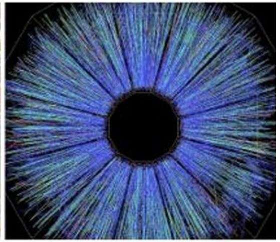

Detector Control System

A glorious run from 2000-2026 : unparalleled scientific output: Quark Gluon Plasma and Nucleon Spin

The Relativistic Heavy Ion Collider

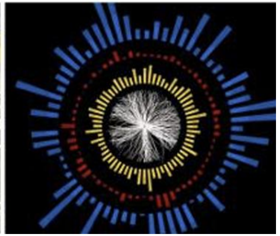
A machine built to explore fundamental matter at the dawn of time

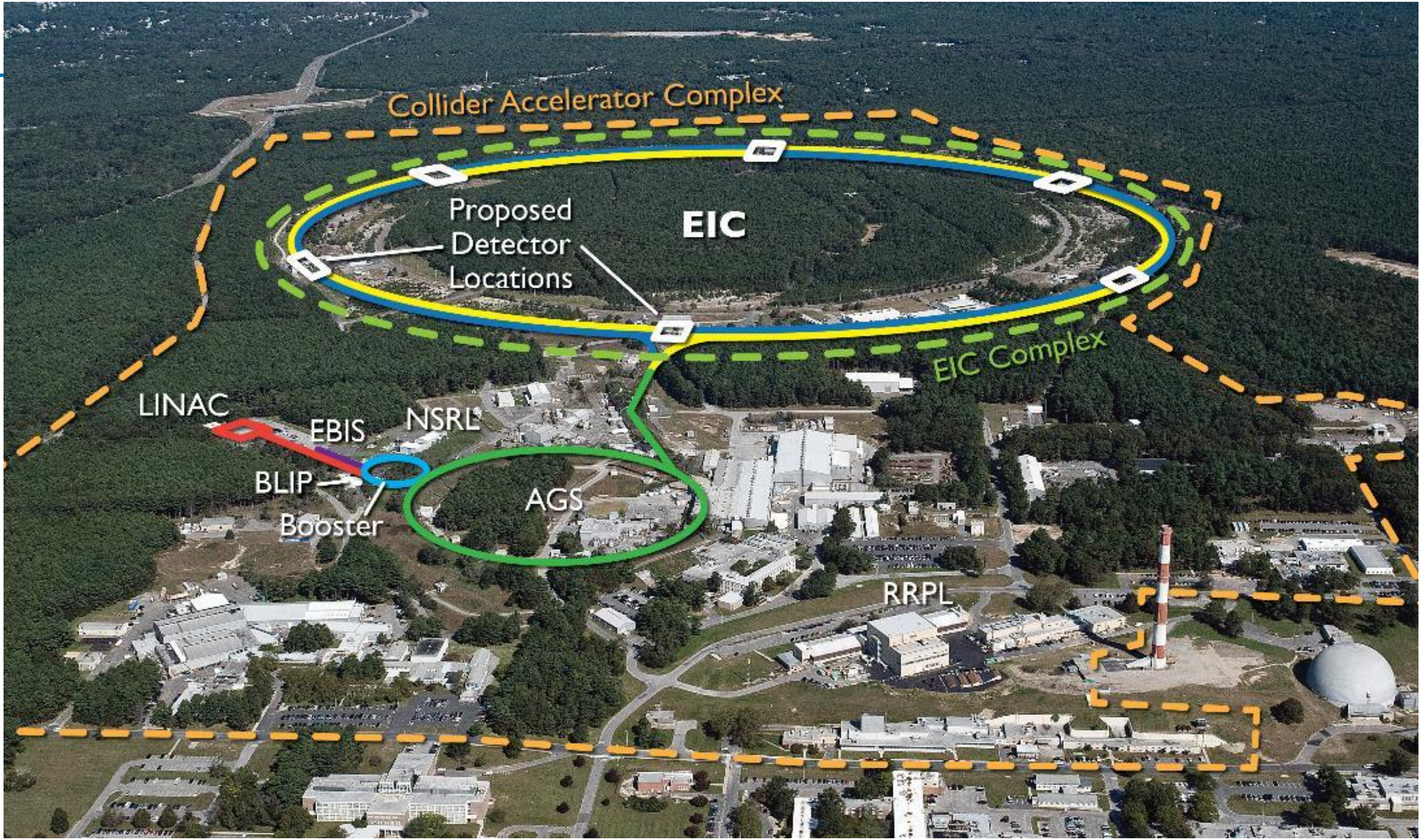




Collaborations, experiments

- PHOBOS: 2000 – 2005
- BRAHMS: 2000 – 2006
- PHENIX: 2000 – 2016
- STAR: 2000 – 2026
- sPHENIX: 2023 – 2026





Collider Accelerator Complex
Proposed
Detector
Locations
EIC
EIC Complex
LINAC
EBIS
NSRL
BLIP
Booster
AGS
RRPL

Heavy Ion Physics

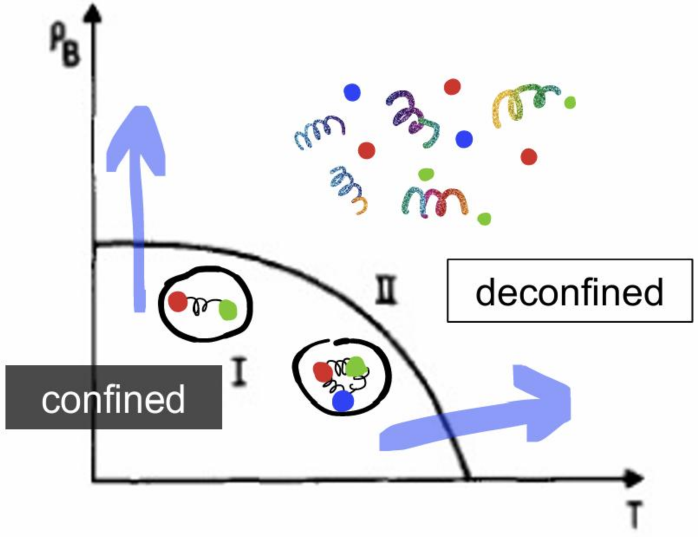
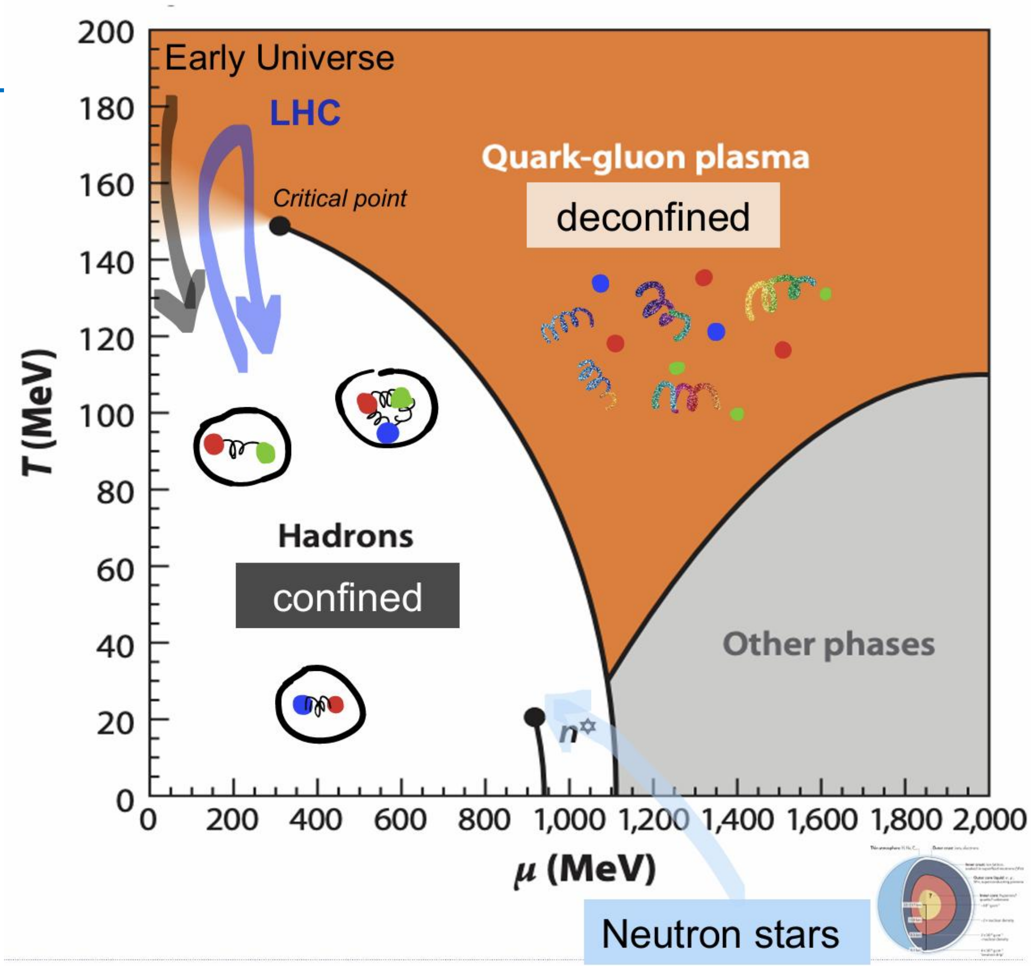


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

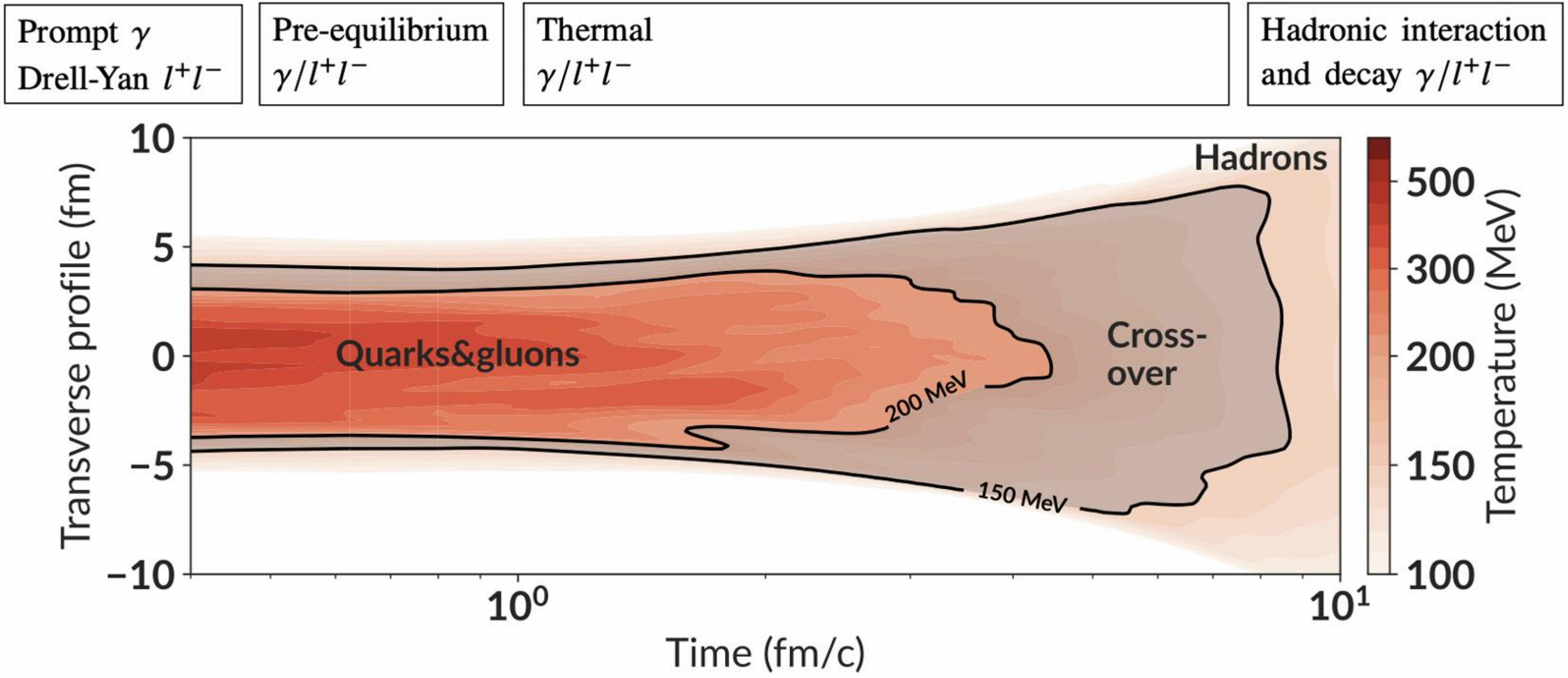
N. Cabibbo, G. Parisi, Phys. Lett. B59 (1975) 67
J.C. Collins, M.J. Perry, Phys. Rev. Lett. 34 (1975) 1353

Credit: F. Bellini

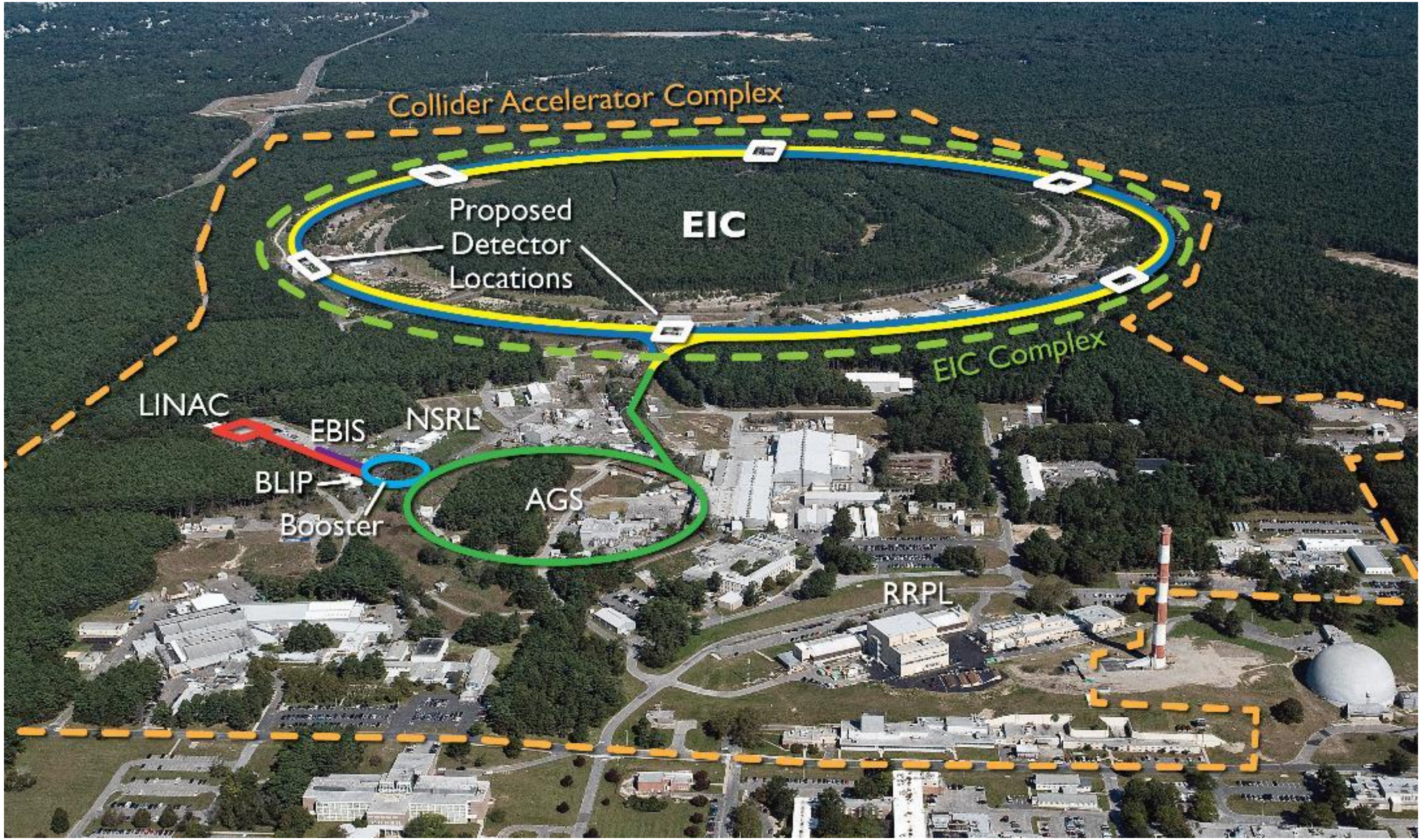


Credit: F. Bellini

Jean-François Paquet
https://arxiv.org/pdf/2307.09967.pdf



The Electron Ion Collider (EIC): next QCD generational facility



Scattering of protons on protons
is like colliding Swiss watches to find out
how they are build.

R. Feynman

We can ask : What is in there, but not how they are built or how they work!

Credit: A. Deshpande

Study of internal structure of a watermelon:

A-A (RHIC/LHC)

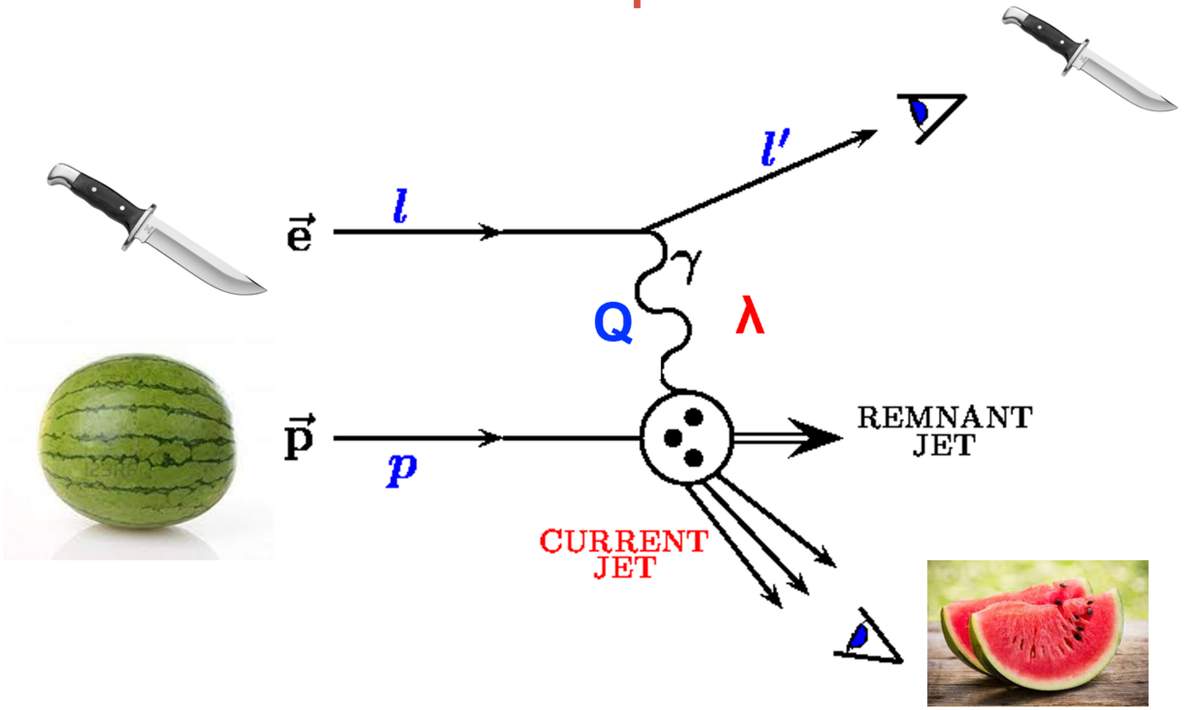
1) Violent collision of melons

2) Cutting the watermelon with a knife

Violent DIS e-A (EIC) and UPC

Credit: A. Deshpande

Deep Inelastic Scattering



$\lambda = (h/2\pi)(1/Q^2)$

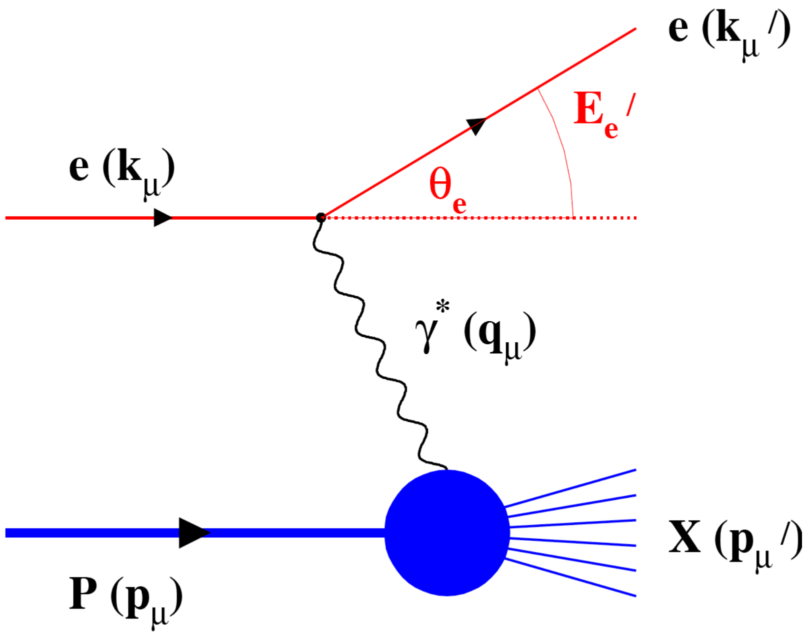
h = constant

λ = wavelength

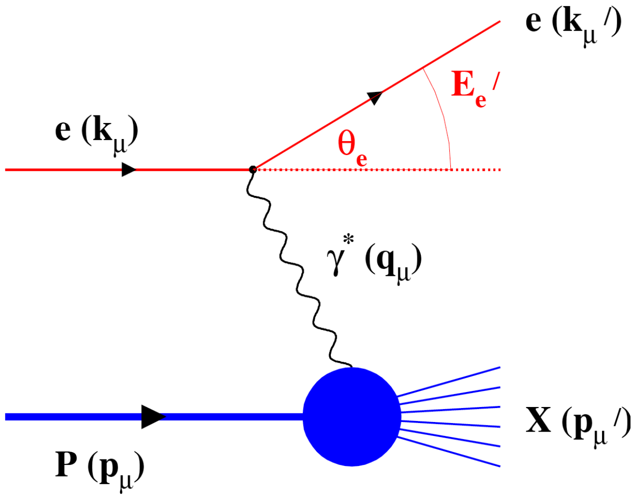
Q^2 = momentum transferred

Deep Inelastic: (**λ** << Proton Size)

Deep Inelastic Scattering



Deep Inelastic Scattering



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

Measure of resolution power

$$Q^2 = 2E_e E'_e (1 - \cos\Theta_{e'})$$

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

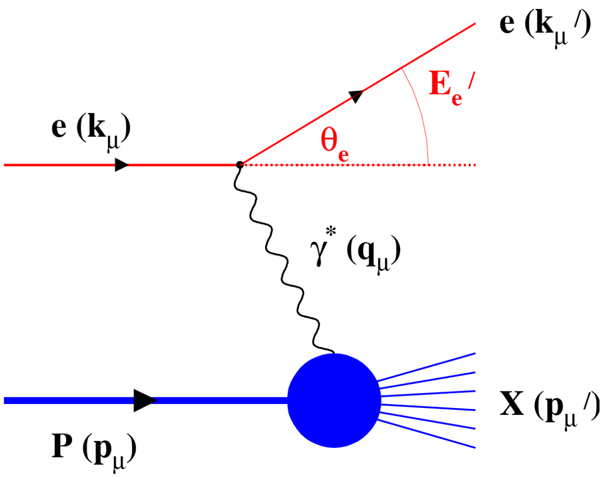
Hadron :

with respect to γ^*

$$z = \frac{E_h}{\nu};\, p_t$$

$$s = 4\, E_h\, E_e$$

Deep Inelastic Scattering



Exclusive DIS

detect & identify *<u>everything</u>* e+p/A → e'+h(π,K,p,jet)+…

Semi-inclusive events:

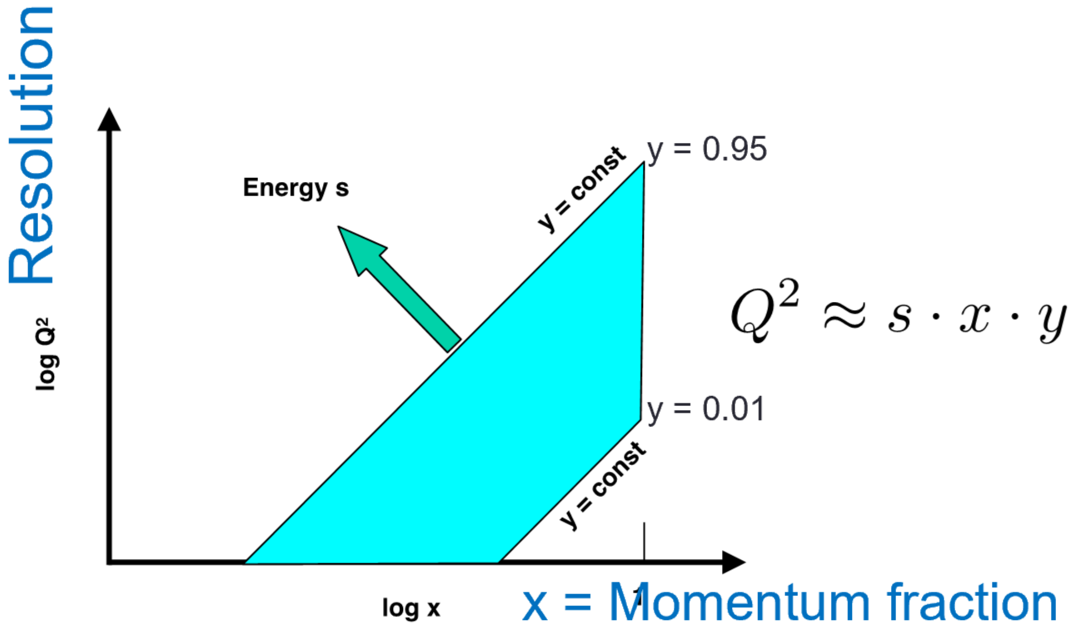
e+p/A → e'+h(π,K,p,jet)+X

detect the scattered lepton in coincidence with <u>identified hadrons/jets</u>

Inclusive events:

e+p/A → e'+X

detect *<u>only the scattered lepton</u>* in the detector

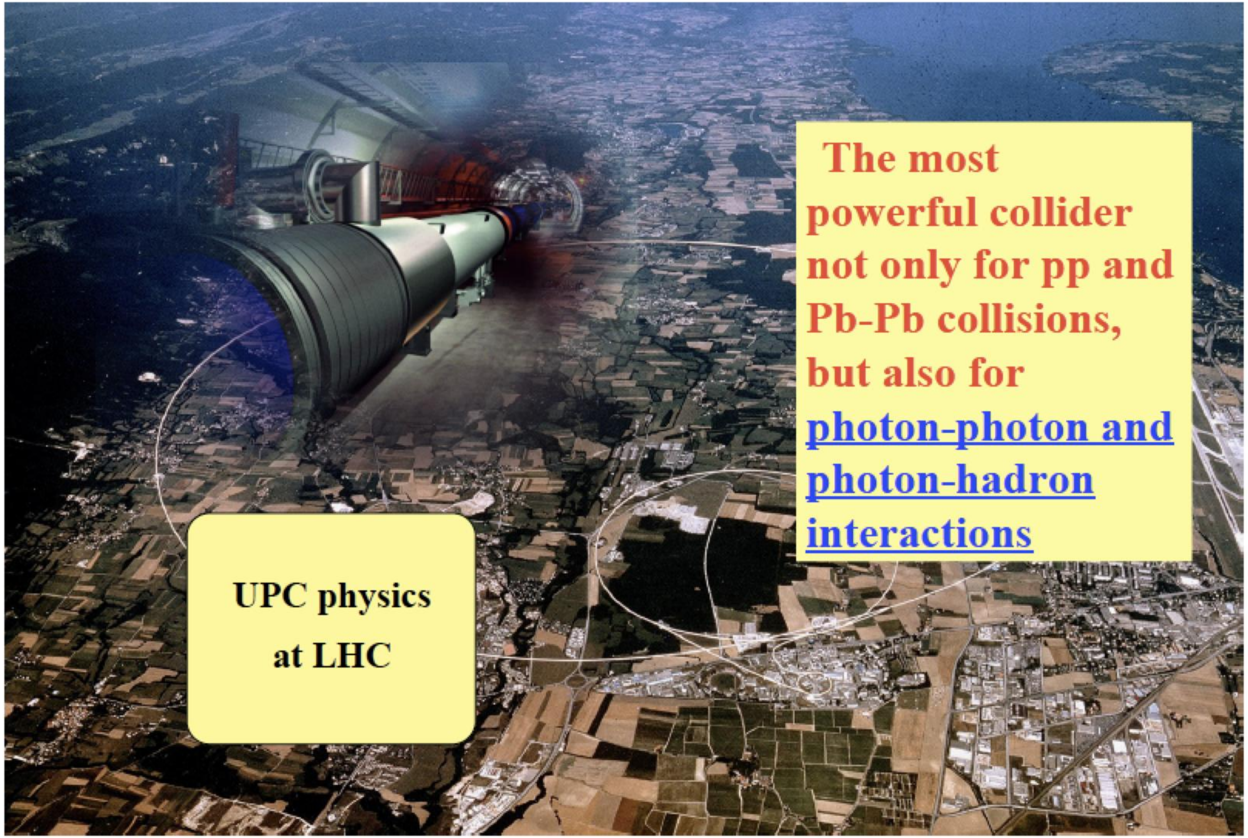


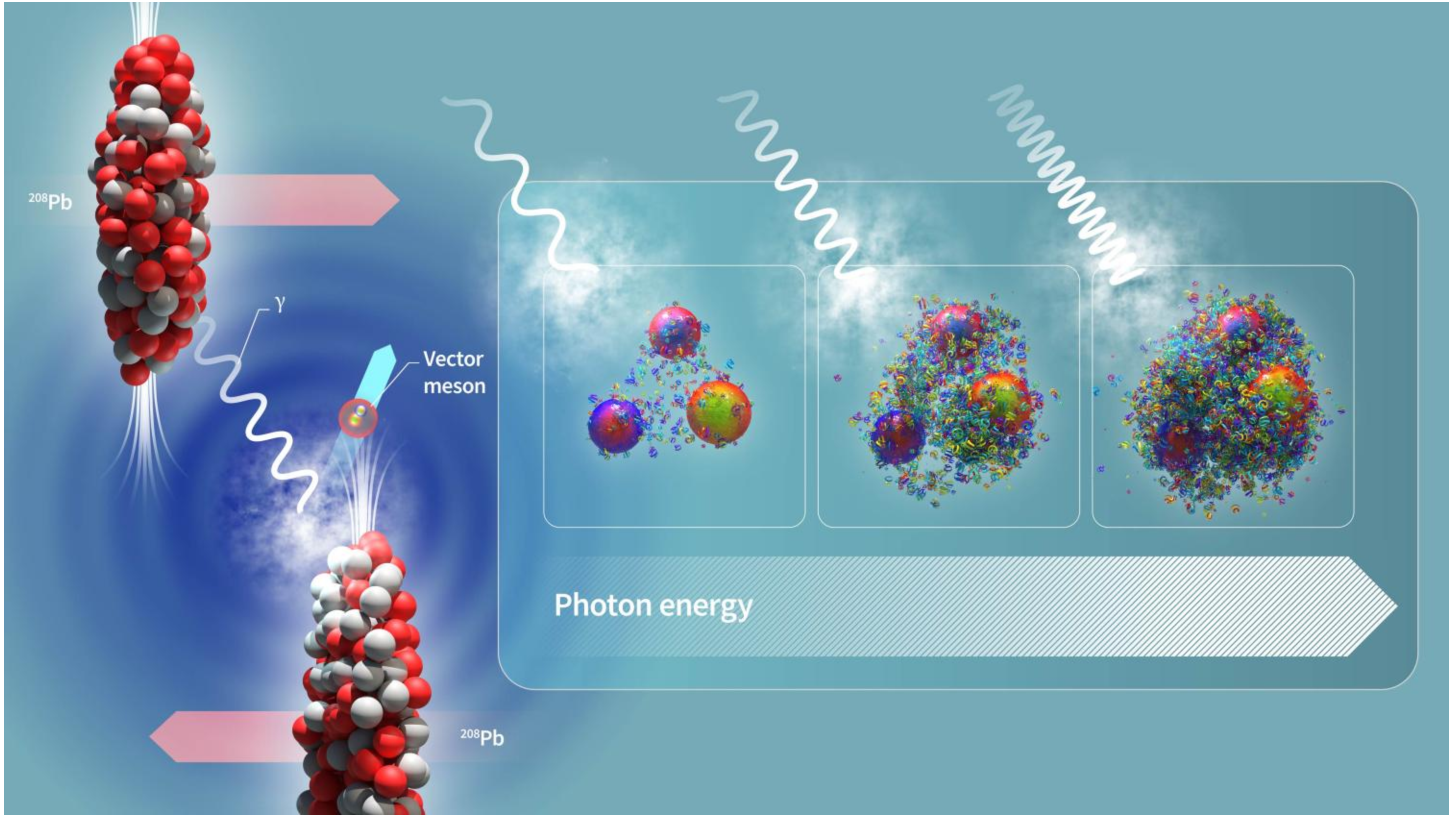
$$Q^2 \approx s \cdot x \cdot y$$

- Low-x reach requires large $\sqrt{s}$
- Large-Q^2 reach requires large $\sqrt{s}$
- *y* at colliders typically limited to $0.95 < y < 0.01$

All CERN LHC experiments are more than pp or AA colliders

The LHC as Photon Collider



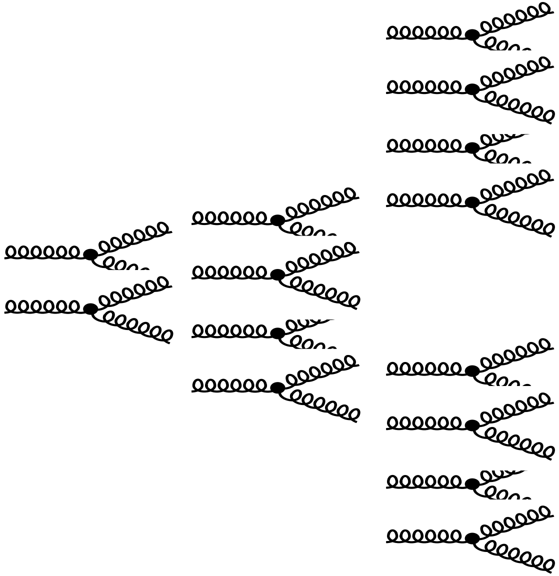


^{208}Pb
γ
Vector meson
Photon energy
^{208}Pb

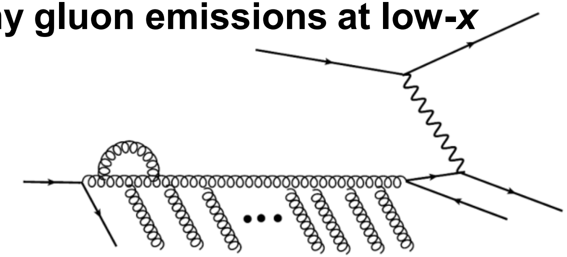
Gluons matter

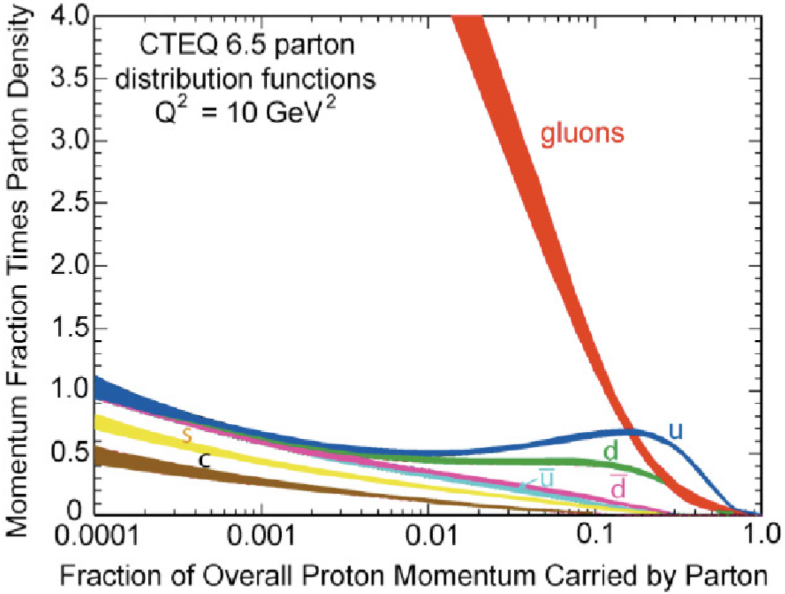
Quarks and gluons dynamics described by QCD

Gluons carry color, thus self-gluon interactions



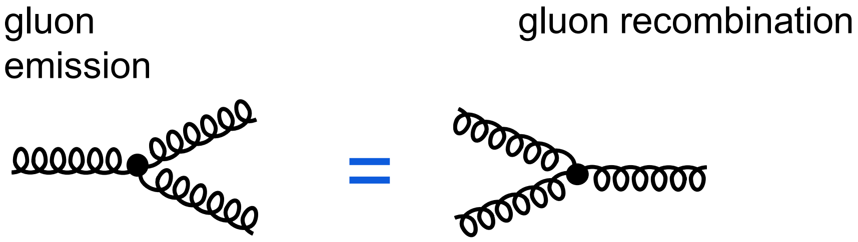
Many gluon emissions at low-*x*





Gluon saturation matters

At high energies, or for heavy nuclei at lower energies, gluon saturation is predicted



Dynamical equilibrium of gluon saturation state reached

- Non-linear QCD evolution equations introduced, but how is gluon saturation triggered?
- Experimental observables needed to map out the transition between the dilute and saturation regimes. The onset of saturation
- Can we determine experimentally the saturation scale (Q_S)?
- Is there a state of matter formed by gluon saturated matter with universal properties?

Gluon saturation matters

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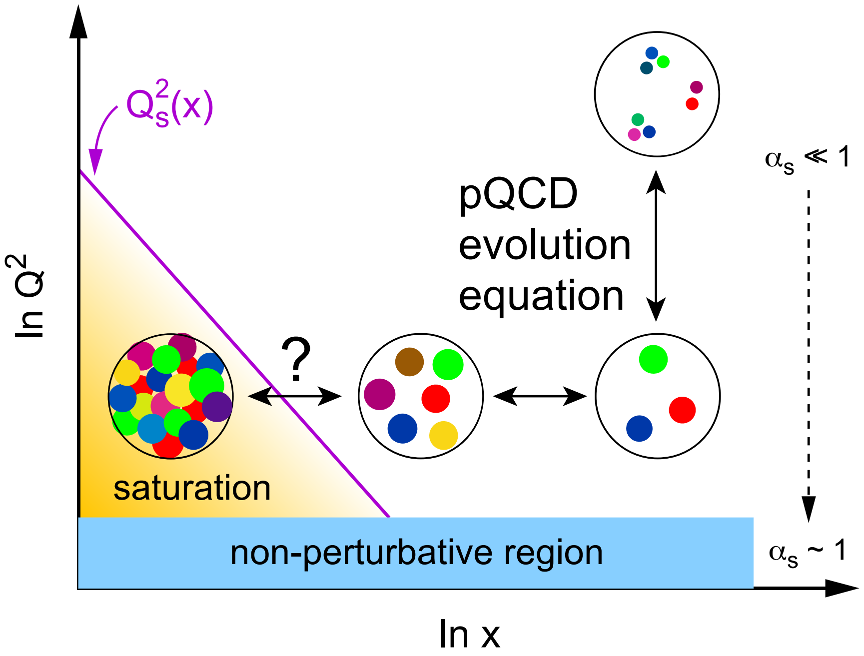

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- Experimental observables needed to map out the transition between the dilute and saturation regimes. The onset of saturation
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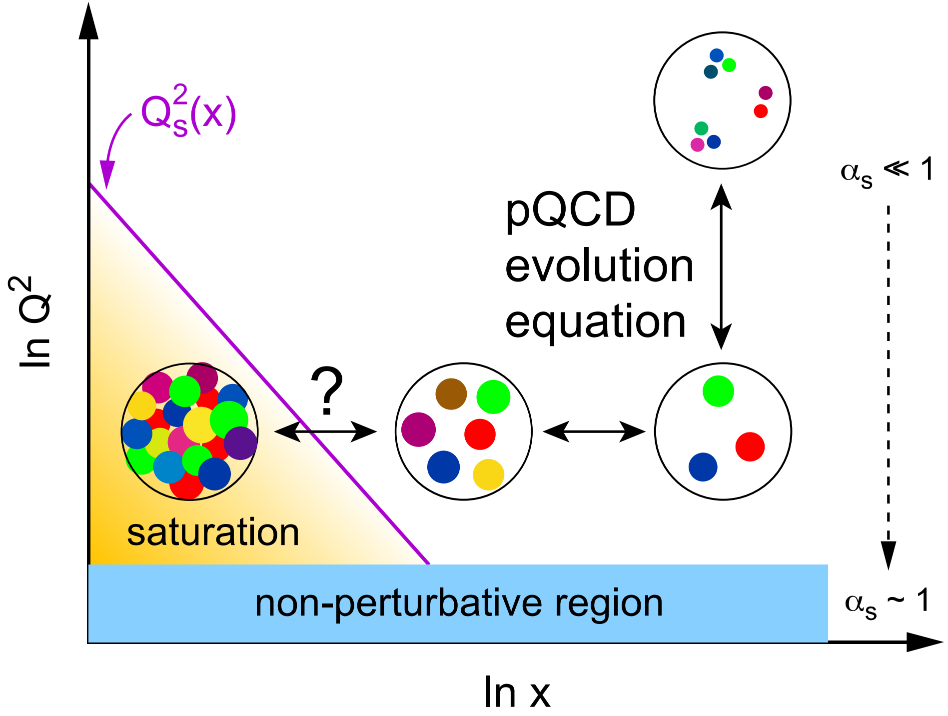
- Is there a state of matter formed by gluon saturated matter with universal properties?

Evolution of the hadronic structure with Bjorken-x and Q^2

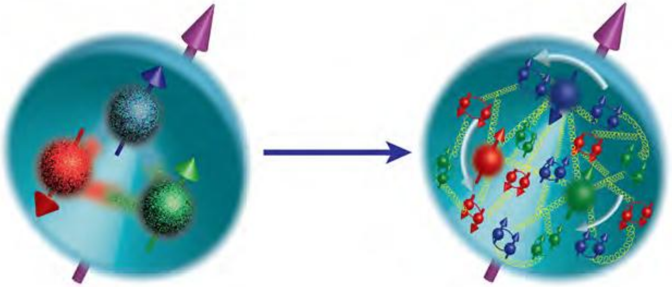


- Experimental observables needed to map out the transition between the dilute and saturation regimes

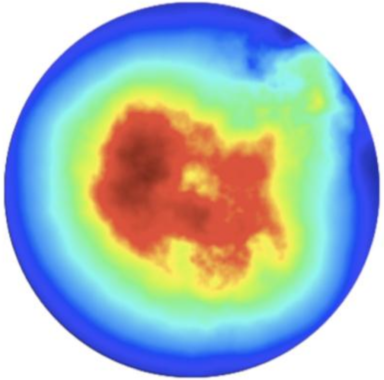
- For nuclei, the saturation scale is enhanced by a $A^{1/3}$ factor

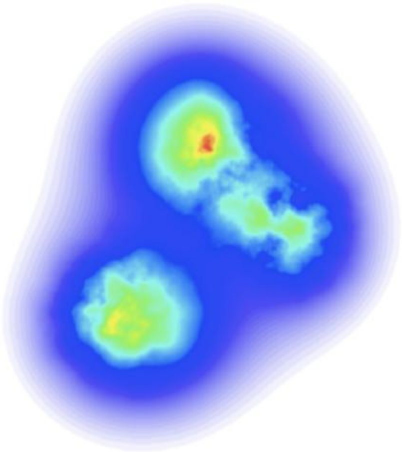
$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

The structure and dynamics of hadrons

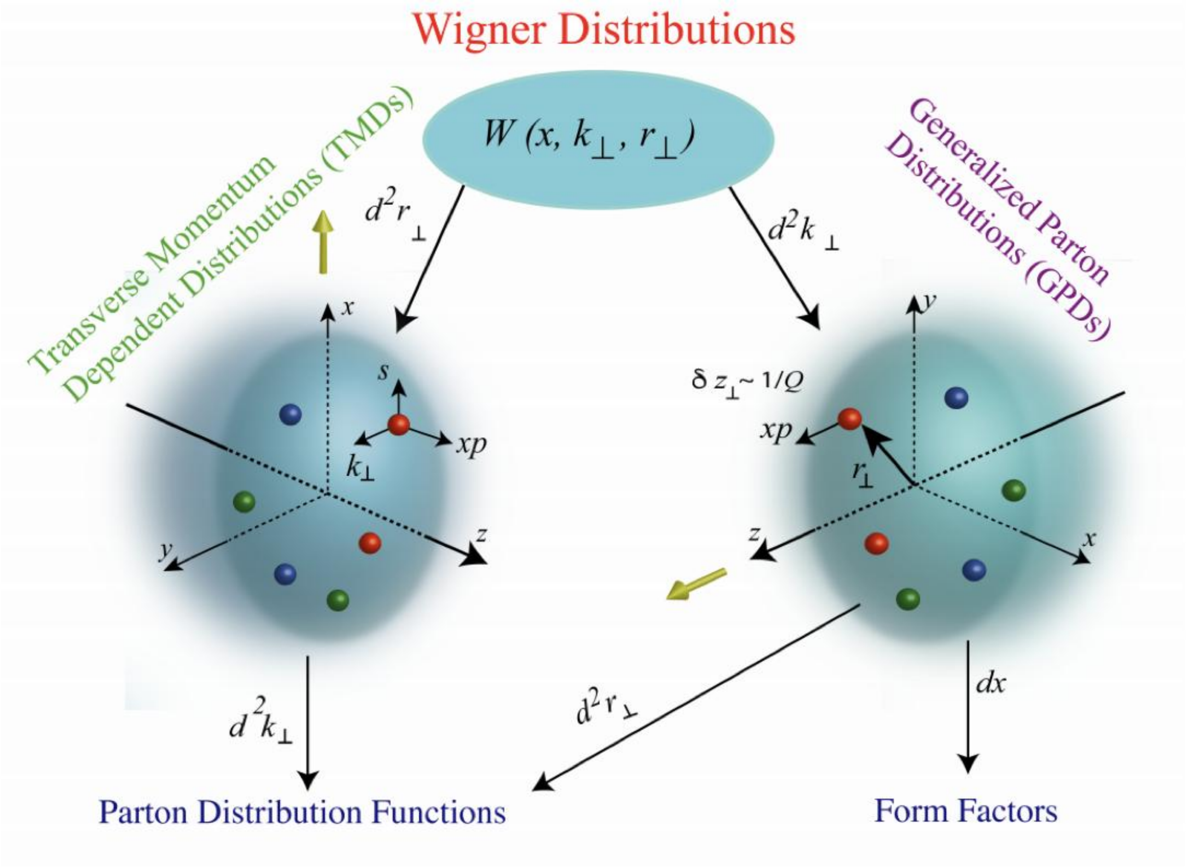


What does the proton look like?

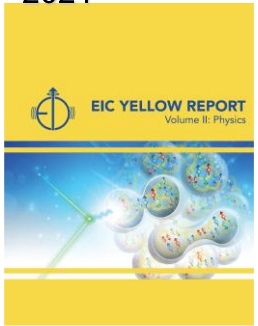




Multi-dimensional picture



2021



The LHC is the Large **Photon** Collider

- **Ultra Peripheral Collisions (UPC)** can explore a wide range of energies using almost real photons

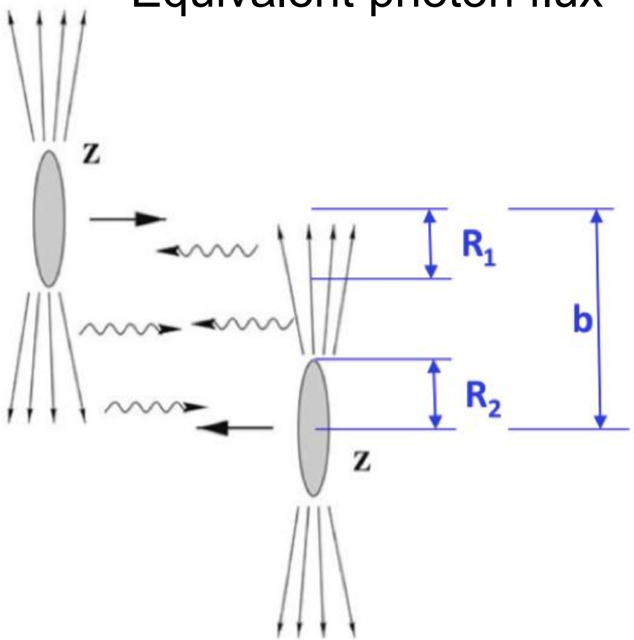
  $k = \gamma M_V \exp(\pm, y)$
  Up to several TeV in γp
  Up to ~ 700 GeV/nucleon in γA
  Up to ~ 150 GeV in $\gamma\gamma$ using UPC PbPb,
  ~ 4 TeV in in $\gamma\gamma$ using UPC pp

- UPCs at the LHC probe the hadronic structure over broad and unique Bjoren *x* region, yet the precision not compatible to DIS machines like the EIC

  $x = M_V/\gamma m_p \exp(\pm, y)$

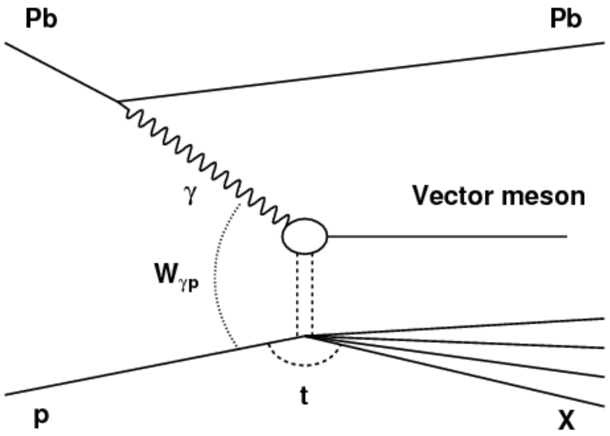
Interactions mediated by the EM interactions

Equivalent photon flux



Vector meson (VM) photoproduction in UPCs

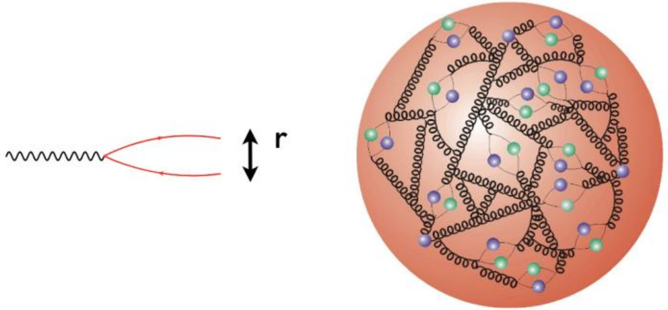
$$W^2_{\gamma p} = 2E_p M_{J/\psi} e^{\pm y}$$



- As in DIS, several reactions are possible in UPCs:
  - -Exclusive photoproduction
  - -Semi-exclusive photoproduction
  - -Inclusive photoproduction

- By studying various VMs, it is possible to study the Q^2 dependence

- In the dipole approach, the light VMs (ϕ, ρ^0) are more sensitive to saturation because of the larger dipole, but pQCD methods not applicable

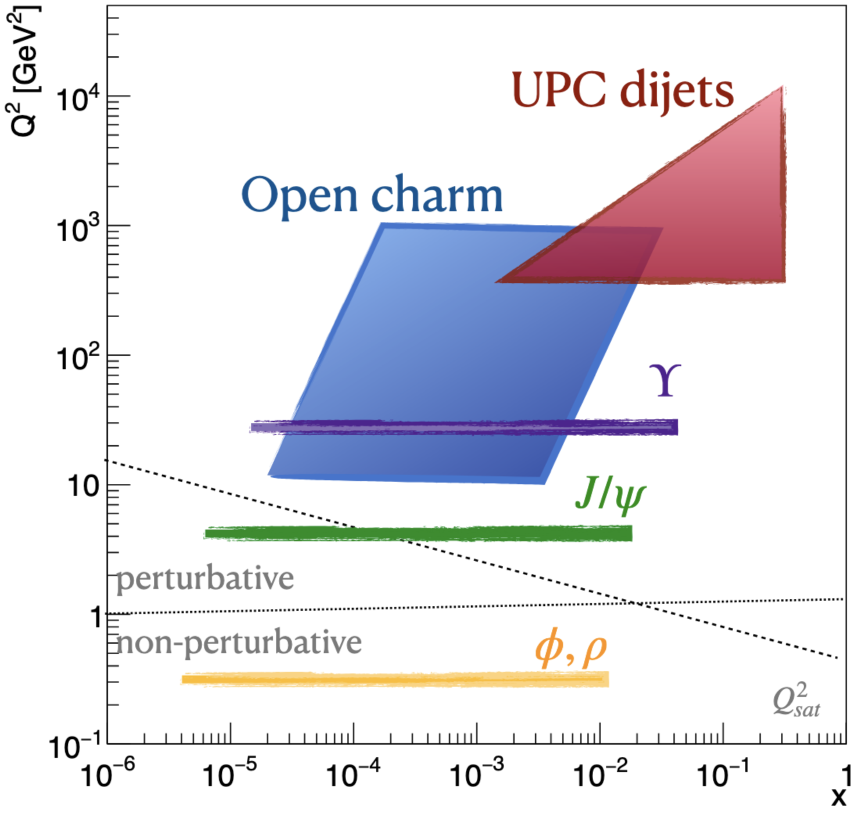


Various processes

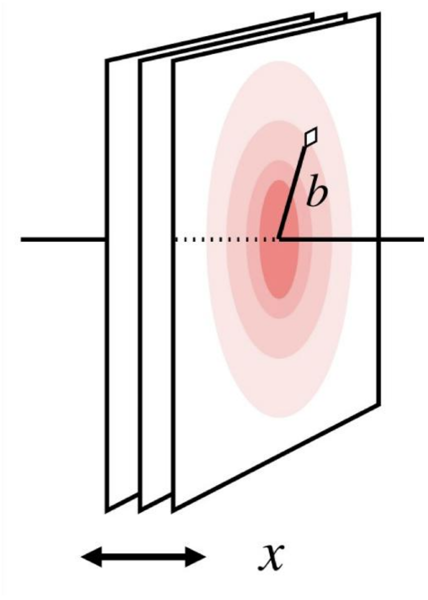
Fig. from A. Ogrodnik

- By studying various processes, it is possible to explore both the Bjorken *x* and Q^2 dependence

- Transition between the dilute and dense QCD region, and from the perturbative and non-perturbative QCD regime

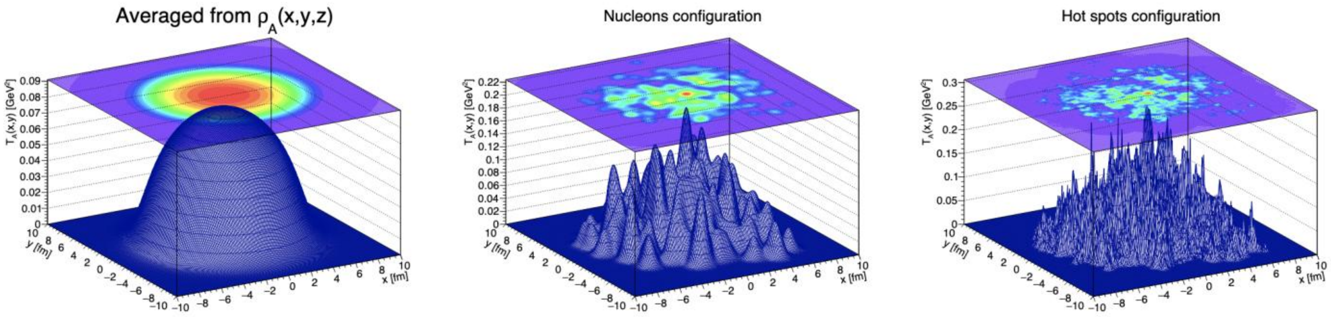


Transverse profile of the target



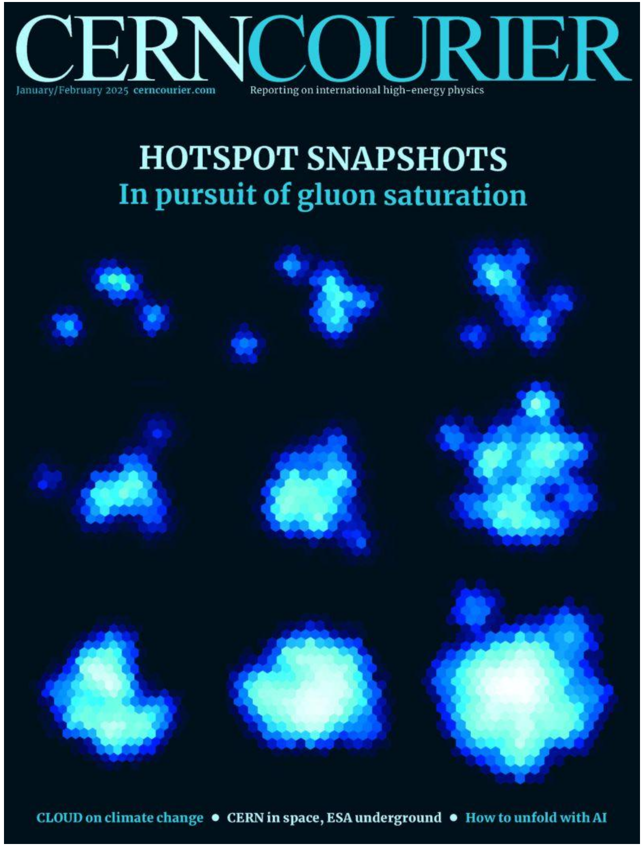
UPCs can probe the transverse profile of the target!

Appearance and location of diffractive dips can be signatures of gluon saturation



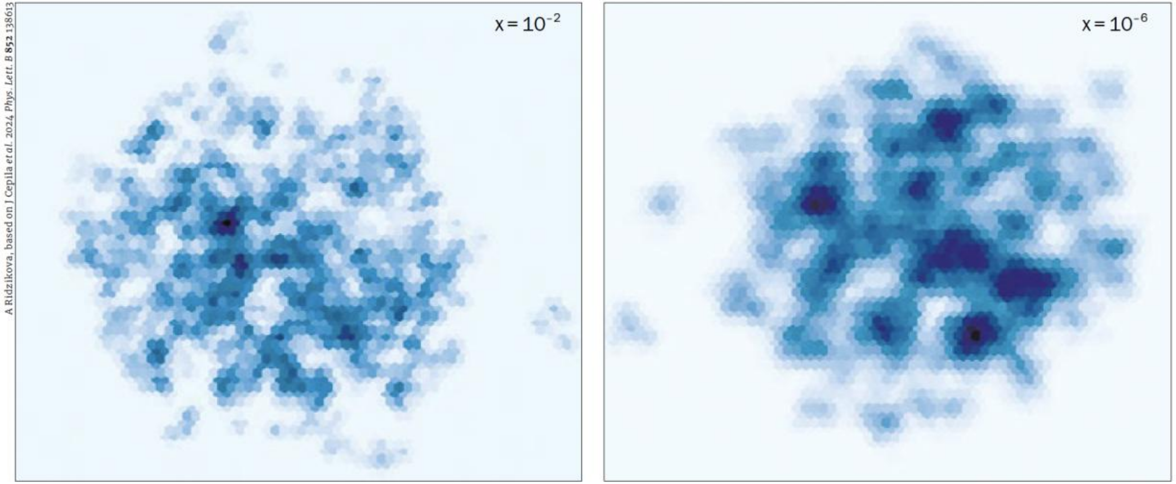
Gluonic hot spots

- https://cerncourier.com/a/the-other-99/



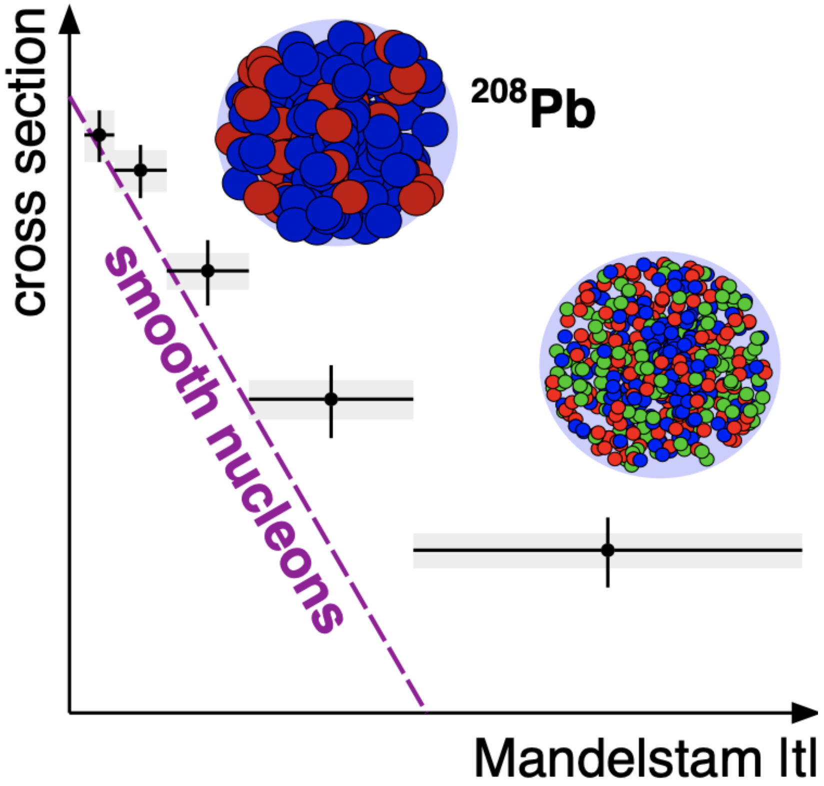
Large Bjorken-*x*

Low Bjorken-*x*



Hotspot snapshots *Simulations of the transverse density of gluons in lead nuclei at Bjorken x of 10^{-2} (left) and 10^{-6} (right). The distributions are 10 times broader than for protons and span almost 15 fm. The number of gluonic hotspots increases from 1,400 to 12,000 as x drops by a factor of 10,000, from left to right.*

t-dependence of incoherent J/ψ in UPC Pb-Pb

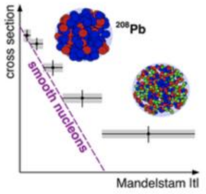


Editors' Suggestion

First Measurement of the $|t|$ Dependence of Incoherent J/ψ Photonuclear Production

S. Acharya *et al.* (ALICE Collaboration)

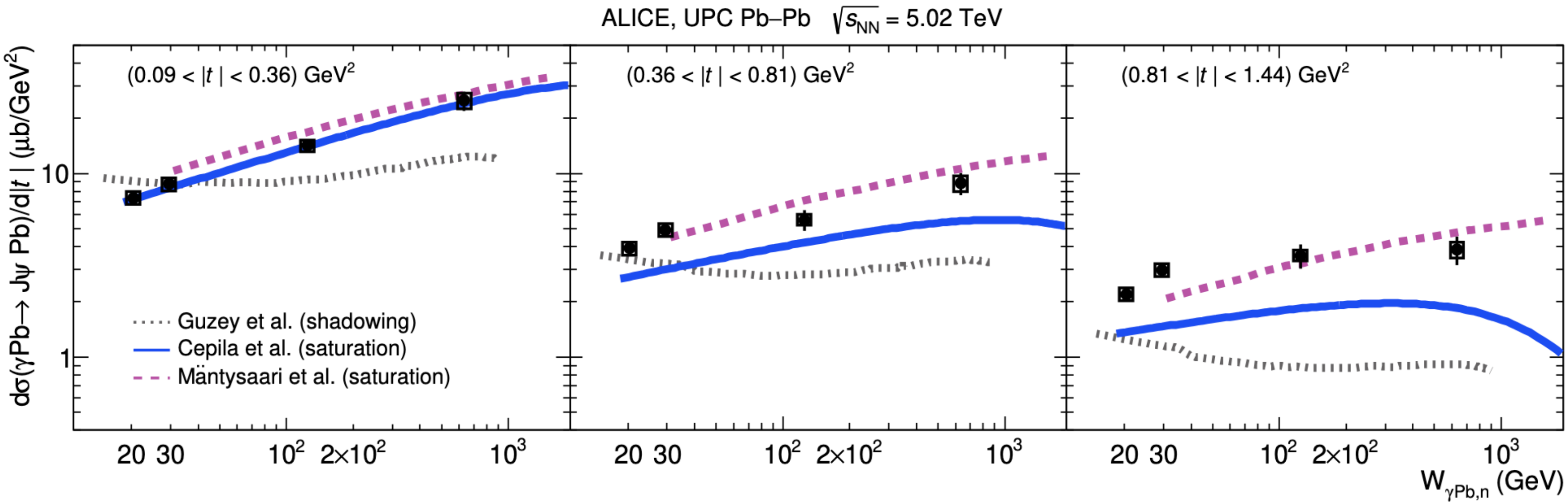
Phys. Rev. Lett. **132**, 162302 (2024) – Published 19 April 2024



The first experimental measurement of the incoherent photonuclear production of J/ψ in ultraperipheral heavy-ion collisions is better explained by the presence of subnuclear quantum fluctuations of the gluon field.

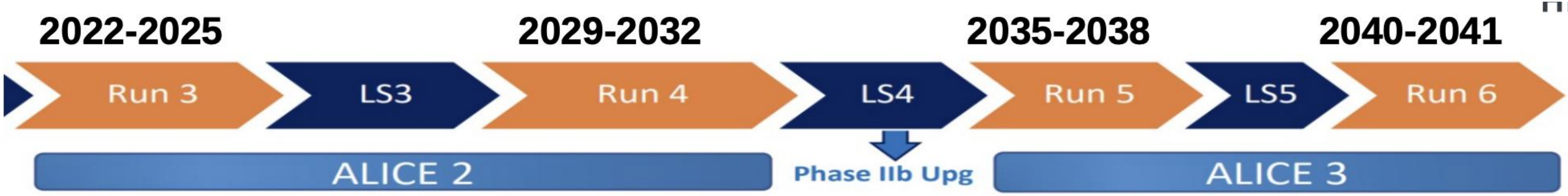
Show Abstract +

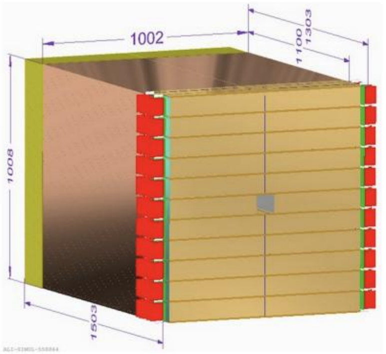
Evidence of incoherent J/ψ suppression in γPb CERN-EP-2025-057

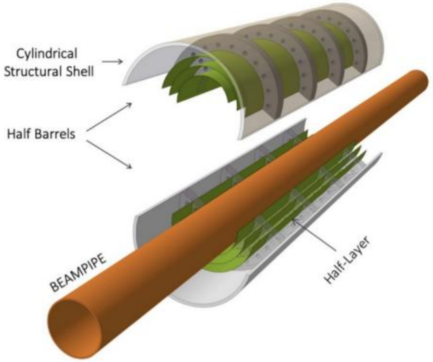


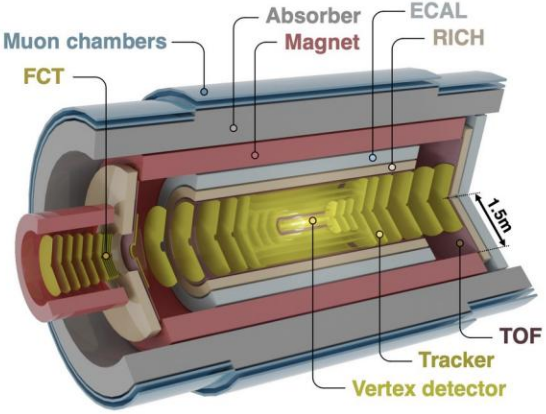
Shadowing model is disfavored across all measurements

The field is now ready for a global analysis of UPC data on coherent and incoherent photoproduction







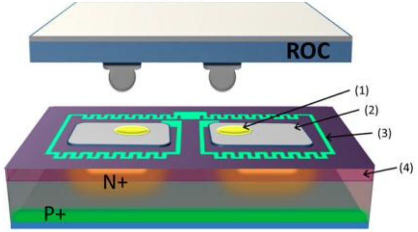


FoCal and ITS3

ALICE3

Also driving innovation in many fronts

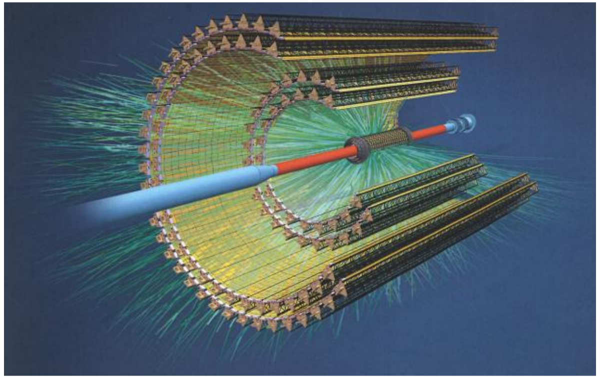
Monolithic Active Pixel Sensors for Collider Physics



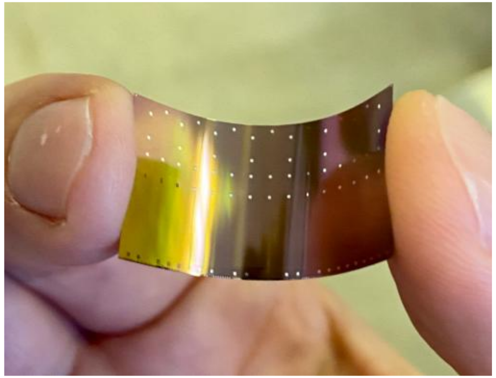
Traditional particle sensors are manufactured connecting the sensors to the readout chip (ROC) using wire-bonding or bump-bonding

To fulfill the requirements of next generation collider physics detectors, Monolithic Active Pixel Sensors are under development

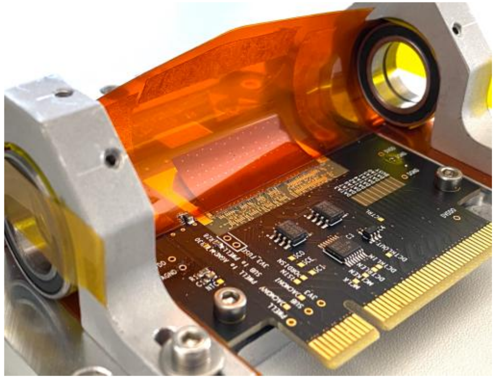
Our group is involved in the characterization of the ALPIDE sensors, developed for the ALICE Inner Tracking System (ITS) and its upgrade program (ITS3)



ALICE Inner Tracker System

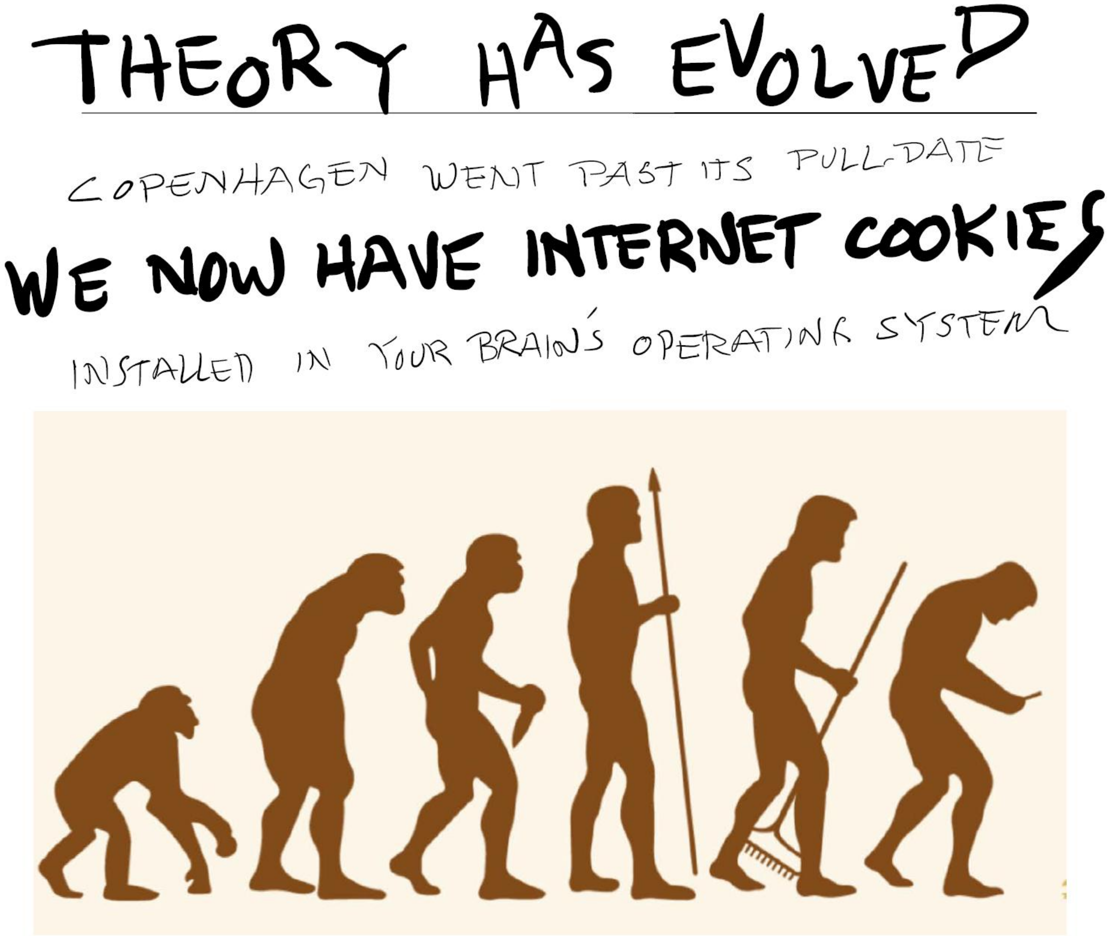


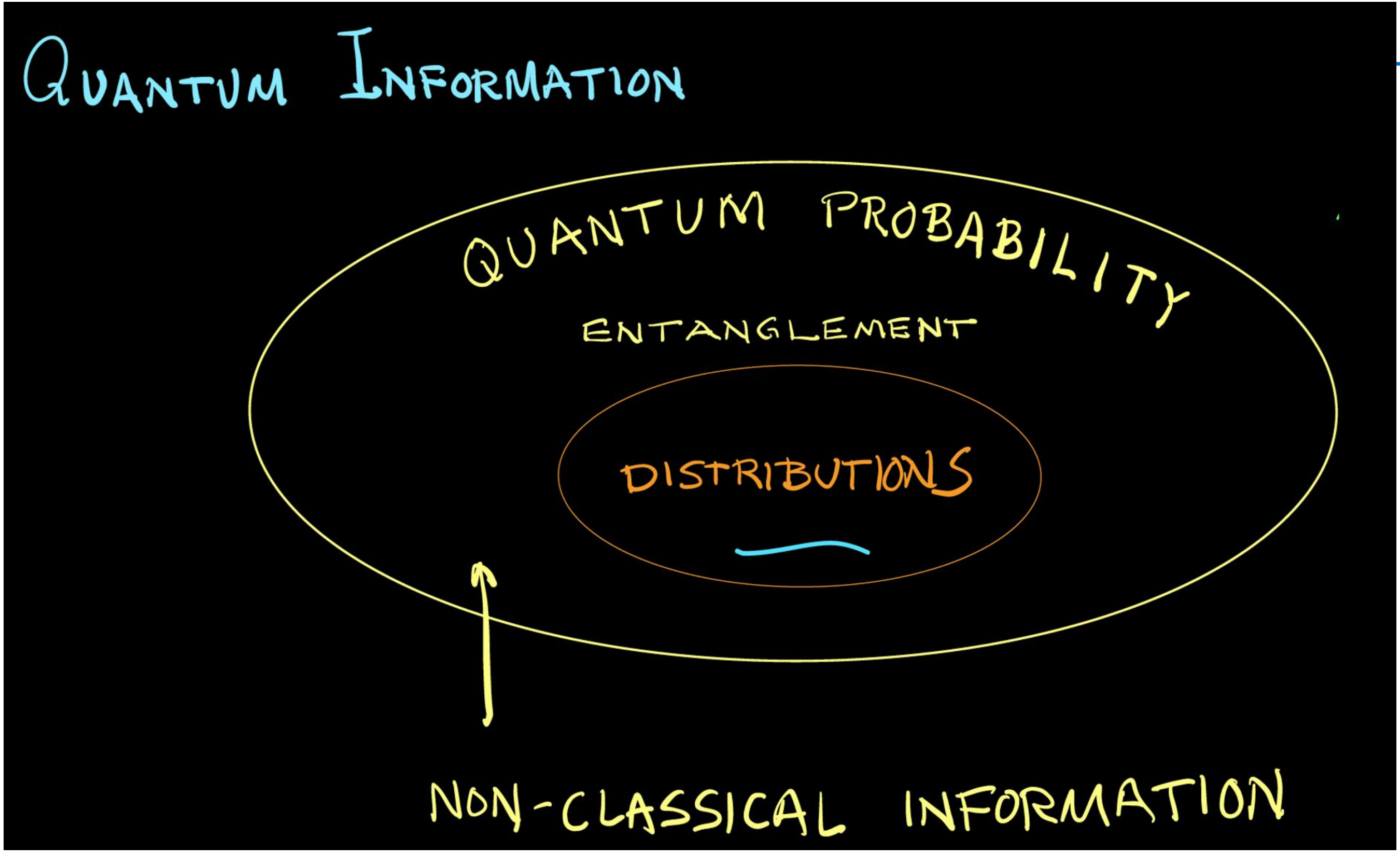
Prototype of next generation MAPS

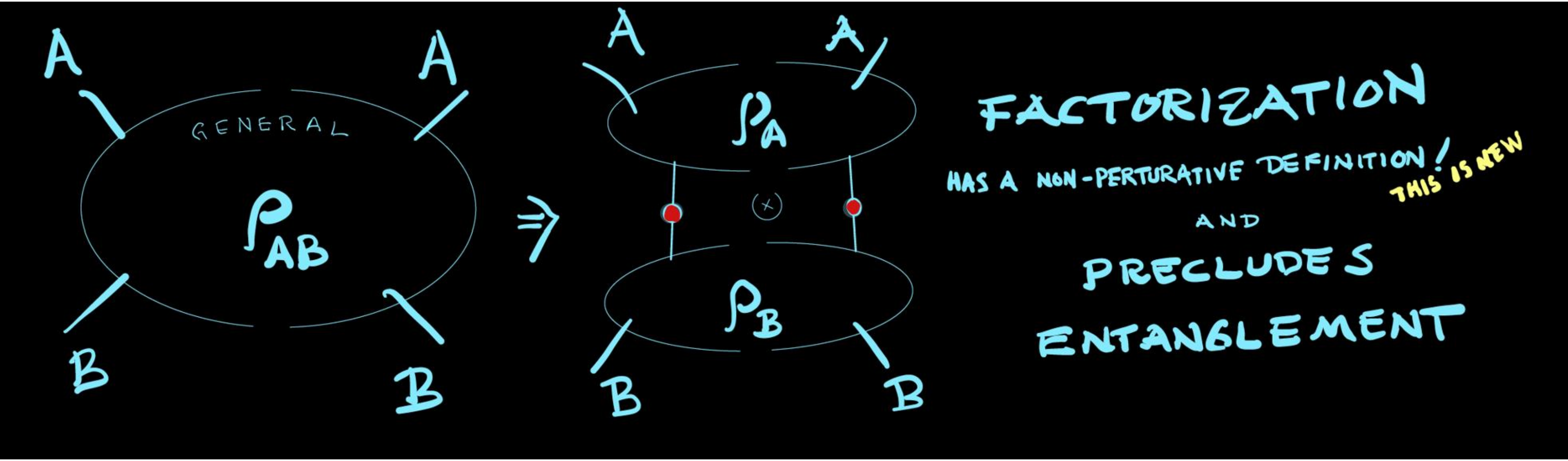


Readout of the ALPIDE3 sensors

New opportunities




Quantum Information
QUANTUM PROBABILITY
ENTANGLEMENT
DISTRIBUTIONS
NON-CLASSICAL INFORMATION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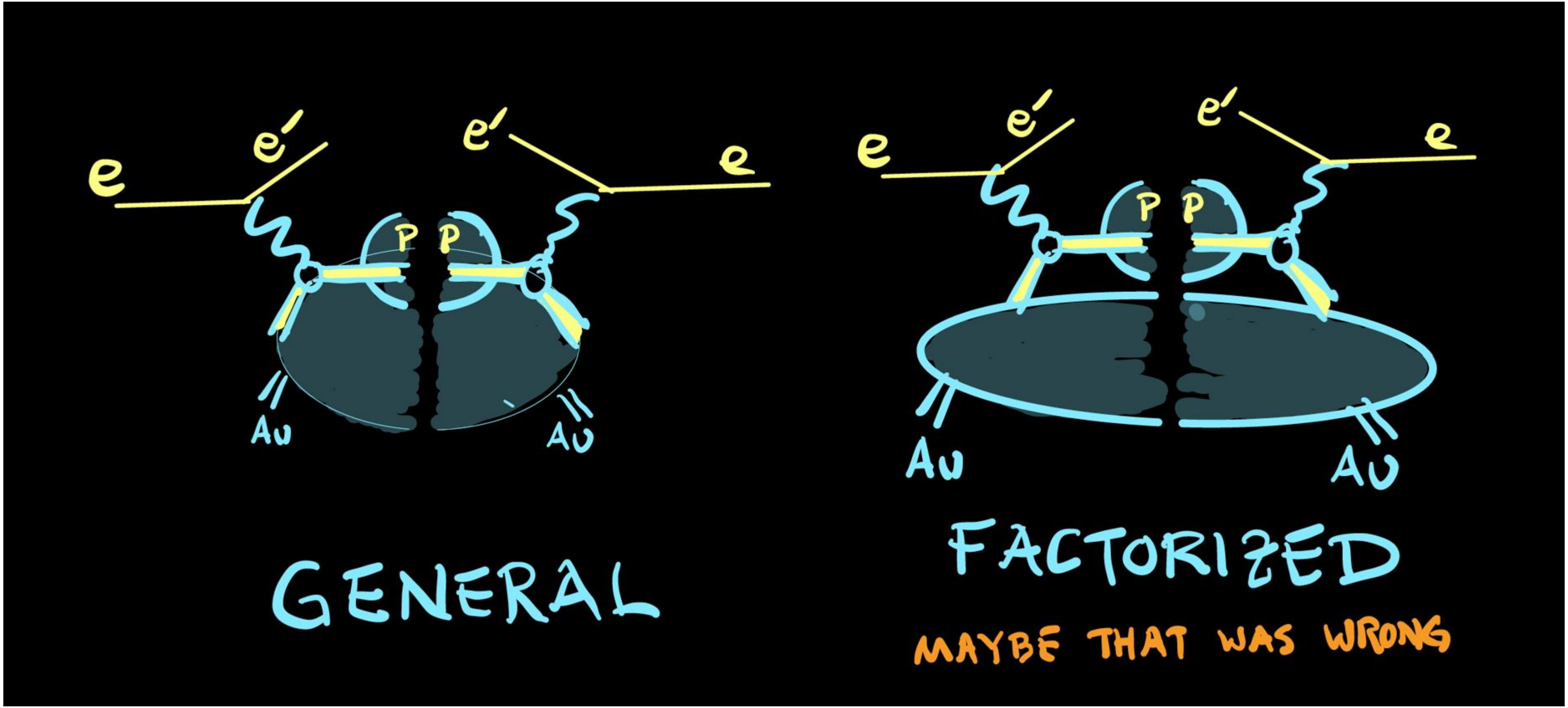

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MAYBE THAT WAS WRONG

The University of Kansas in Lawrence, KS

U. Kansas Physics PhD
https://physics.ku.edu/admissions/graduate-admissions

E-mail: jdtt@ku.edu

Thank you!

References and further reading

https://www.scientificamerican.com/article/physicists-finally-know-how-the-strong-force-gets-its-strength/

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