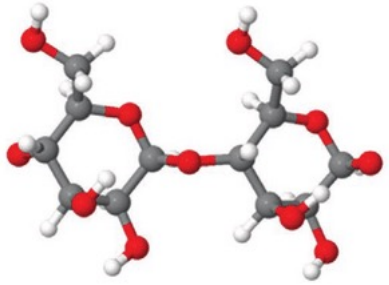
# Liquid of quarks and gluons

Jasmine Brewer


Morning of Theoretical Physics

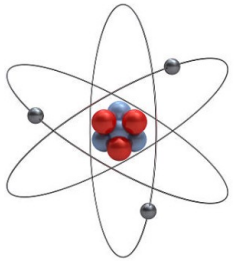
# Composition of the matter around us

molecules

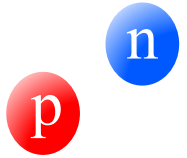


Cellulose

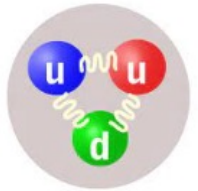
atoms

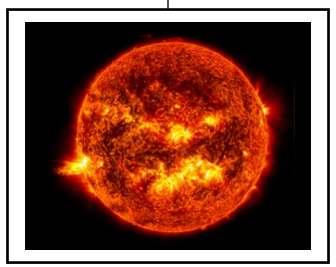


protons, neutrons




quarks, gluons



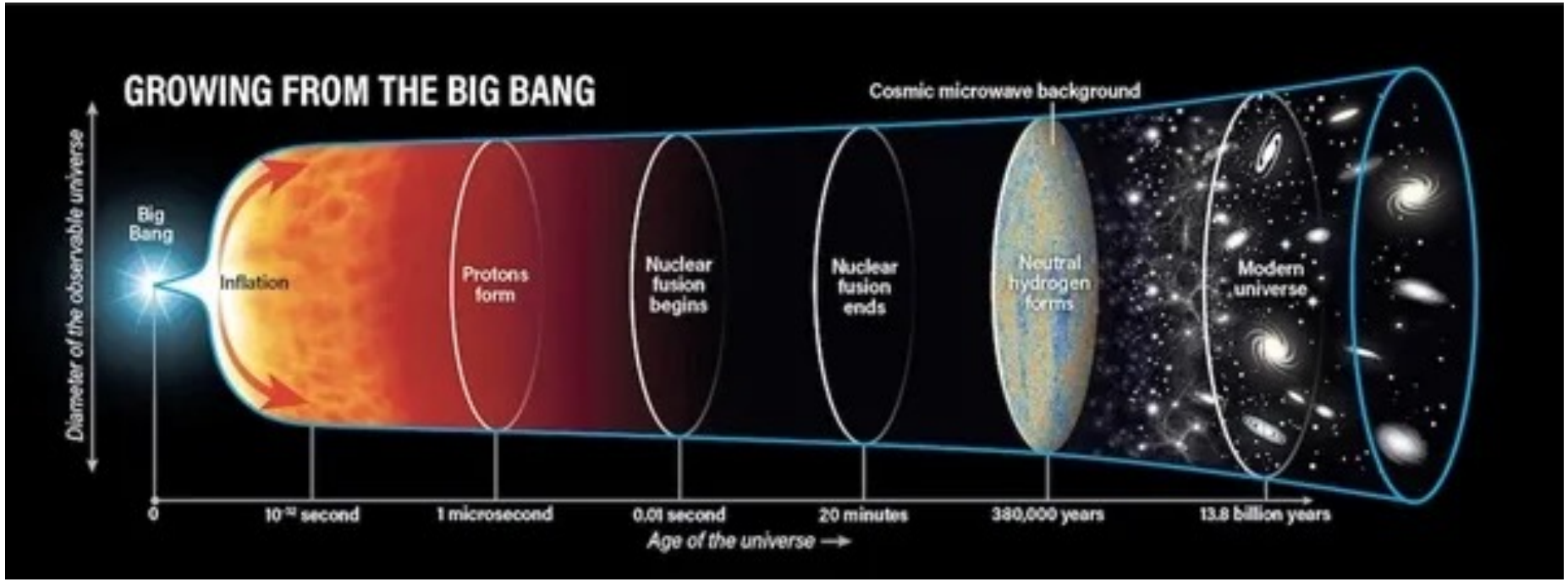
At higher temperatures, objects break down into their components

fundamental particles

What does it take to "melt" protons and neutrons into quarks and gluons?

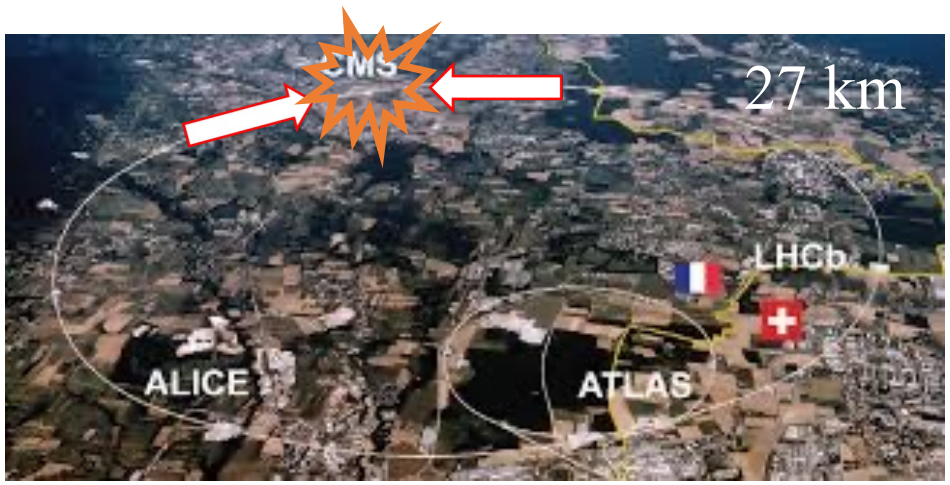
# What does it take to "melt" protons and neutrons into quarks and gluons?

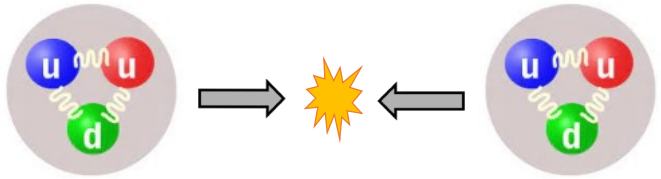
- Microseconds after the big bang, it was so hot that protons could not form!



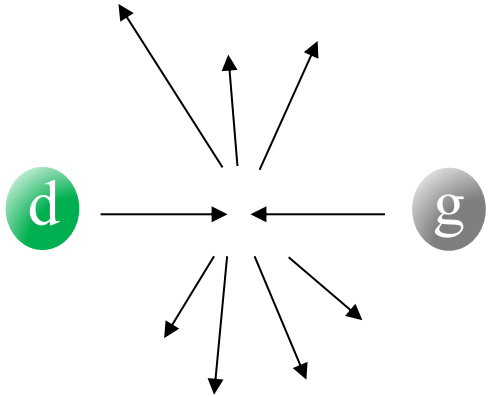

- Today we can recreate these extreme conditions in high-energy collider experiments

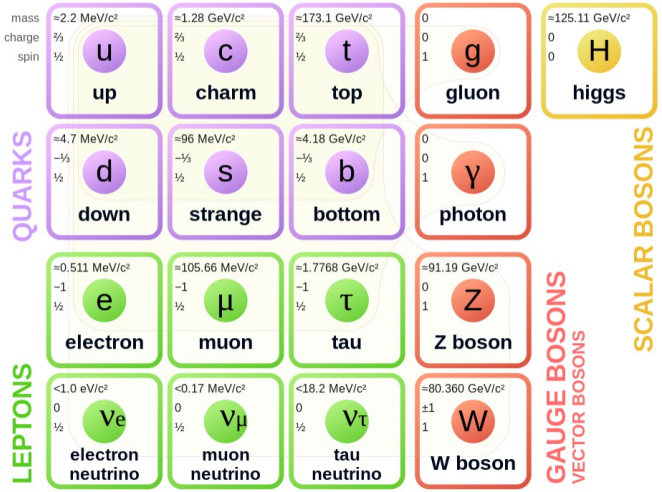
# Looking inside protons at the Large Hadron Collider



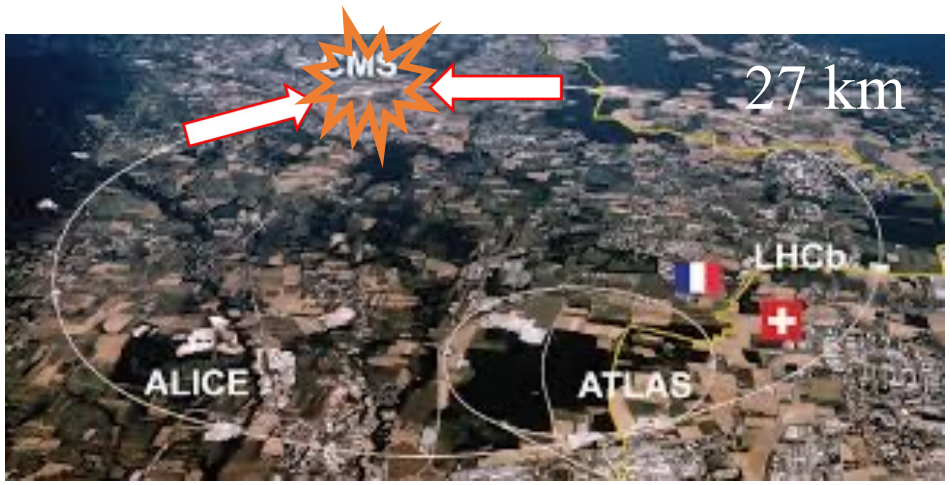

When protons collide at high energies, quarks and gluons inside them collide with each other

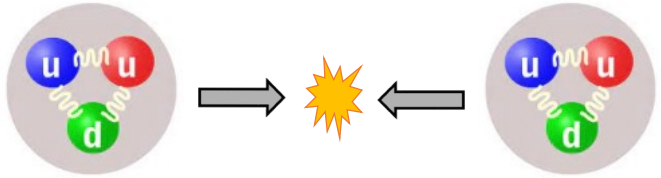



Can produce a suite of particles from the standard model of particle physics and study their interactions

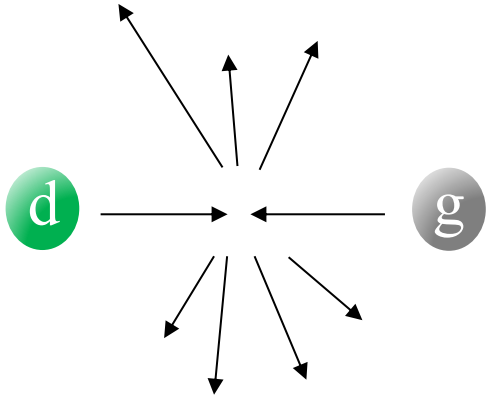
# Looking inside protons at the Large Hadron Collider

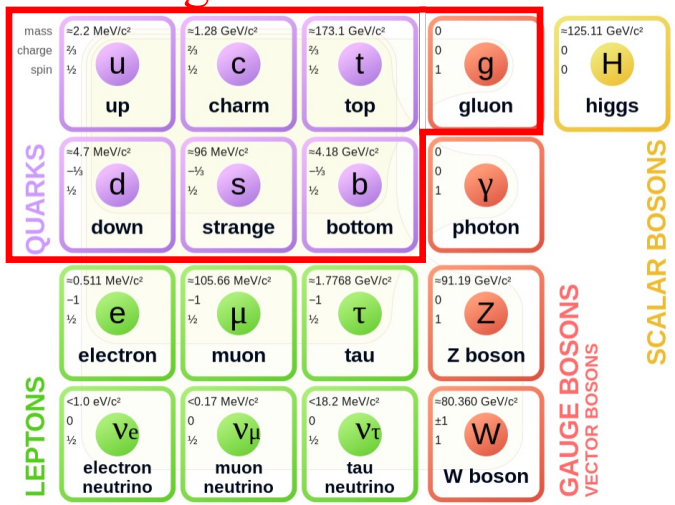



When protons collide at high energies, quarks and gluons inside them collide with each other

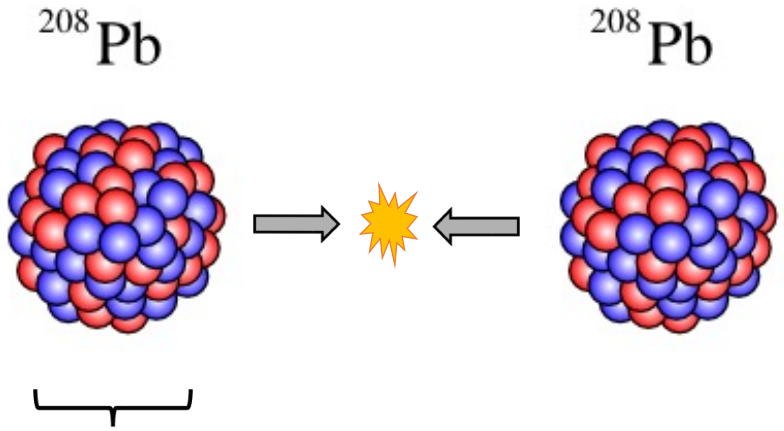
Strong nuclear force



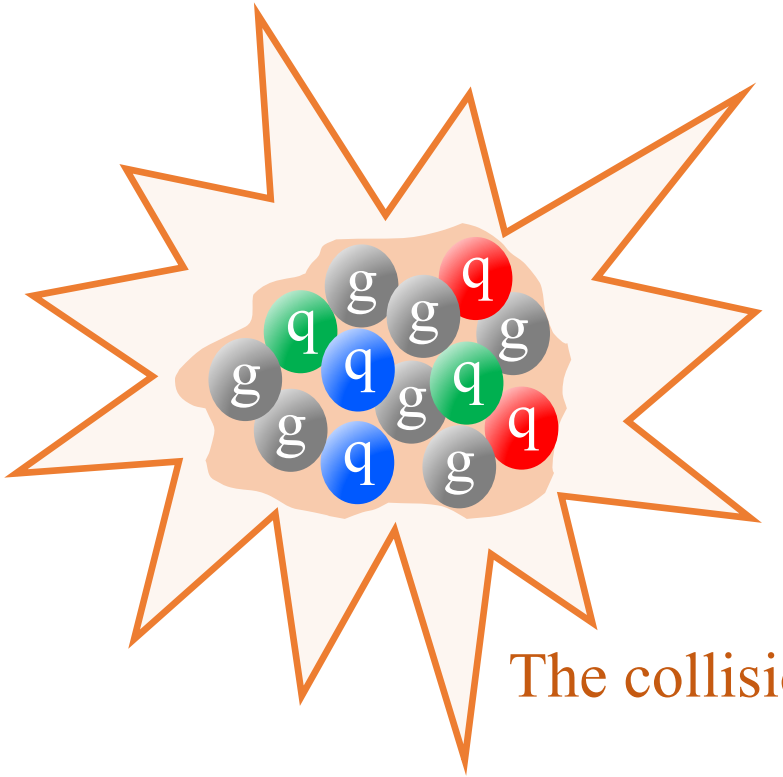




Today's focus: quarks and gluons, particles of the strong nuclear force

# Creating the hottest temperatures in the universe: colliding heavy nuclei




82 protons and 126 neutrons!

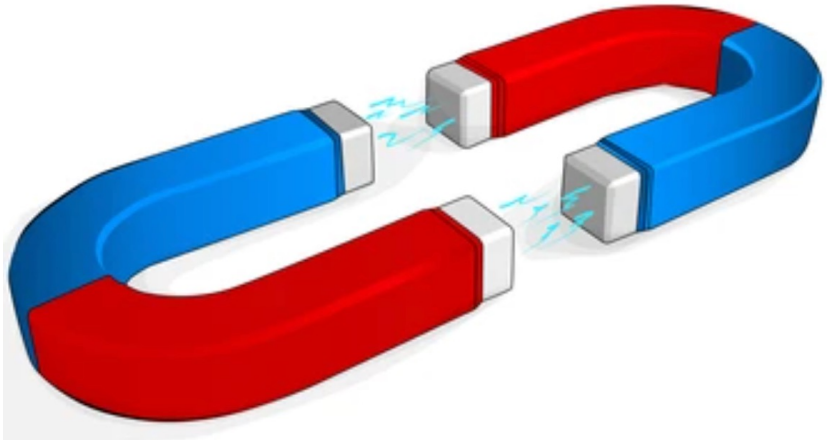



- Temperatures 250,000 times the core of the sun
- In a size 10,000 times smaller than an atom

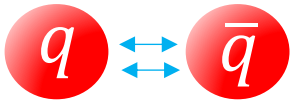
Produces a novel phase of matter of free quarks and gluons: the quark-gluon plasma

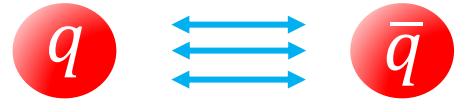
# Quarks and gluons: an unusual attraction

Ordinary forces:
decrease in strength with distance



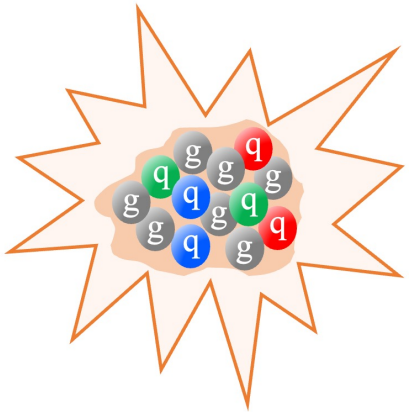
Quarks and gluons:
*increase** in strength with distance!



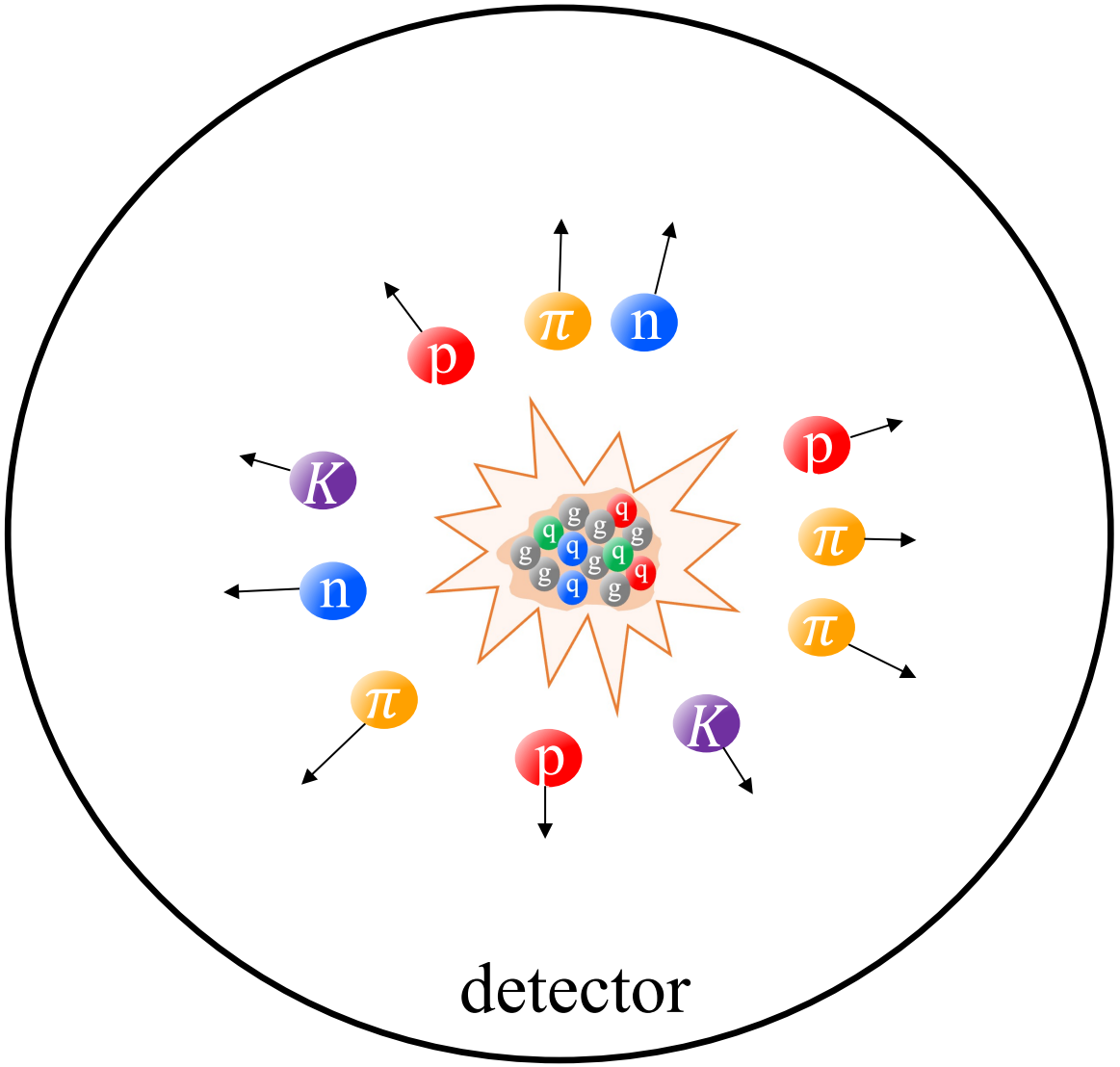



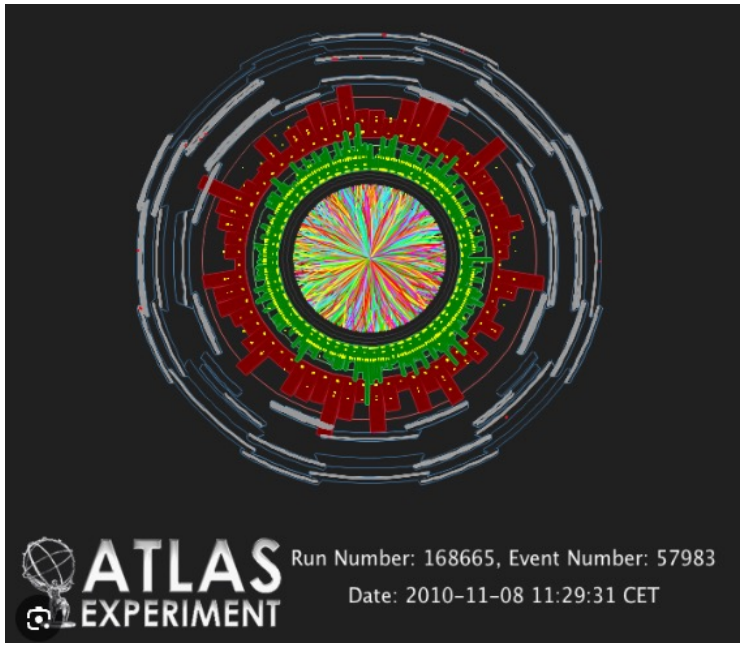

What is the material like when you bring lots of quarks and gluons together? How strong are their interactions?

Many thought it would be a gas, but it's the most strongly-interacting liquid!



# How can we study the quark-gluon plasma in heavy-ion collisions?

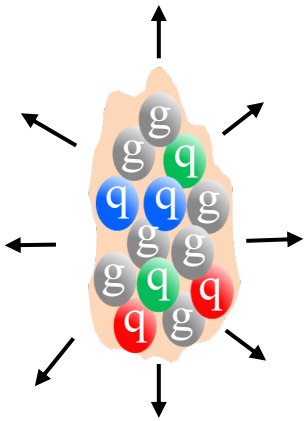


# Properties of a material of quarks and gluons

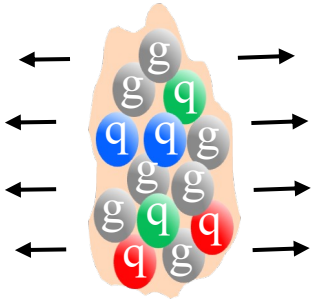
## Weak interactions (gas)

- Equal expansion in all directions

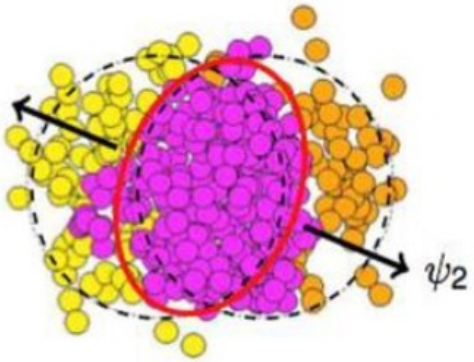


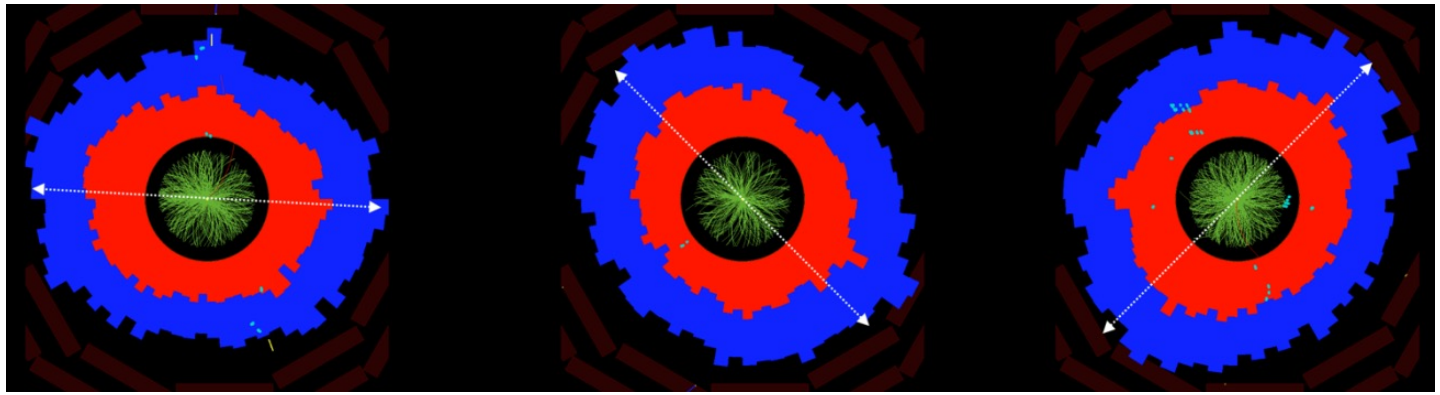
## Strong interactions (liquid)

- Pressure-driven expansion



Overlap of nuclei colliding

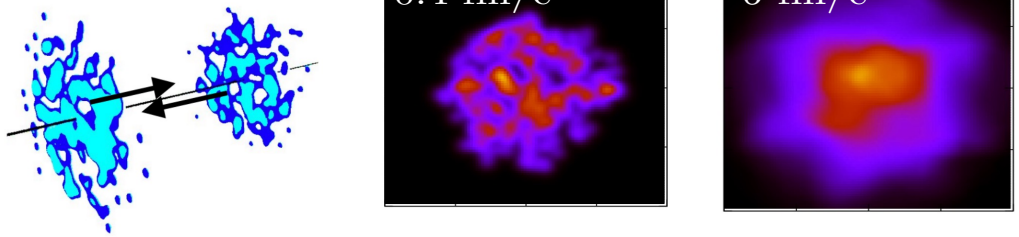


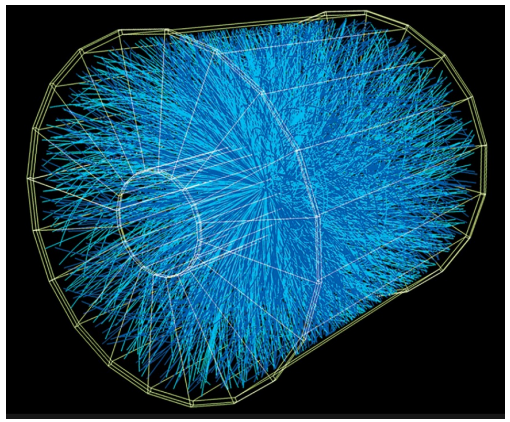
It's a strongly-interacting liquid!

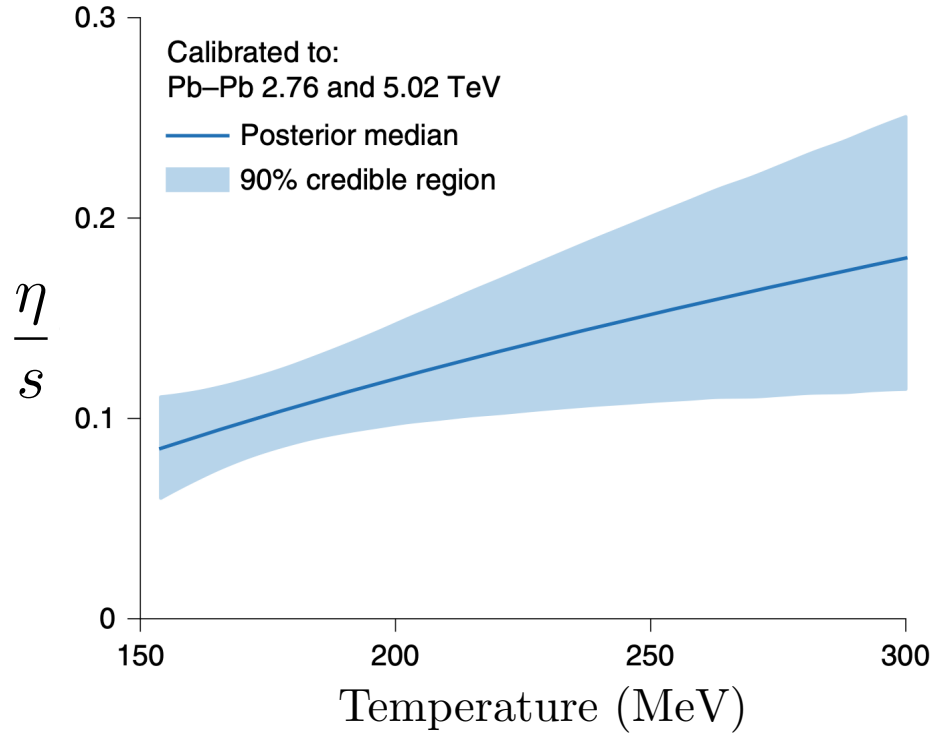
# Accessing the viscosity of the quark-gluon plasma

hydrodynamic simulations




measured particles






Bernhard, Moreland, Bass *Nature Phys.* 15 (2019) 11
Nijs, v.d. Schee, et al *Phys.Rev.Lett.* 126 (2021) 20, 202301
JETSCAPE *Phys. Rev. C* 103, 054904 (2021)

# Accessing the viscosity of the quark-gluon plasma

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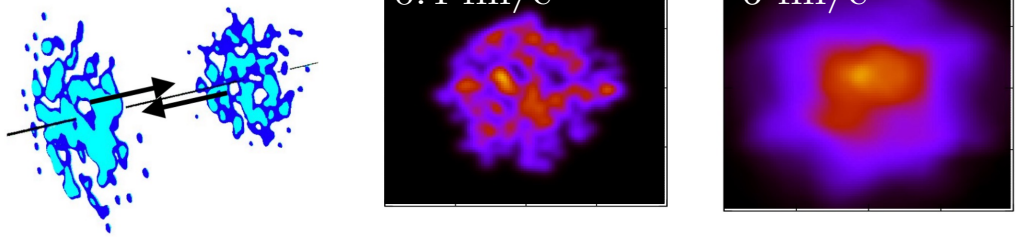
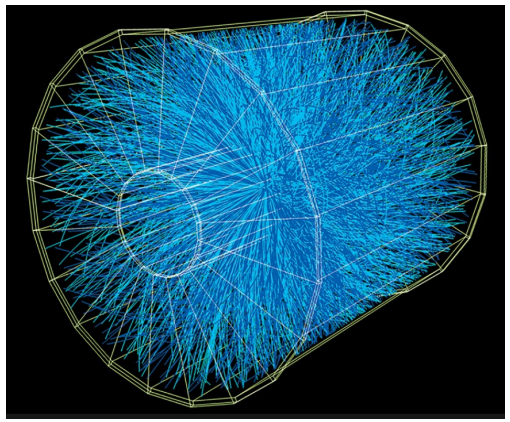
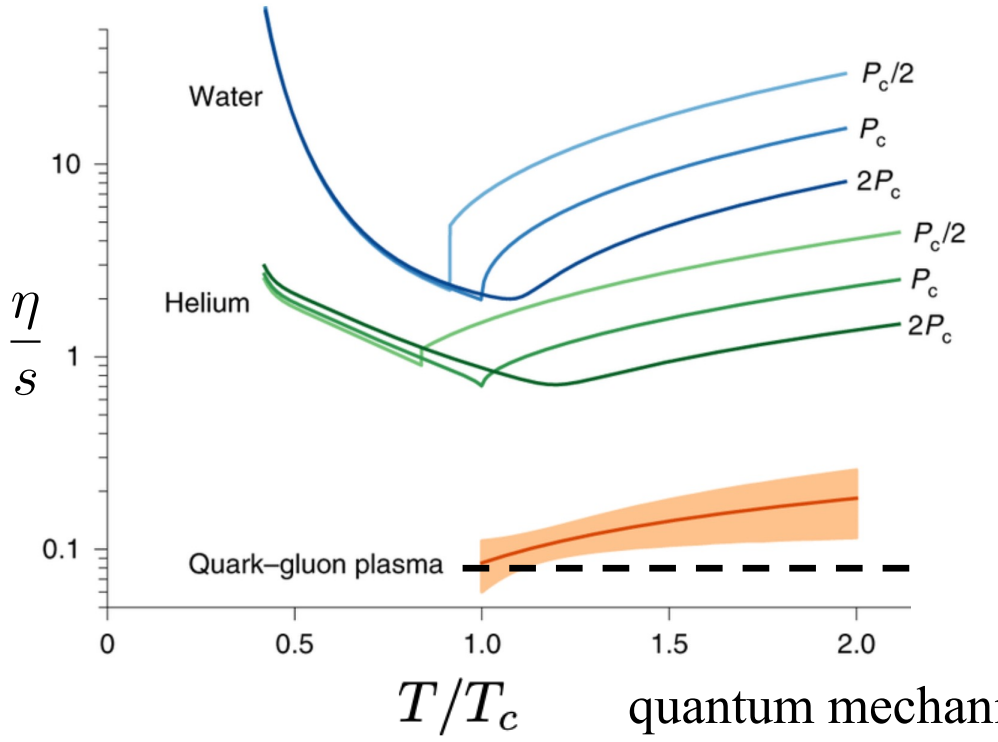



measured particles



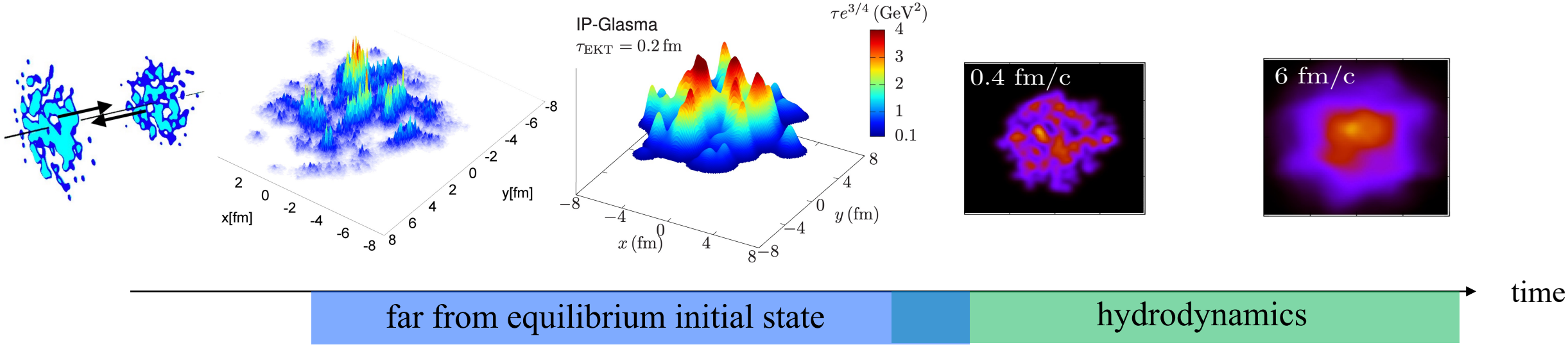
most perfect fluid in nature!




quantum mechanical viscosity bound

Bernhard, Moreland, Bass *Nature Phys.* 15 (2019) 11
Kovtun, Son, Starinets [0405231]

# Frontier: how do quarks and gluons interact to form the quark-gluon plasma?

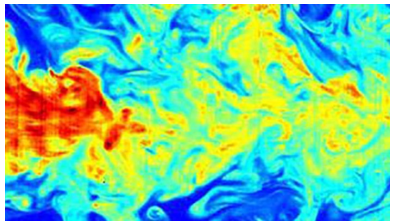



This phase holds key insights on the many-body physics of quarks and gluons

If quarks and gluons interact..

very weakly

turbulent thermalization



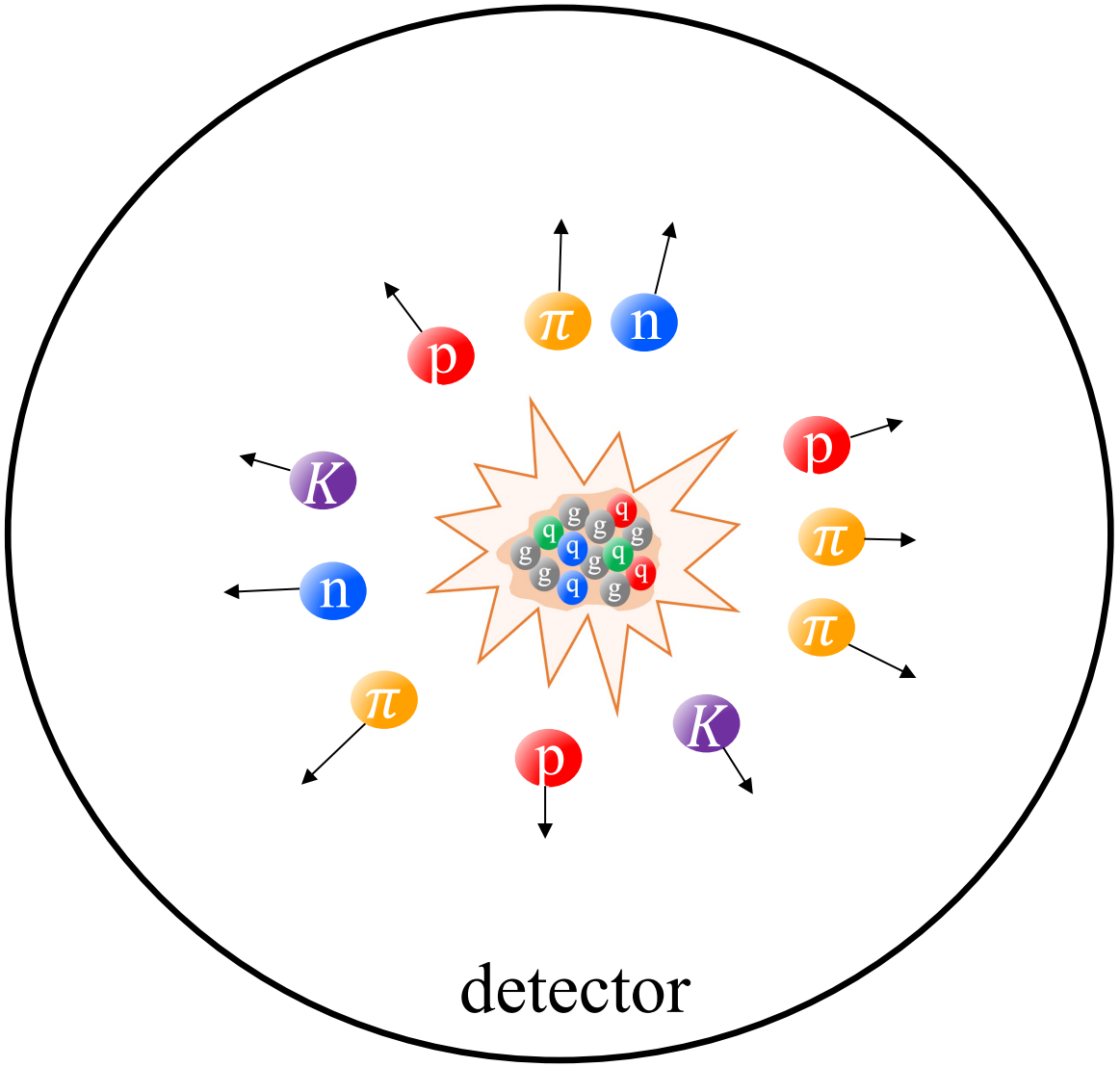
strongly?

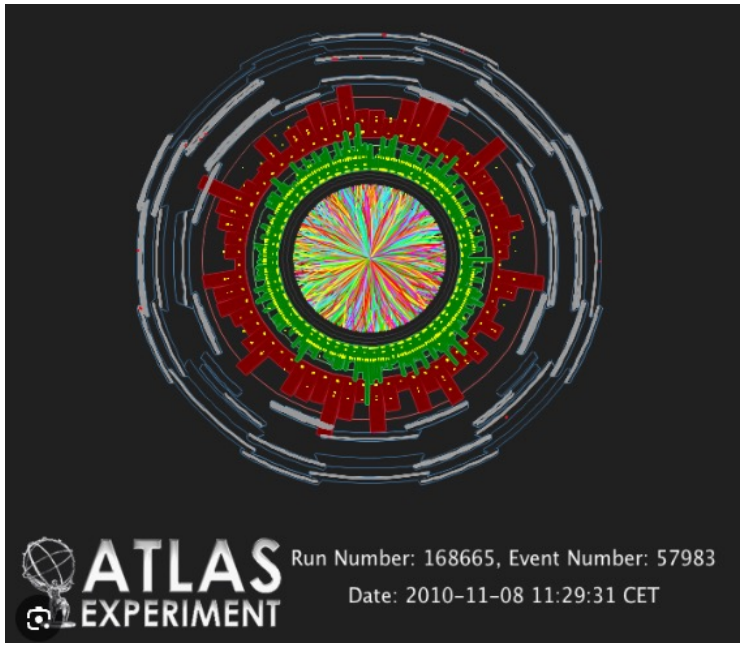
general features of equilibration at intermediate and strong coupling



Berges, Boguslavski, Schlichting, Venugopalan *Phys. Rev. D* 89, 074011 (2014)

# How can we study the quark-gluon plasma in heavy-ion collisions?

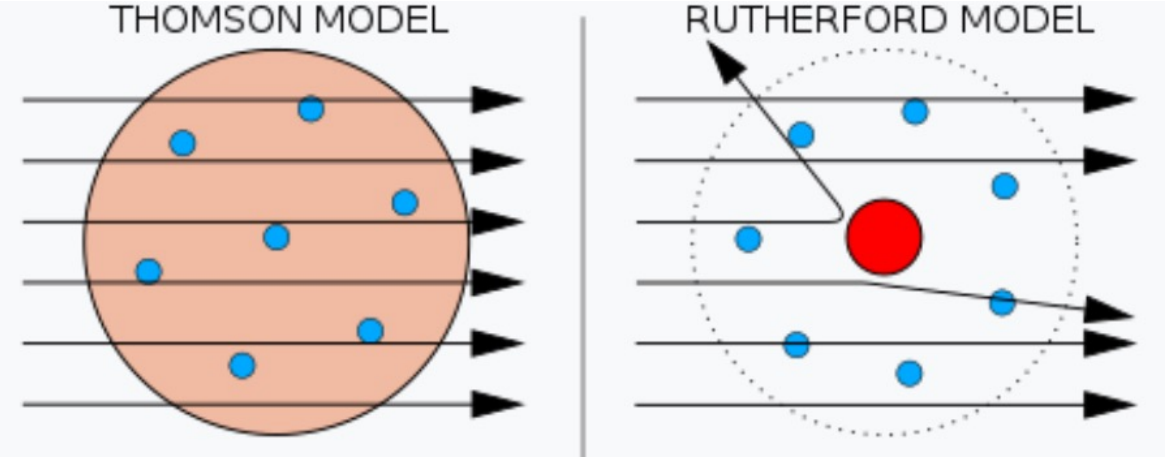


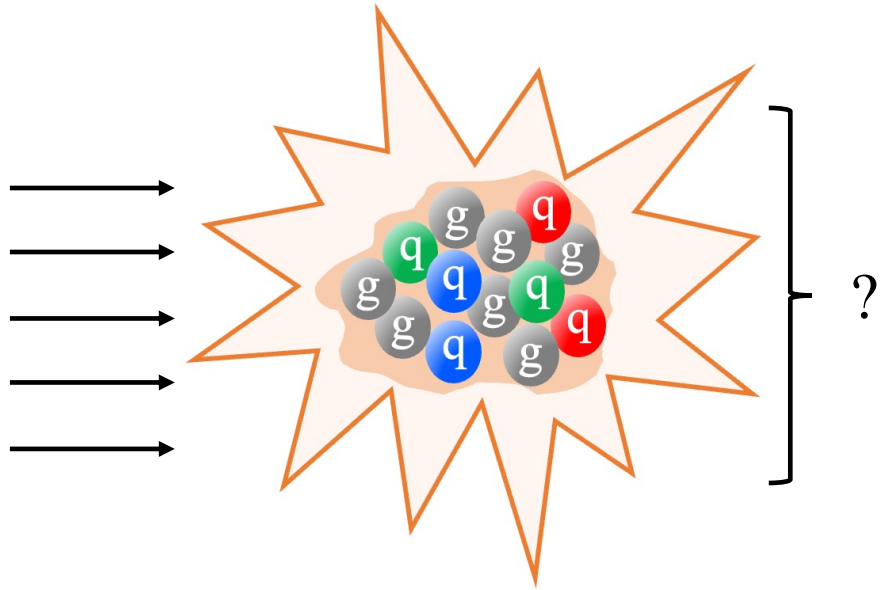
# How can we study the quark-gluon plasma in heavy-ion collisions?

A key strategy to discover the structure of a material is to scatter high-energy particles on it

Used to discover the nucleus inside atoms



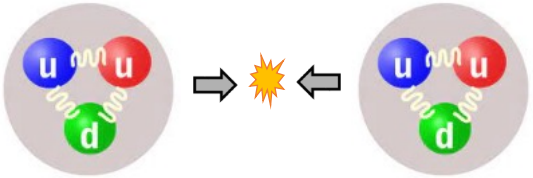

Ideally…

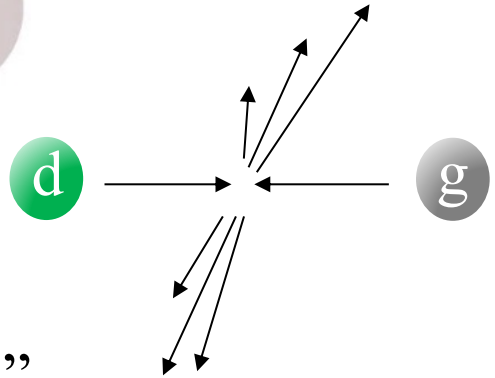



Unfortunately the quark-gluon plasma is too short-lived to achieve this with particles external to the collision itself

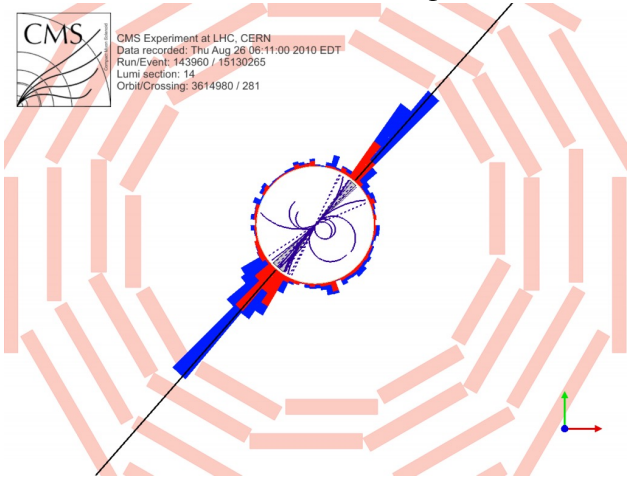
# Scattering high-energy particles off the quark-gluon plasma

proton collisions

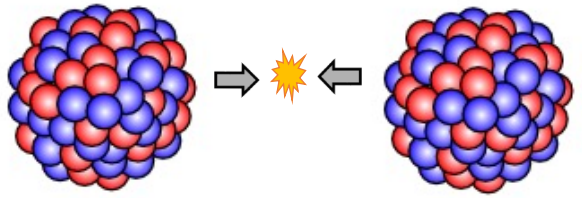


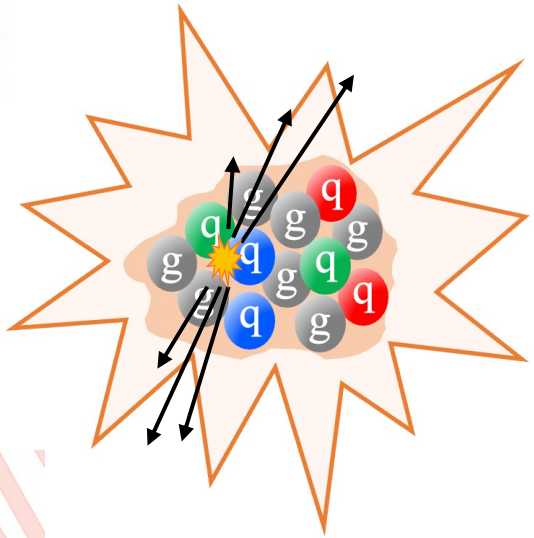



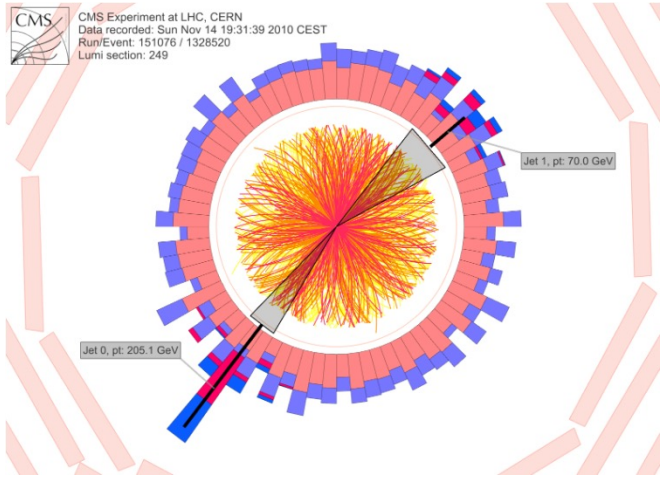

“jets”



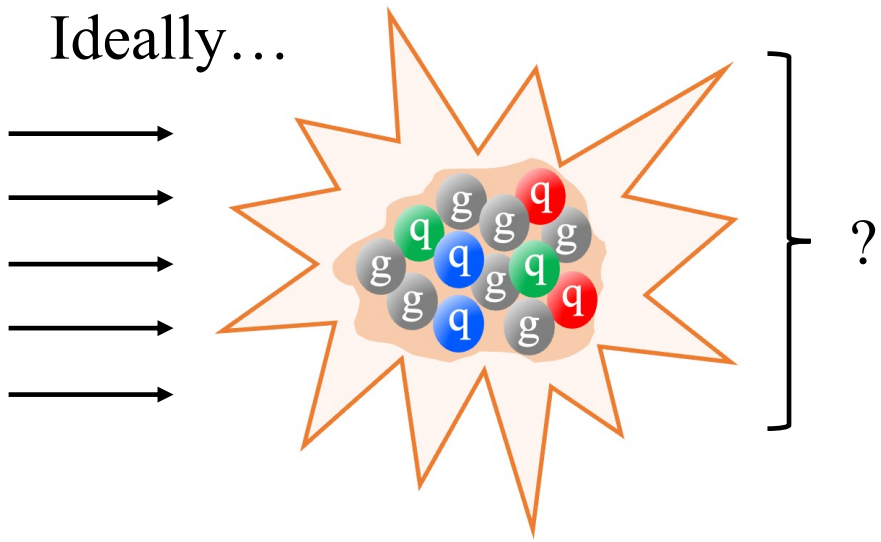

heavy-ion collisions

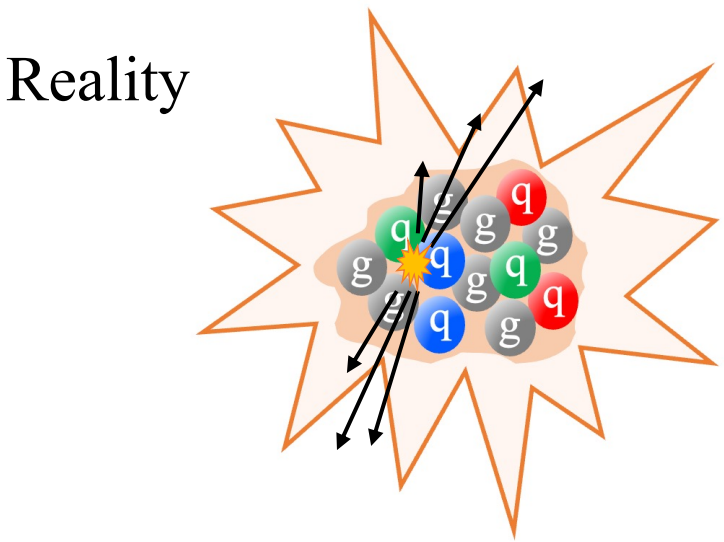




# Using jets to study the structure of the quark-gluon plasma




Key signatures of the formation of quark-gluon plasma and its interaction with jets

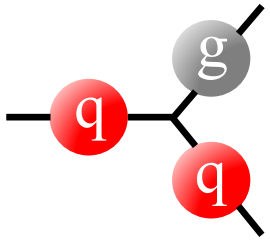
Compared to proton collisions, in heavy-ion collisions there are

- Half as many jets
- Increased momentum imbalance between back-to-back jets

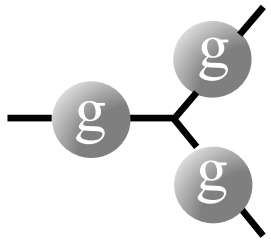
# Jets: built out of quarks and gluons

## Building blocks of a jet

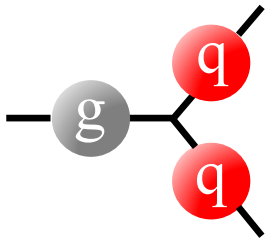
quark splitting into quark and gluon



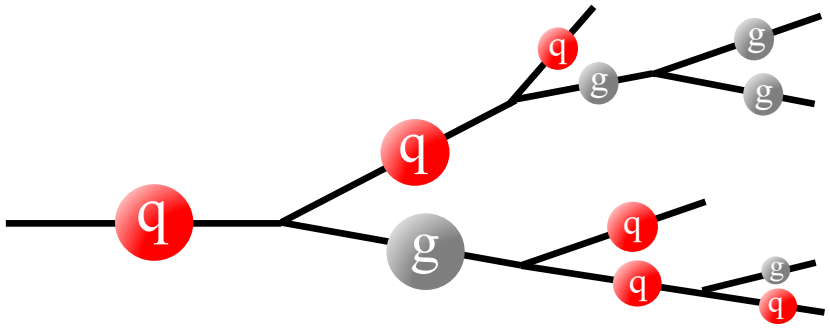

gluon splitting into two gluons




gluon splitting into two quarks

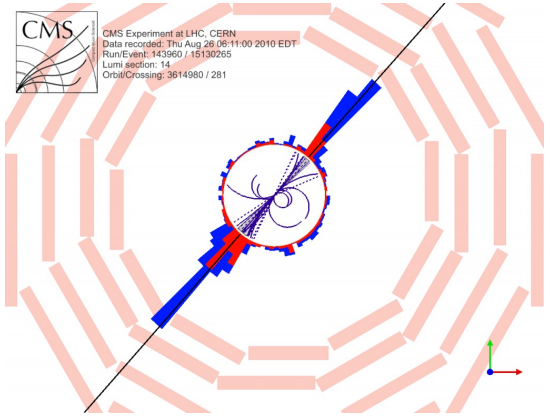



Quarks and gluons become bound




HUGE variety of jets from all different ways to assemble these building blocks

→ Spray of particles in the detector



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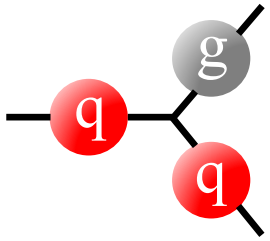
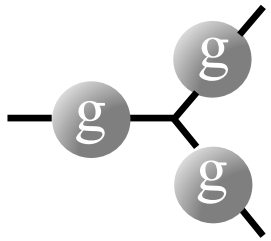
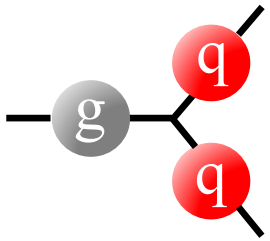


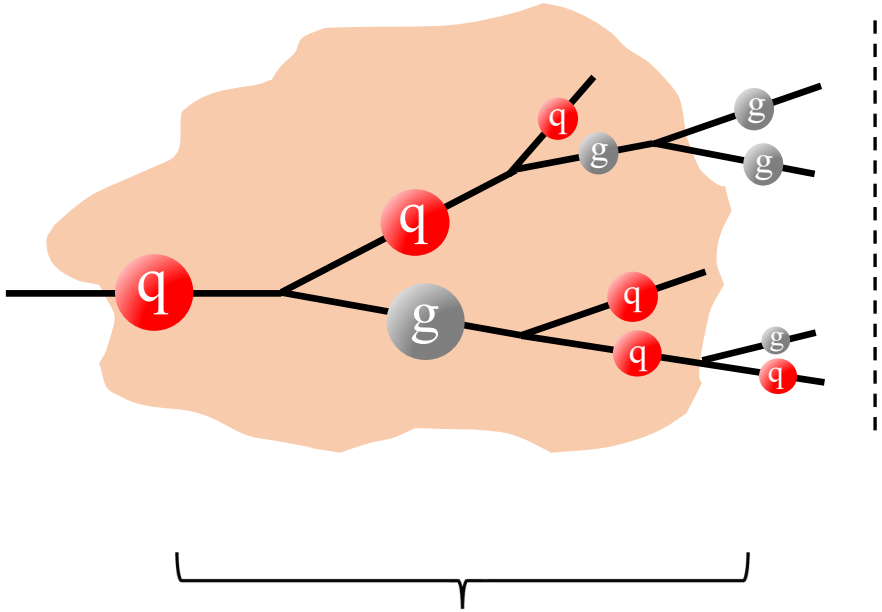

gluon splitting into two gluons



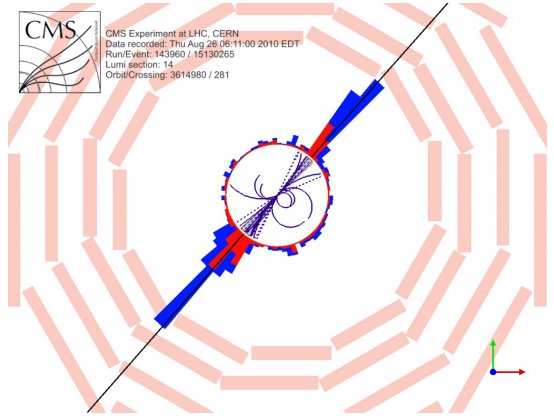

gluon splitting into two quarks




Quarks and gluons become bound



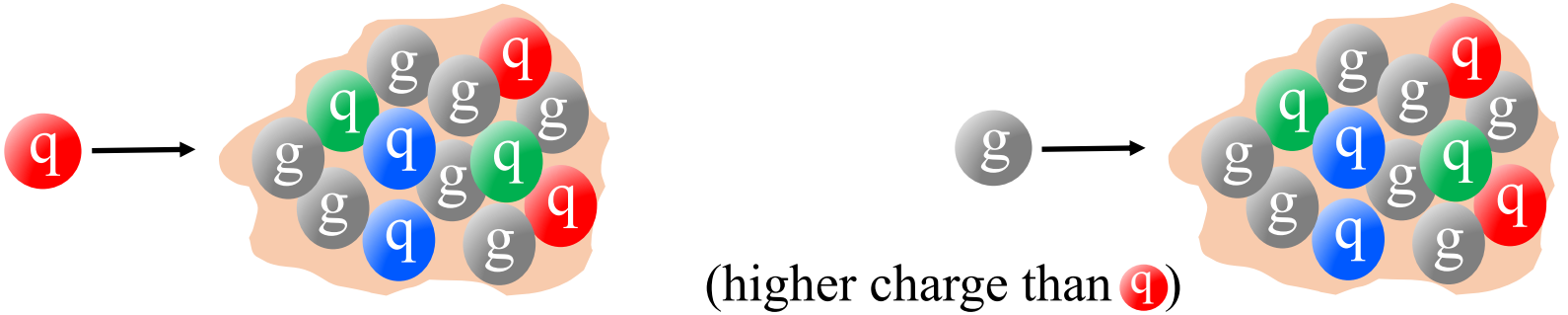

→ Spray of particles in the detector




HUGE variety of jets from all different ways to assemble these building blocks

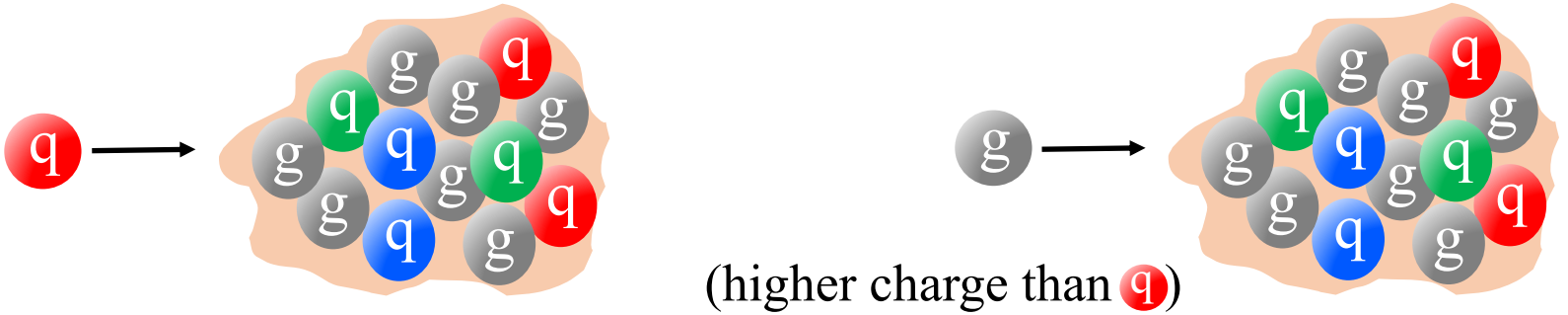
Each interacts in a unique way with the quark-gluon plasma depending on the building blocks

# Using jets as a controlled probe of the quark-gluon plasma

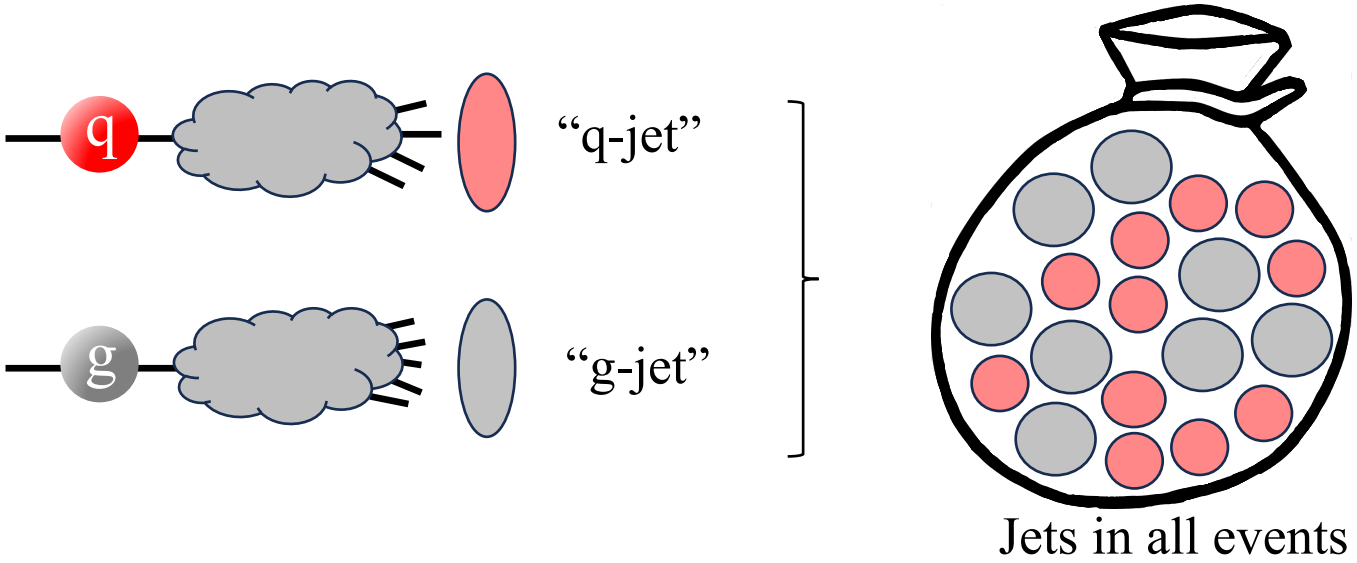



gluons should interact more strongly, but by how much is a key property of the medium

# Using jets as a controlled probe of the quark-gluon plasma




gluons should interact more strongly, but by how much is a key property of the medium




Classify unlabelled "bag of jets" into quark and gluon categories

Metodiev and Thaler [1802.00008]
Komiske, Metodiev, Thaler [1809.01140]
JB, Thaler, Turner [2008.08596]
Ying, JB, Chen, Lee [2204.00641]

Measure differences in how charges (quarks and gluons) interact with the quark-gluon plasma!

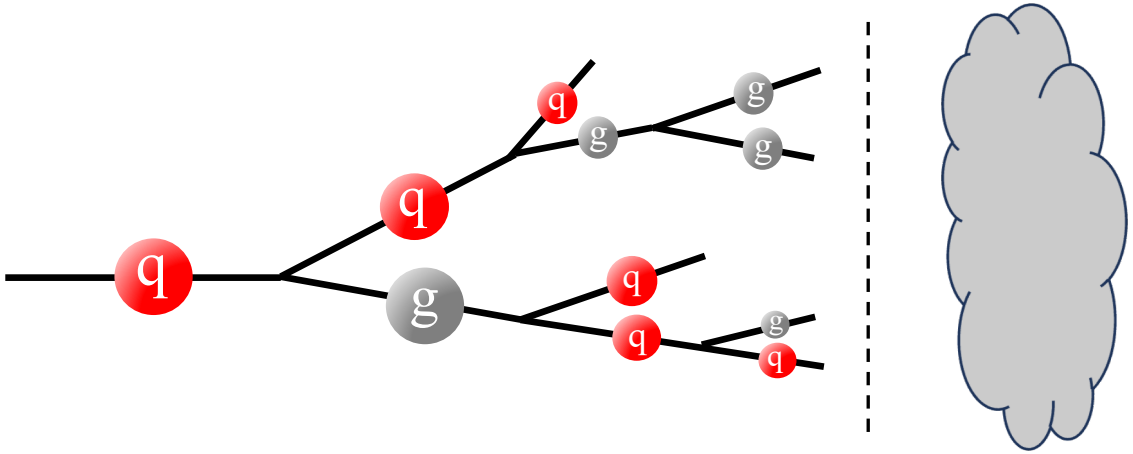
# Using jets as a controlled probe of the quark-gluon plasma


"q-jet"


"g-jet"

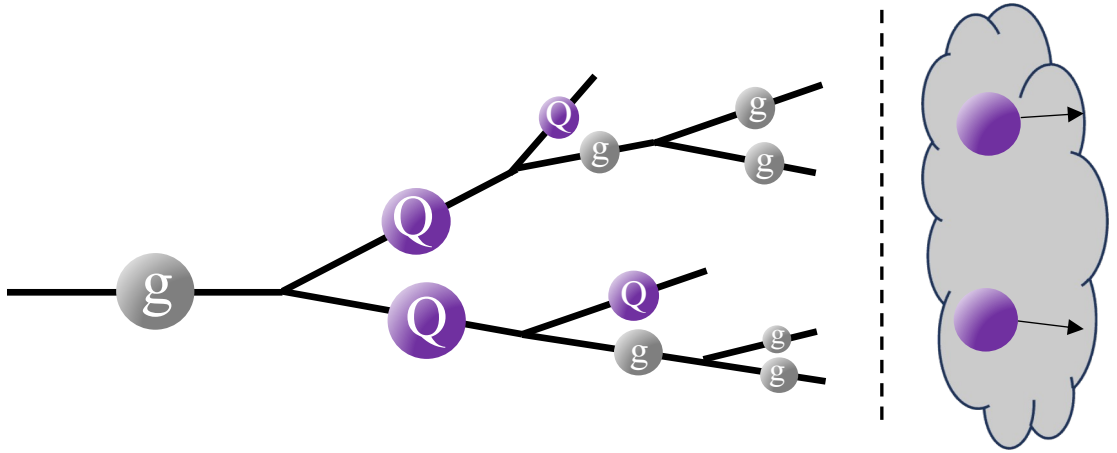
"Regular" jets:

Quarks and gluons become bound




can't measure which particles were quarks or gluons

Exception: special types of quarks (heavy ones) can be used to see back in time how a jet formed

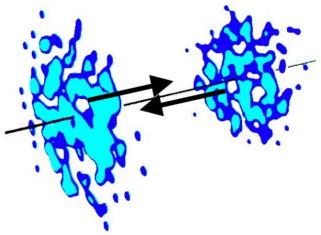


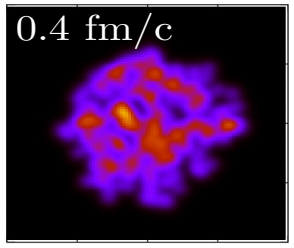

can know the building blocks of these jets in detail!

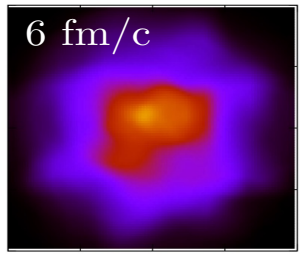
Attems, JB, Innocenti, et al [2203.11241, 2209.13600]

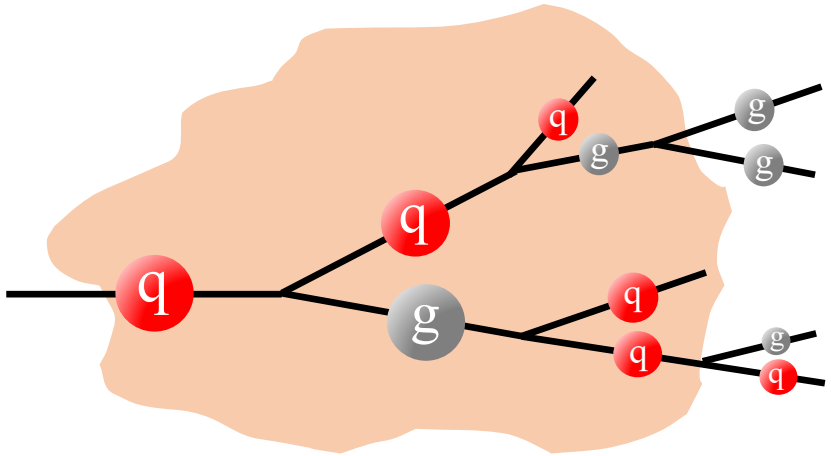
Unique opportunity for precision understanding of the medium interaction by carefully constraining the properties of the high-energy probe

# Coming full circle: bringing together jet measurements and hydrodynamics





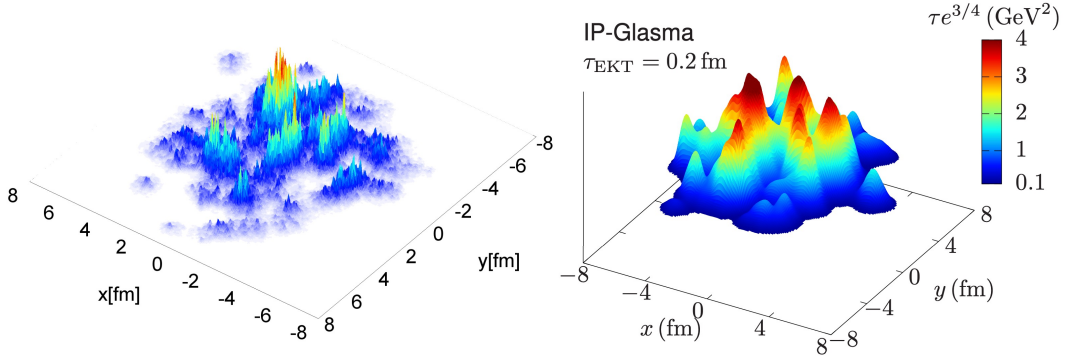



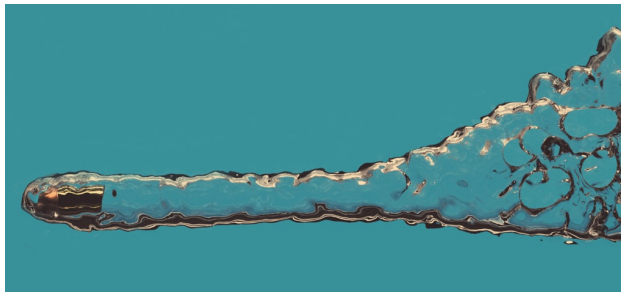




In between…

Equilibration of the medium itself

Equilibration in the wake of jets



Significant theoretical effort and new experiments aim at addressing this intersection

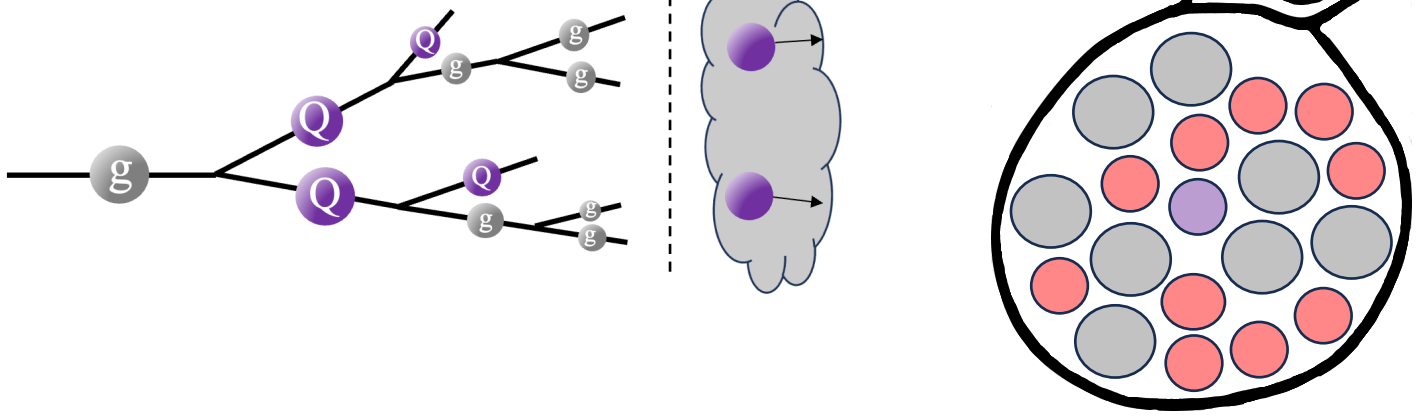
# Zooming out: the open questions driving the future

- Can we access the microscopic structure of the quark-gluon plasma using jets?

Necessitates excellent control over the properties of the jets themselves

Rare processes can hold unique insights, but need a lot of collisions to observe them

Example from this talk



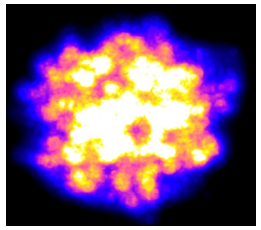

Other examples

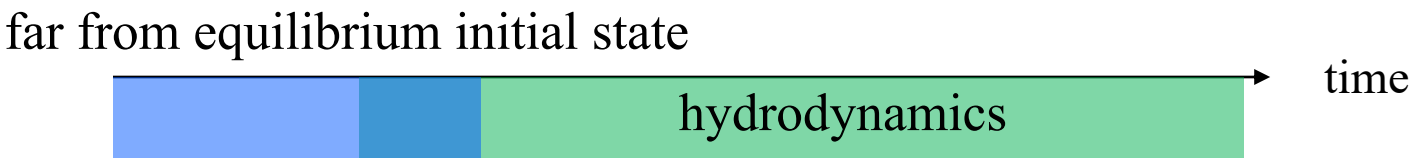

Extensive new data provided in coming years of running the LHC

# Zooming out: the open questions driving the future

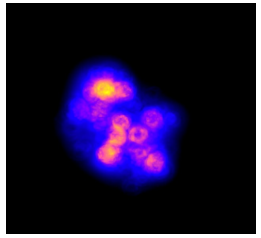
- Can we access the microscopic structure of the quark-gluon plasma using jets?
- How do quarks and gluons equilibrate to form the quark-gluon plasma?

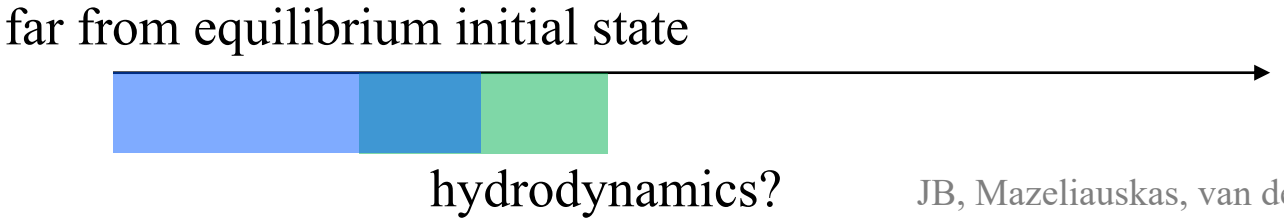
lead collision






oxygen collision






JB, Mazeliauskas, van der Schee [2103.01939]

Recent and upcoming experiments on new collision systems

# Zooming out: the open questions driving the future

- Can we access the microscopic structure of the quark-gluon plasma using jets?
- How do quarks and gluons equilibrate to form the quark-gluon plasma?

| | | |
|---|---|---|
| HiLumi HL-LHC PROJECT | 2028 - 2040 | Lead-lead, proton-lead, oxygen-oxygen |
| sPHENIX | 2023 - 2025 | Gold-gold, proton-gold |

Stay tuned for exciting progress in the coming years!