

# QCD and Heavy-Ion Physics

Liliana Apolinário



TÉCNICO  
LISBOA

July 2026

LIP Internships

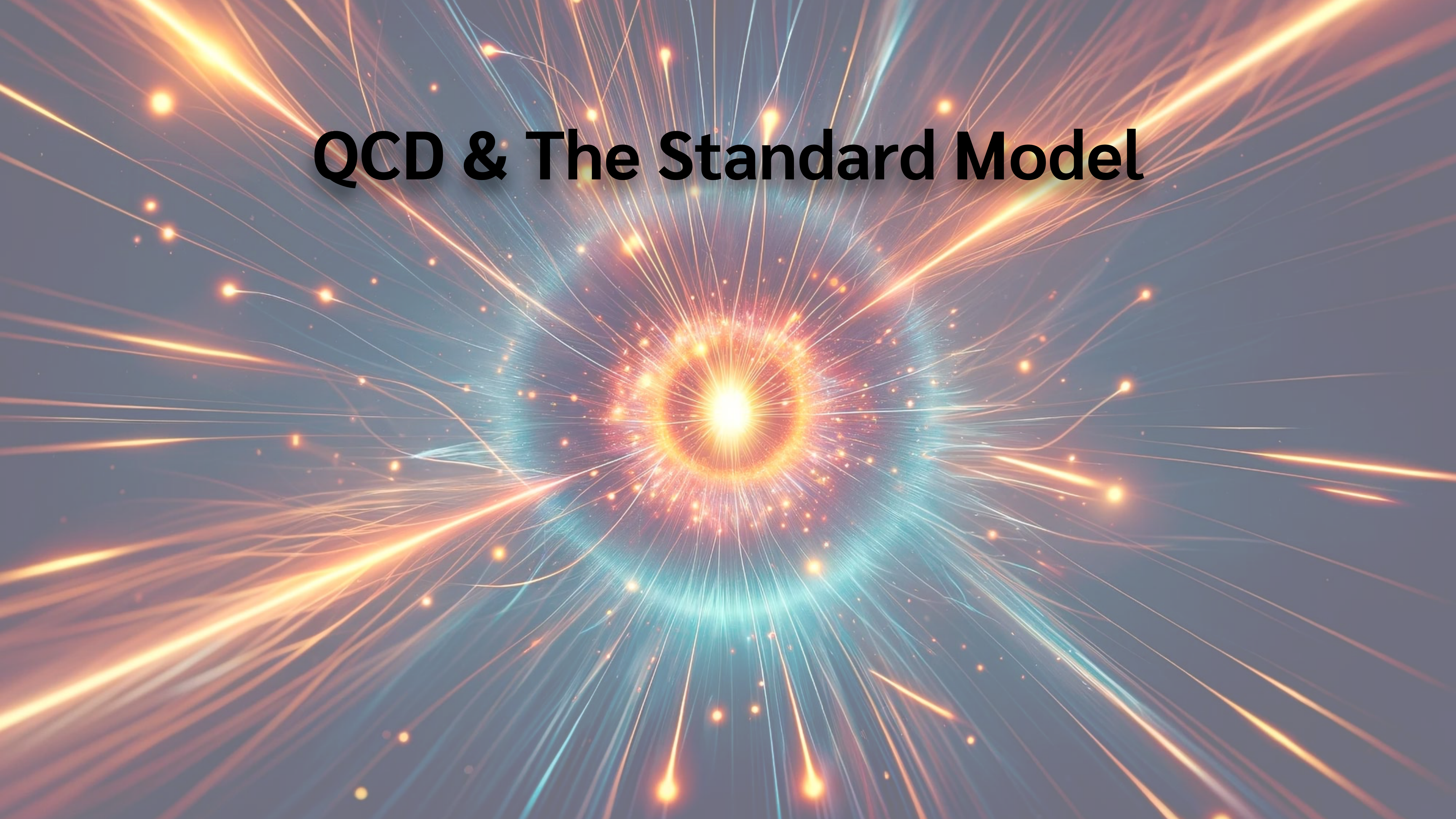


# What is this talk about?

- QCD is more than protons and neutrons
  - Understanding the strong force means exploring new forms of matter.
- Heavy-ion collisions as a QCD laboratory
  - We use energetic ion collisions to create and study extreme QCD environments.
- How do we study a plasma of quarks and gluons?
  - From collective behavior to jets: different tools reveal different properties.



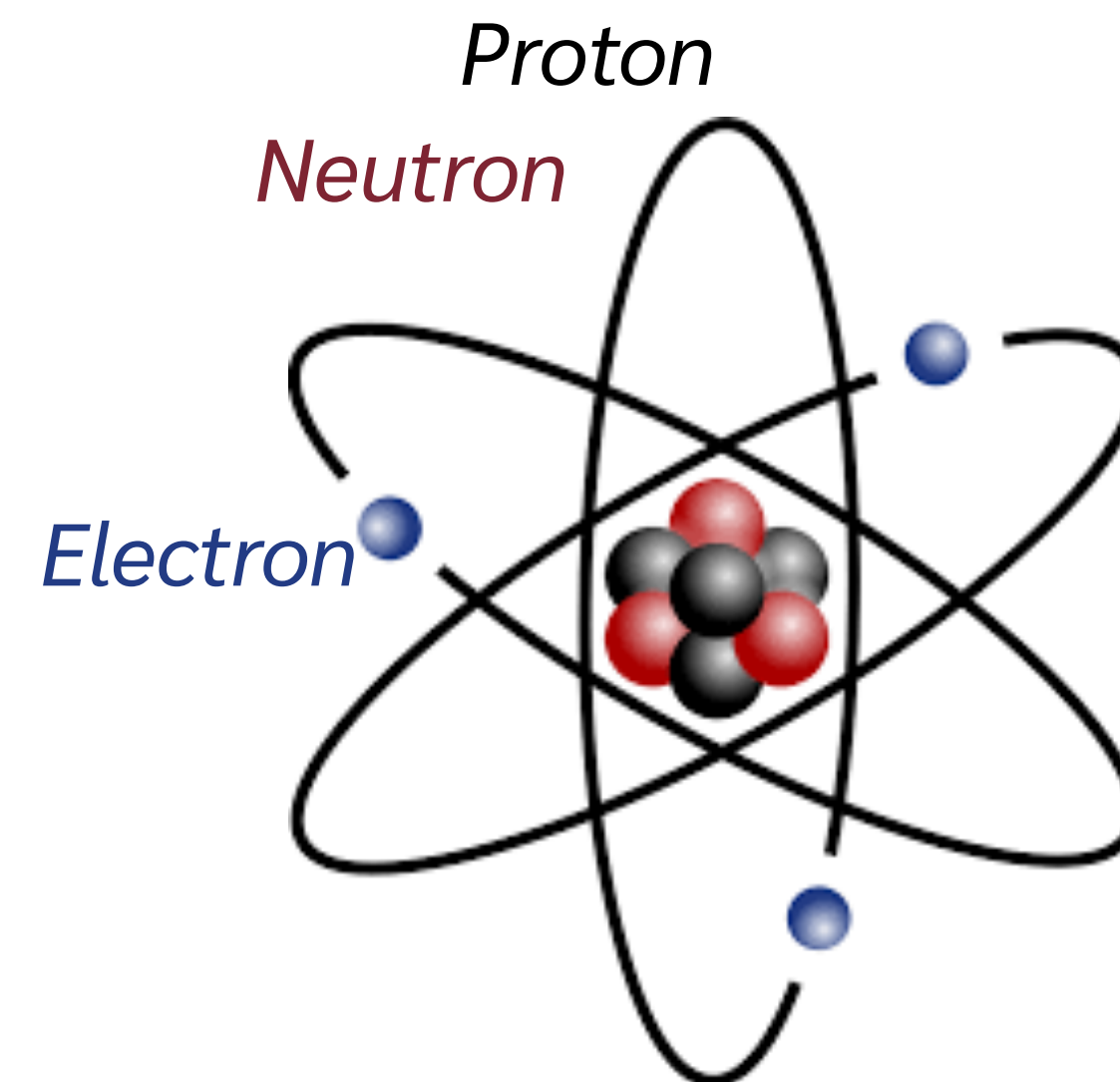
# QCD & The Standard Model

The background of the slide is a complex, abstract visualization. At the center is a bright, glowing yellow-orange sphere with a textured, almost crystalline surface. From this central point, a dense network of fine, radiating lines extends outwards. These lines are primarily blue and cyan, with some thicker, more prominent orange and yellow lines. The lines appear to be composed of many smaller, overlapping strands, creating a sense of depth and movement. The overall effect is reminiscent of a high-energy particle collision or a complex network of quantum fields. The colors transition from the warm yellow-orange at the center to cooler blues and cyans as they move towards the edges of the frame.



# Standard Model

- Particle Physics: Matter can be explained via:
  - 6 Quarks + 6 Leptons
  - Interactions mediated by 4(+1) bosons



## Standard Model of Elementary Particles

| three generations of matter (fermions) |                                           |                                       |                                      |                                 |  | interactions / force carriers (bosons) |  |
|----------------------------------------|-------------------------------------------|---------------------------------------|--------------------------------------|---------------------------------|--|----------------------------------------|--|
|                                        | I                                         | II                                    | III                                  |                                 |  |                                        |  |
| mass                                   | $\approx 2.2 \text{ MeV}/c^2$             | $\approx 1.28 \text{ GeV}/c^2$        | $\approx 173.1 \text{ GeV}/c^2$      | 0                               |  | $\approx 124.97 \text{ GeV}/c^2$       |  |
| charge                                 | $\frac{2}{3}$                             | $\frac{2}{3}$                         | $\frac{2}{3}$                        | 0                               |  | 0                                      |  |
| spin                                   | $\frac{1}{2}$                             | $\frac{1}{2}$                         | $\frac{1}{2}$                        | 1                               |  | 0                                      |  |
| QUARKS                                 | <b>u</b><br>up                            | <b>c</b><br>charm                     | <b>t</b><br>top                      | <b>g</b><br>gluon               |  | <b>H</b><br>higgs                      |  |
|                                        | $\approx 4.7 \text{ MeV}/c^2$             | $\approx 96 \text{ MeV}/c^2$          | $\approx 4.18 \text{ GeV}/c^2$       | 0                               |  |                                        |  |
|                                        | $-\frac{1}{3}$                            | $-\frac{1}{3}$                        | $-\frac{1}{3}$                       | 0                               |  |                                        |  |
|                                        | $\frac{1}{2}$                             | $\frac{1}{2}$                         | $\frac{1}{2}$                        | 1                               |  |                                        |  |
|                                        | <b>d</b><br>down                          | <b>s</b><br>strange                   | <b>b</b><br>bottom                   | <b>γ</b><br>photon              |  |                                        |  |
| LEPTONS                                | $\approx 0.511 \text{ MeV}/c^2$           | $\approx 105.66 \text{ MeV}/c^2$      | $\approx 1.7768 \text{ GeV}/c^2$     | $\approx 91.19 \text{ GeV}/c^2$ |  |                                        |  |
|                                        | -1                                        | -1                                    | -1                                   | 0                               |  |                                        |  |
|                                        | $\frac{1}{2}$                             | $\frac{1}{2}$                         | $\frac{1}{2}$                        | 1                               |  |                                        |  |
|                                        | <b>e</b><br>electron                      | <b>μ</b><br>muon                      | <b>τ</b><br>tau                      | <b>Z</b><br>Z boson             |  |                                        |  |
|                                        | $< 1.0 \text{ eV}/c^2$                    | $< 0.17 \text{ MeV}/c^2$              | $< 18.2 \text{ MeV}/c^2$             | $\approx 80.39 \text{ GeV}/c^2$ |  |                                        |  |
|                                        | 0                                         | 0                                     | 0                                    | $\pm 1$                         |  |                                        |  |
|                                        | $\frac{1}{2}$                             | $\frac{1}{2}$                         | $\frac{1}{2}$                        | 1                               |  |                                        |  |
|                                        | <b>ν<sub>e</sub></b><br>electron neutrino | <b>ν<sub>μ</sub></b><br>muon neutrino | <b>ν<sub>τ</sub></b><br>tau neutrino | <b>W</b><br>W boson             |  |                                        |  |

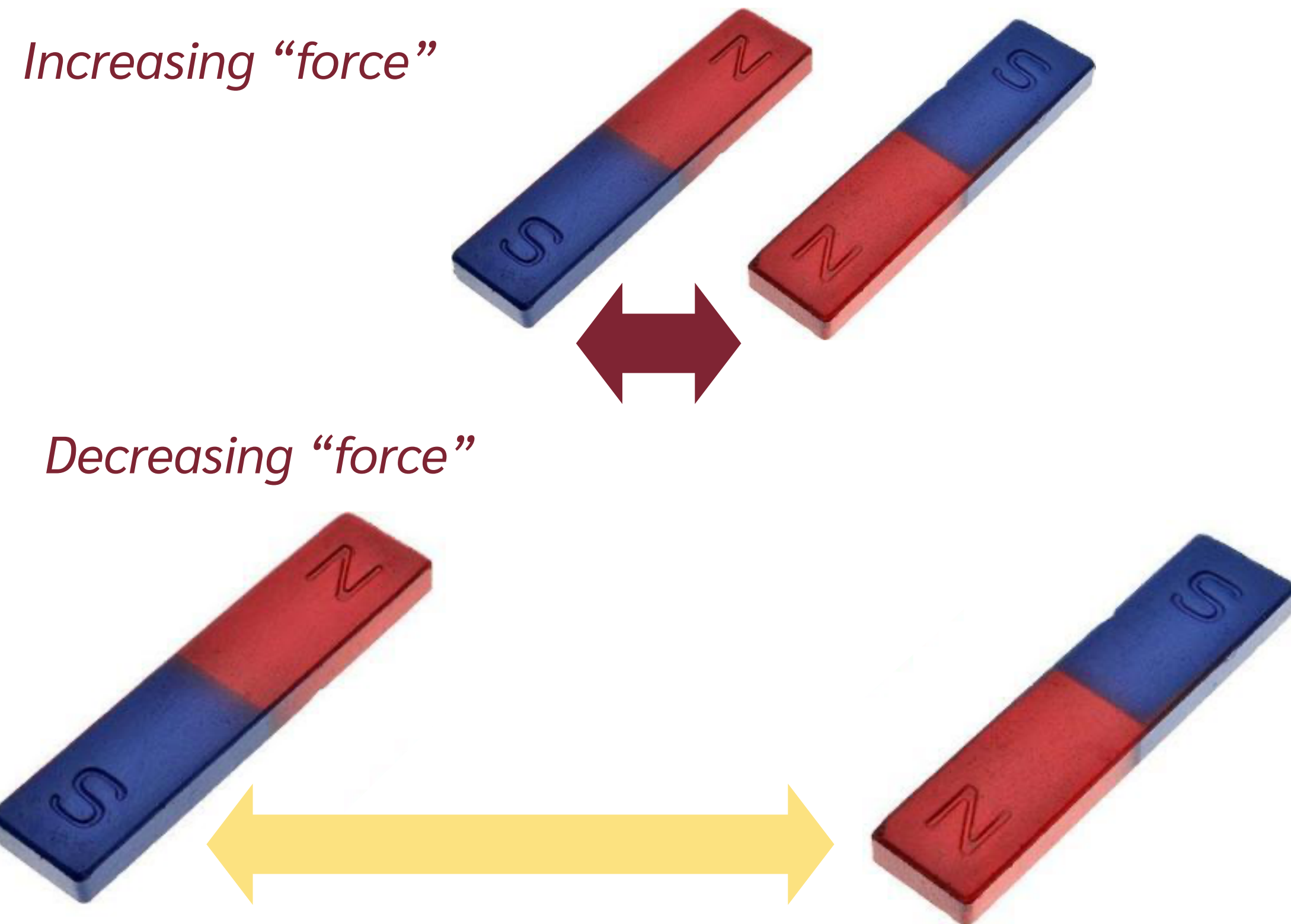
SCALAR BOSONS

GAUGE BOSONS  
VECTOR BOSONS



# Standard Model Sectors

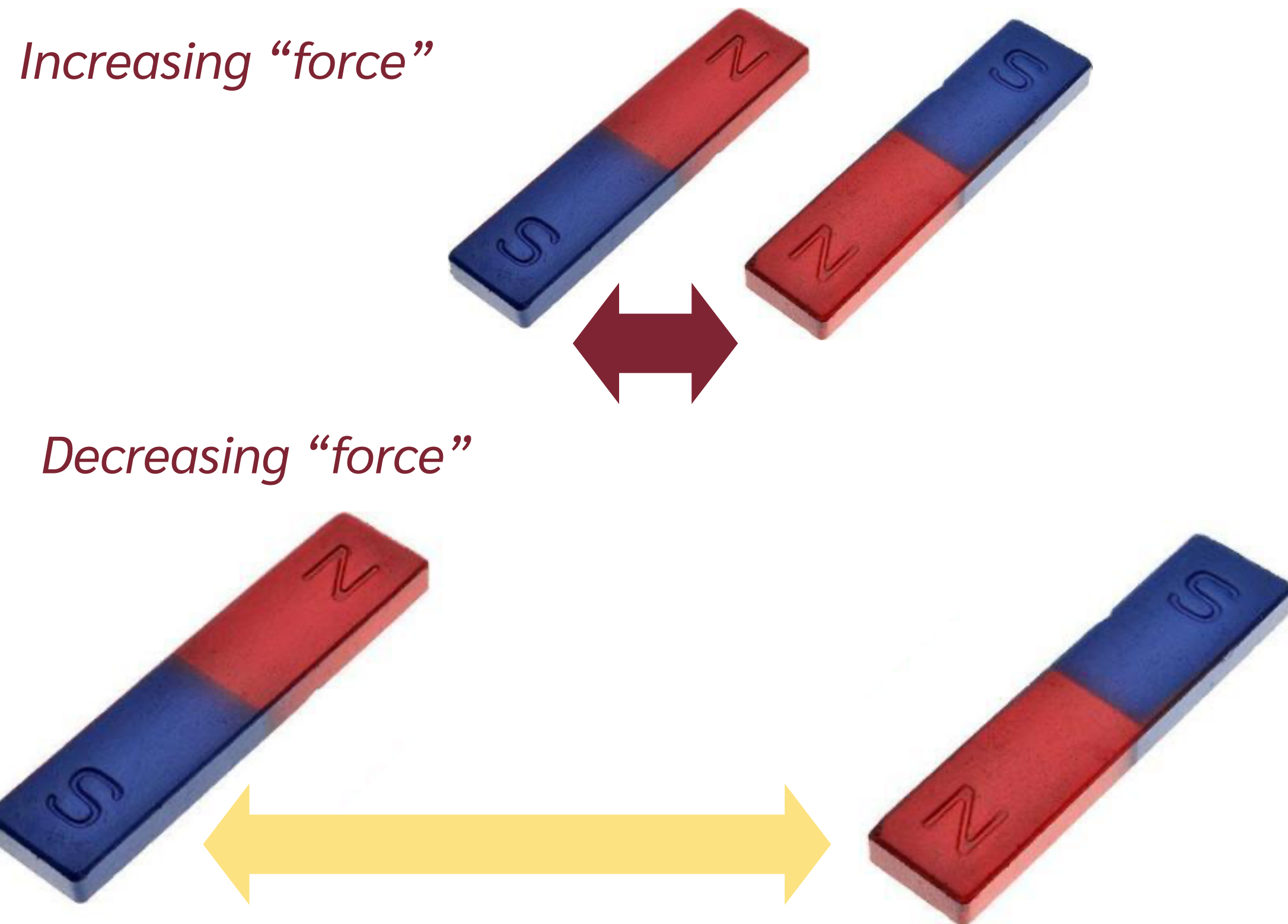
- Quantum Electrodynamics



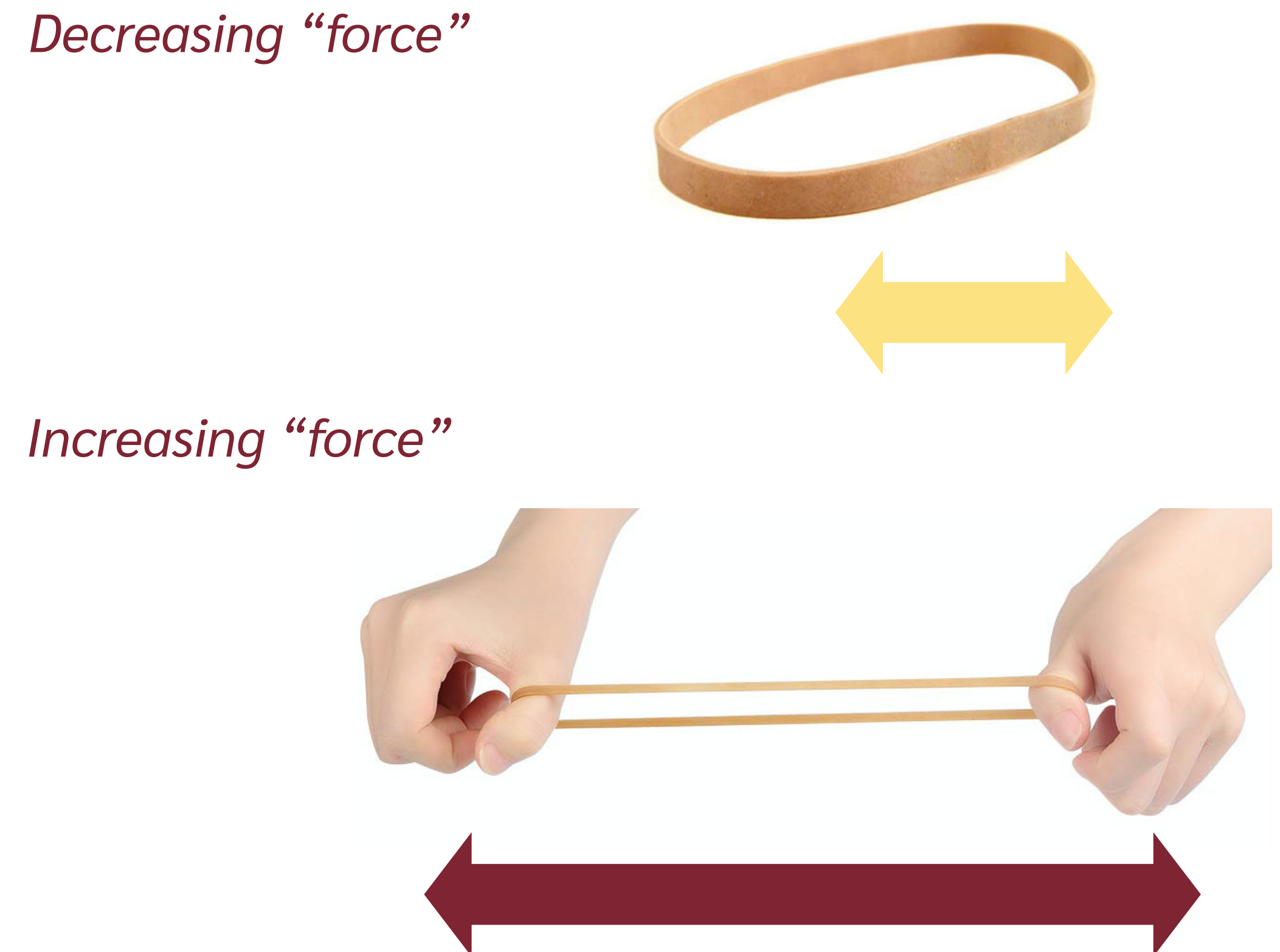


# Standard Model Sectors

- Quantum **E**lectrodynamics



- Quantum **C**hromodynamics





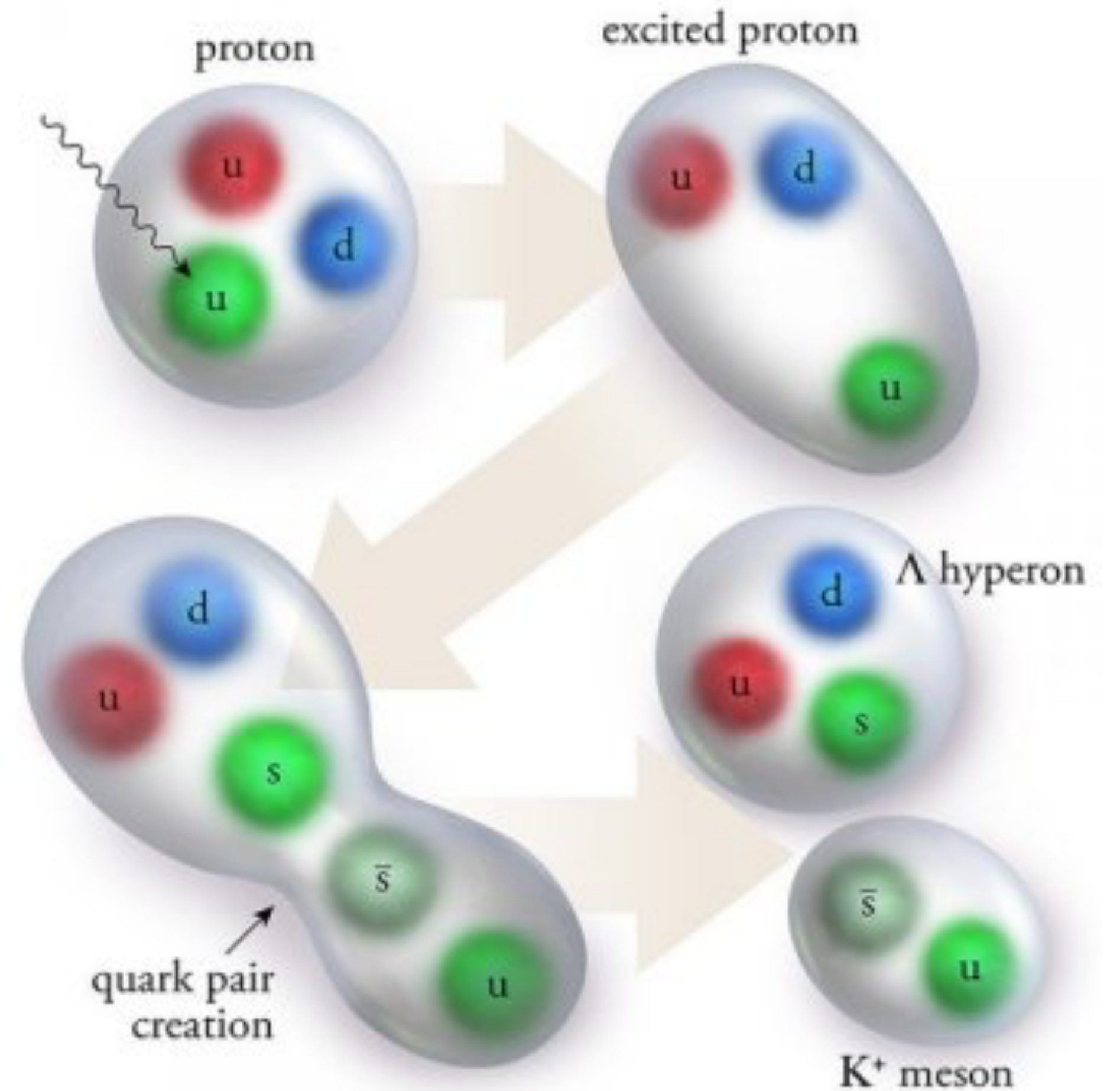
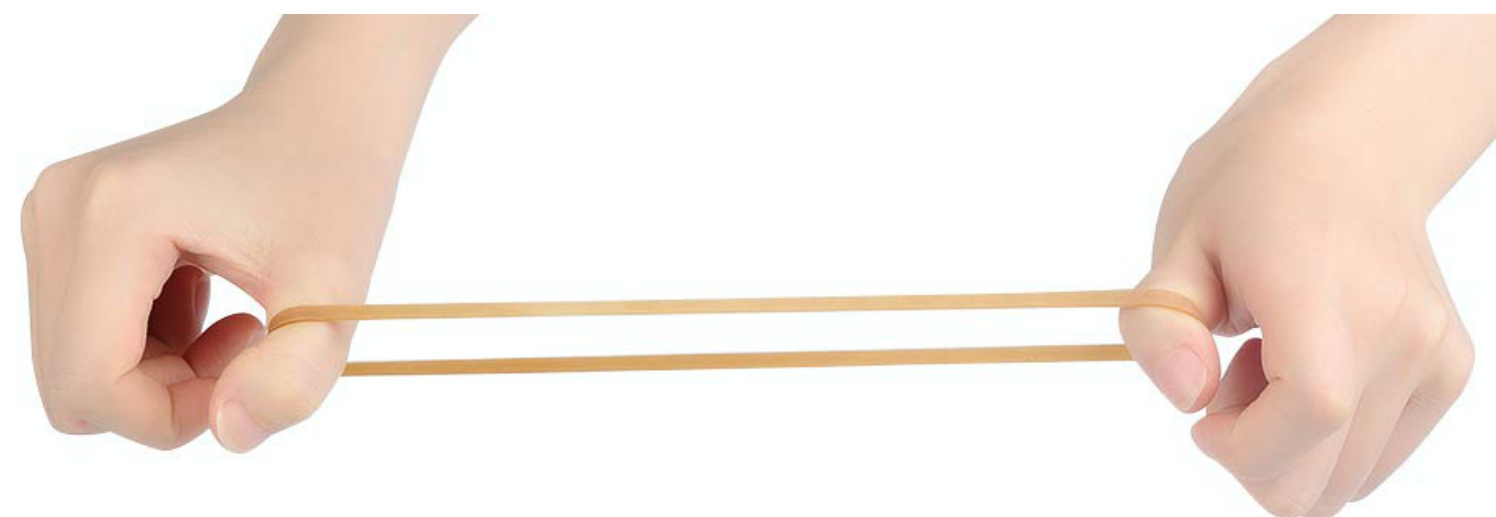
# Confinement

- What does it happen when I try to “pull” a quark from inside a proton?

Decreasing “force”



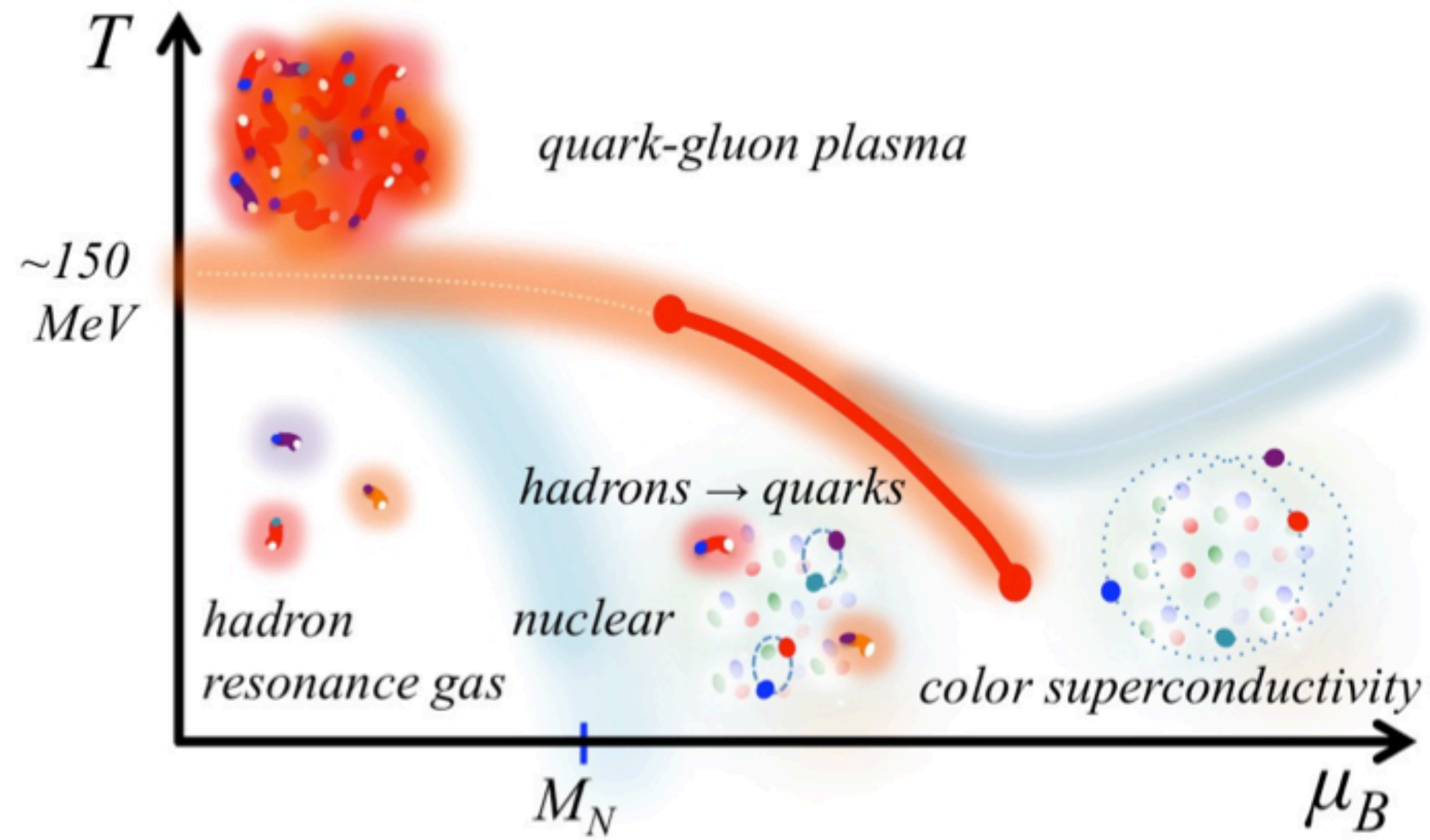
Increasing “force”





# QCD Phase Space

- Our matter is just one of the possible phase-space states:





A vibrant, abstract visualization of a heavy-ion collision. At the center is a bright, glowing yellow and orange sphere, representing the collision point. From this center, a dense network of fine, radiating lines in shades of blue, cyan, and orange extends outwards, creating a starburst effect. The background is a deep blue, filled with numerous thin, curved lines and small, bright orange and yellow dots, suggesting a complex, high-energy environment. The overall composition is symmetrical and dynamic, capturing the intense energy and particle production of such collisions.

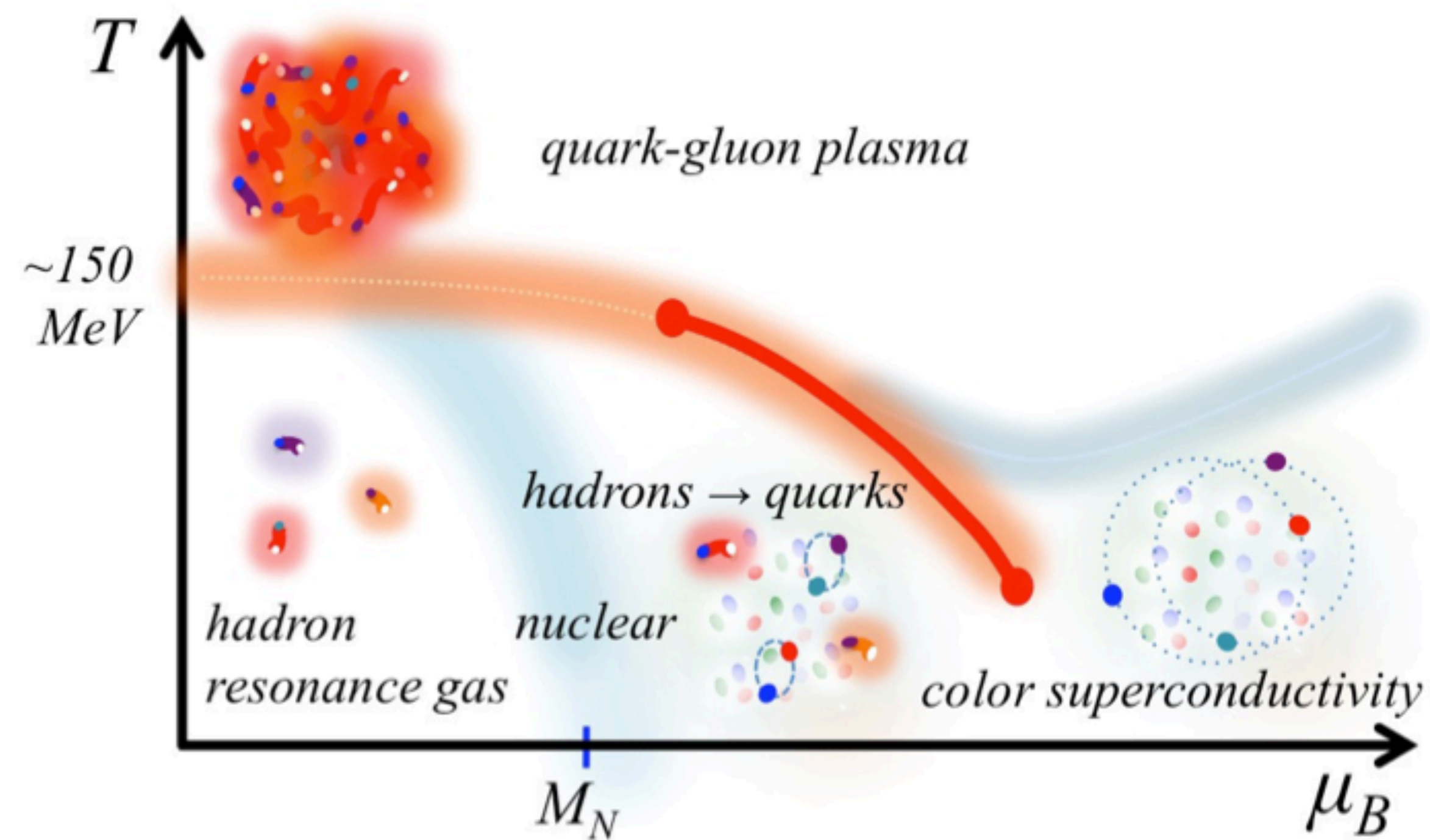
**How to reach other states of matter?**

**Heavy-Ion Collisions**



# Heavy-Ion Collisions

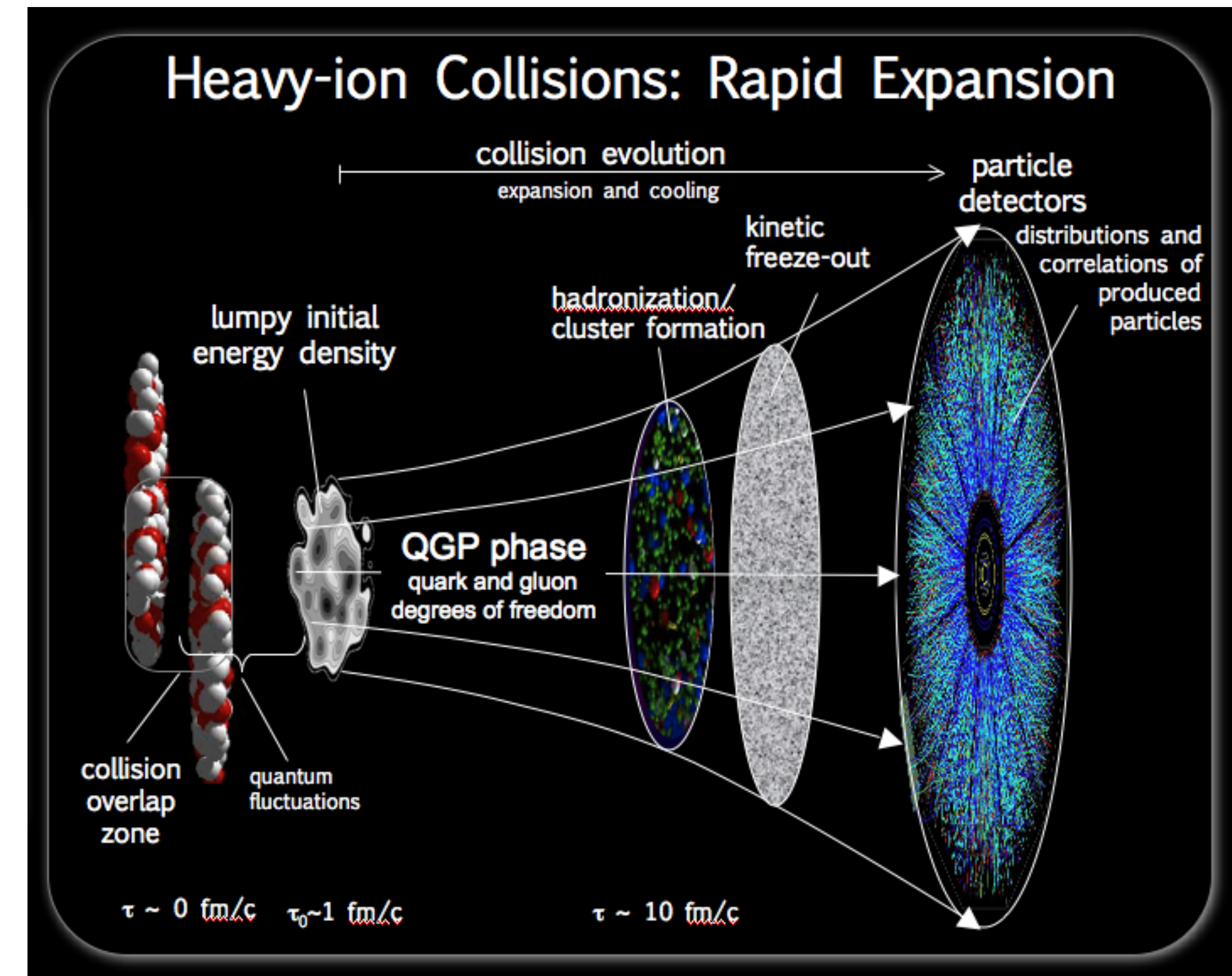
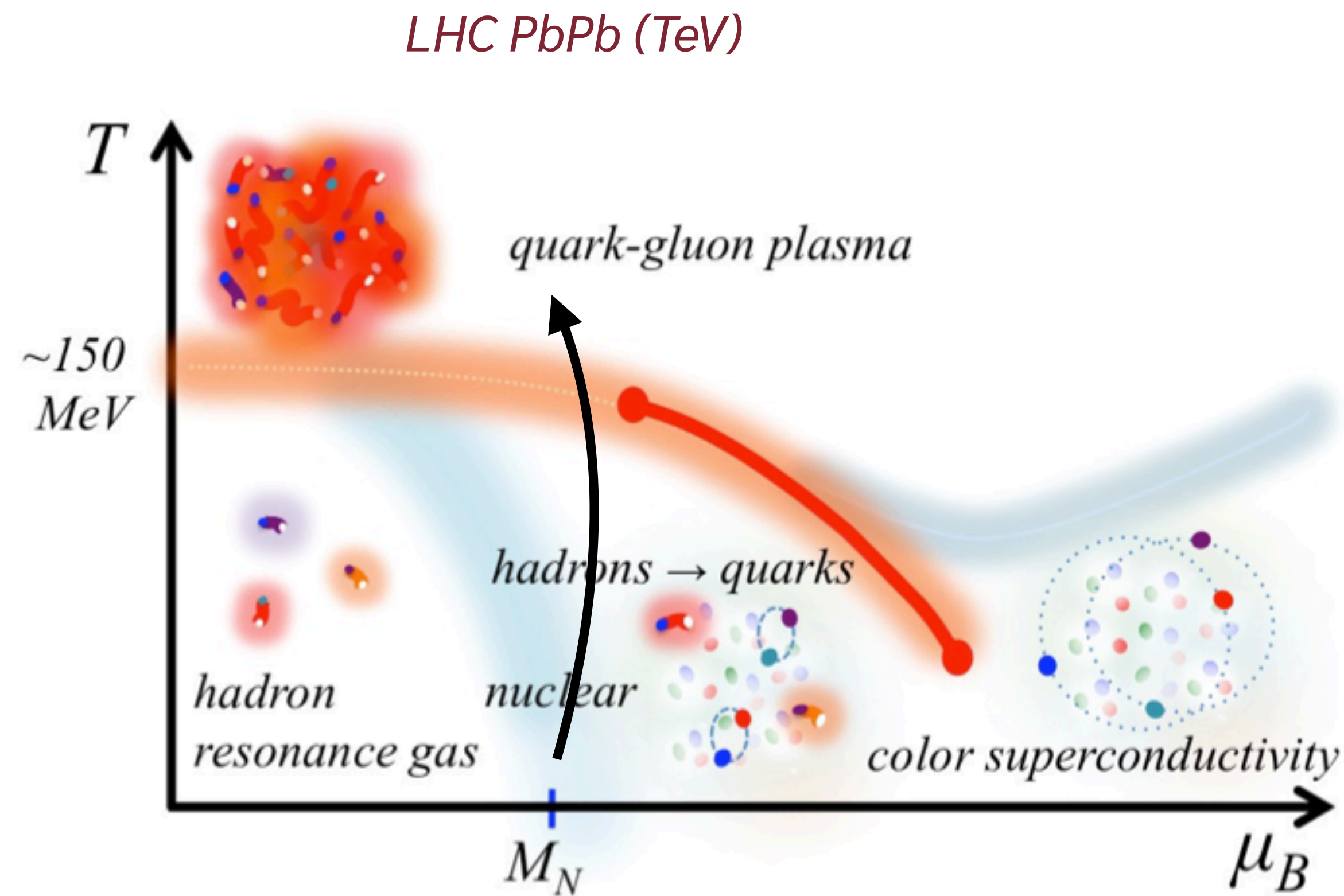
- Heavy-Ion Collisions allow to probe, in a controlled way, the QCD Phase Space





# Heavy-Ion Collisions

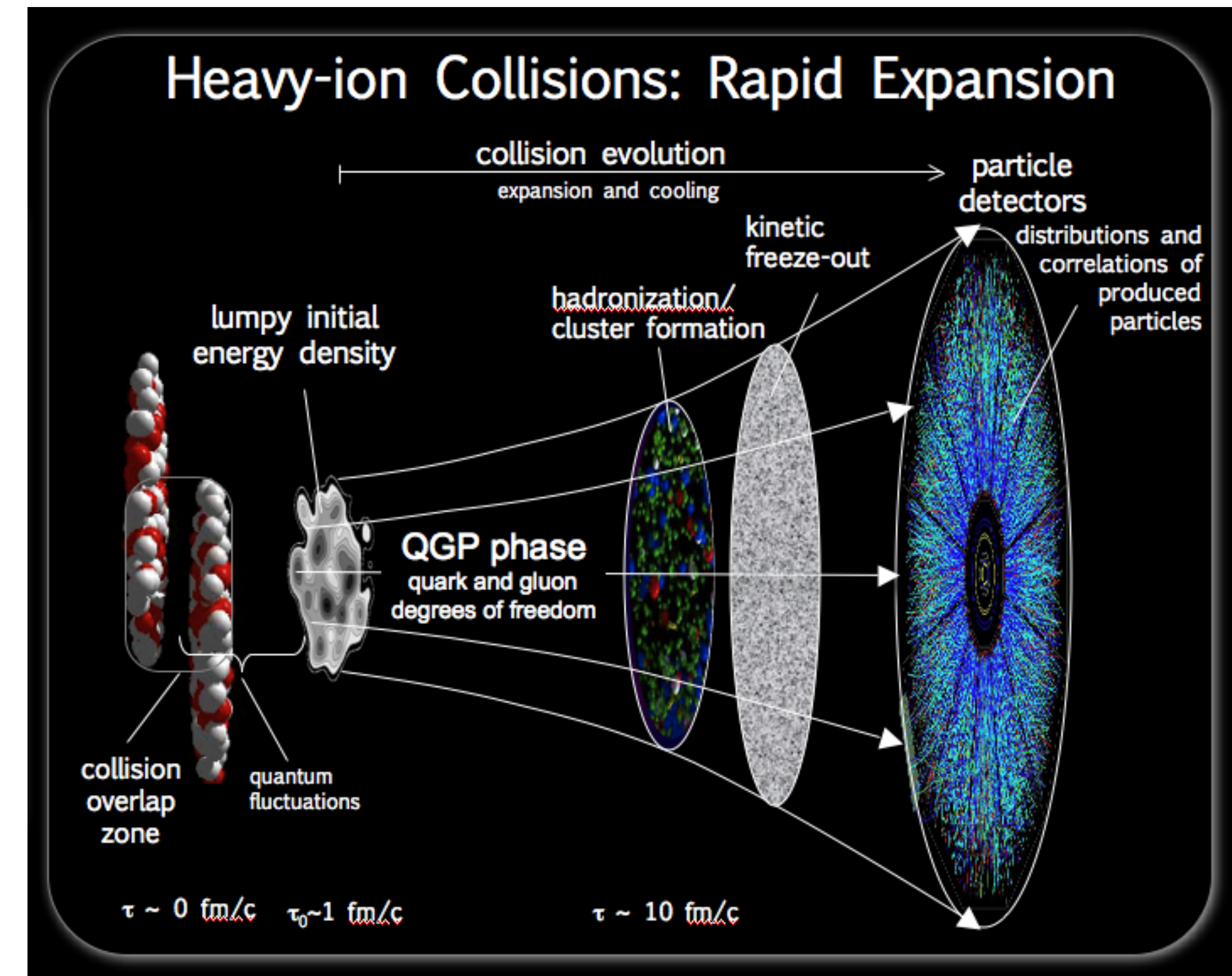
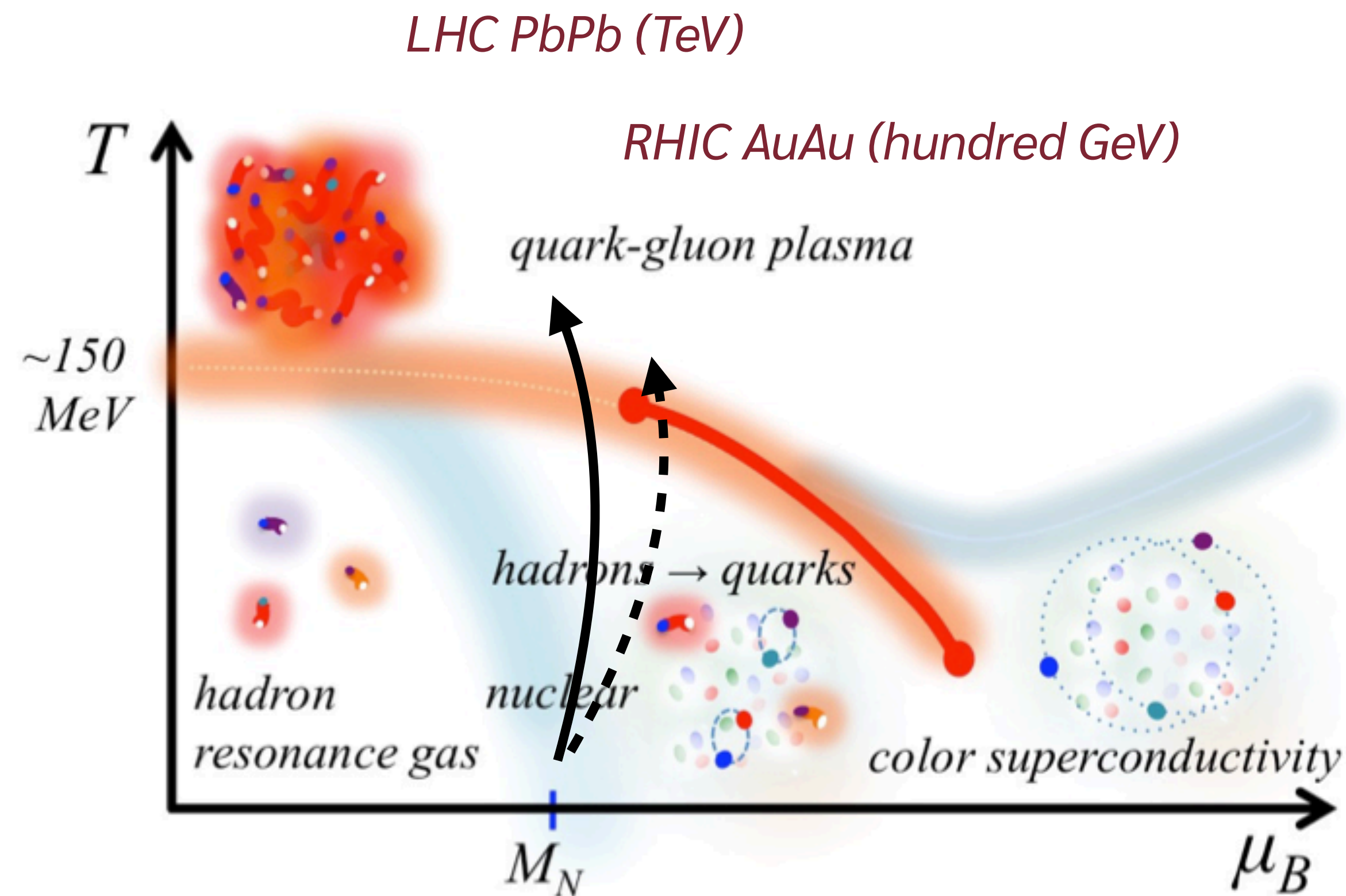
- Heavy-Ion Collisions allow to probe, in a controlled way, the QCD Phase Space





# Heavy-Ion Collisions

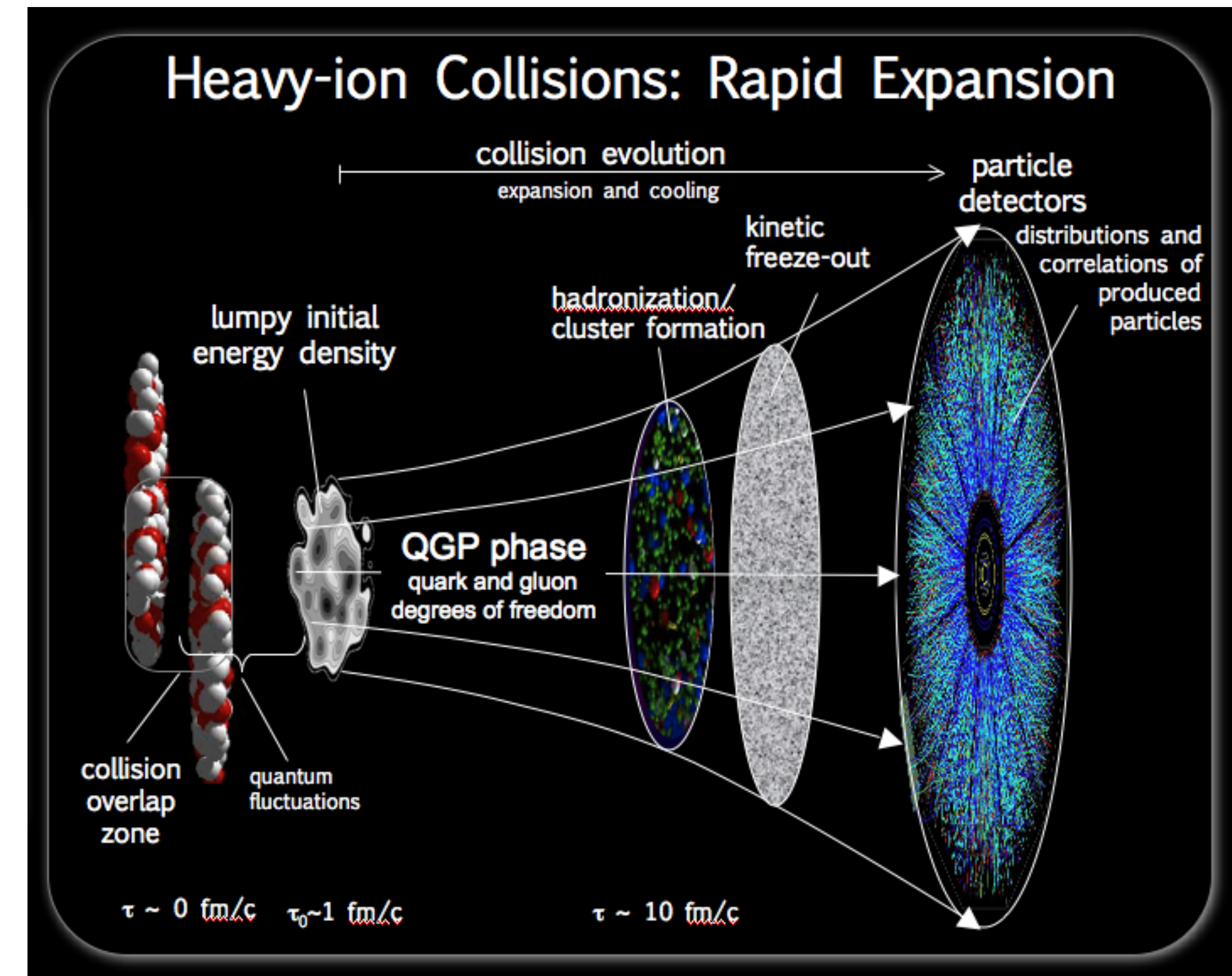
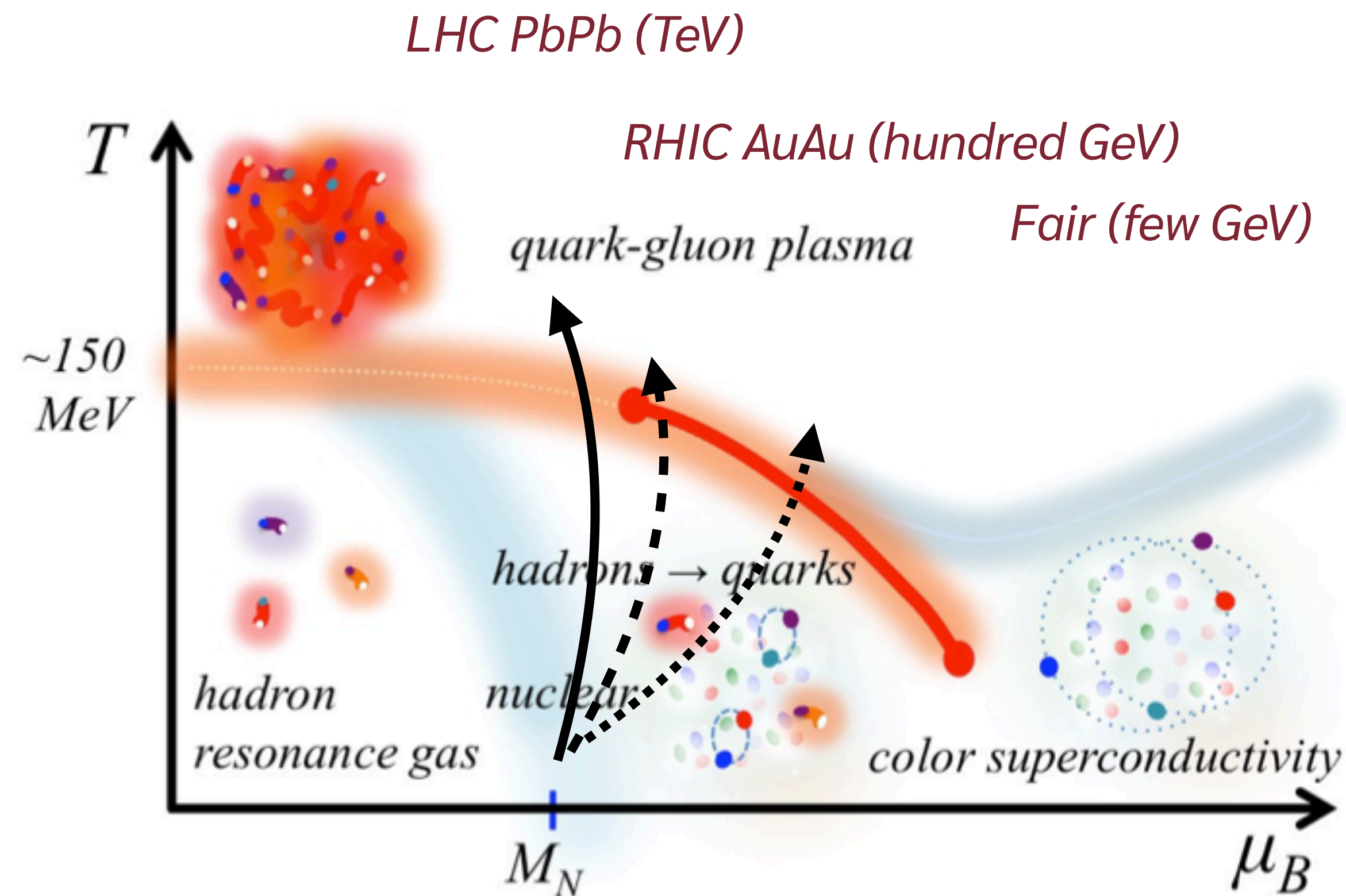
- Heavy-Ion Collisions allow to probe, in a controlled way, the QCD Phase Space





# Heavy-Ion Collisions

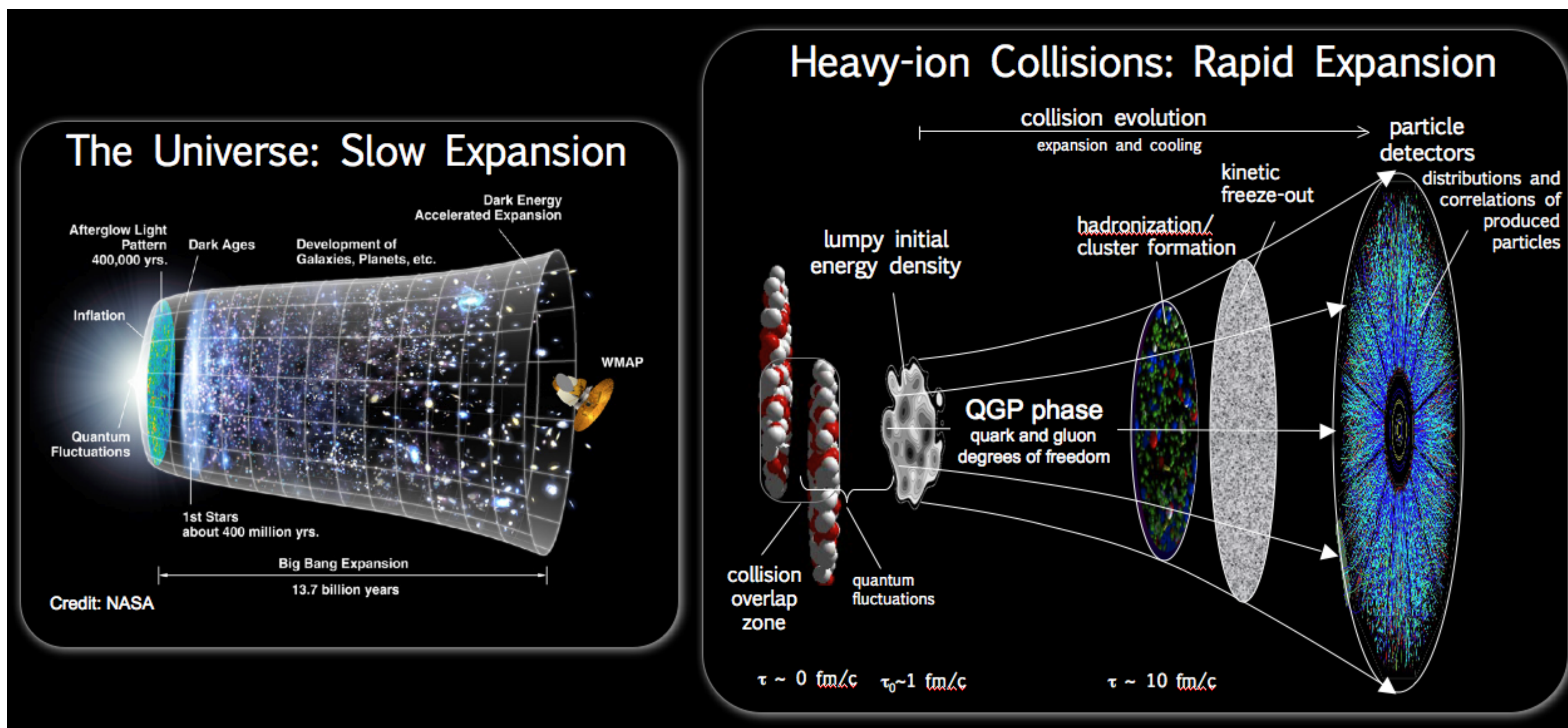
- Heavy-Ion Collisions allow to probe, in a controlled way, the QCD Phase Space





# QGP: Universe to the Laboratory

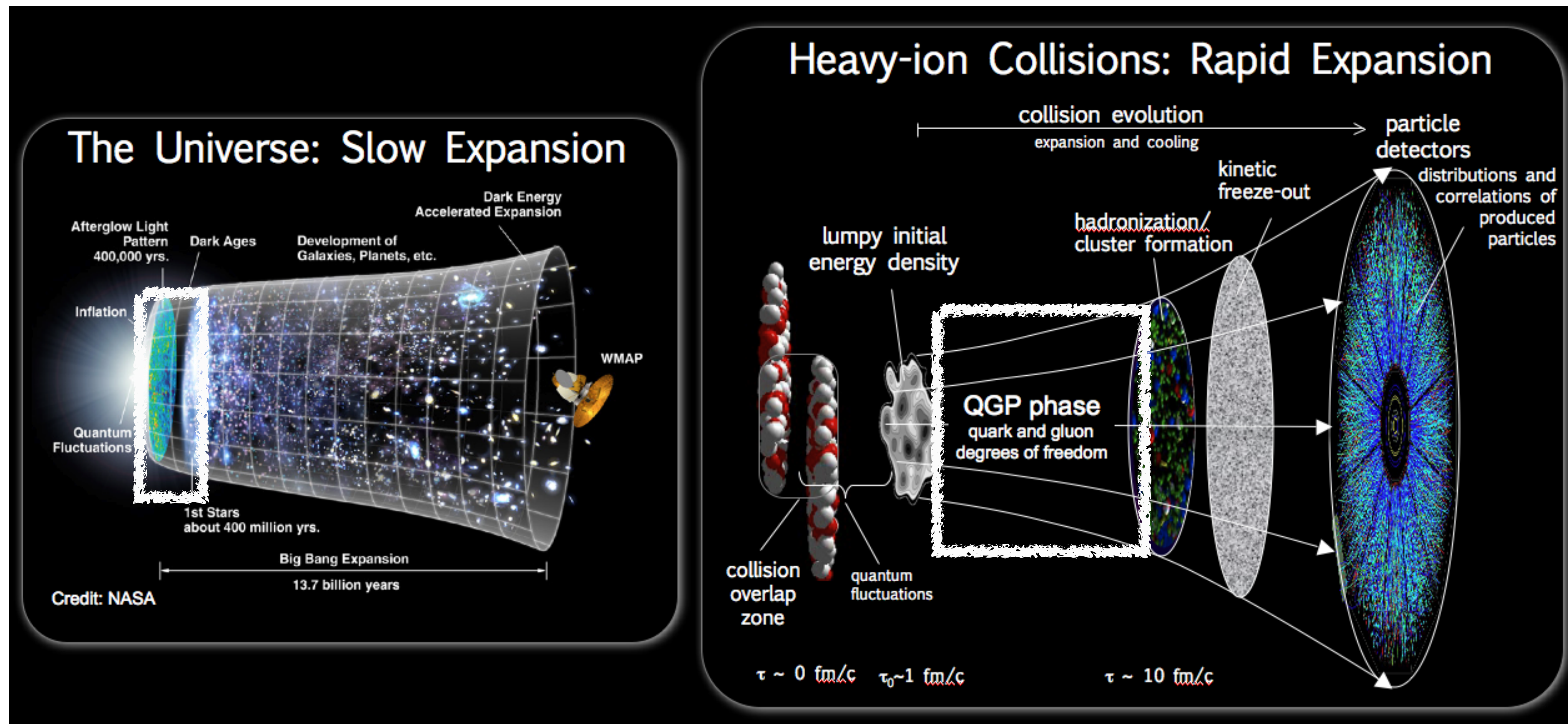
- QGP Phase was also the primordial state of our Universe





# QGP: Universe to the Laboratory

- QGP Phase was also the primordial state of our Universe





# Current Colliders

*Brookhaven National Lab (USA)  
Relativistic Heavy-Ion Collider (RHIC)*

*CERN  
Large Hadron Collider (LHC)*





# Current Colliders

*Brookhaven National Lab (USA)*  
*Relativistic Heavy-Ion Collider (RHIC)*

Perimeter: 3.8 km



*CERN*  
*Large Hadron Collider (LHC)*

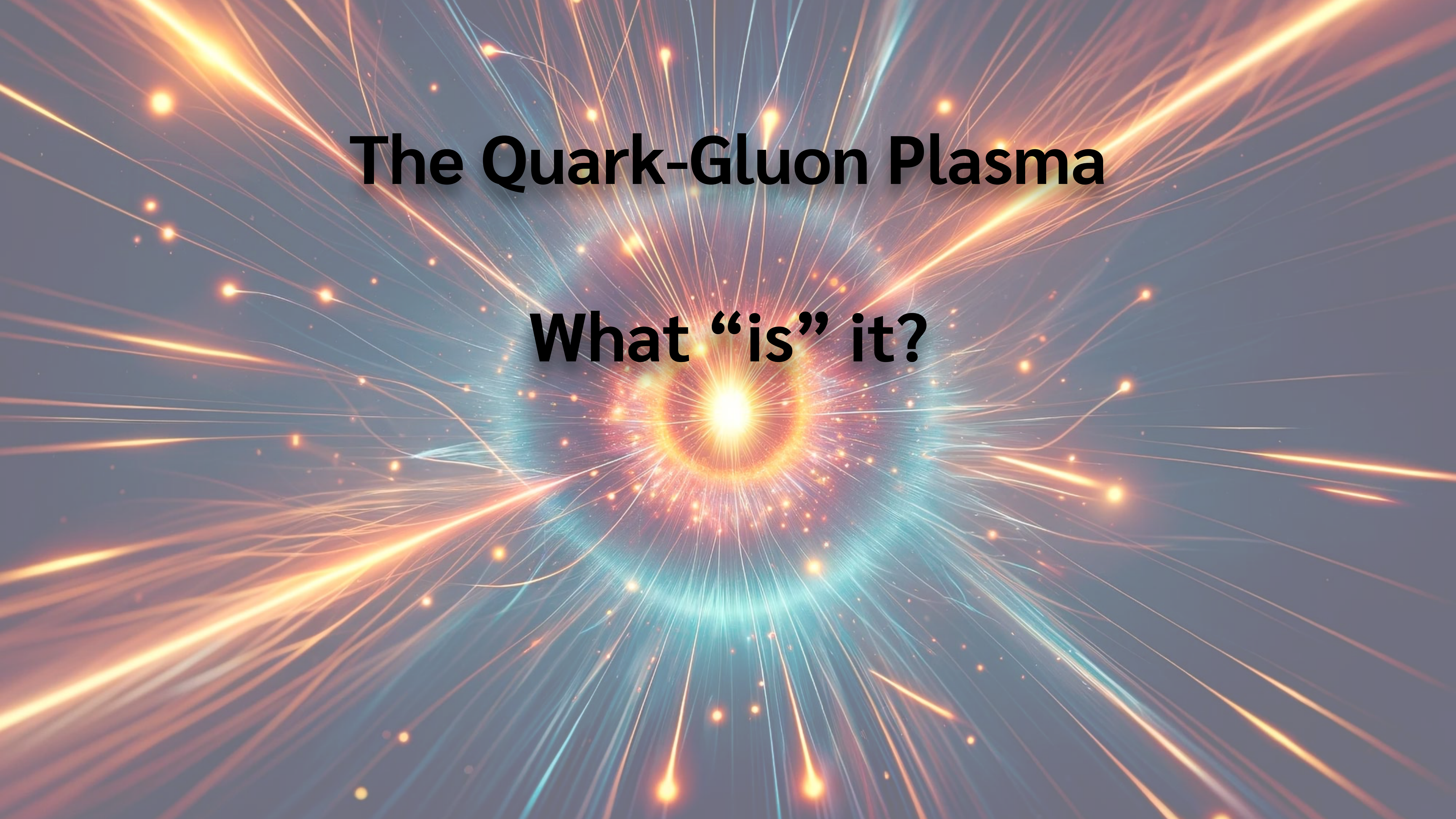
Perimeter: 27 km





# The Quark-Gluon Plasma

What “is” it?

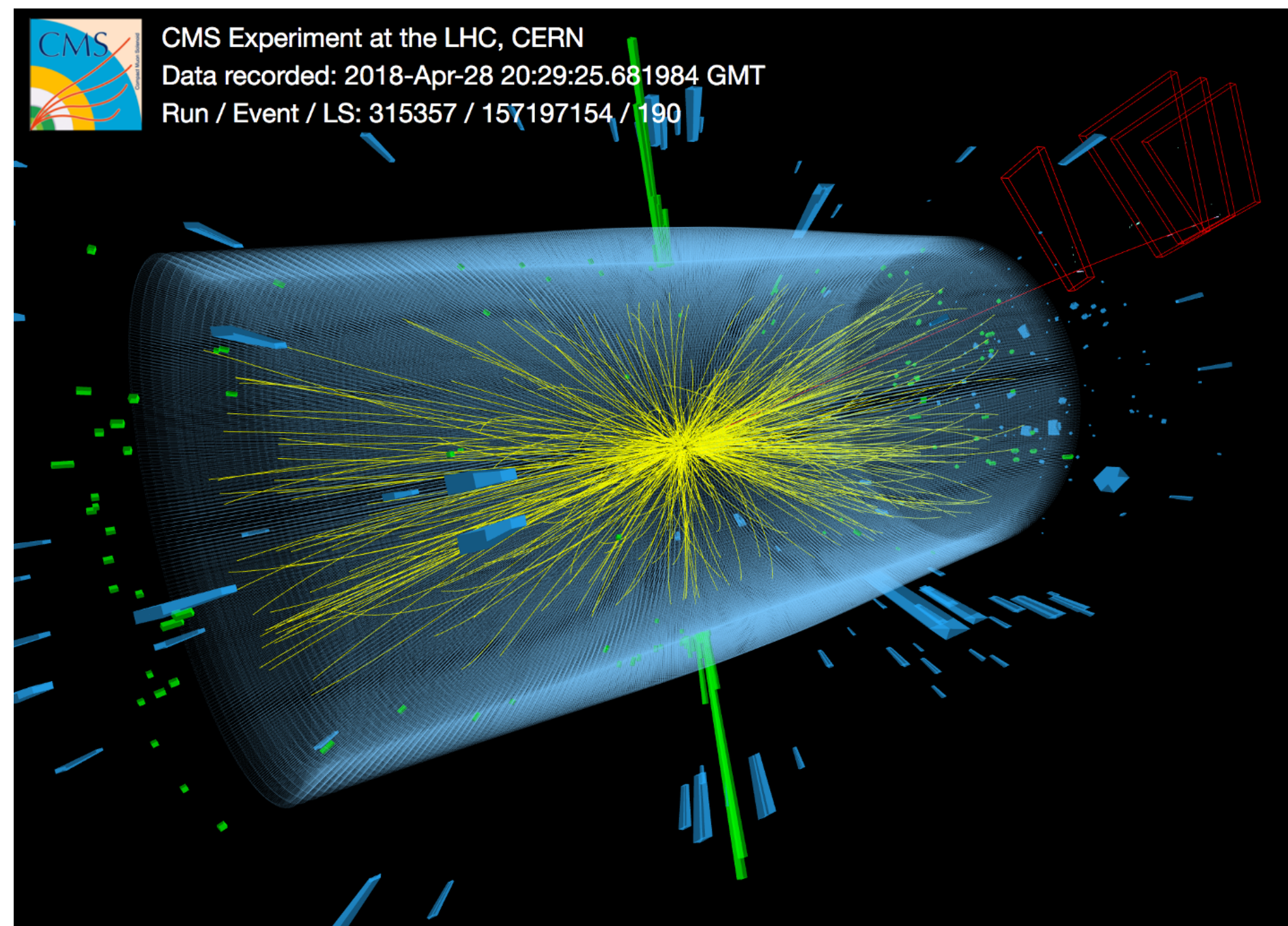




# How to probe the QGP @ lab?

- Look to the result of the collision (Soft probes)

*Proton-proton collisions*



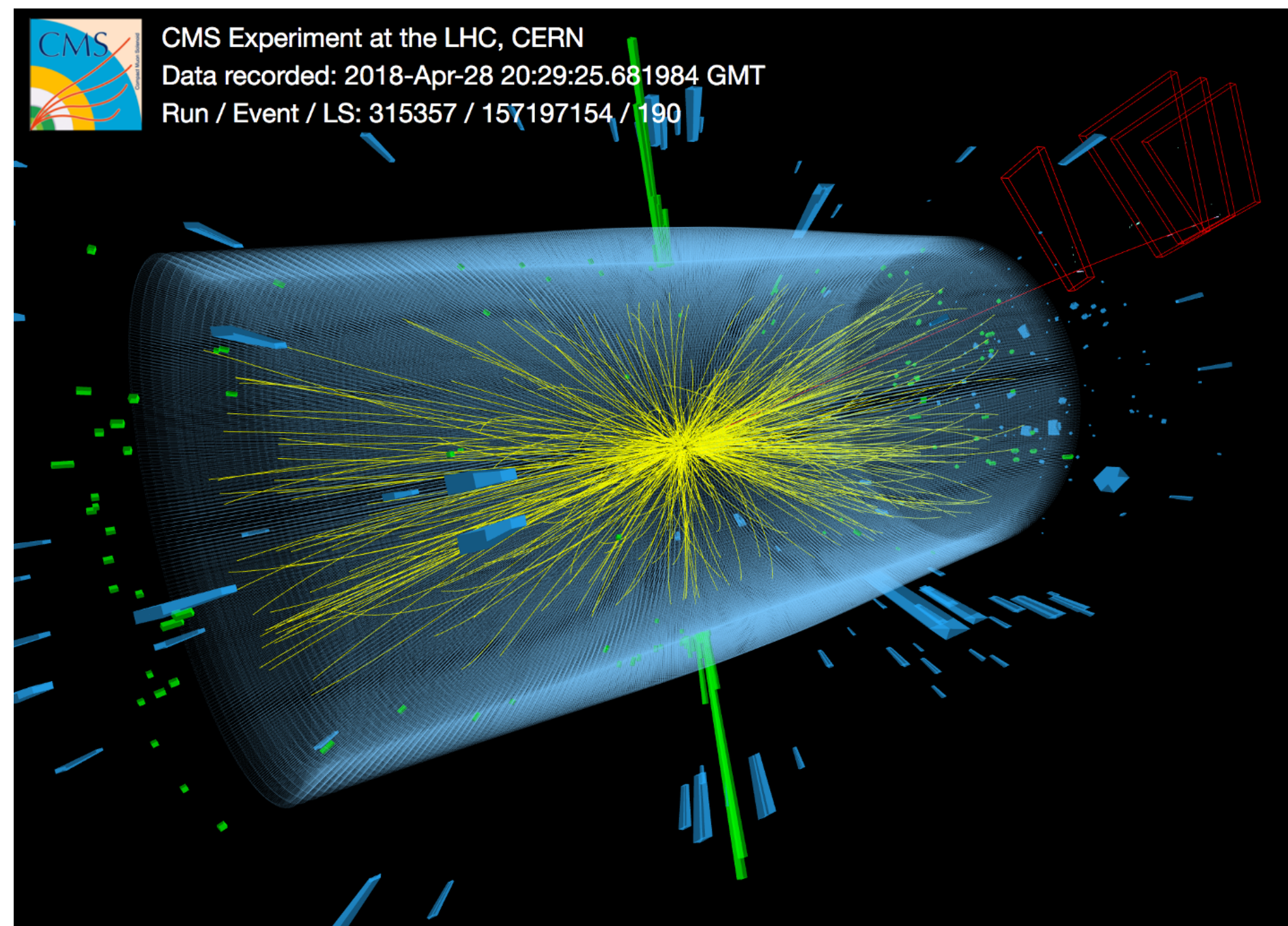
*Low multiplicity event (few particles...)*



# How to probe the QGP @ lab?

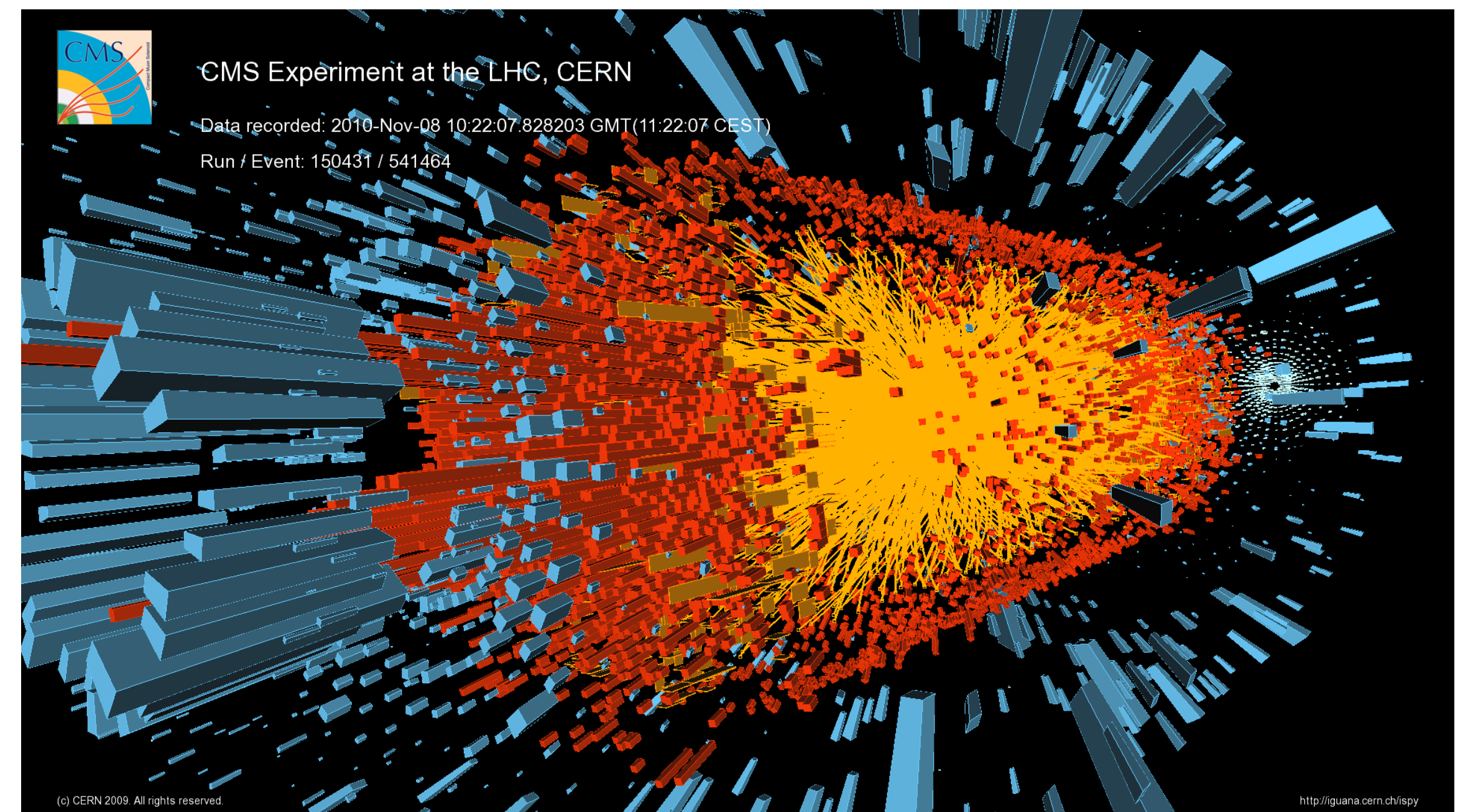
- Look to the result of the collision (Soft probes)

*Proton-proton collisions*



*Low multiplicity event (few particles...)*

*Lead-Lead collisions*

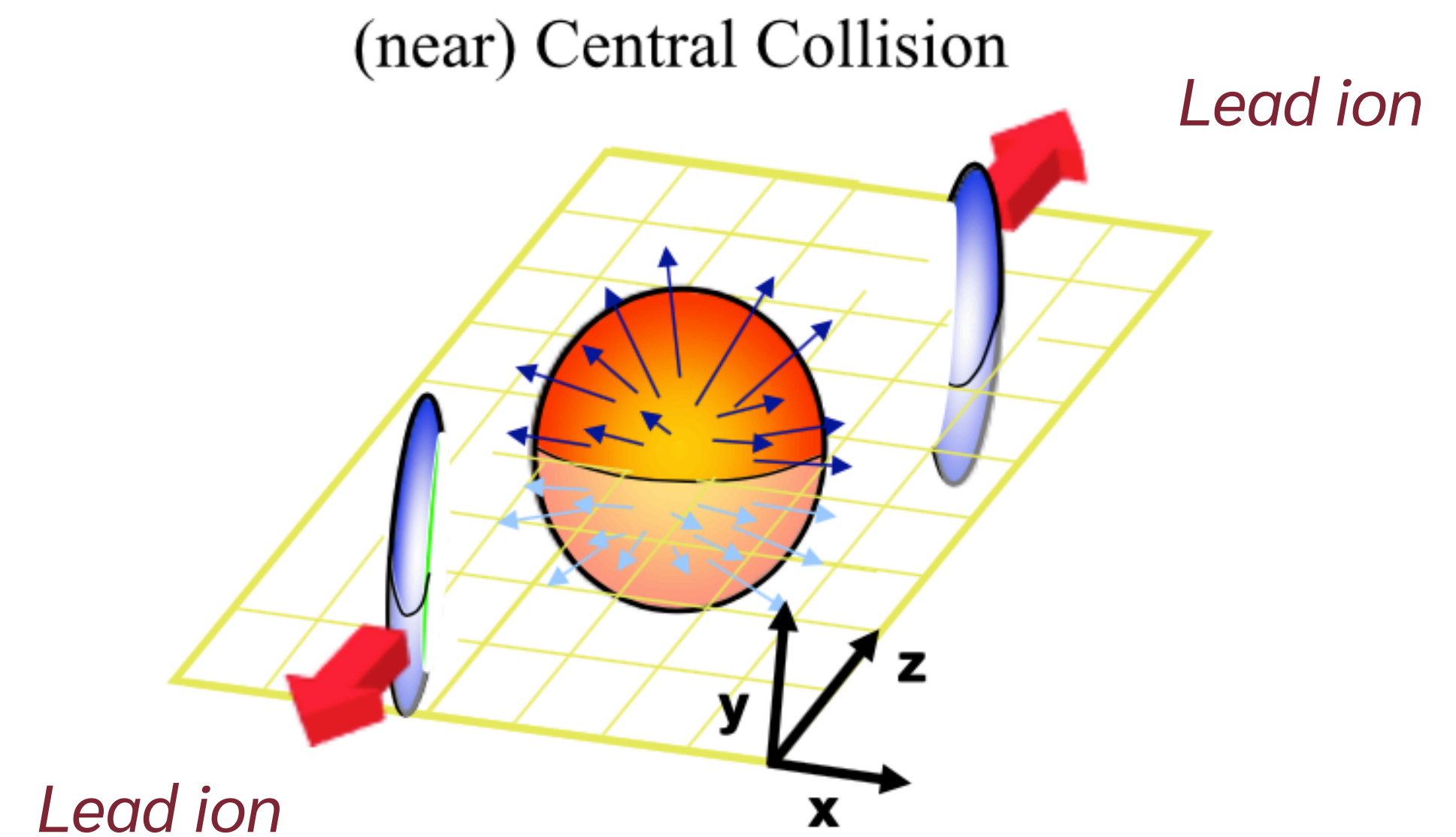
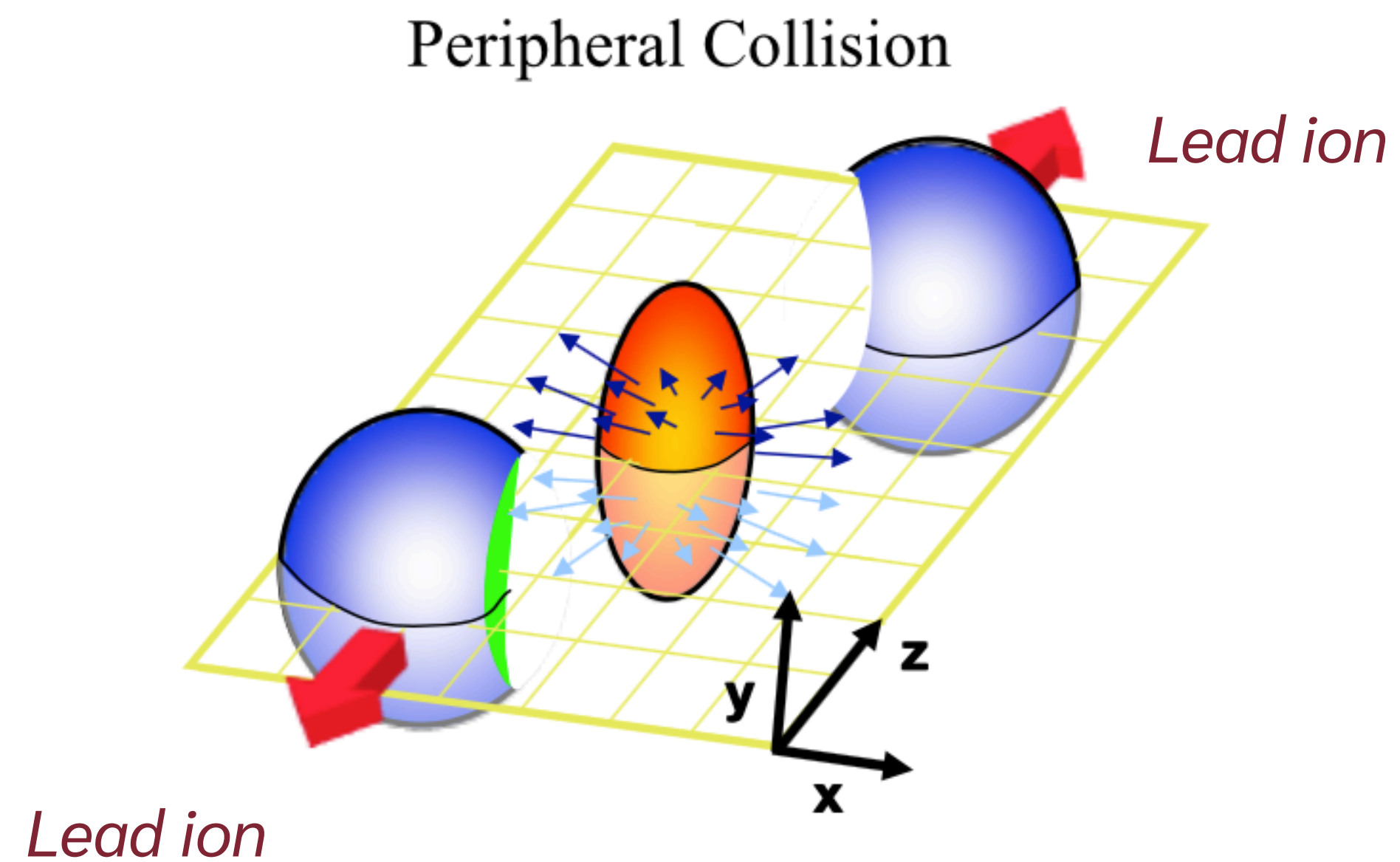


*High multiplicity event (many particles!)  
Result of QGP formation*



# Centrality of the collision

- Try to control overlap region between incoming nuclei (centrality)

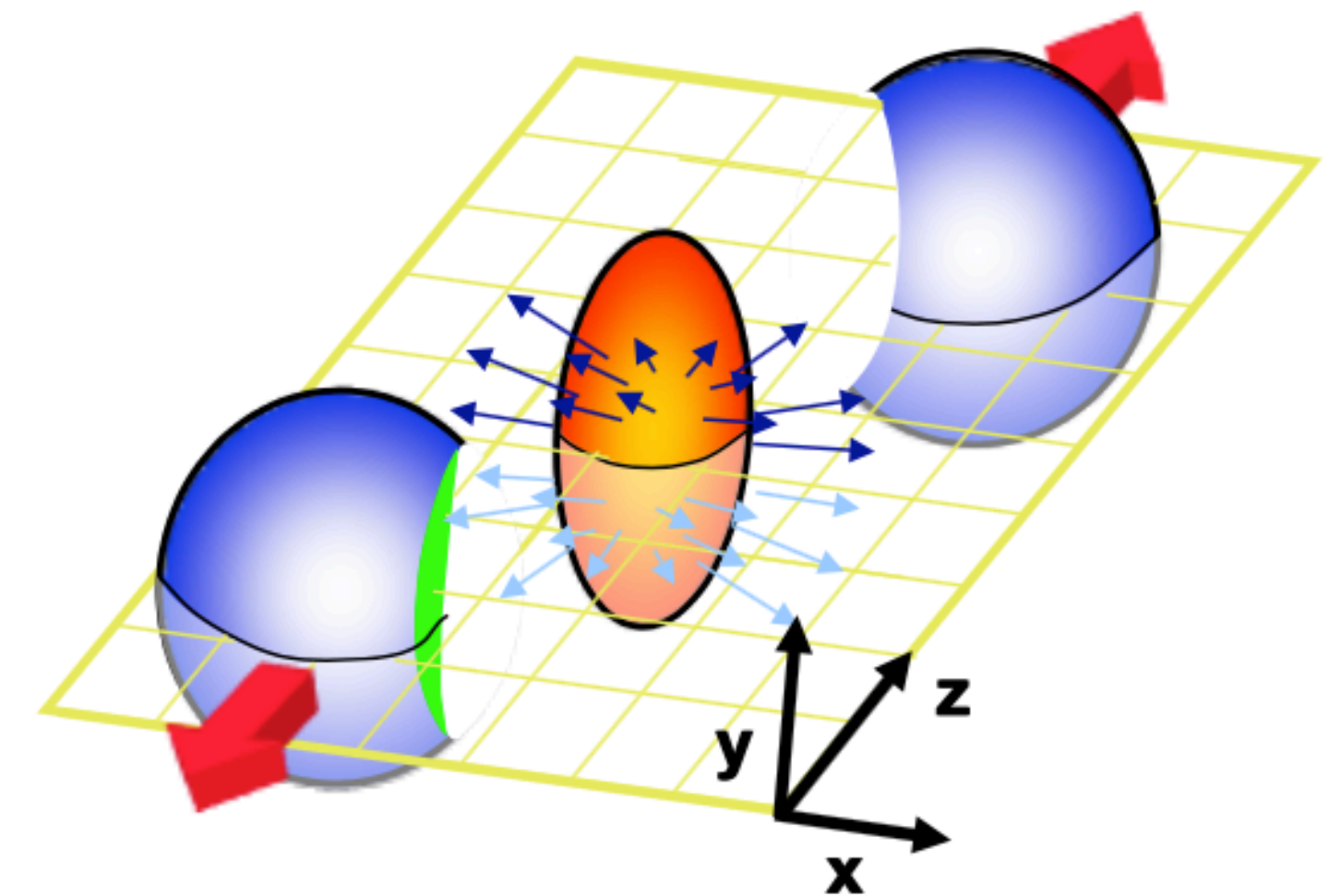




# Centrality of the collision

- Try to control overlap region between incoming nuclei (centrality)
- Local or large scale collective behaviour? *“Gas-like” behaviour?*

Peripheral Collision

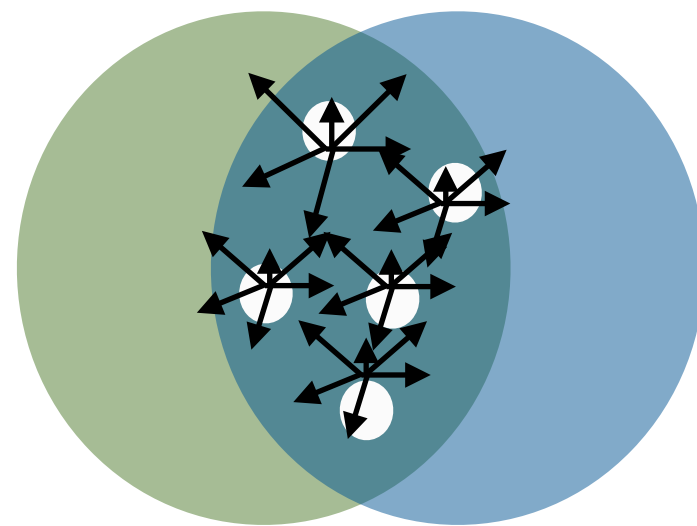




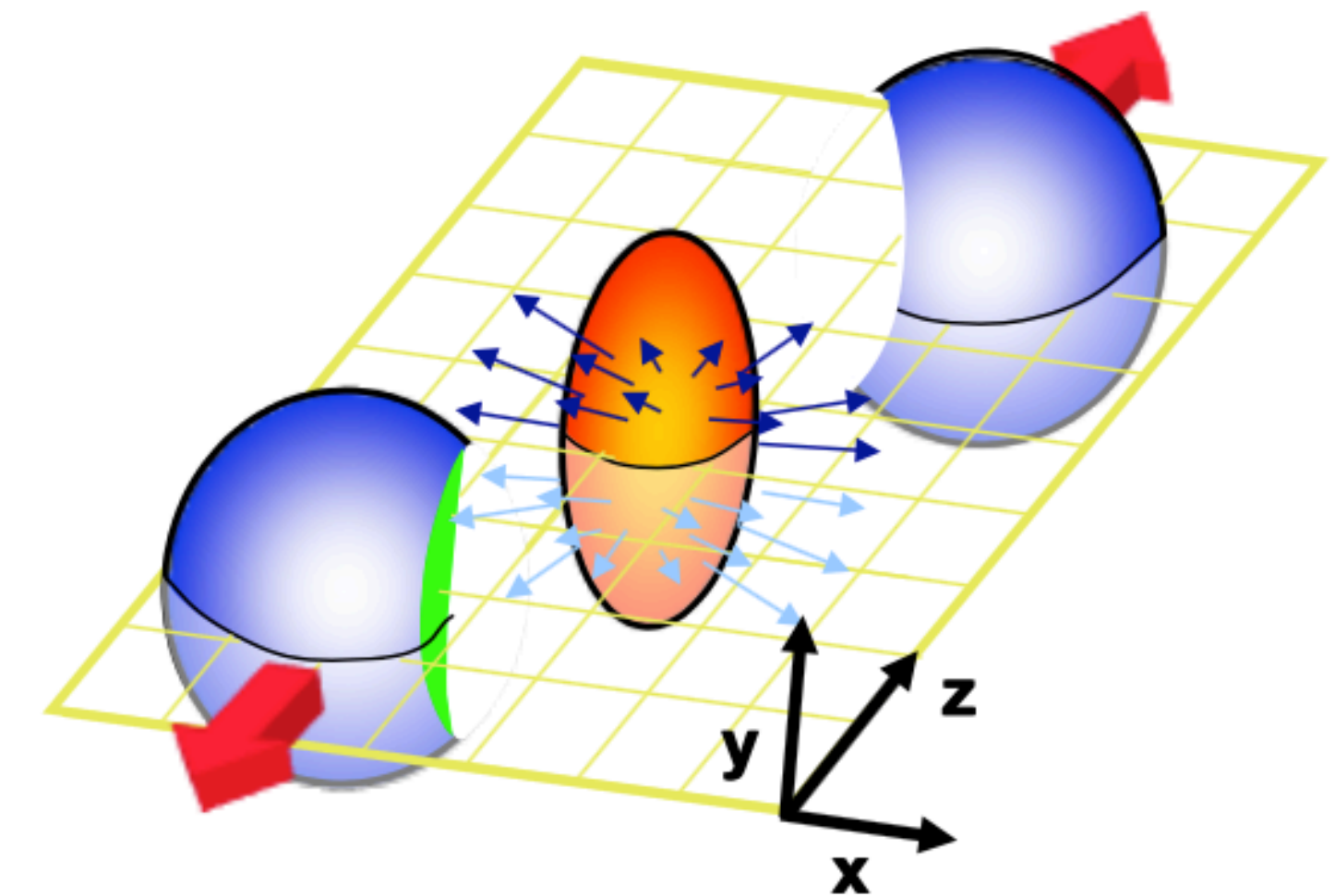
# Centrality of the collision

- Try to control overlap region between incoming nuclei (centrality)
- Local or large scale collective behaviour? *“Gas-like” behaviour?*

Superposition of multiple pp collisions



Peripheral Collision

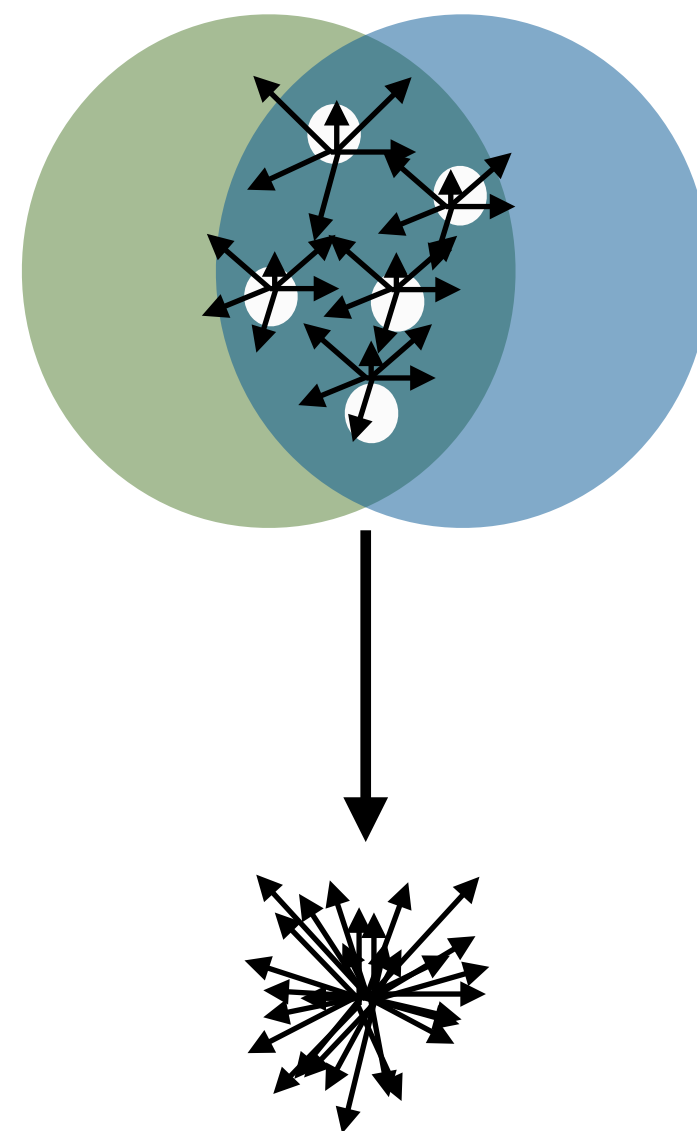




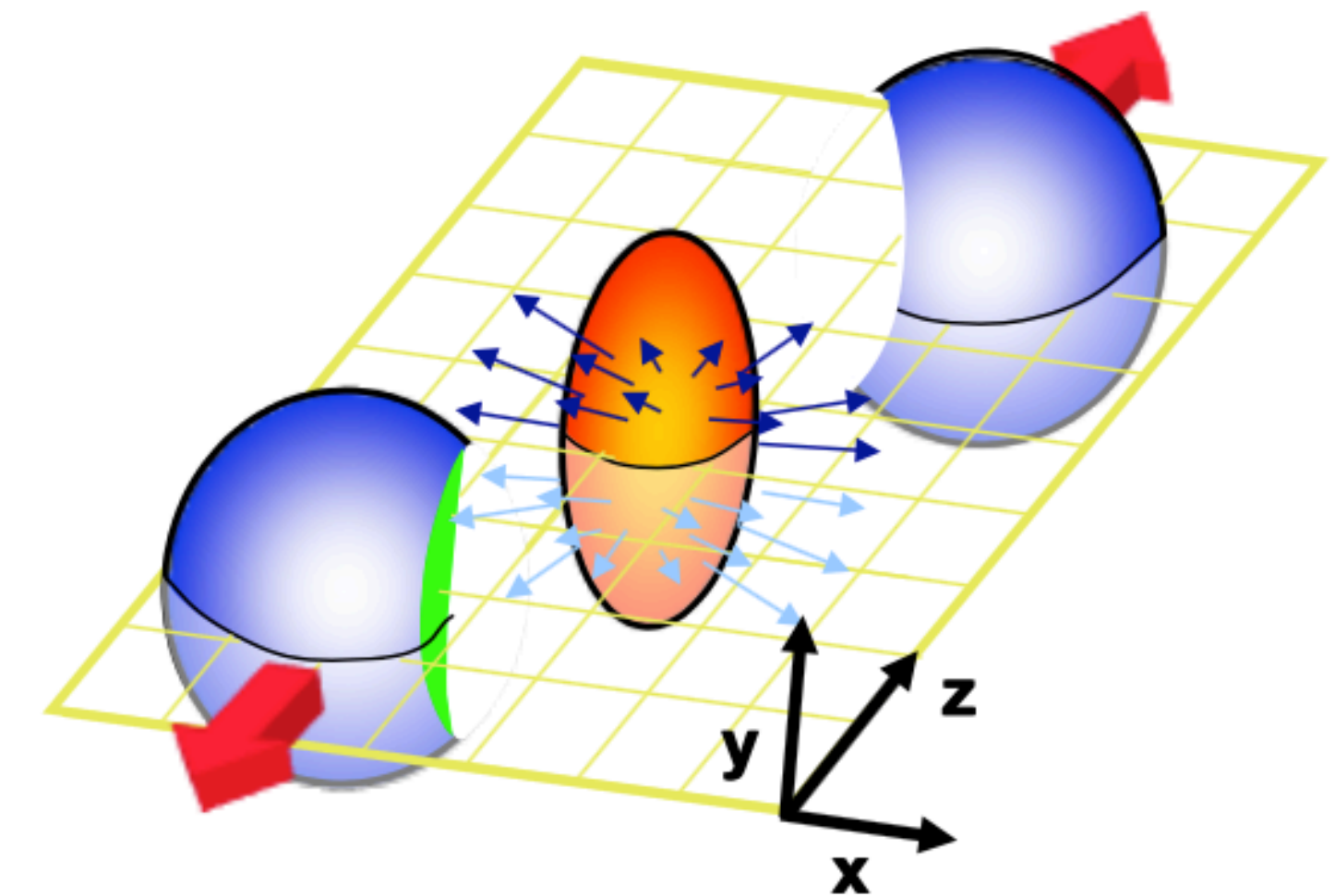
# Centrality of the collision

- Try to control overlap region between incoming nuclei (centrality)
- Local or large scale collective behaviour? *“Gas-like” behaviour?*

Superposition of multiple pp collisions



Peripheral Collision

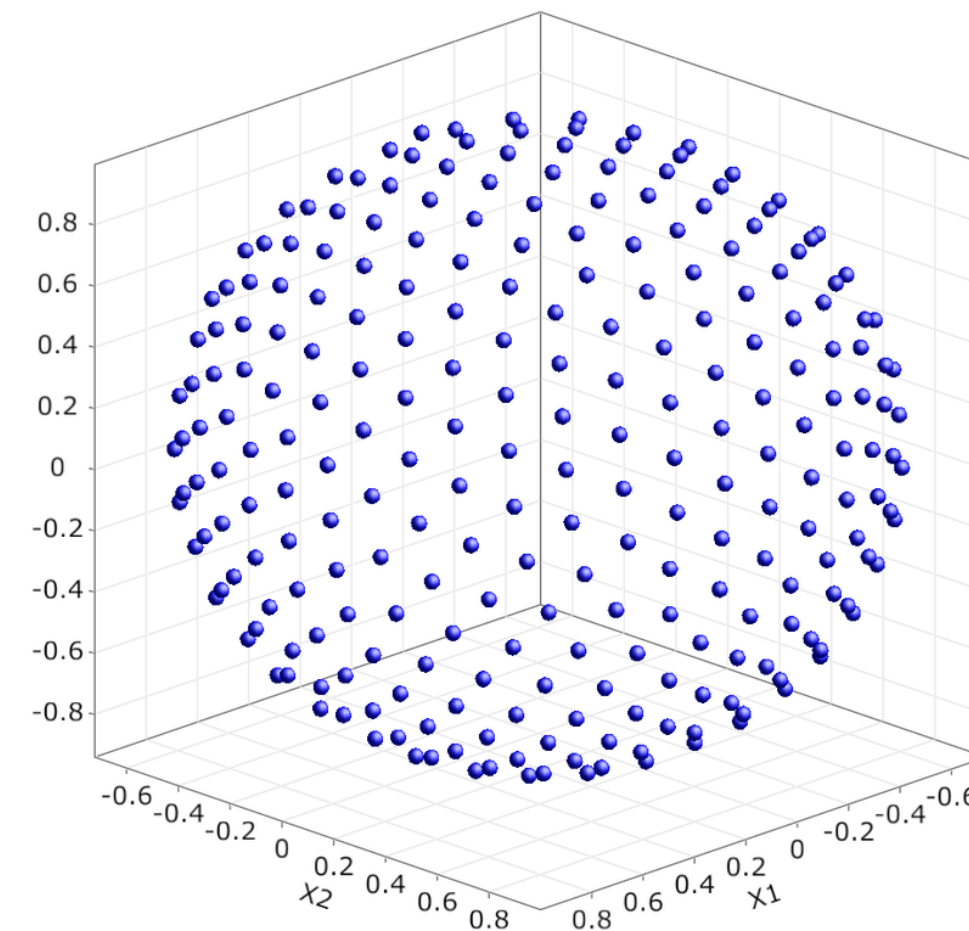
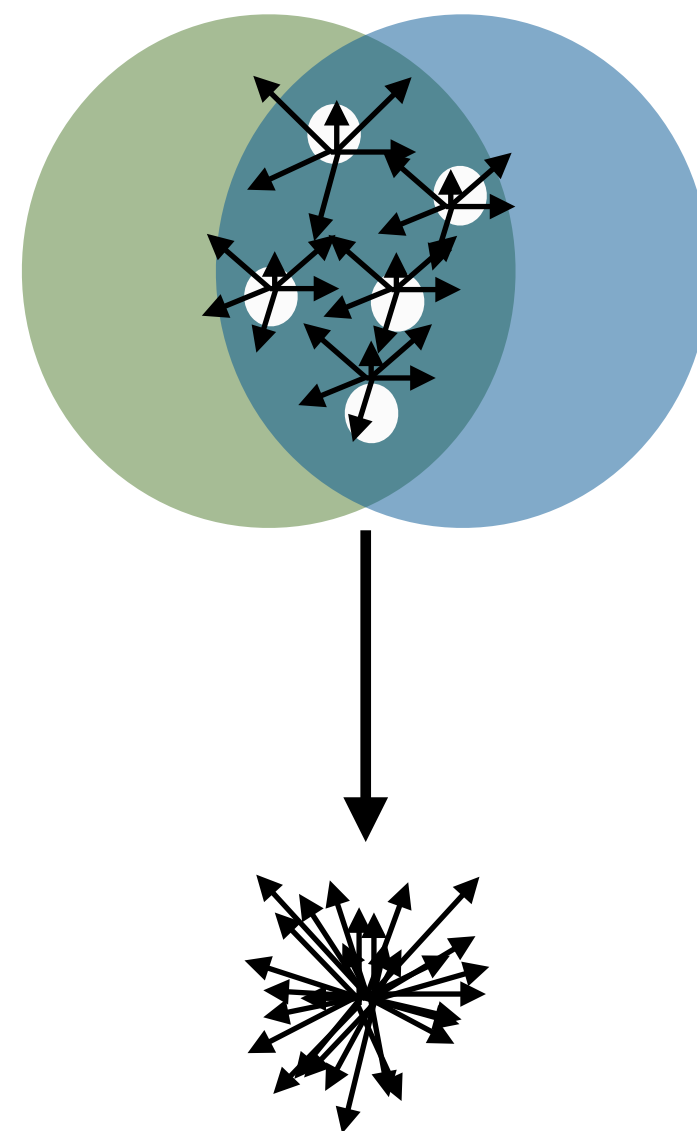




# Centrality of the collision

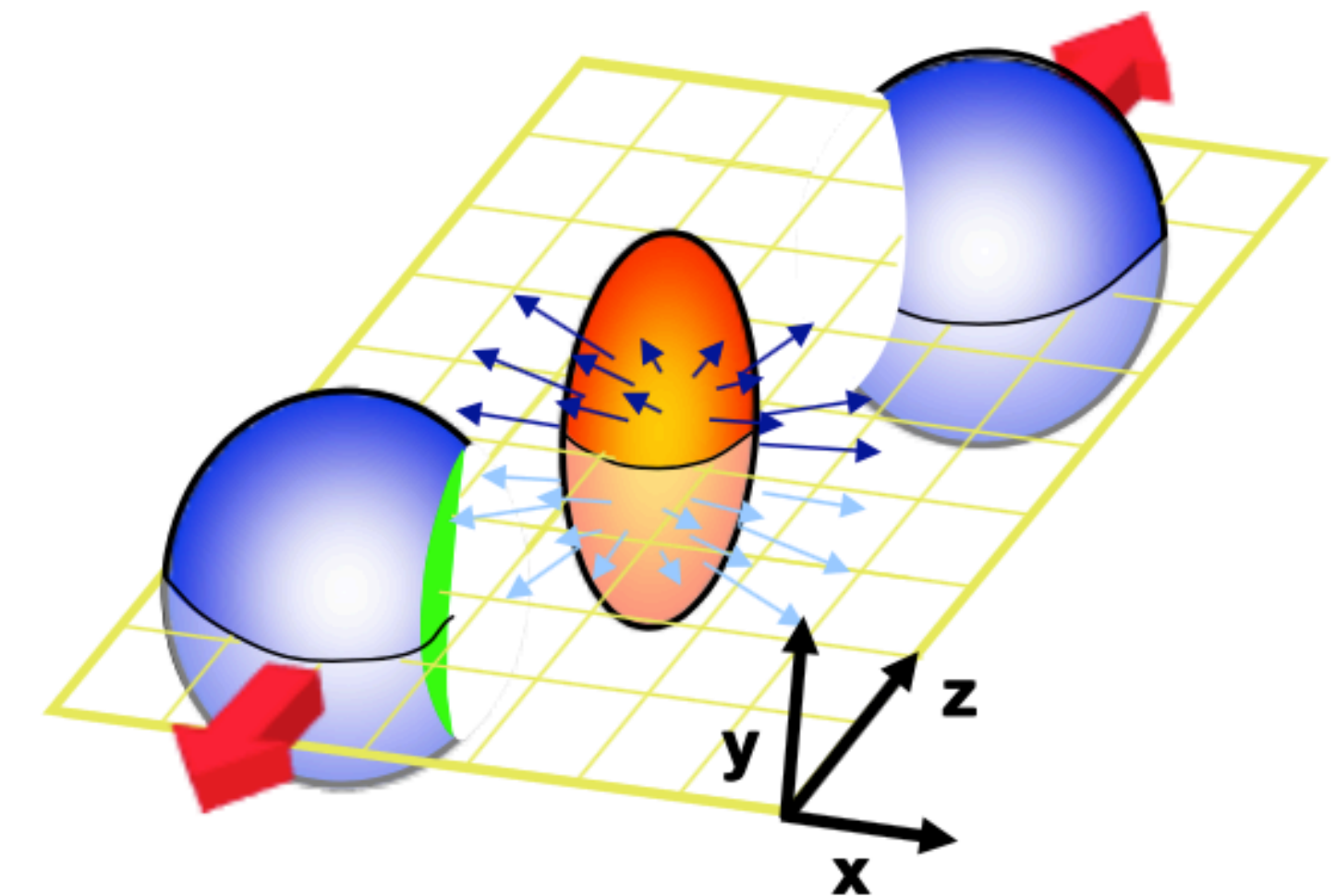
- Try to control overlap region between incoming nuclei (centrality)
- Local or large scale collective behaviour? *“Gas-like” behaviour?*

Superposition of multiple pp collisions



*Uniform distribution of final particles*

Peripheral Collision

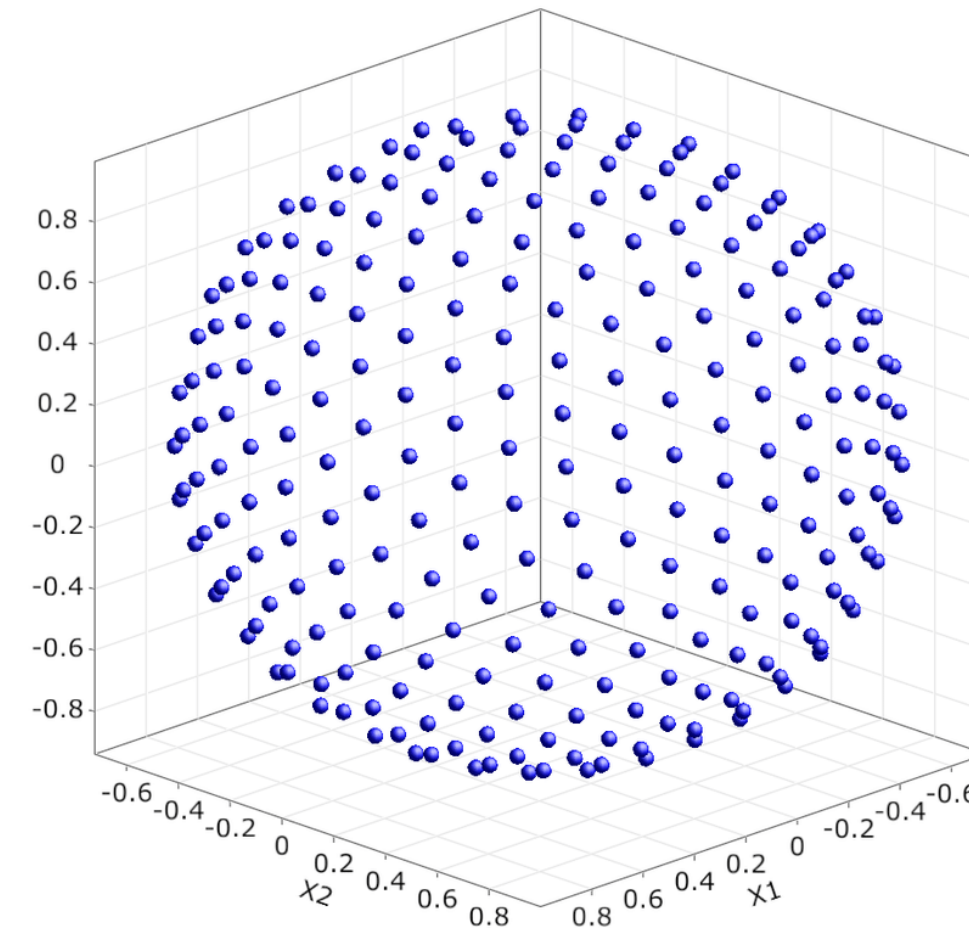
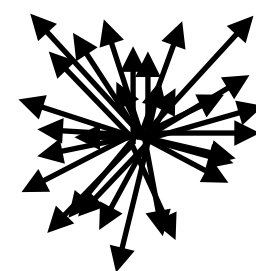
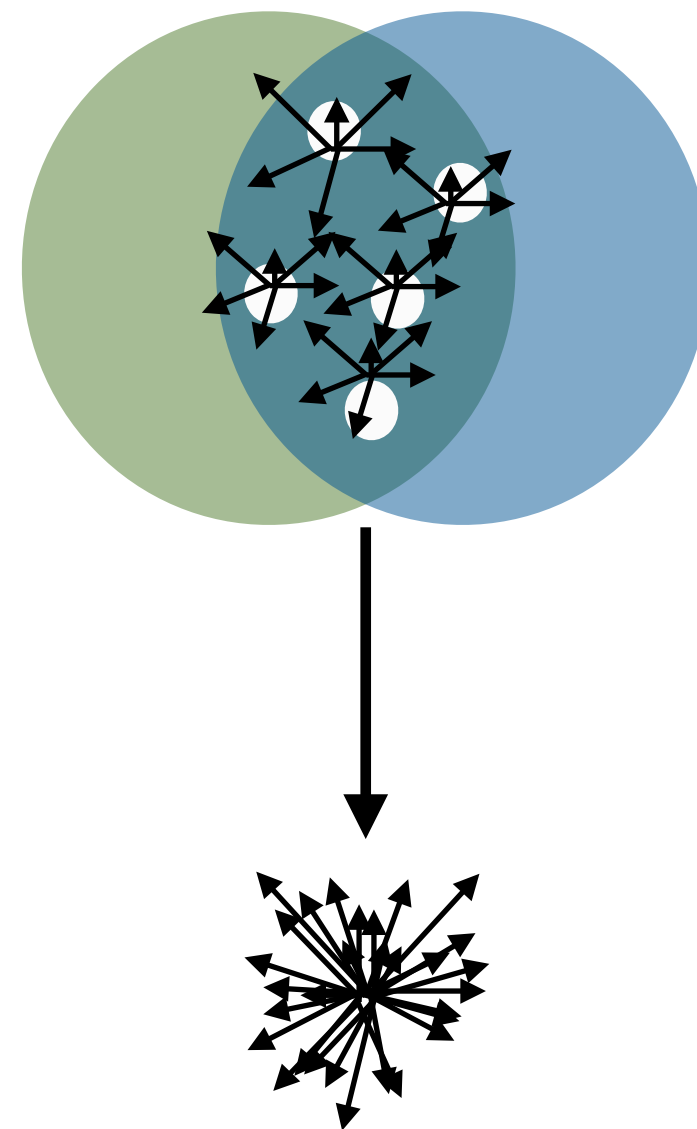




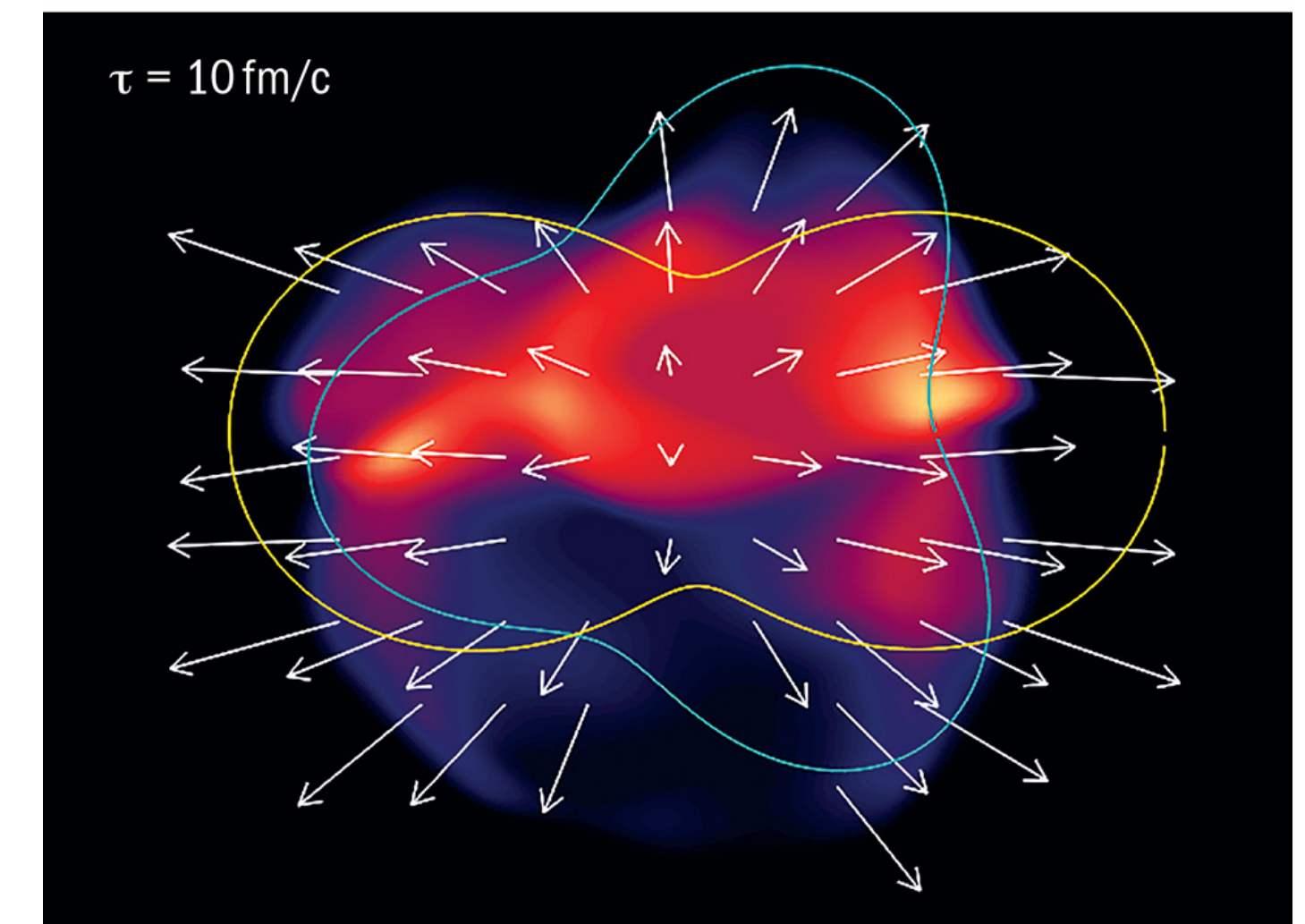
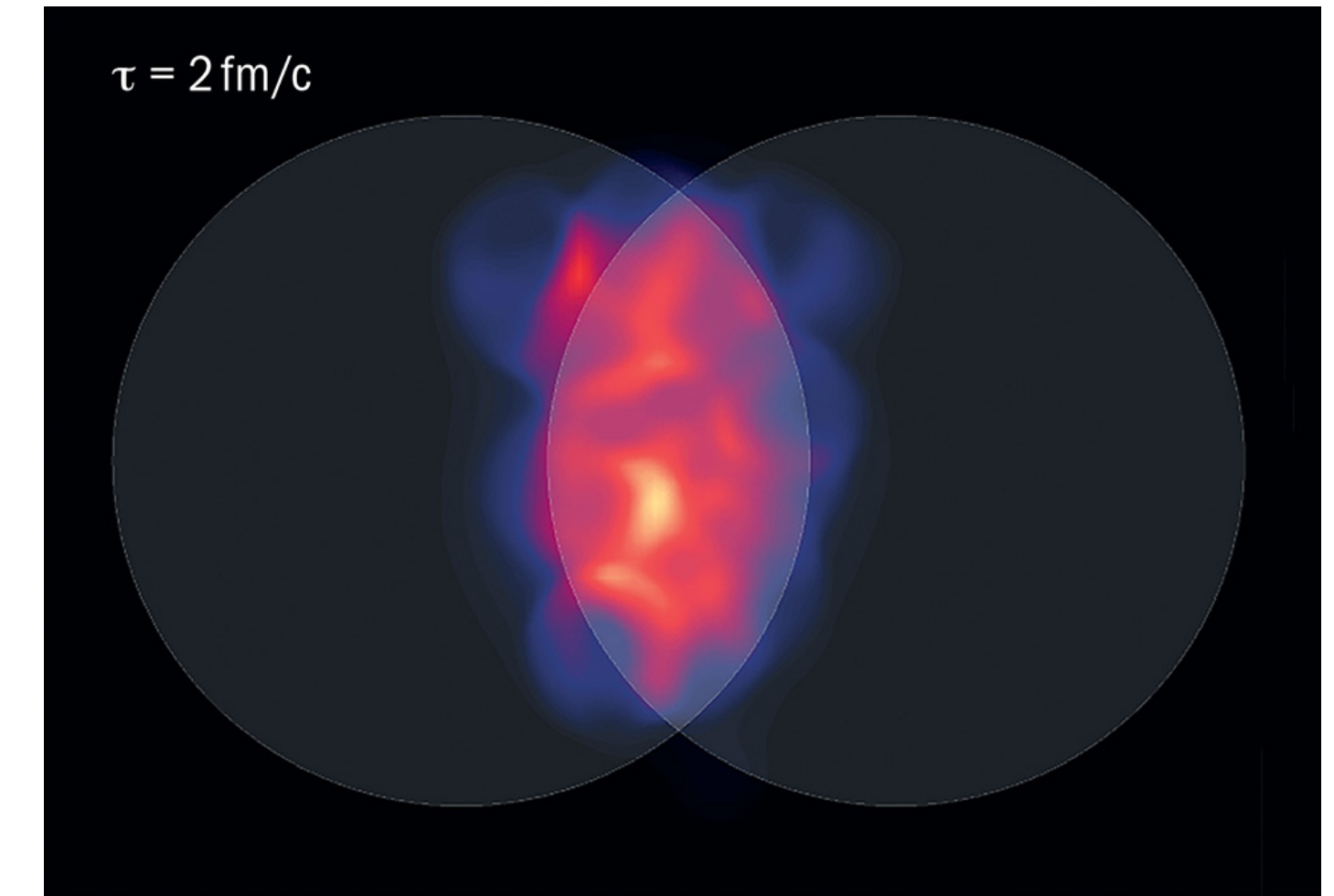
# Centrality of the collision

- Try to control overlap region between incoming nuclei (centrality)
- Local or large scale collective behaviour? *“Gas-like” behaviour?*

Superposition of multiple pp collisions



*Uniform distribution of final particles*  
*??? Not quite...*

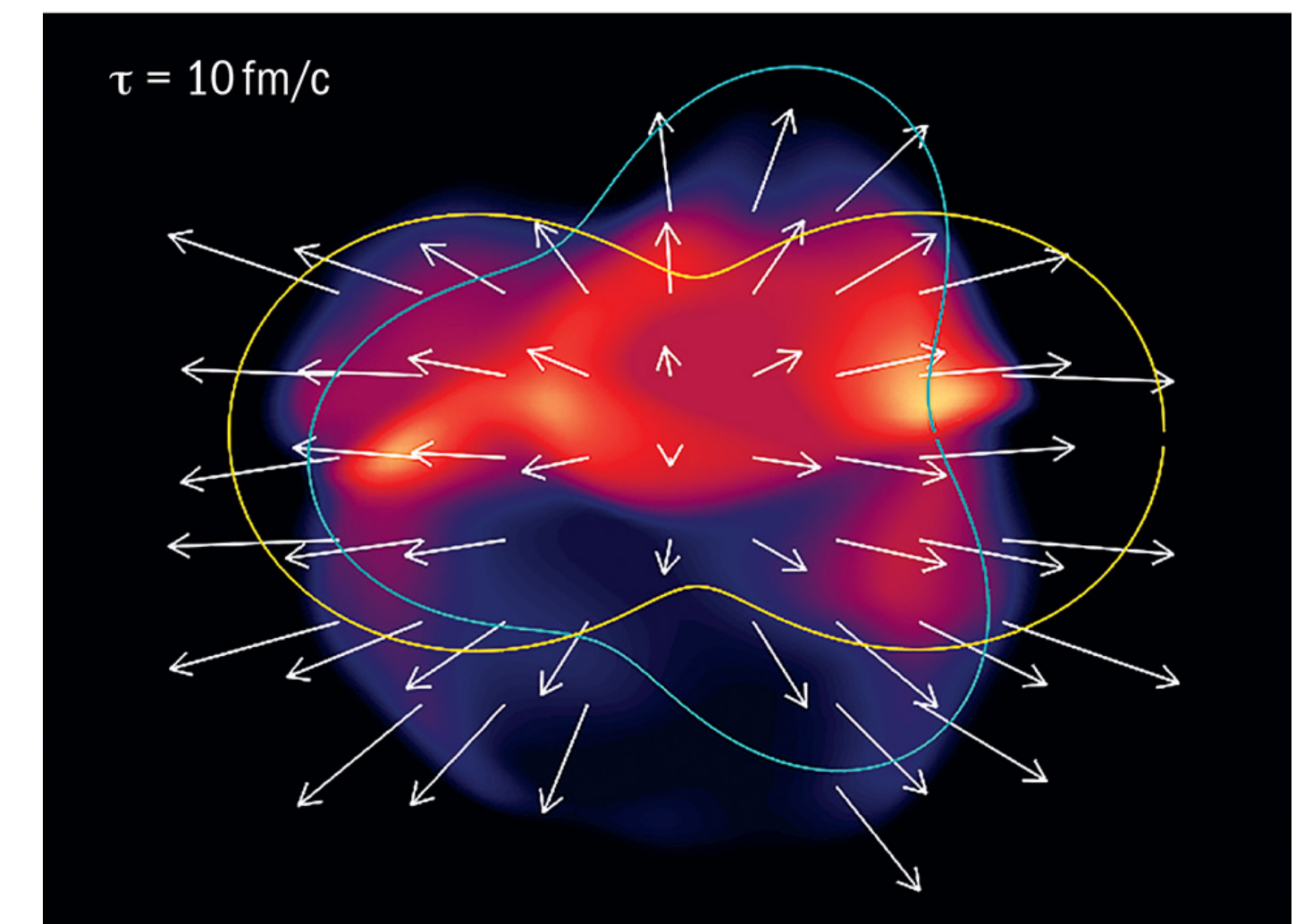
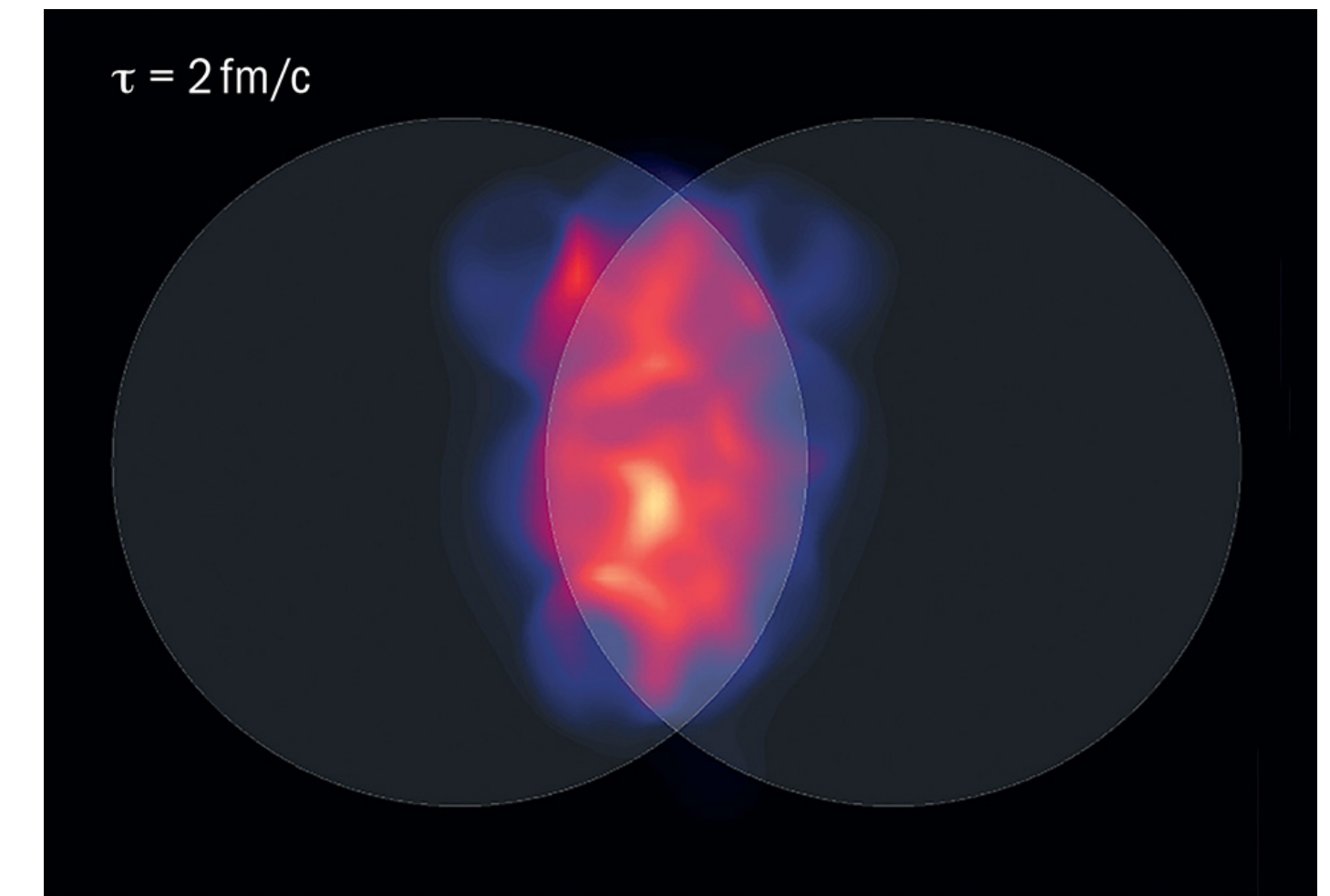
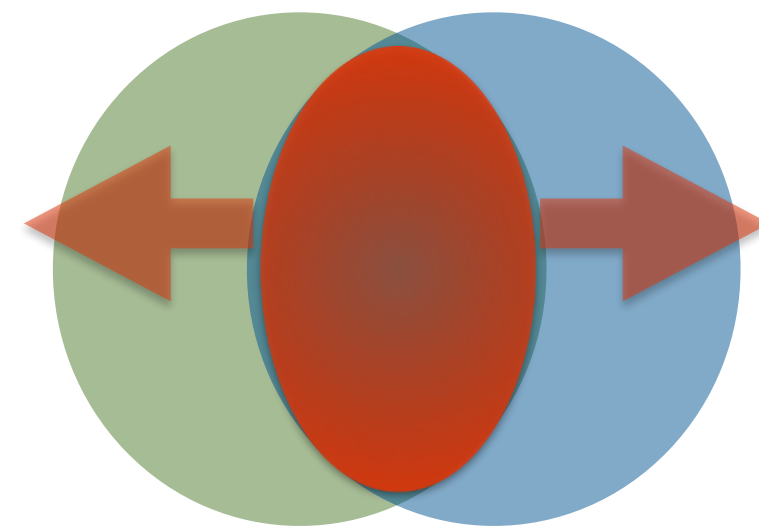




# Centrality of the collision

- Try to control overlap region between incoming nuclei (centrality)
- Local or large scale collective behaviour? *“Fluid-like” behaviour?*

Collective bulk

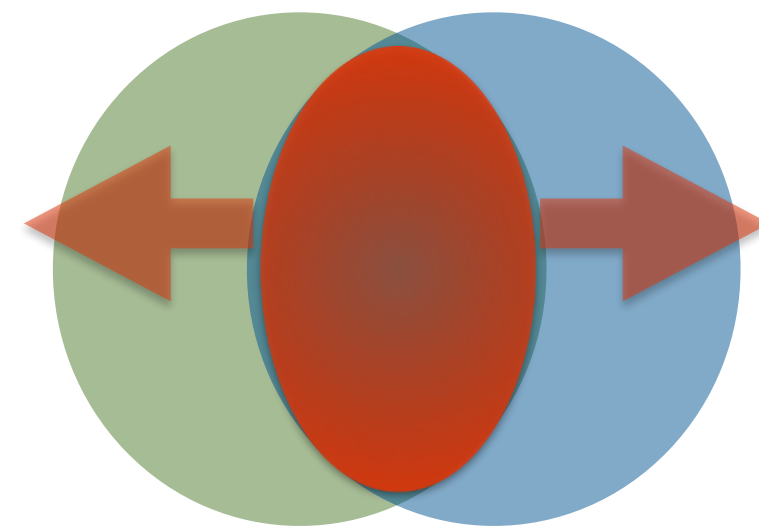




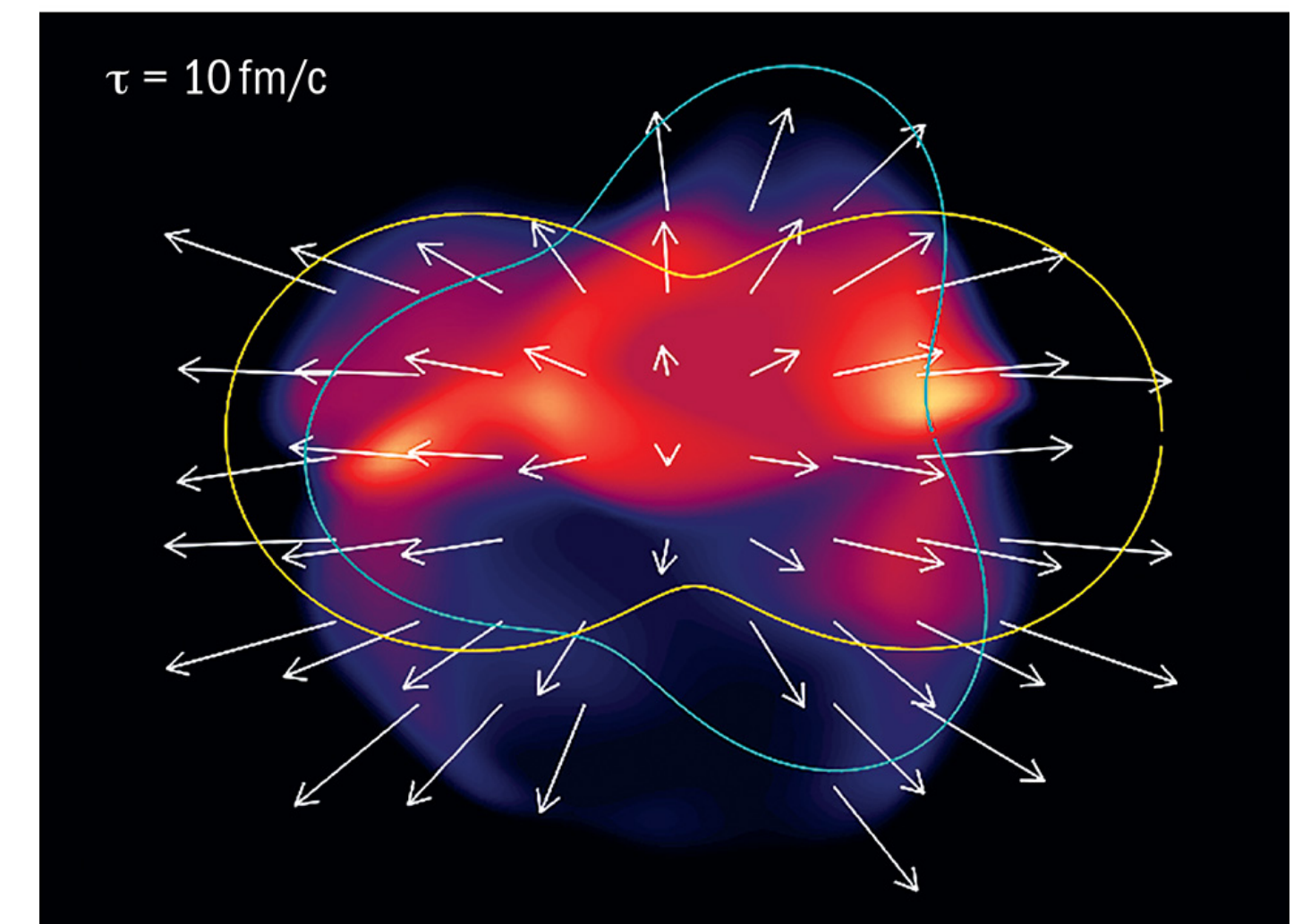
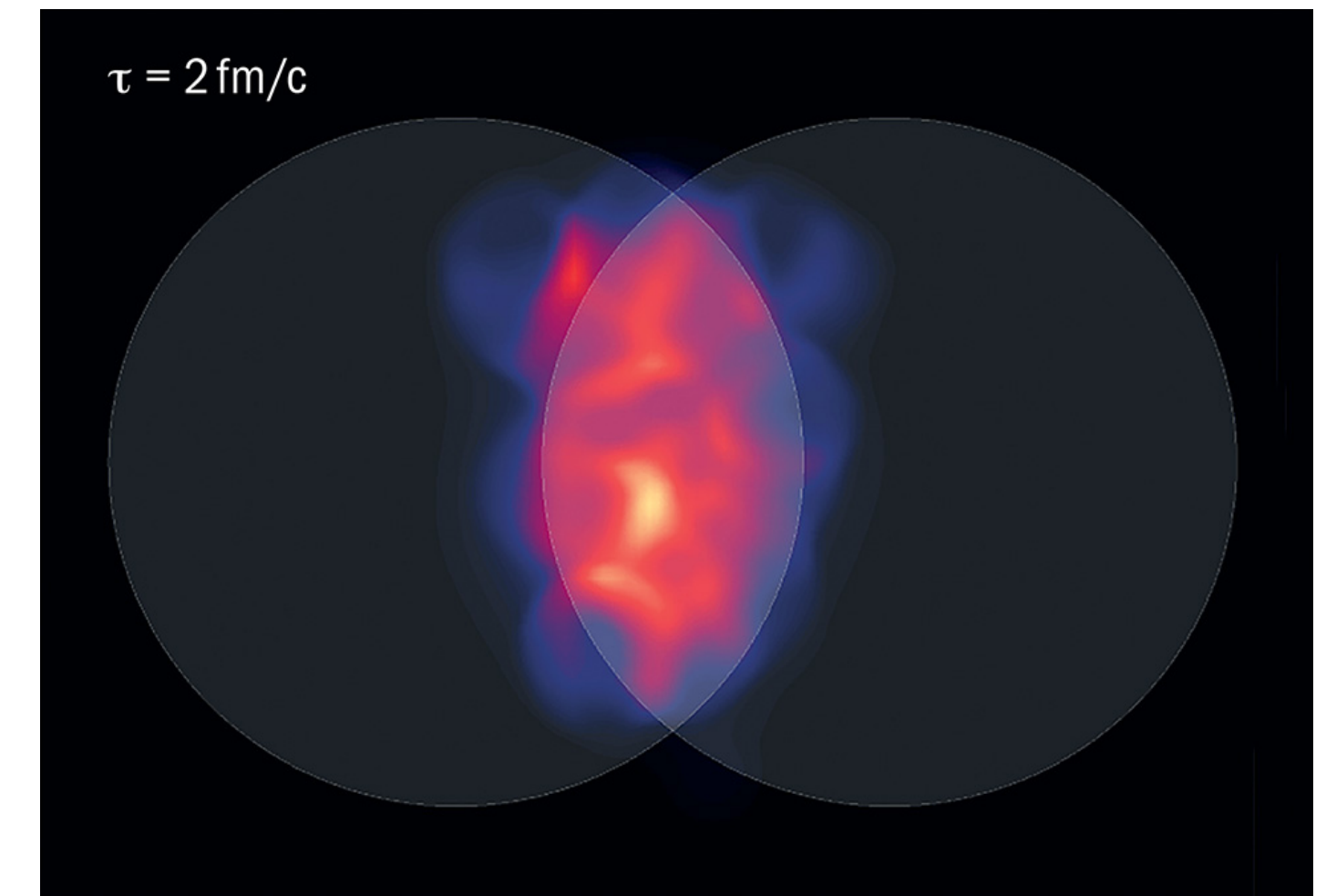
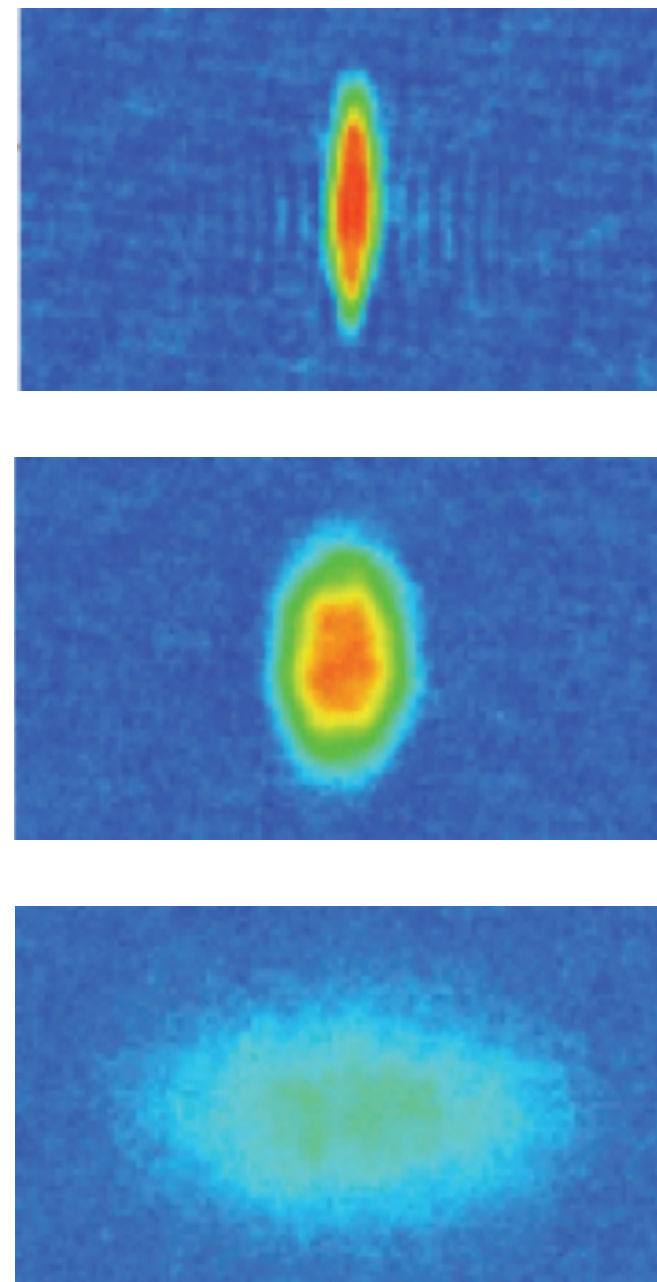
# Centrality of the collision

- Try to control overlap region between incoming nuclei (centrality)
- Local or large scale collective behaviour? *“Fluid-like” behaviour?*

Collective bulk



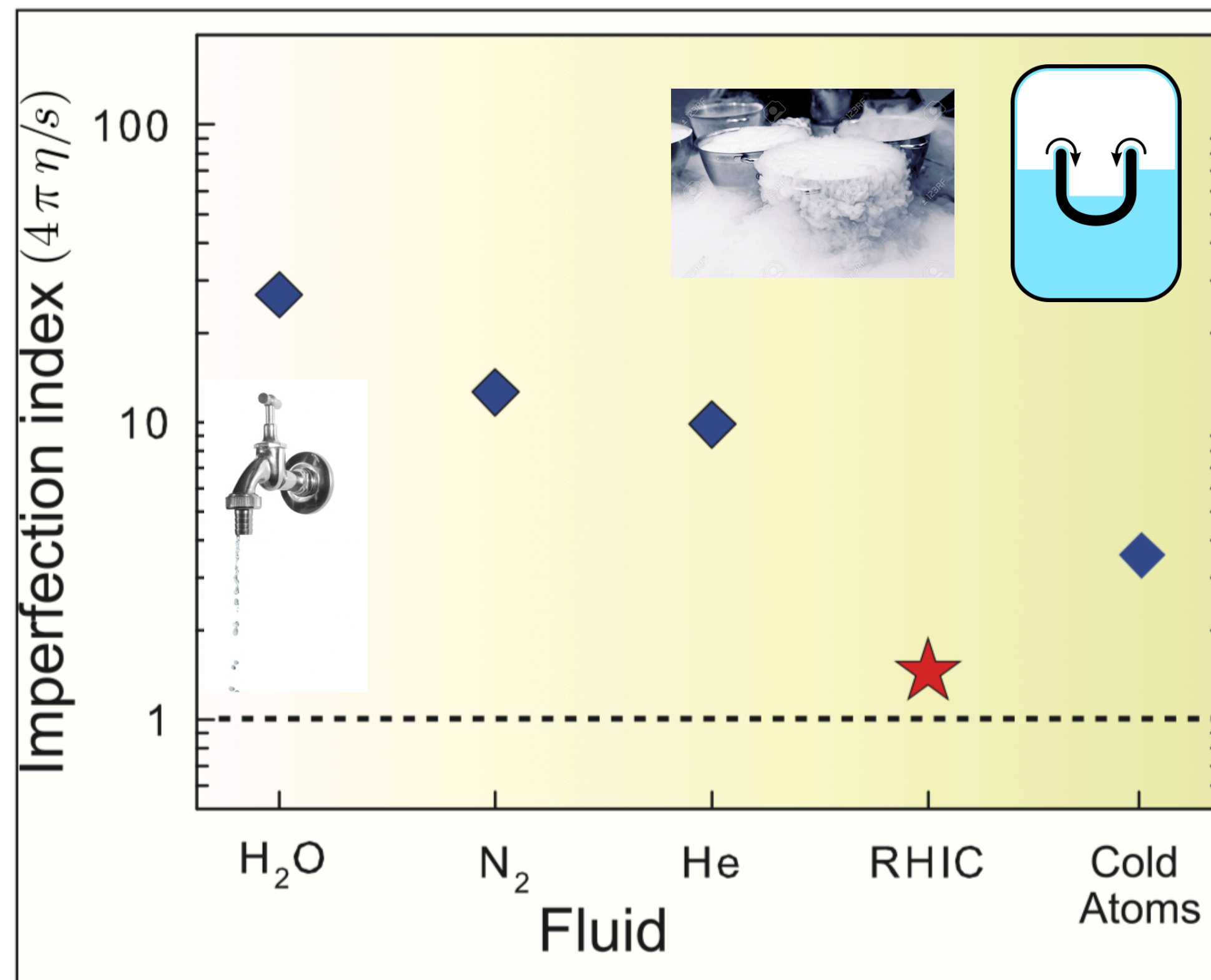
*Initial anisotropies propagate to the final state!*



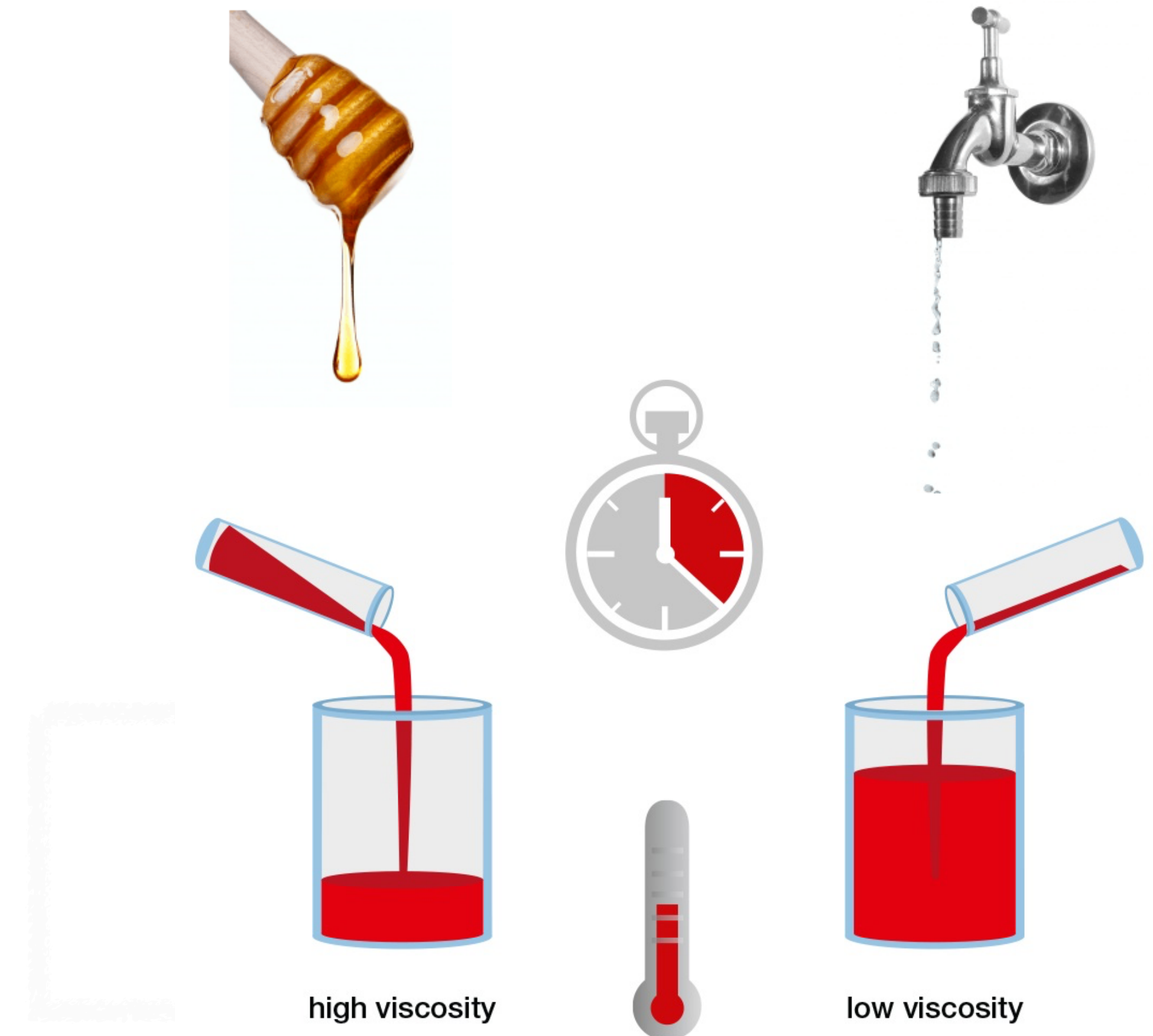


# Soft probes

- QGP is not a hot gas of quarks and gluons... is a fluid! Measuring the imperfection factor (viscosity)....

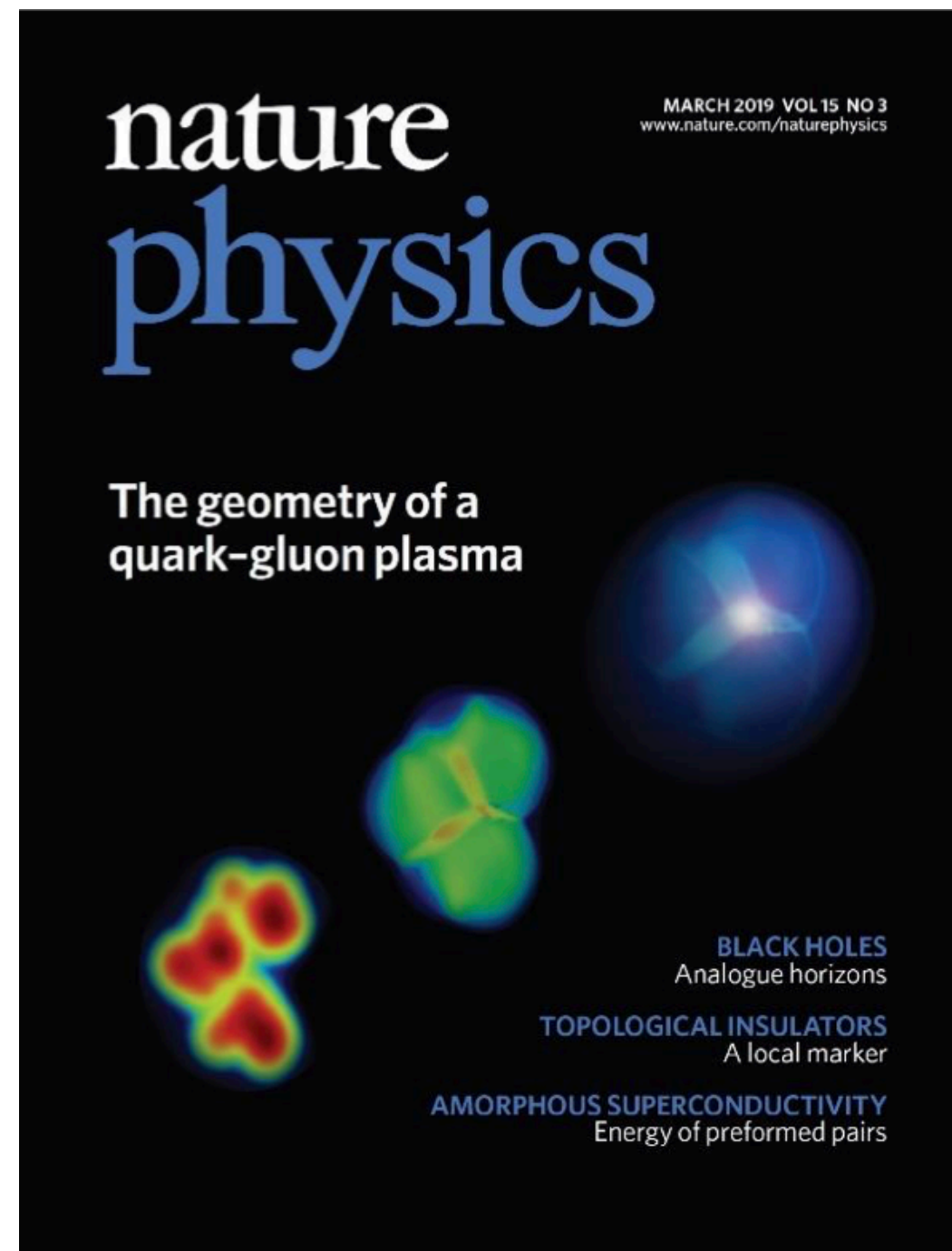


***QGP is the most perfect fluid!***





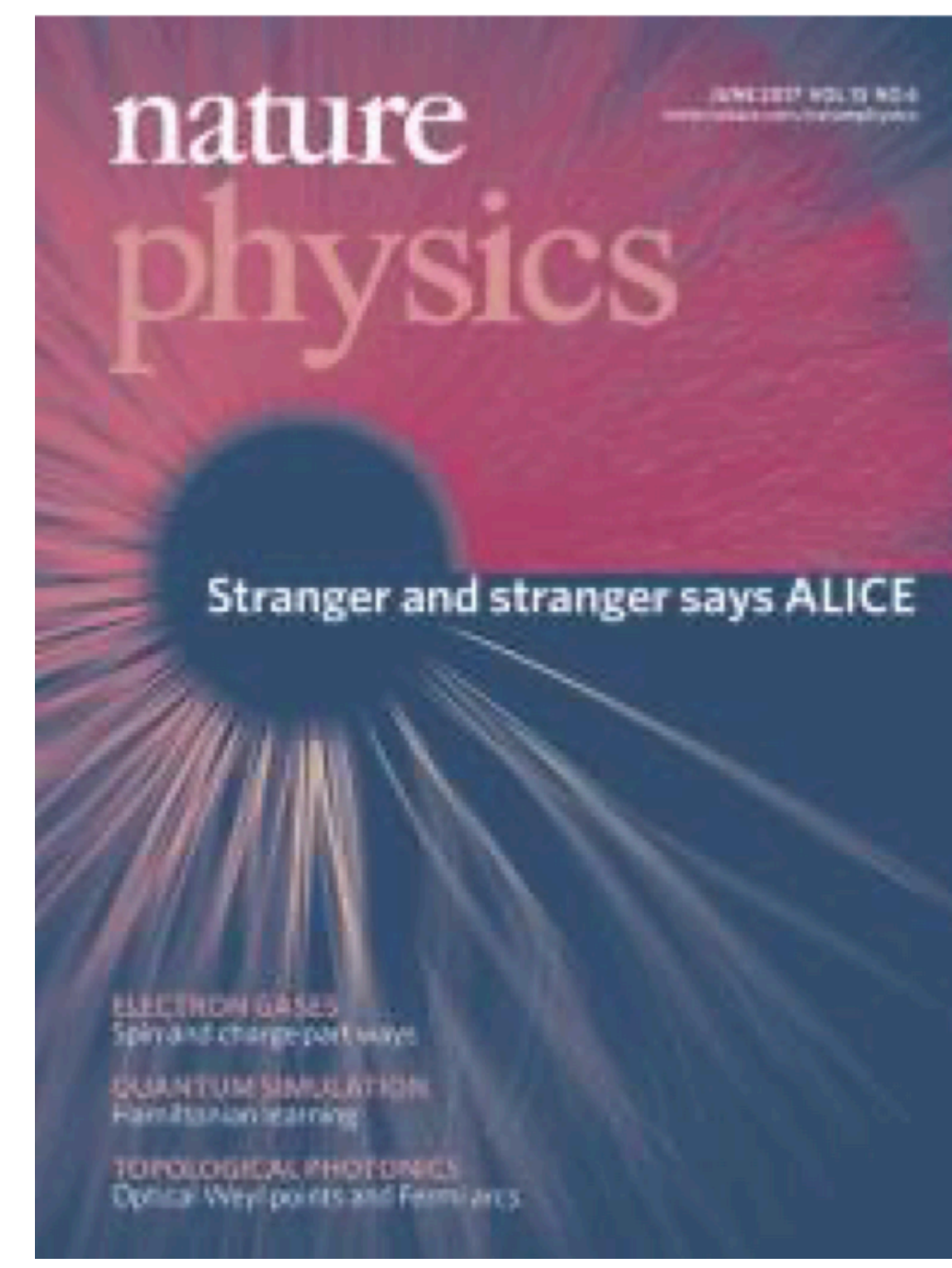
# What do we know so far?



**(Almost) perfect fluid!**



**Temperatures higher than the Sun.**

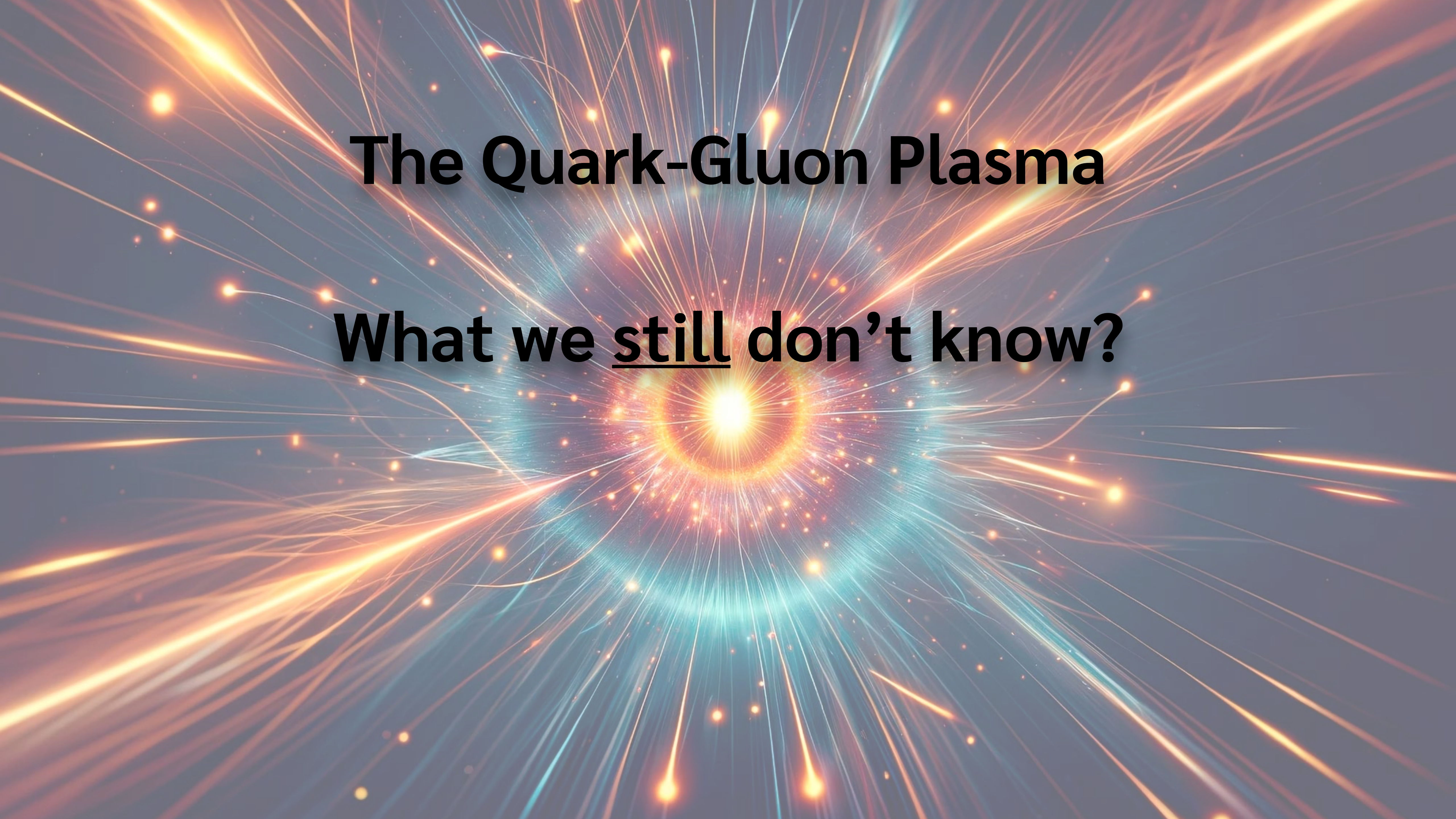


**Fluid with strange particles...**



**Higher vorticity than Jupiter?**





# The Quark-Gluon Plasma

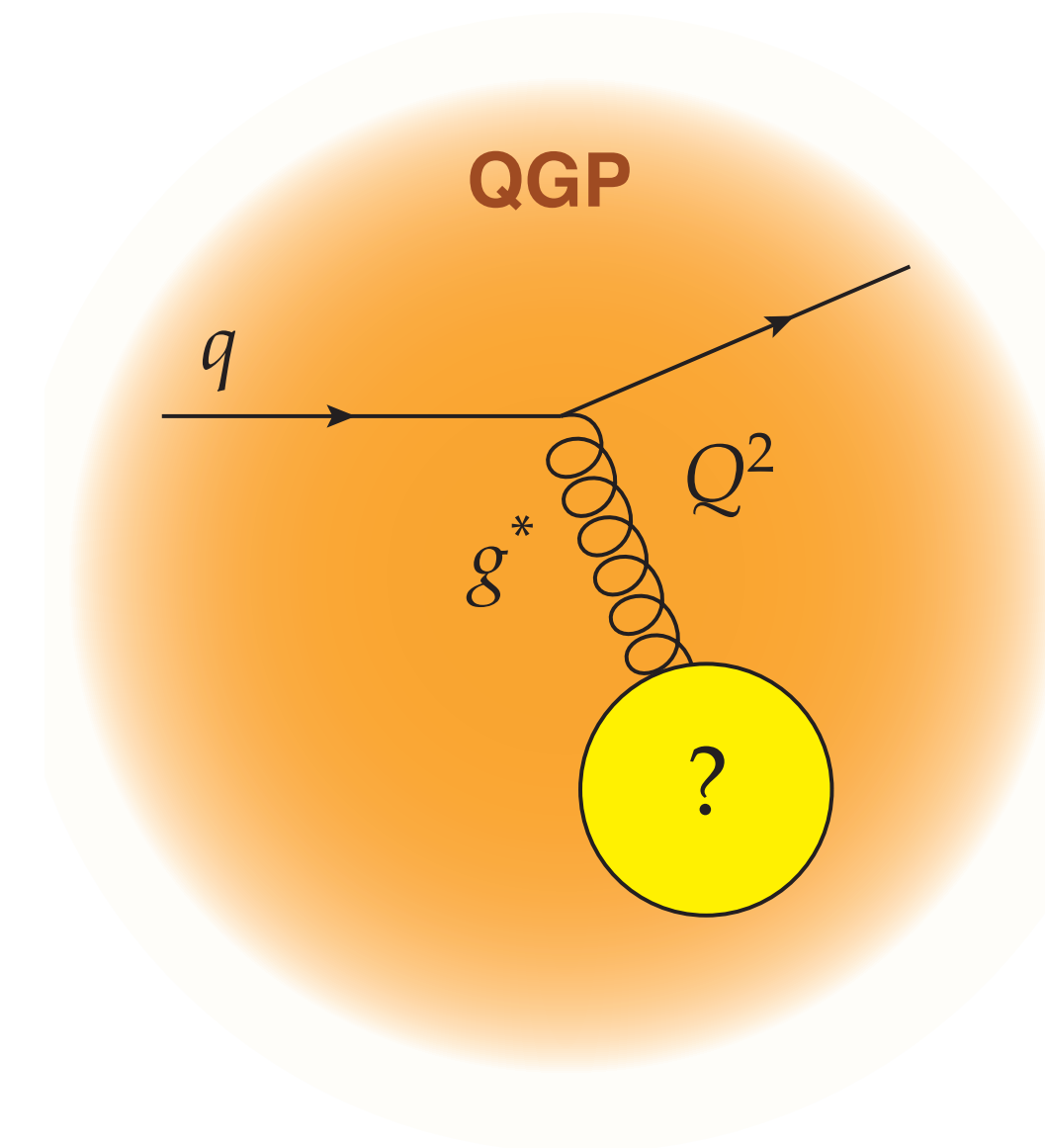
What we still don't know?



# From Collectivity to Fundamental

- We know how to characterise QGP properties and how it behaves.
- How to describe collectivity using QCD building blocks?

|        | I                             | II                             | III                             |                   |
|--------|-------------------------------|--------------------------------|---------------------------------|-------------------|
| mass   | $\approx 2.2 \text{ MeV}/c^2$ | $\approx 1.28 \text{ GeV}/c^2$ | $\approx 173.1 \text{ GeV}/c^2$ | 0                 |
| charge | $\frac{2}{3}$                 | $\frac{2}{3}$                  | $\frac{2}{3}$                   | 0                 |
| spin   | $\frac{1}{2}$                 | $\frac{1}{2}$                  | $\frac{1}{2}$                   | 1                 |
| QUARKS | <b>u</b><br>up                | <b>c</b><br>charm              | <b>t</b><br>top                 | <b>g</b><br>gluon |
|        | $\approx 4.7 \text{ MeV}/c^2$ | $\approx 96 \text{ MeV}/c^2$   | $\approx 4.18 \text{ GeV}/c^2$  |                   |
|        | $-\frac{1}{3}$                | $-\frac{1}{3}$                 | $-\frac{1}{3}$                  |                   |
|        | $\frac{1}{2}$                 | $\frac{1}{2}$                  | $\frac{1}{2}$                   |                   |
|        | <b>d</b><br>down              | <b>s</b><br>strange            | <b>b</b><br>bottom              |                   |





# Hard Probes of the QGP

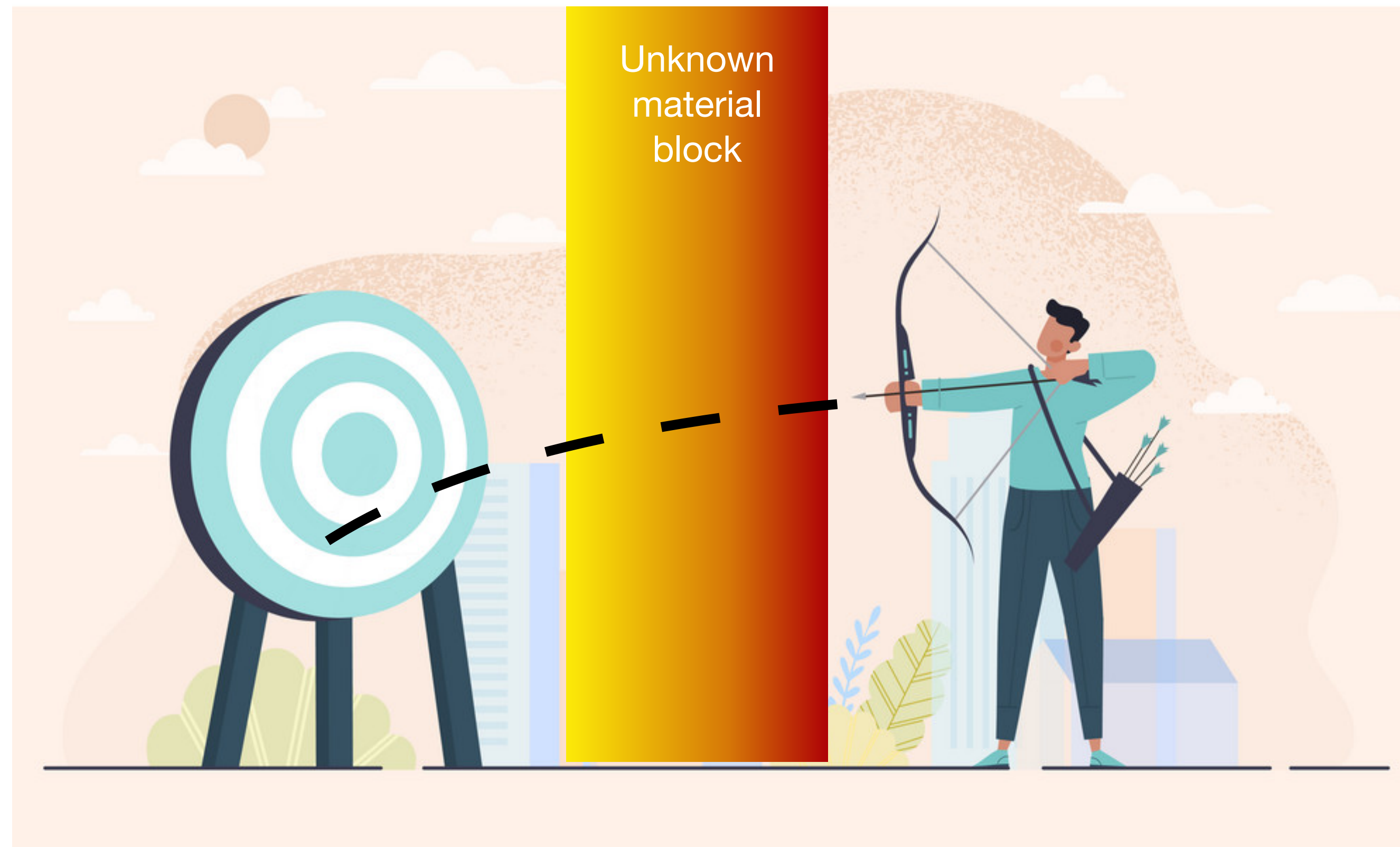
- Use something we know to probe the unknown:





# Hard Probes of the QGP

- Use something we know to probe the unknown:





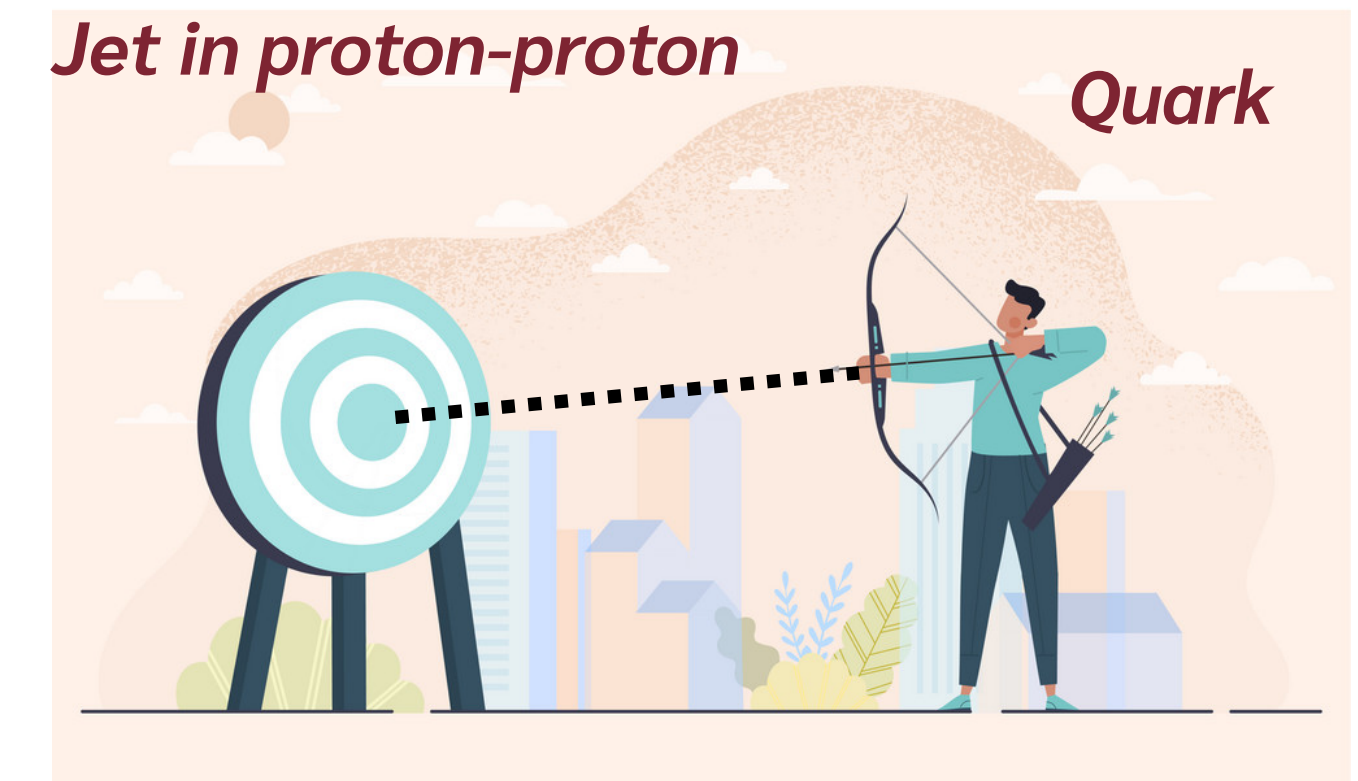
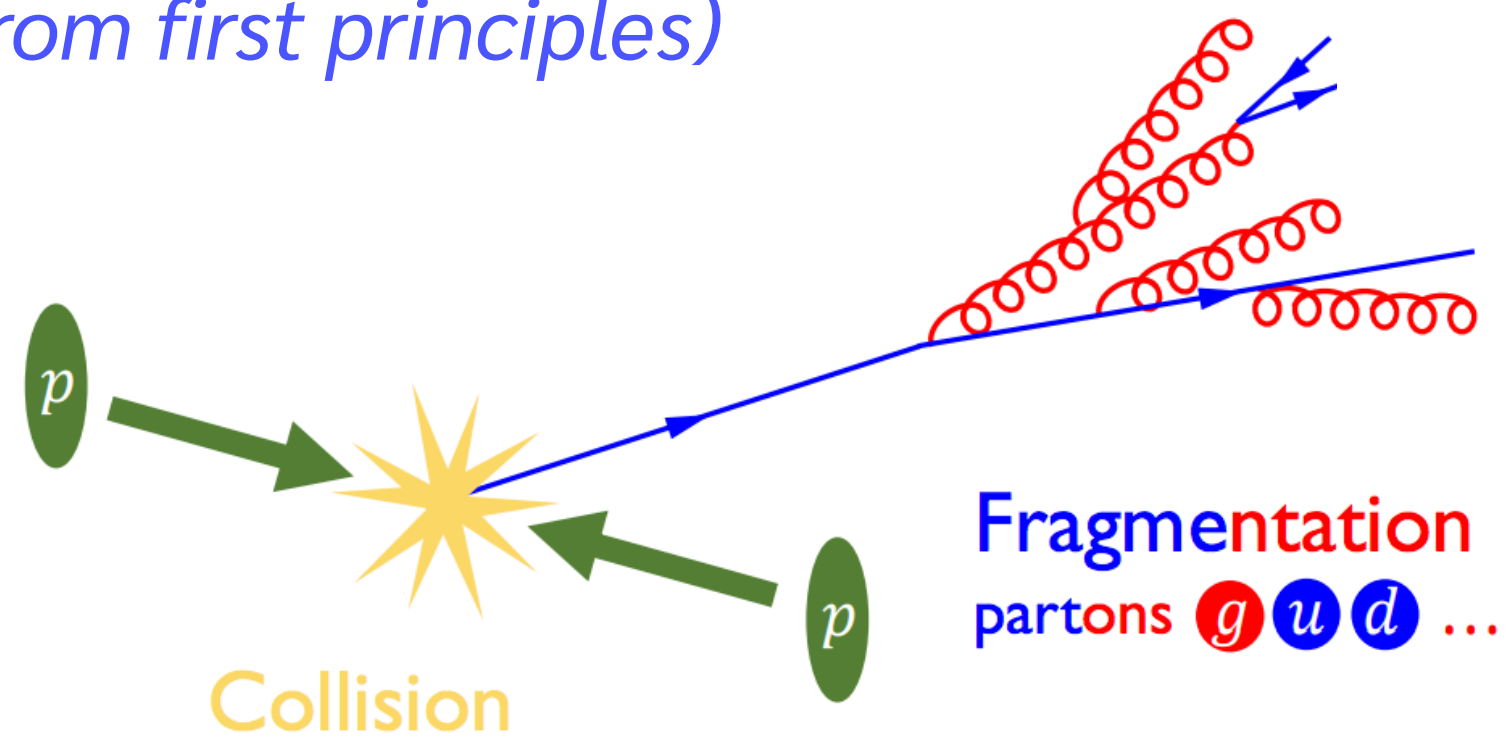
# Jets in Proton-Proton

- How quarks and gluons behave in “vacuum”?

*Small distance (“High-energy”)*

=

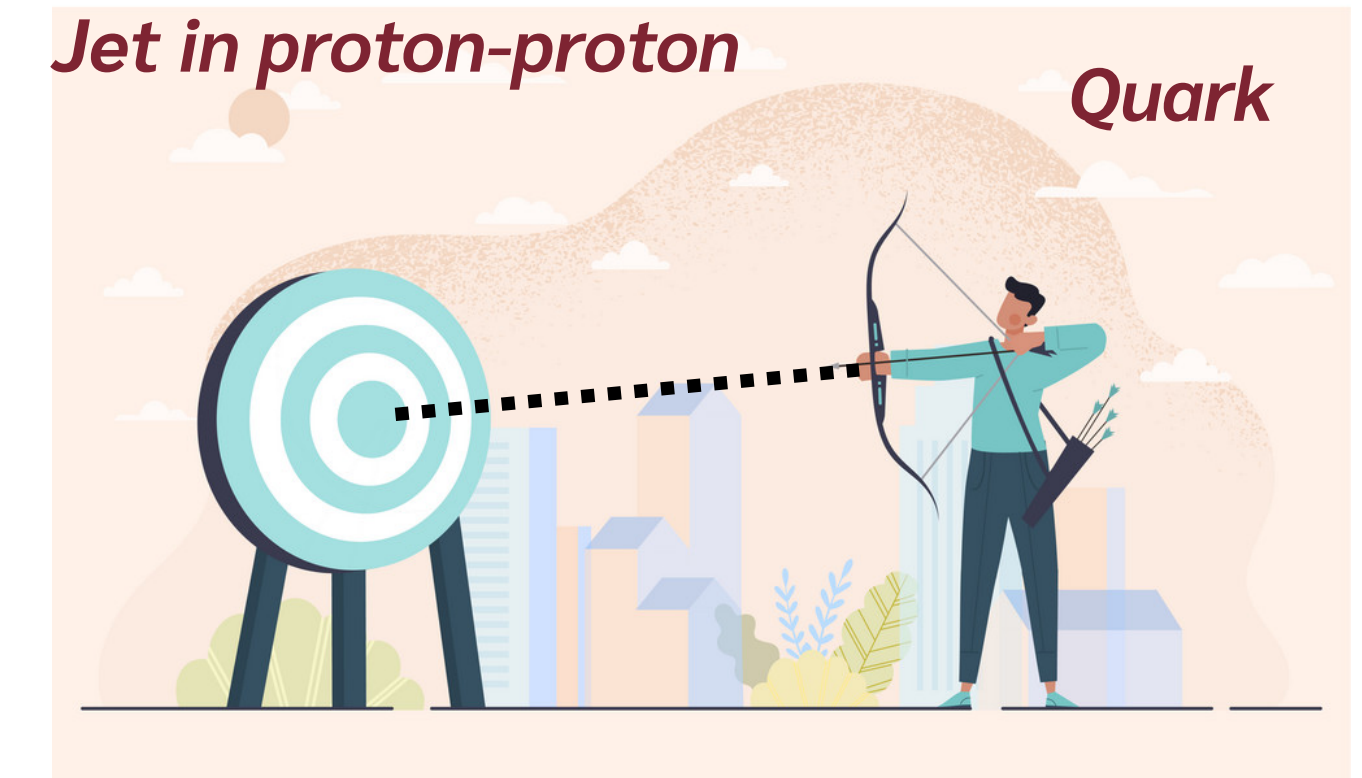
*Can be described analytically  
(From first principles)*





# Jets in Proton-Proton

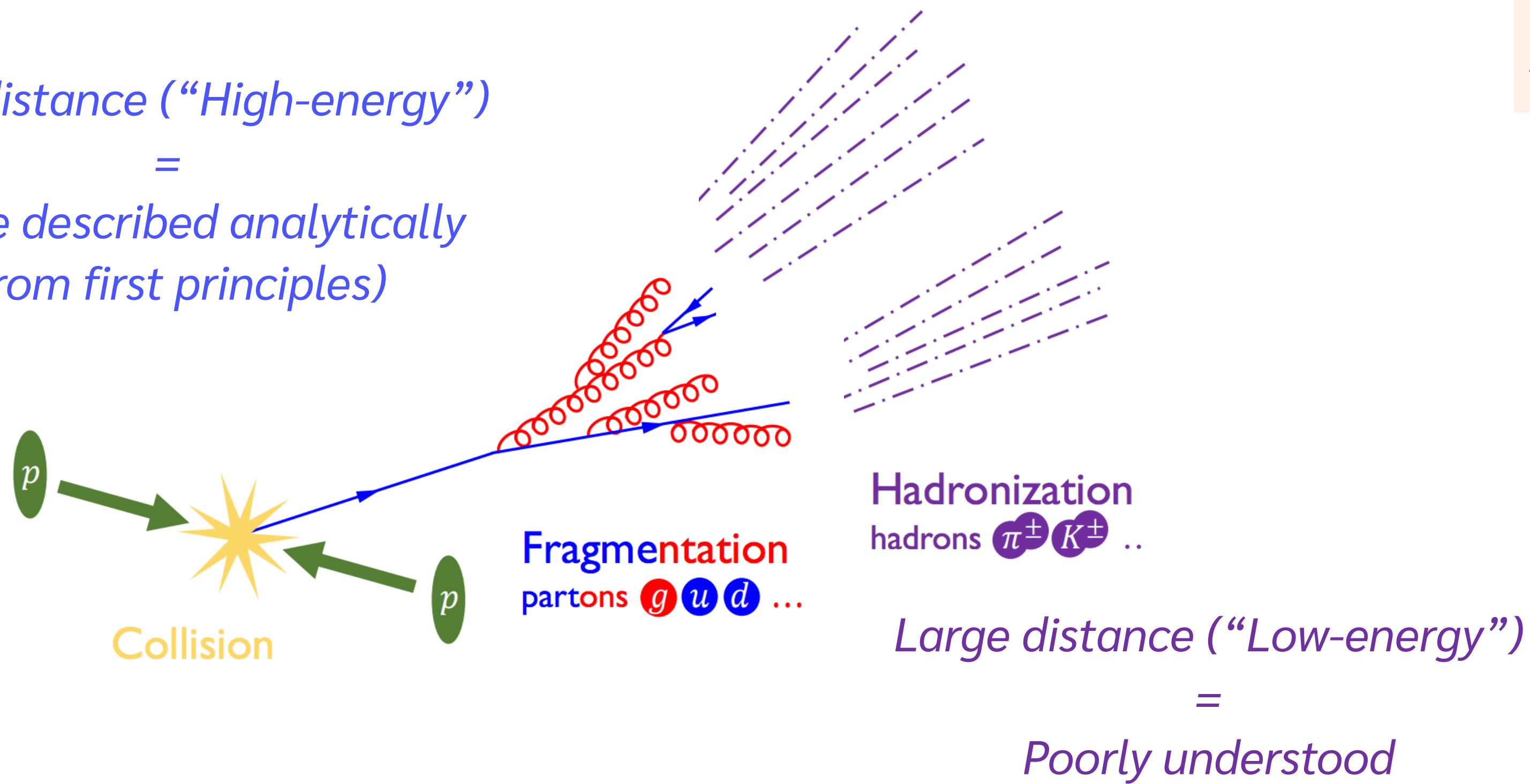
- How quarks and gluons behave in “vacuum”?



Small distance (“High-energy”)

=

Can be described analytically  
(From first principles)





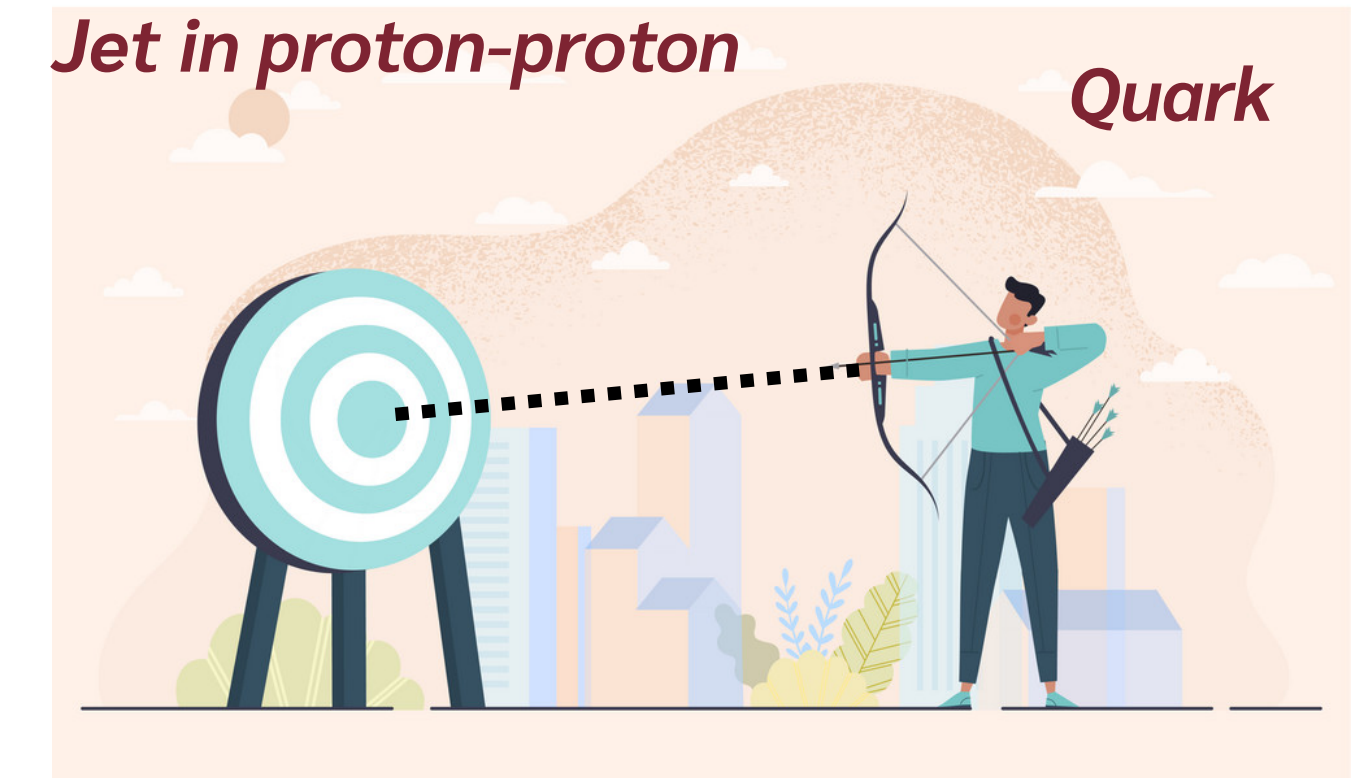
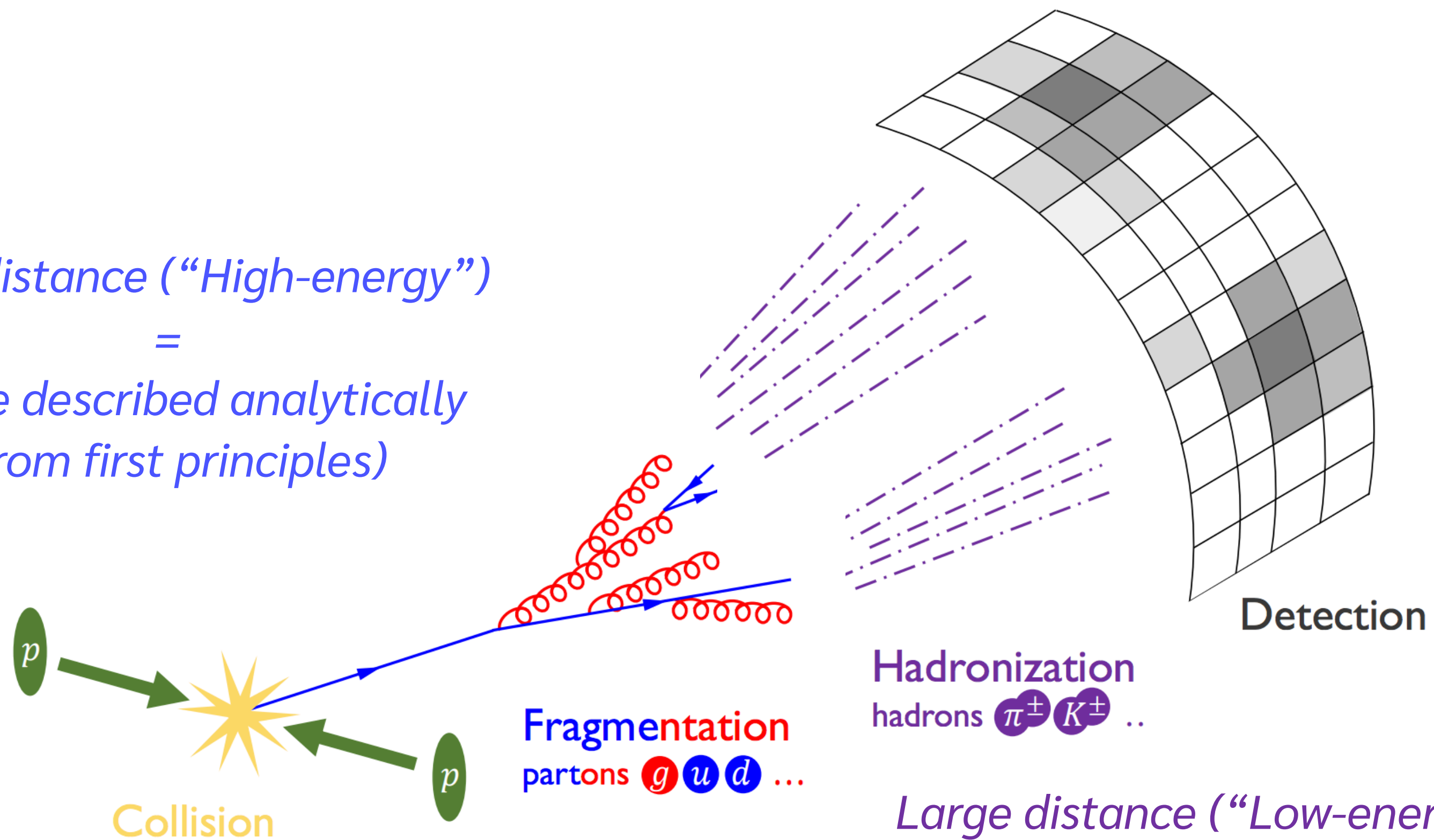
# Jets in Proton-Proton

- How quarks and gluons behave in “vacuum”?

Small distance (“High-energy”)

=

Can be described analytically  
(From first principles)





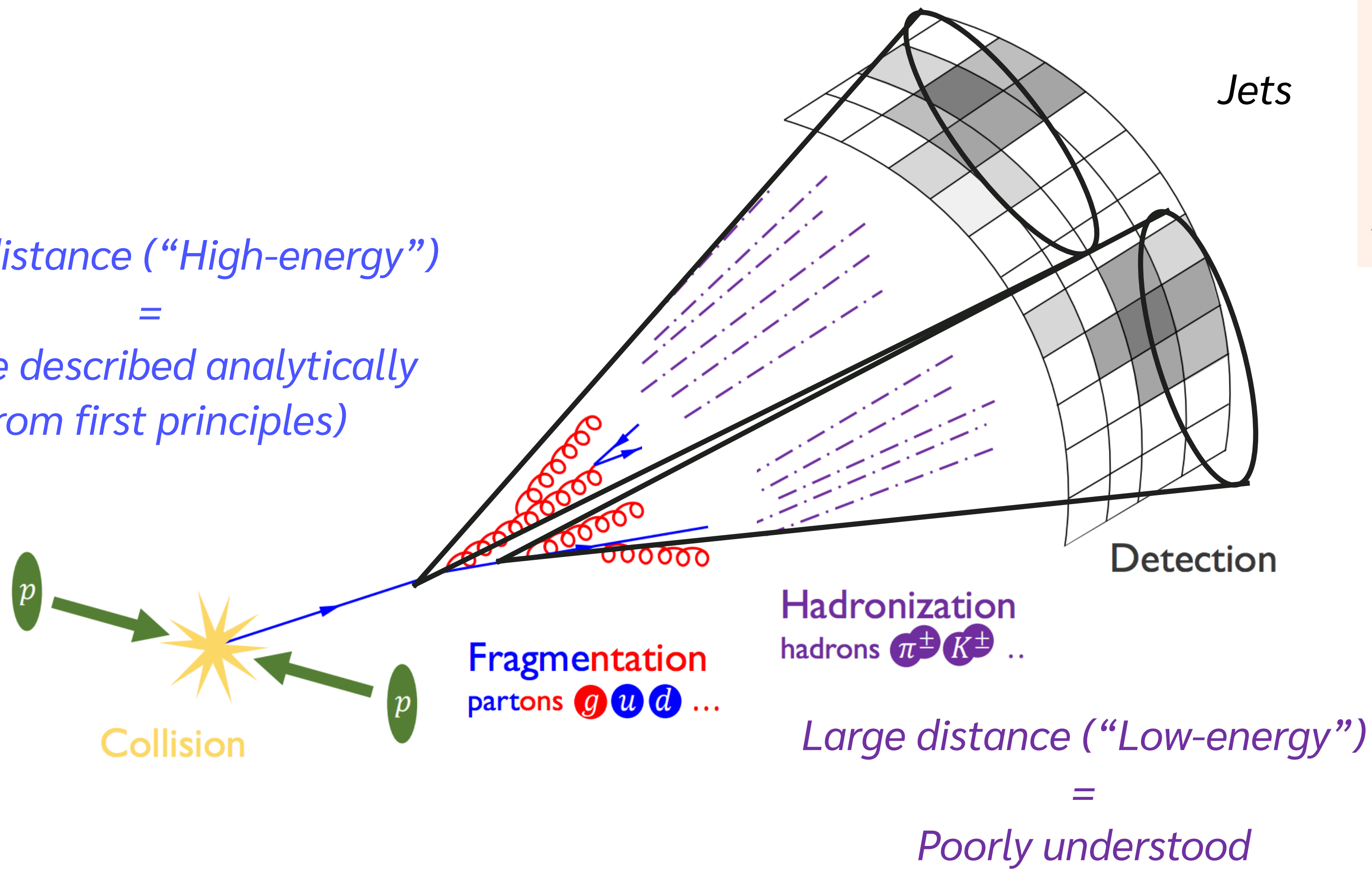
# Jets in Proton-Proton

- How quarks and gluons behave in “vacuum”?

Small distance (“High-energy”)

=

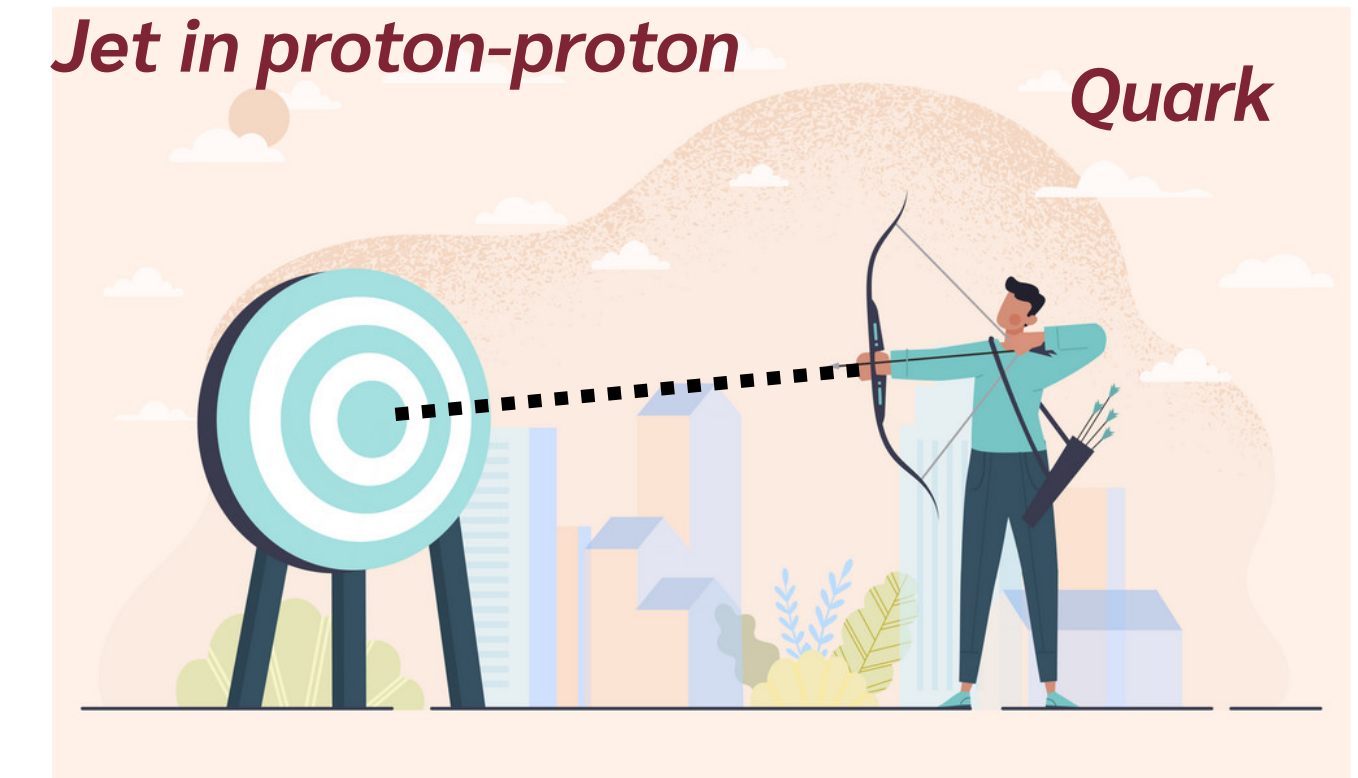
Can be described analytically  
(From first principles)



Large distance (“Low-energy”)

=

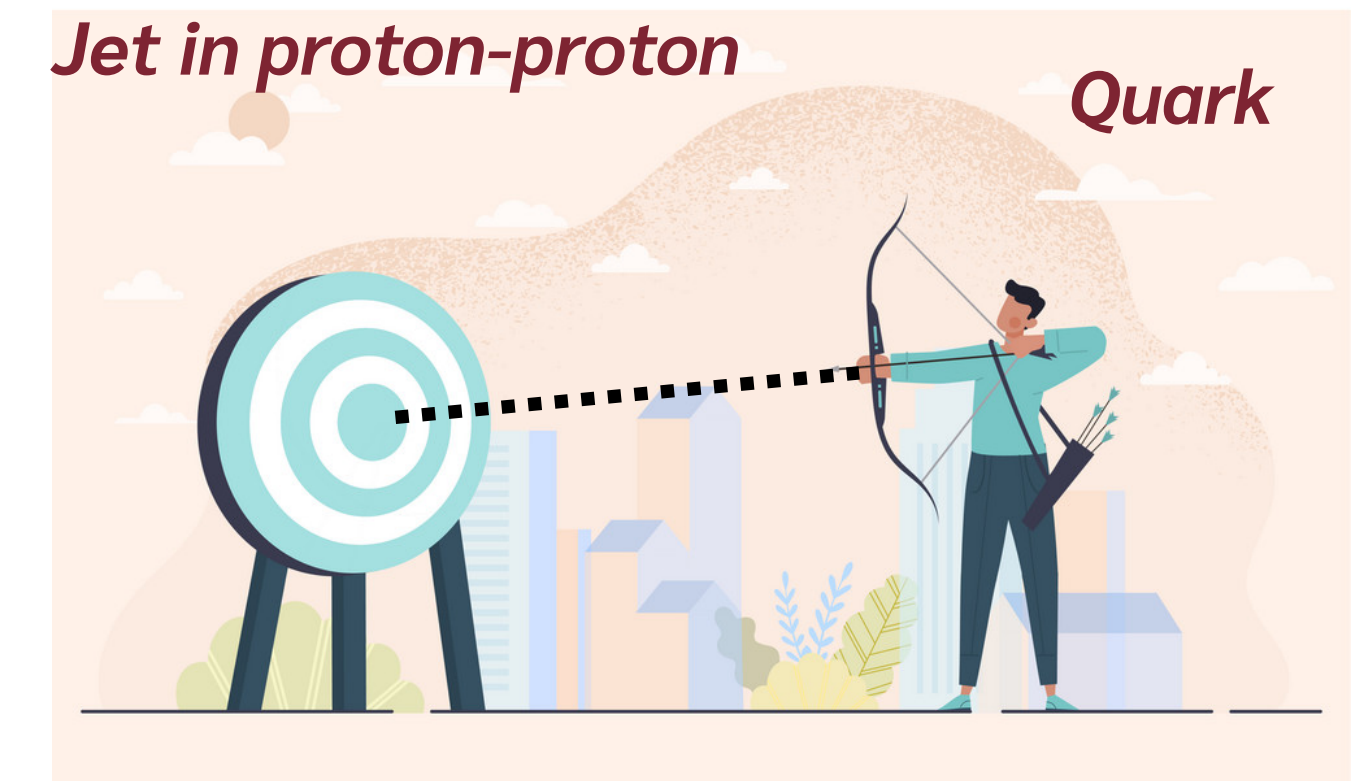
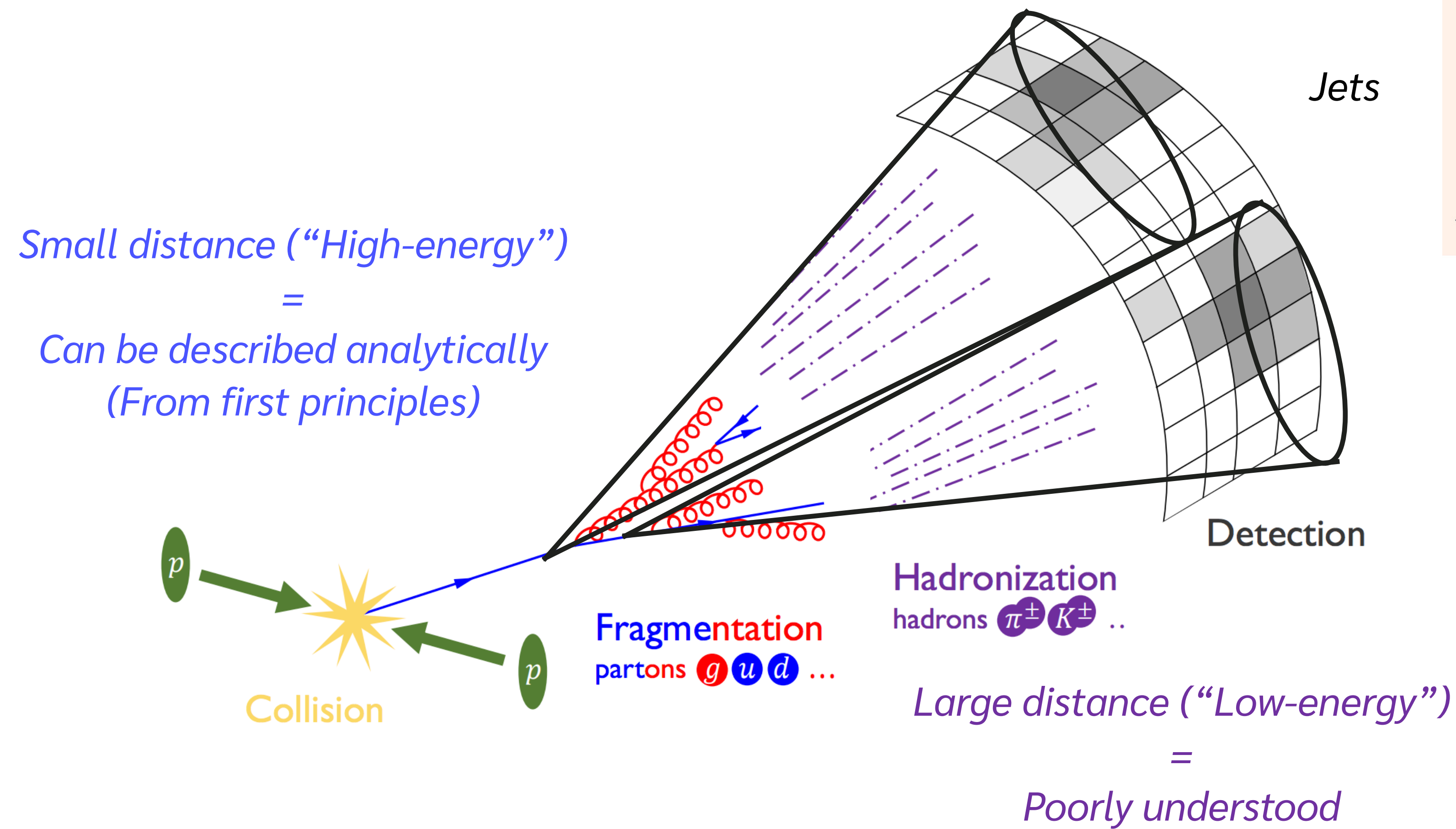
Poorly understood





# Jets in Proton-Proton

- How quarks and gluons behave in “vacuum”?

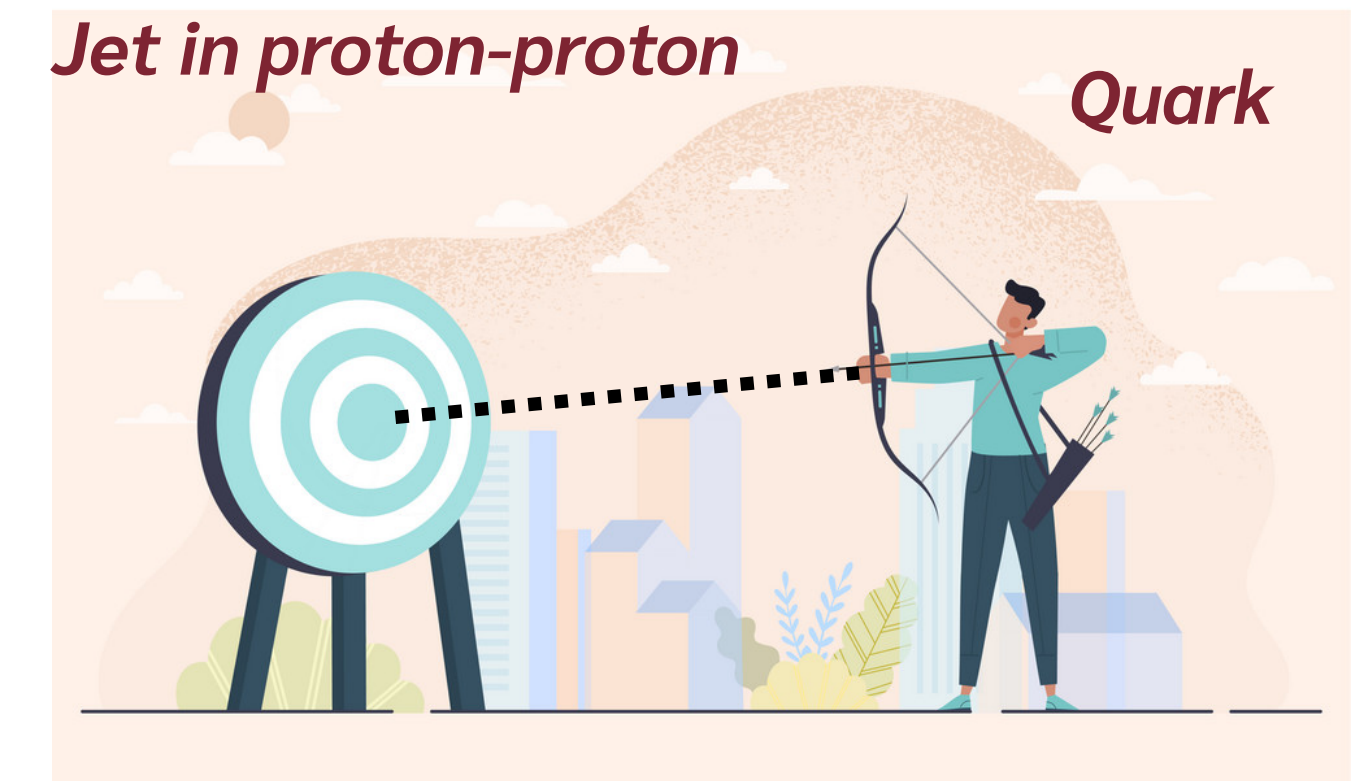
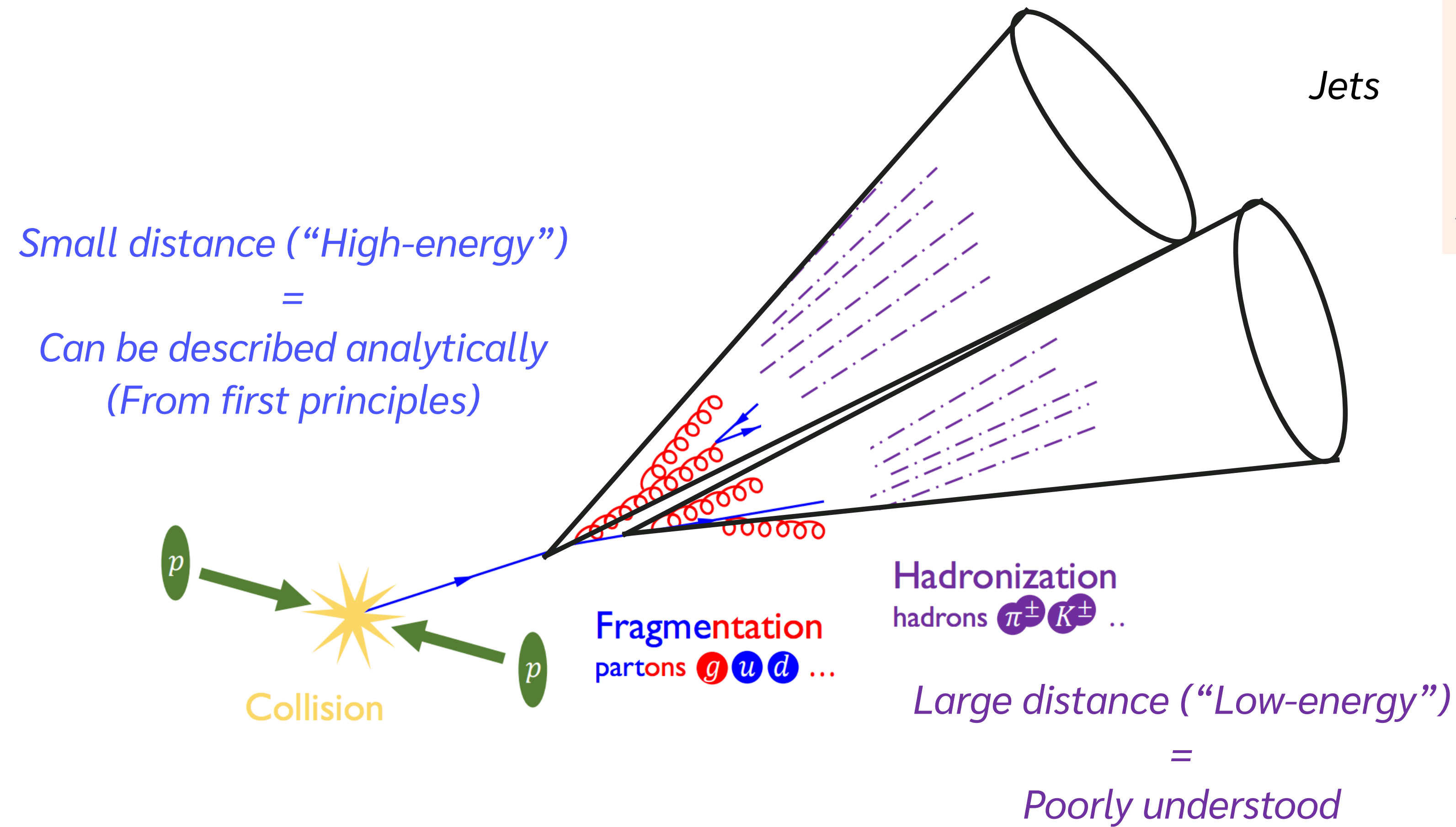


QCD jets defined based on  
a set of rules: a **jet**  
clustering algorithm



# Jets in Proton-Proton

- How quarks and gluons behave in “vacuum”?



QCD jets defined based on  
a set of rules: a **jet**  
clustering algorithm

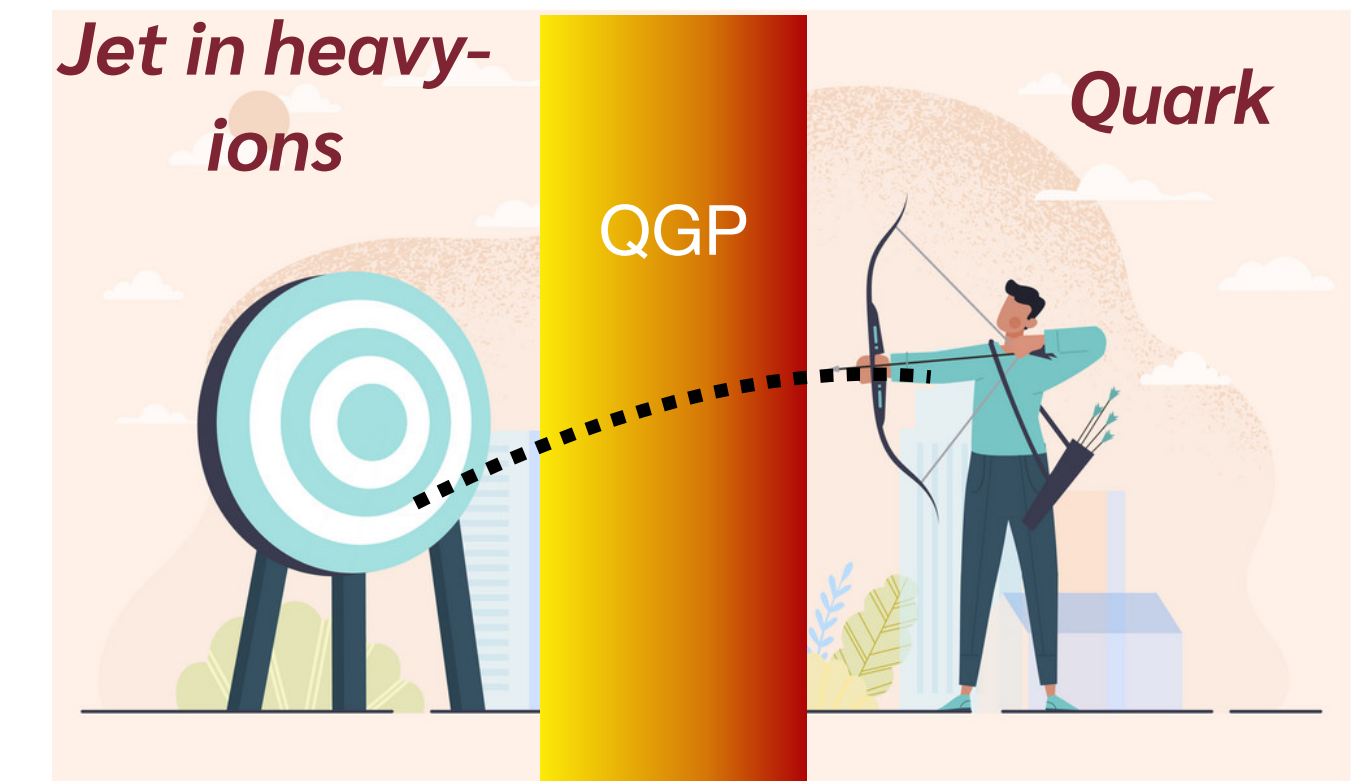
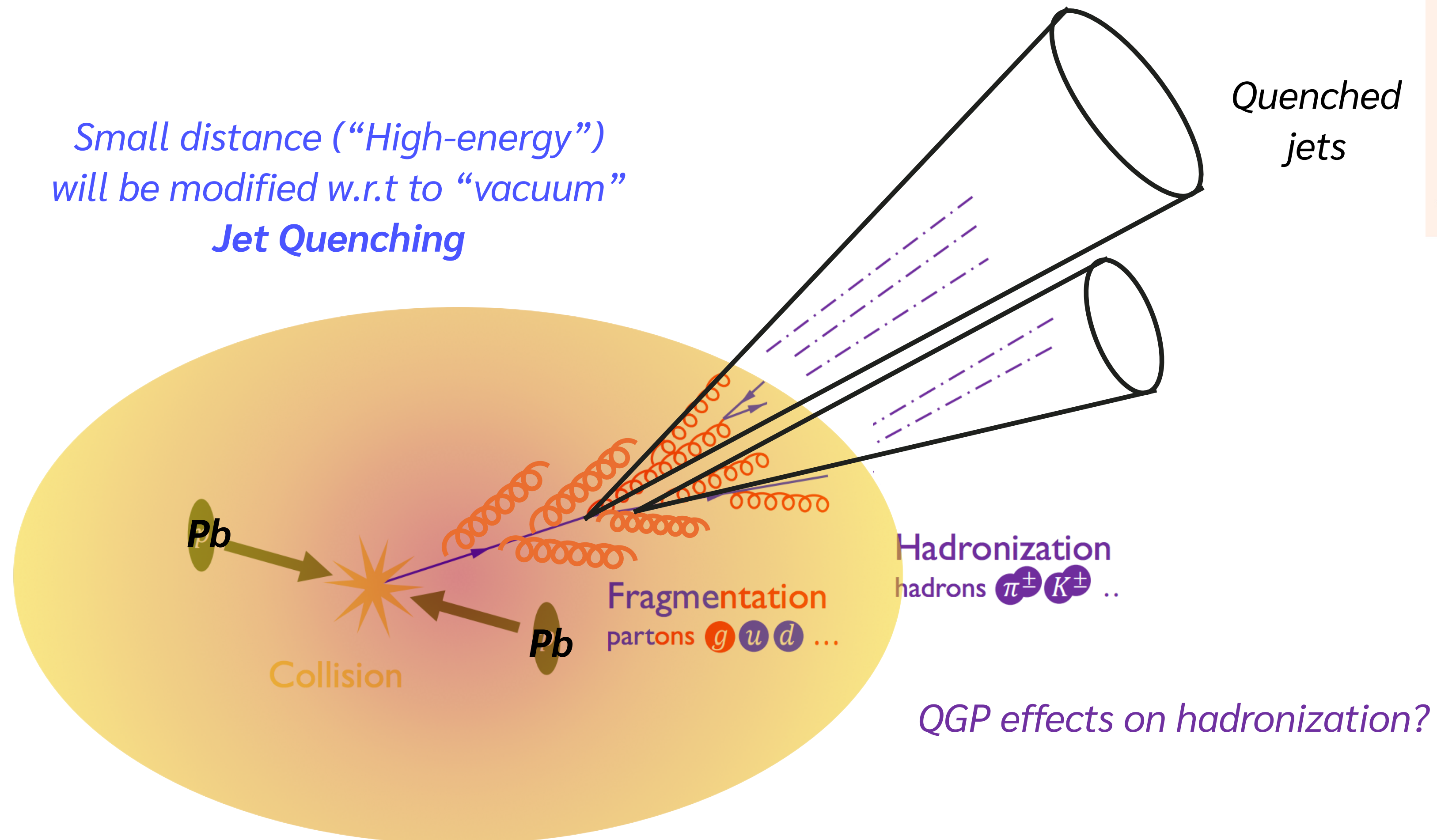
They are the closest  
**proxy** to the original  
**quark/gluon**



# Jets in Heavy-Ions

- How quarks and gluons behave in the presence of a QCD medium?

*Small distance (“High-energy”)  
will be modified w.r.t to “vacuum”  
Jet Quenching*

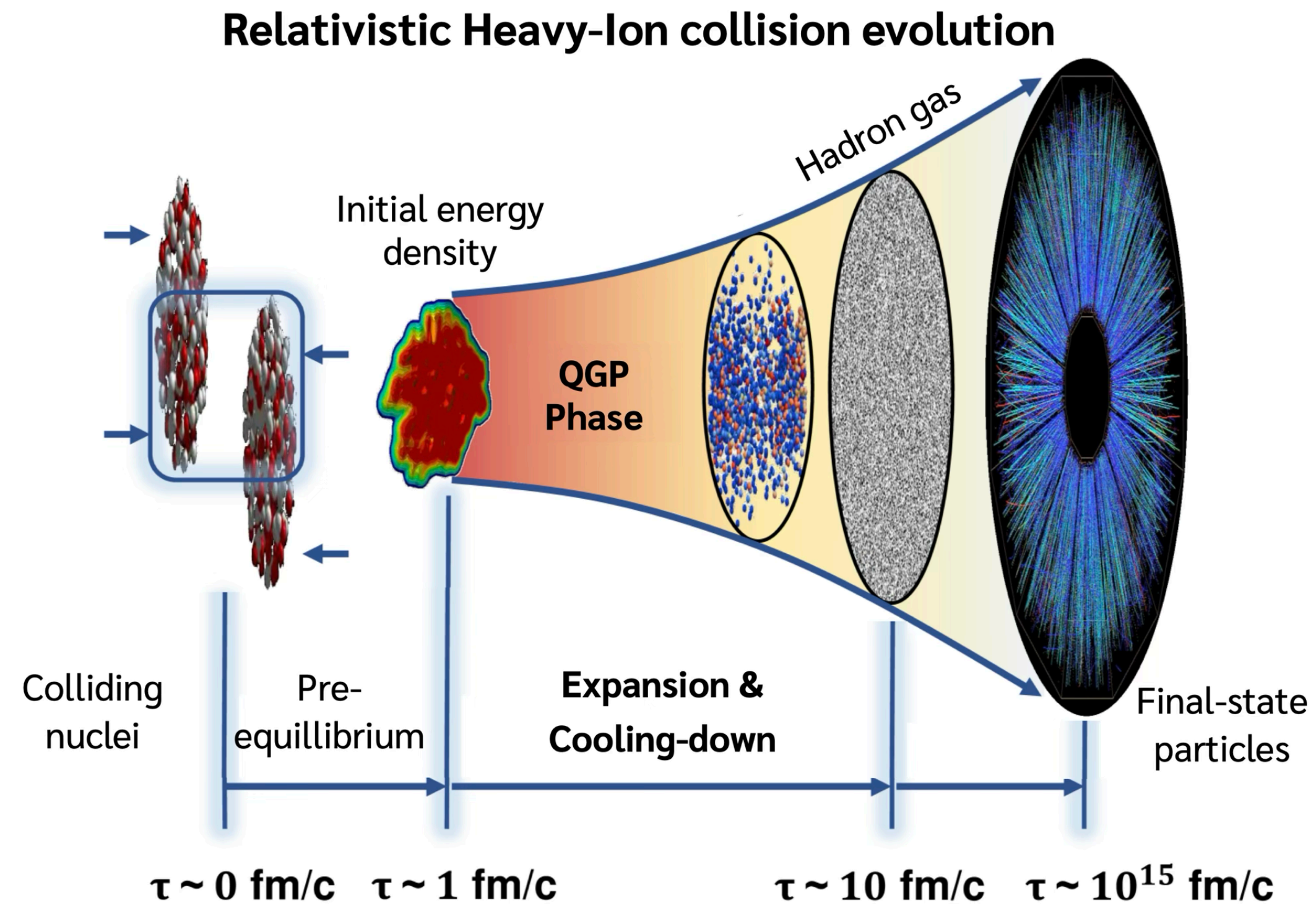


*QCD jets defined based on  
a set of rules: a **jet**  
clustering algorithm*

*They carry  
information about  
the QGP  
characteristics.*



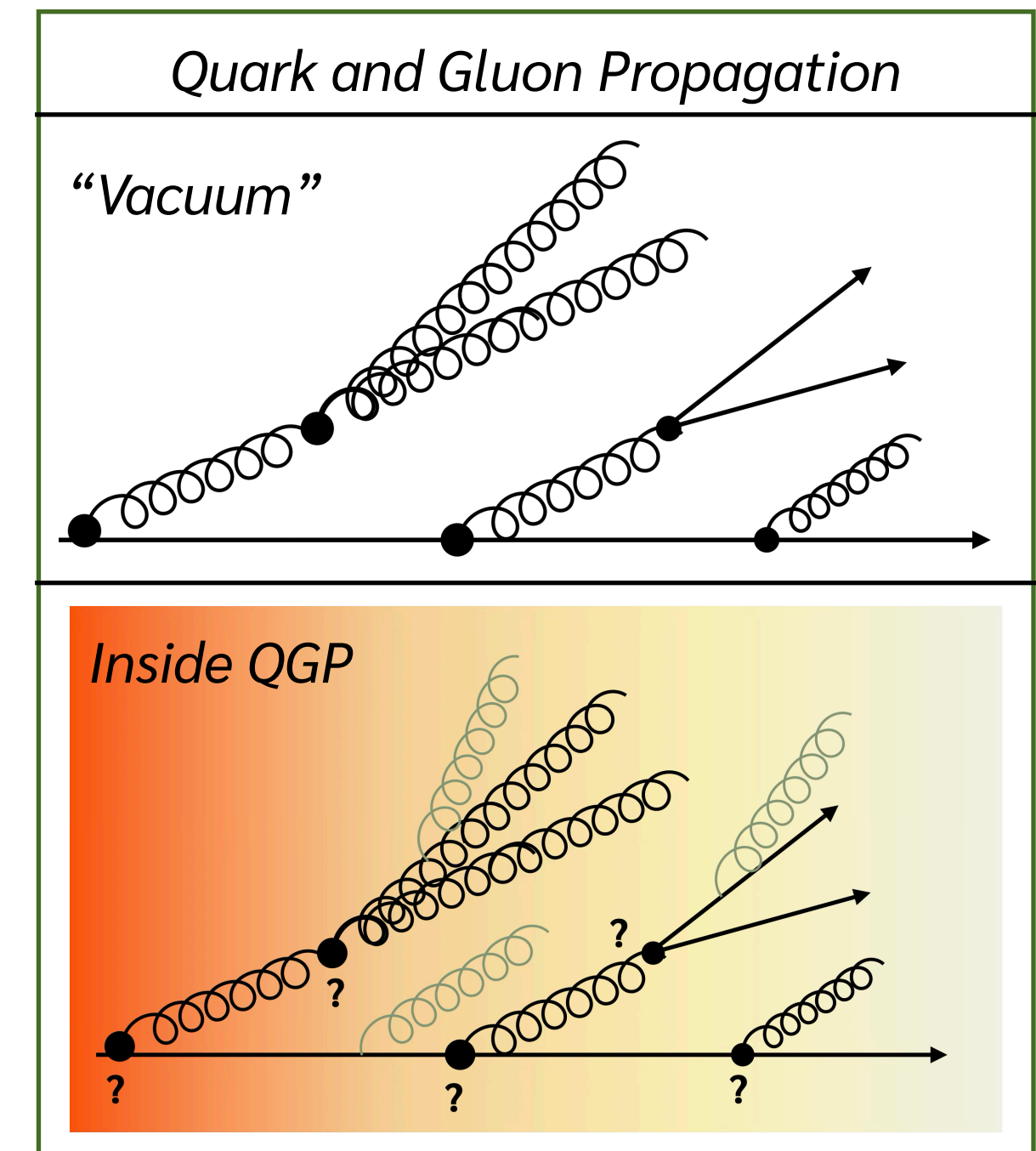
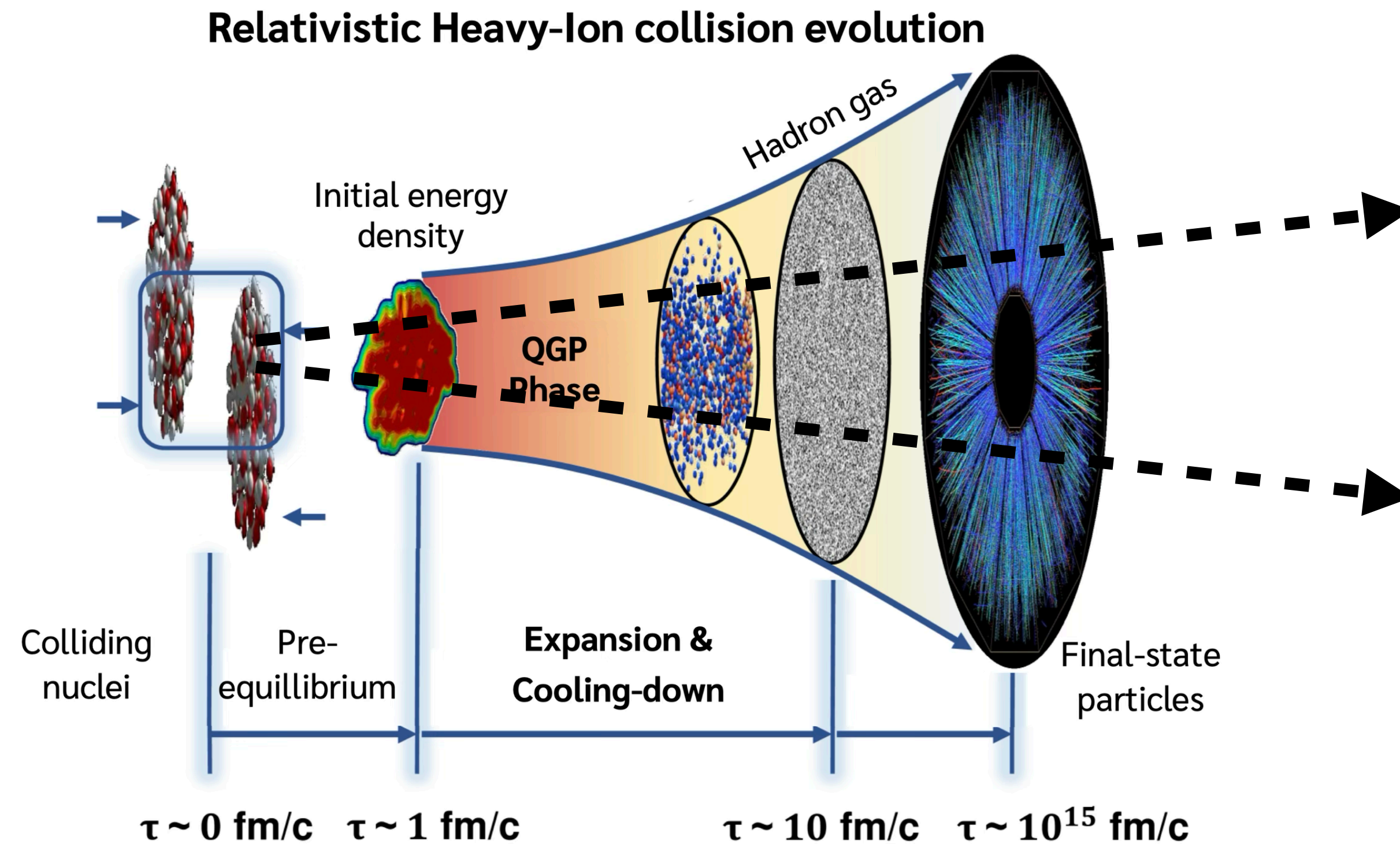
# On-going QGP studies



*What are the conditions to form a QGP? How does it evolve?*



# On-going QGP studies



*What are the conditions to form a QGP? How does it evolve?*

*What underlying mechanisms govern the interaction of the QGP with the propagating particles?*



# Take-home messages





# Summary

- Ordinary matter (hadrons) is just one among the **many complex states of QCD**
- **Quark-Gluon Plasma** is a **hot** and almost perfect **fluid** made of quarks and gluons
- **Heavy-Ion Collisions** help us study **QCD's most challenging frontier**: strongly interacting many-body systems

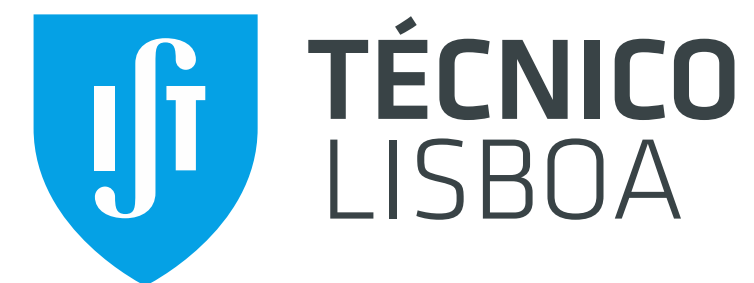




**Questions?**



# Acknowledgements





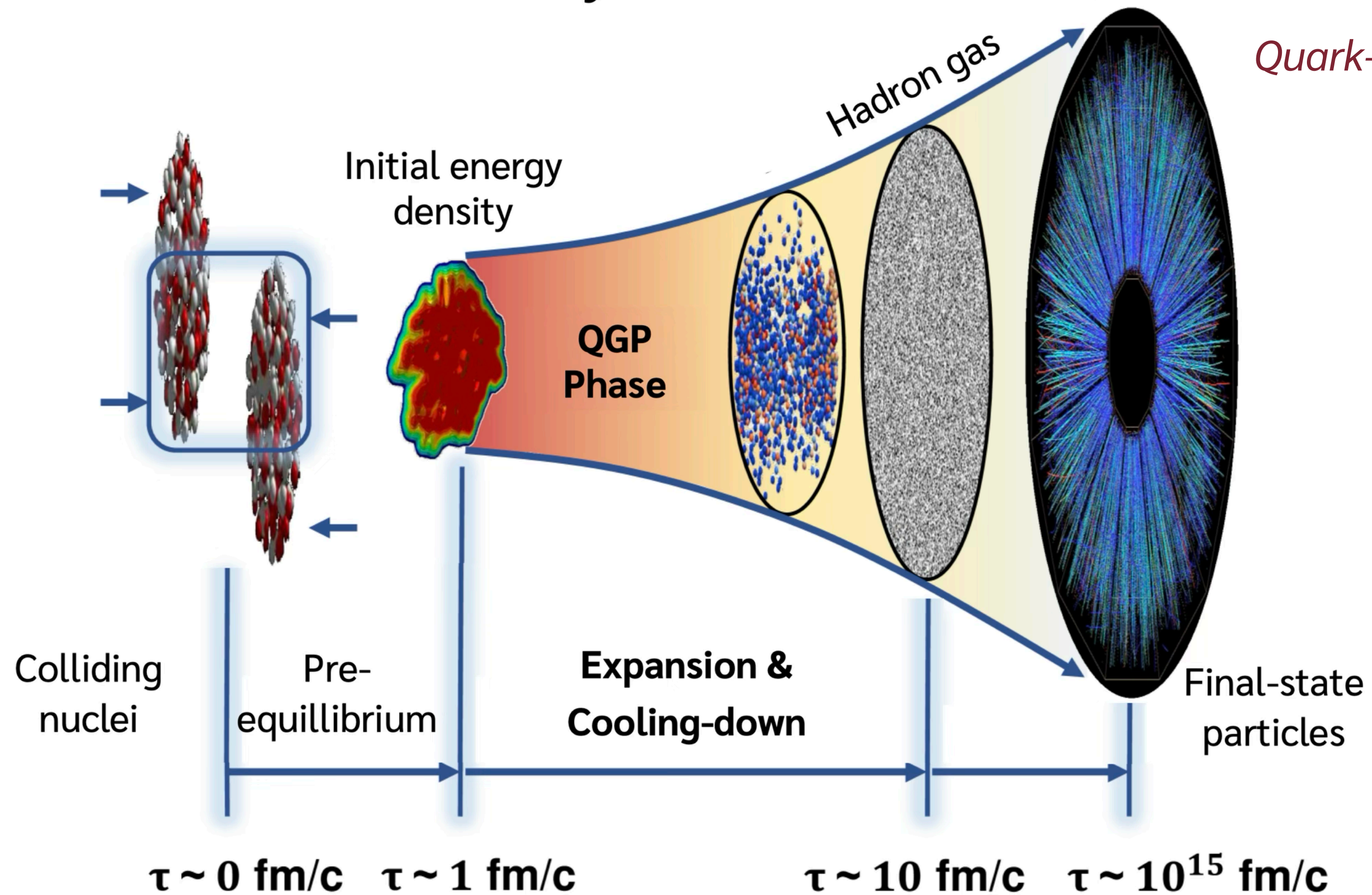


**Backup Slides**



# Heavy-Ion Collisions

## Relativistic Heavy-Ion collision evolution

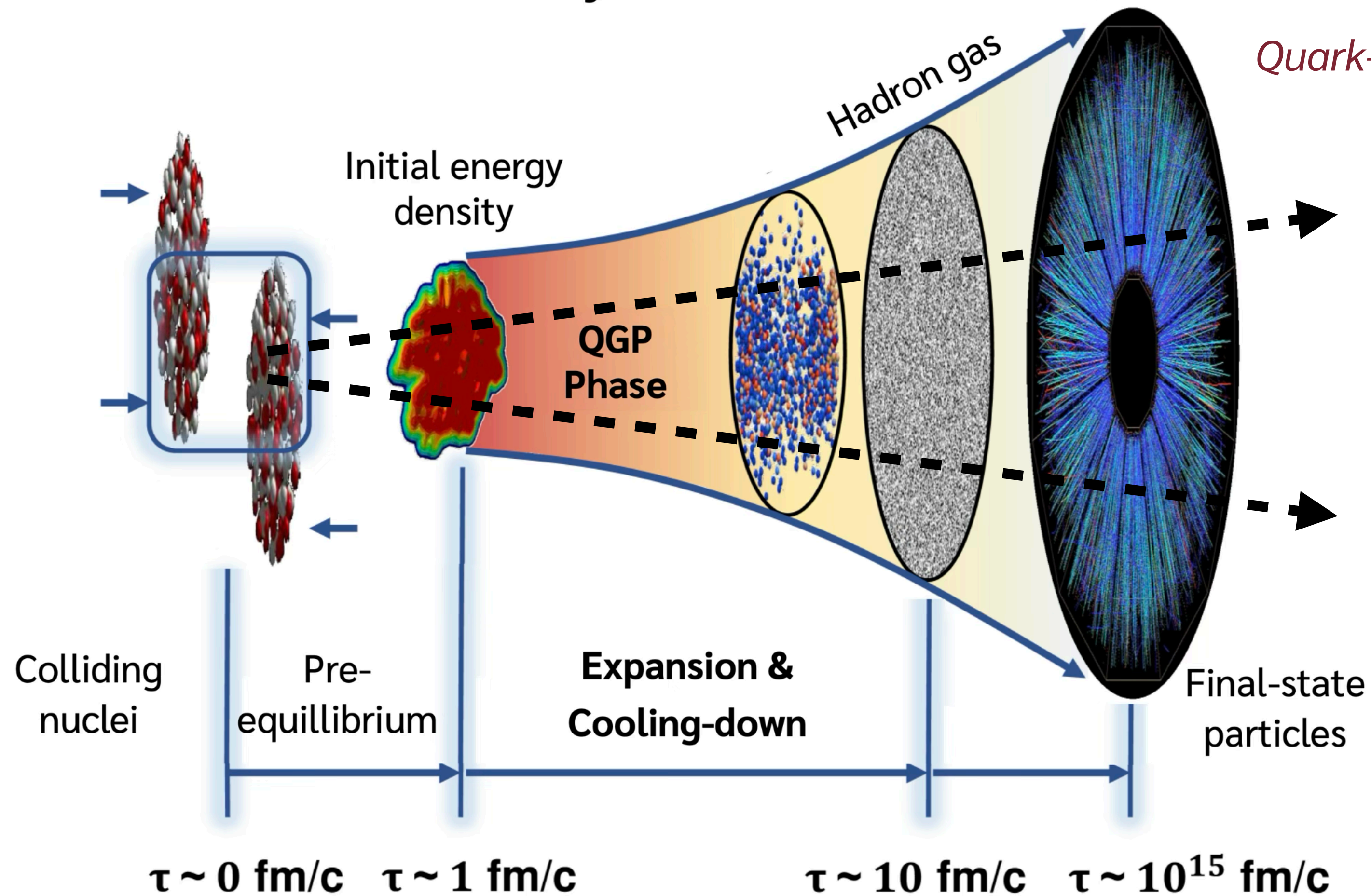


*Quark-Gluon Plasma (QGP) has an extremely short lifetime*



# Heavy-Ion Collisions

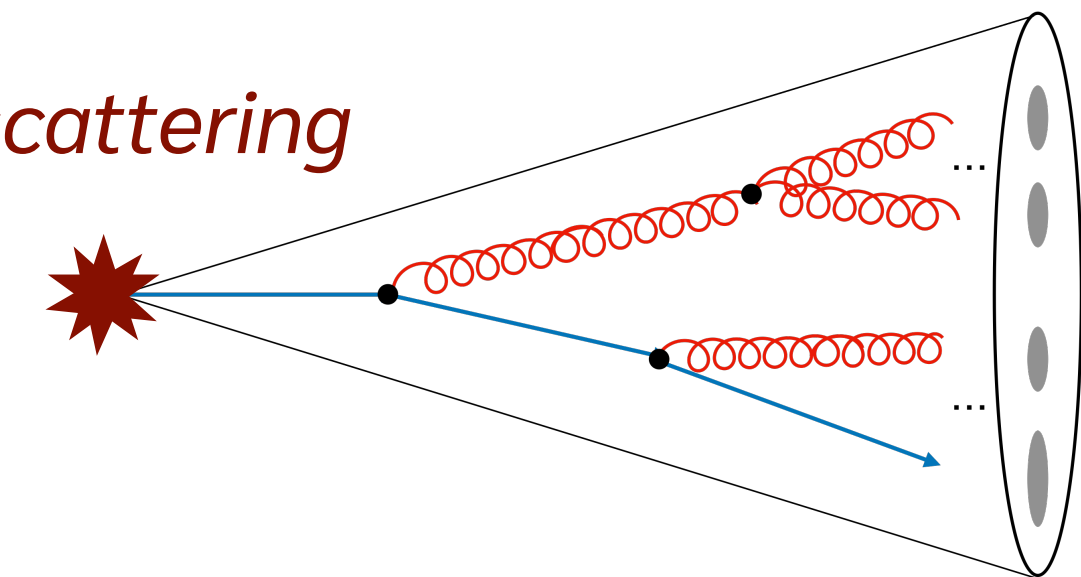
## Relativistic Heavy-Ion collision evolution



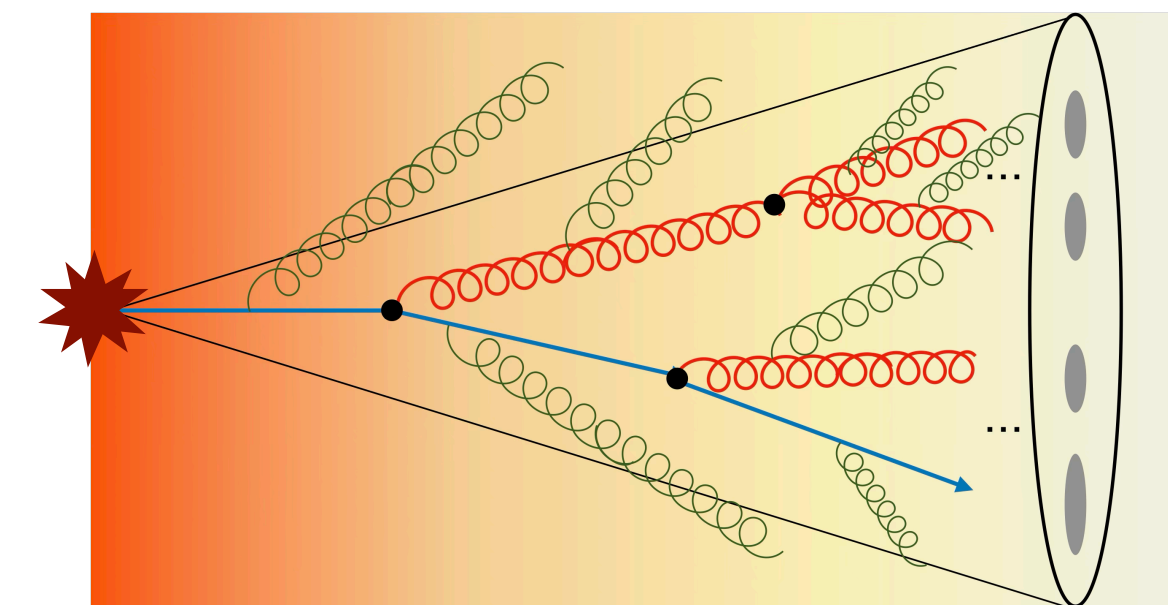
*Quark-Gluon Plasma (QGP) has an extremely short lifetime*

*Solution: use jets as probing tool*

*Hard scattering*



*"Vacuum" jets*



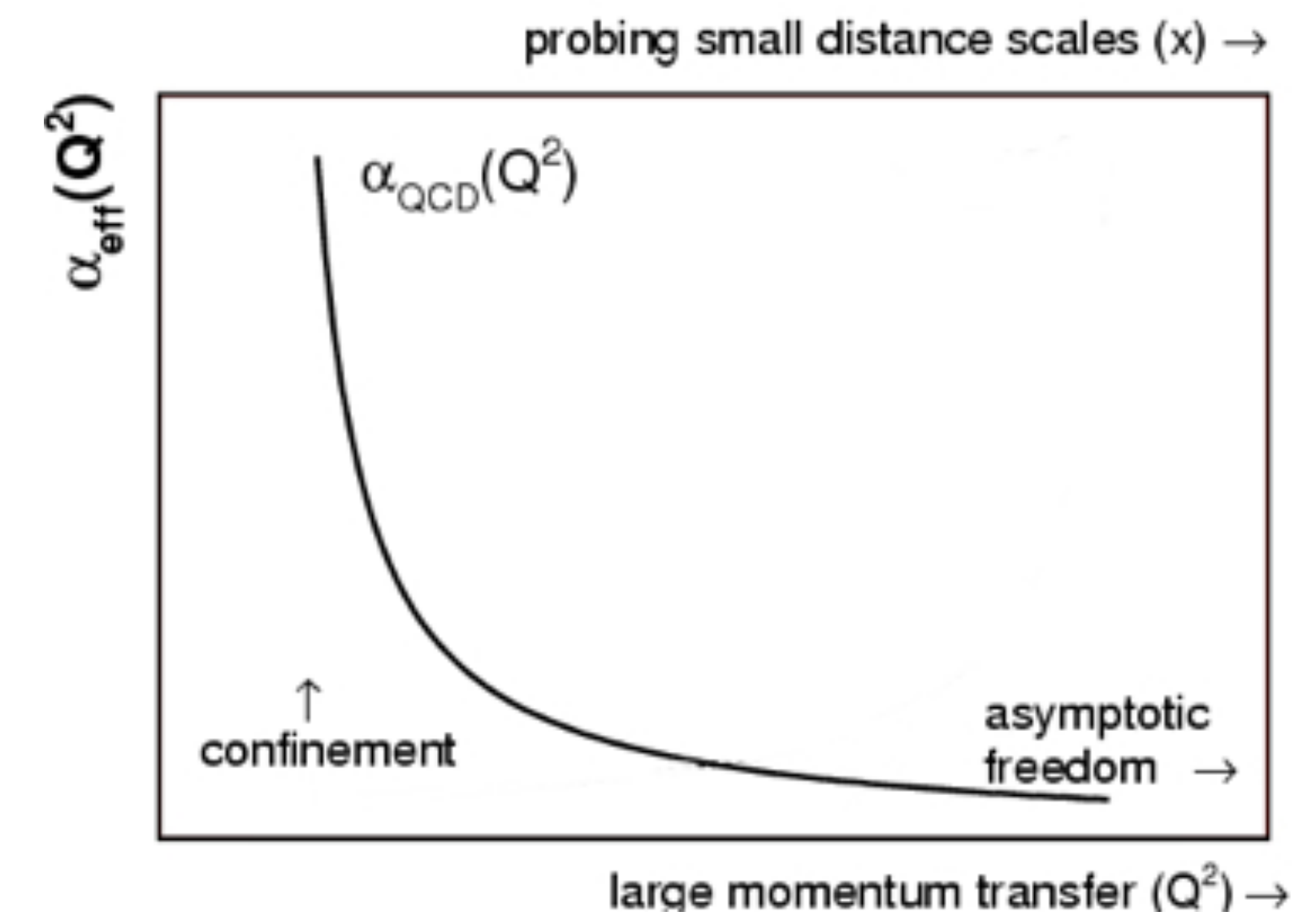
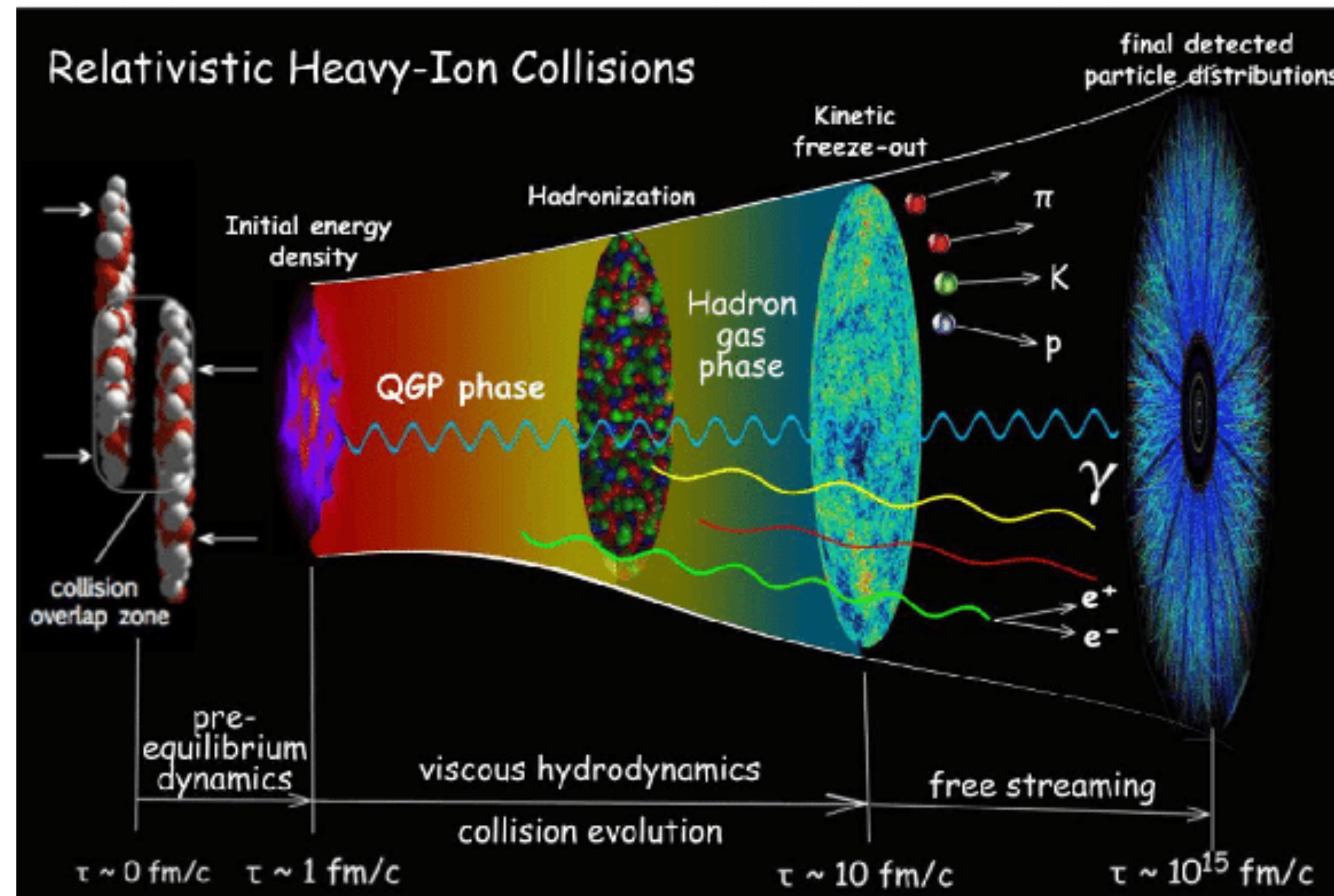
*"In-medium" jets (Jet Quenching)*

QGP



# Probes of the QGP

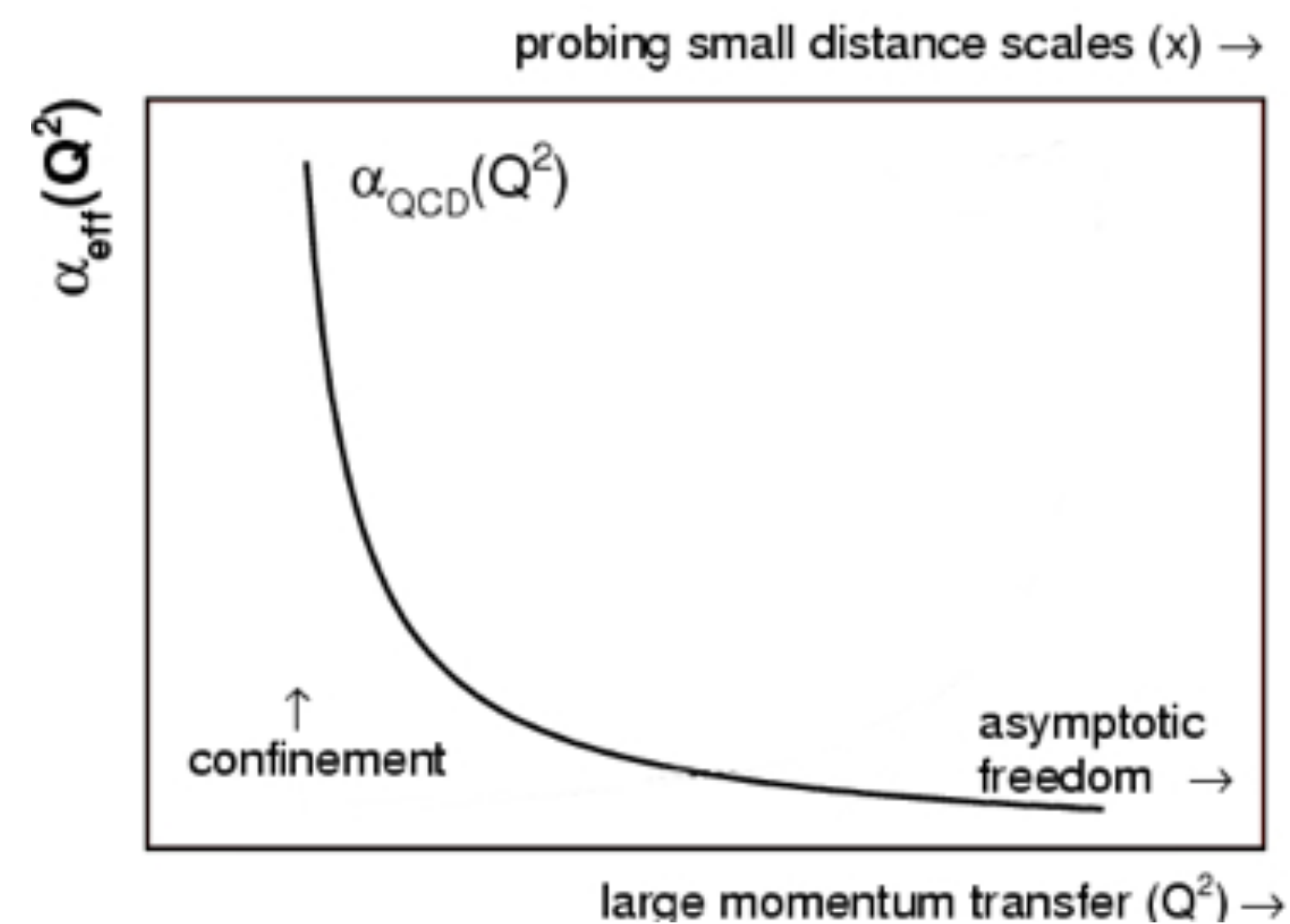
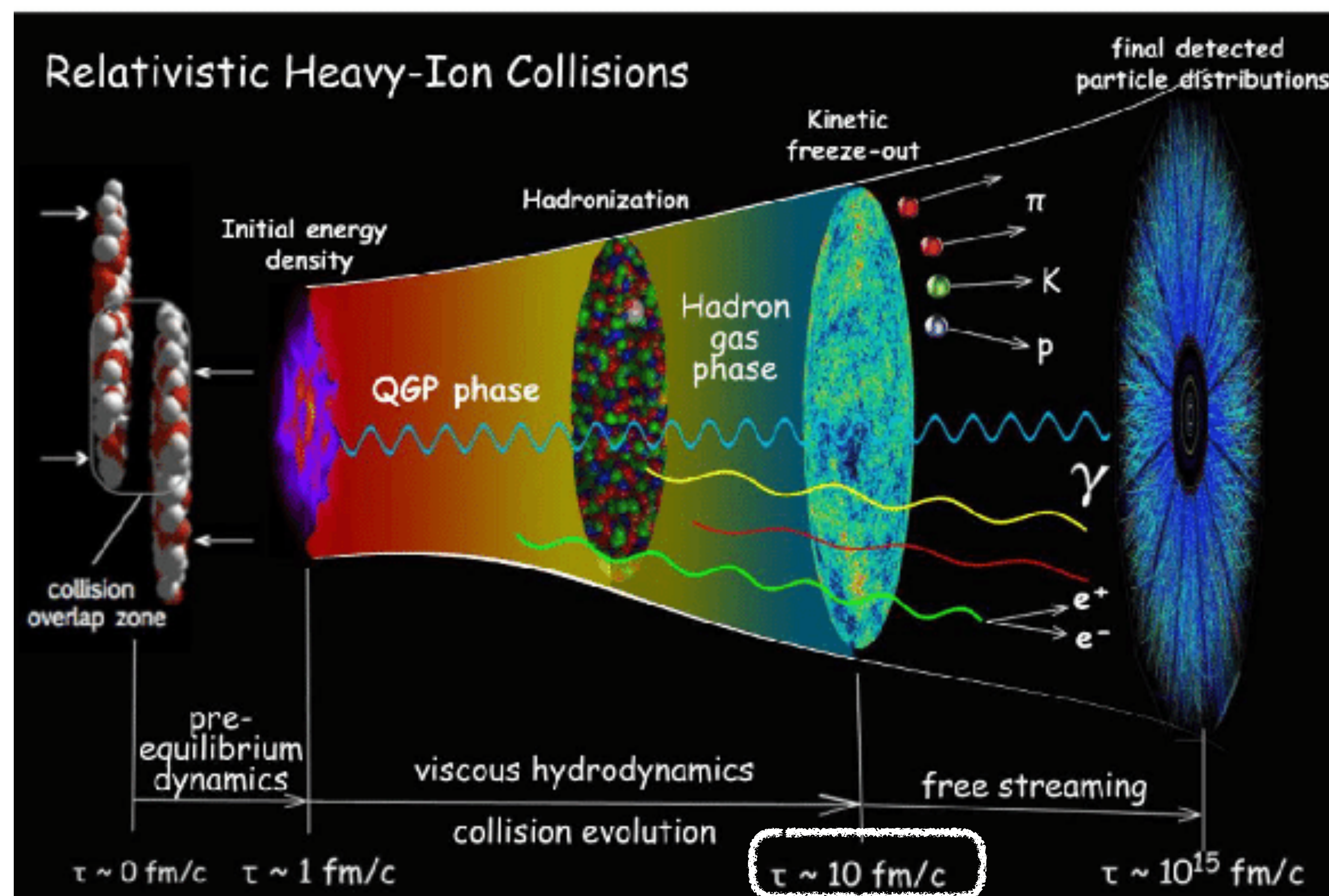
- We can create it in the lab. But how to study it?





# Probes of the QGP

- We can create it in the lab. But how to study it?

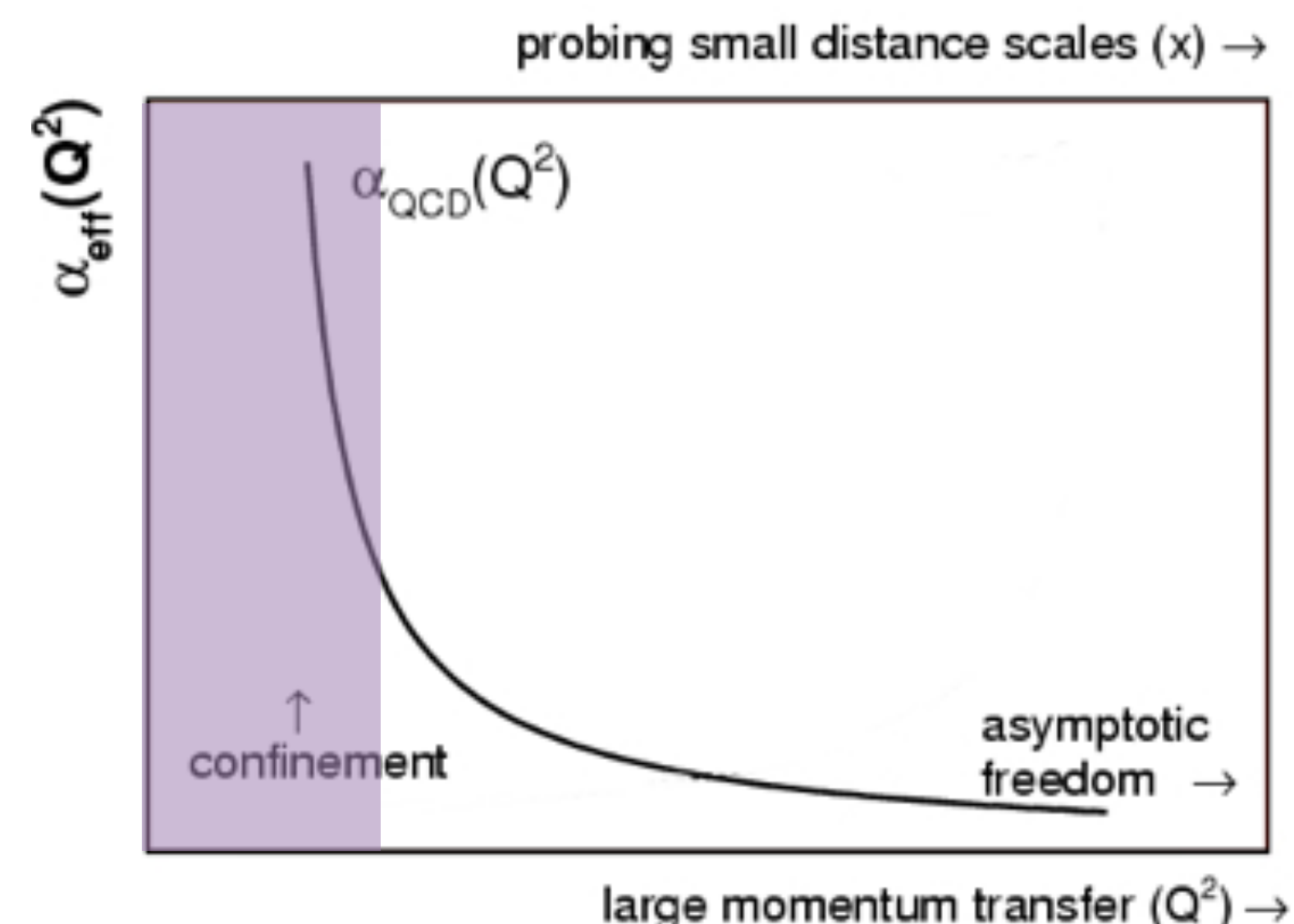
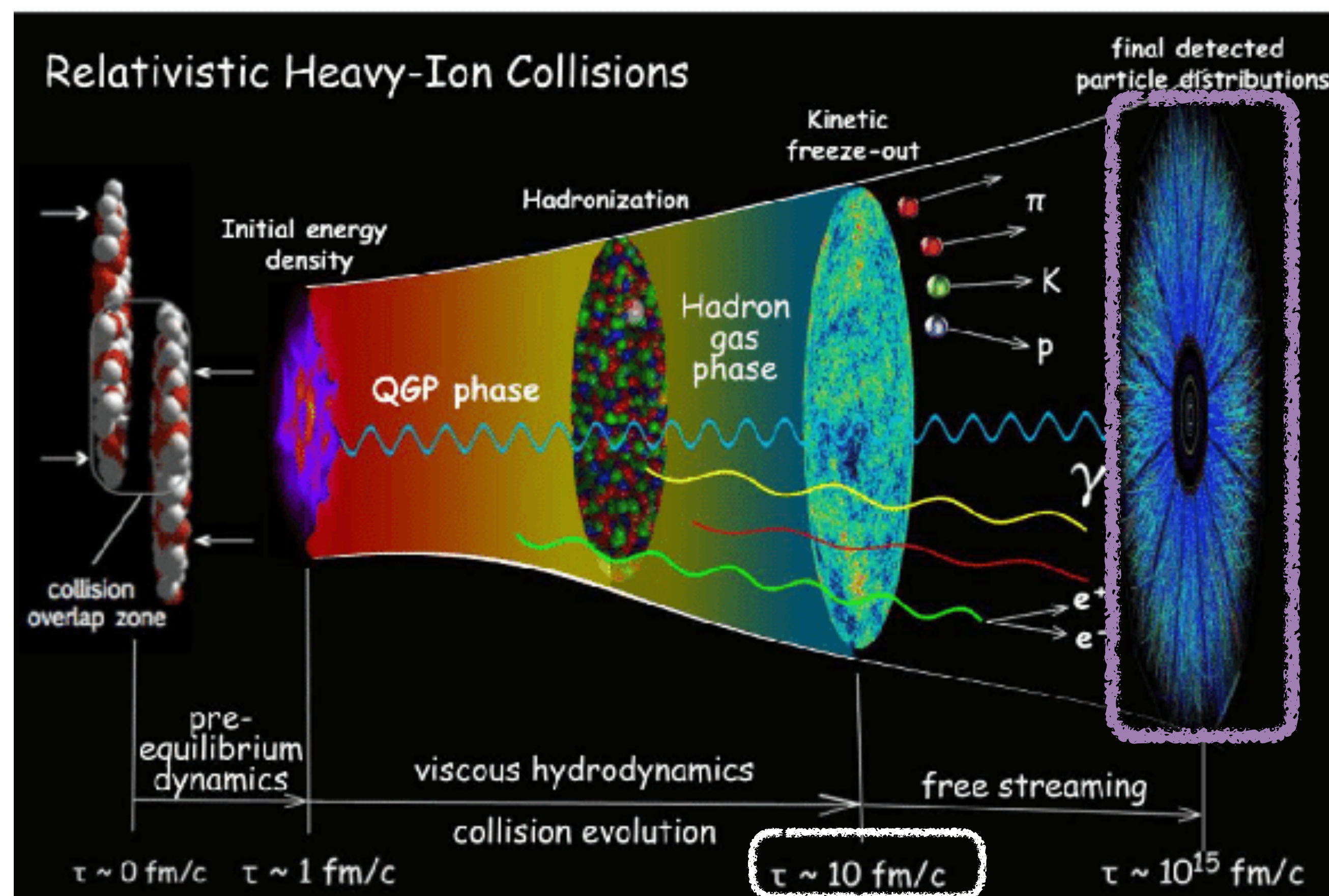


Caveat: need to rely on self-generated probes



# Probes of the QGP

- We can create it in the lab. But how to study it?



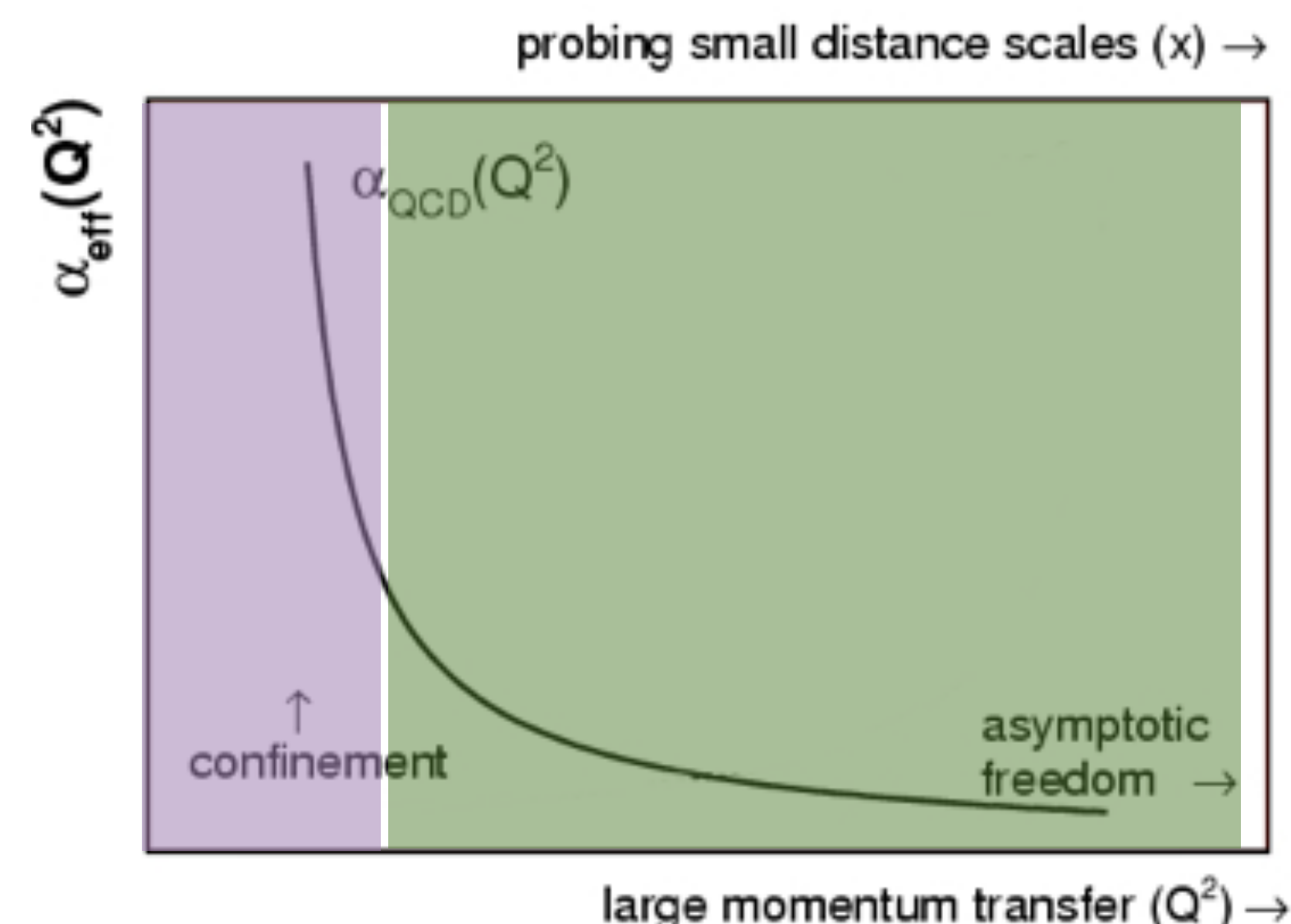
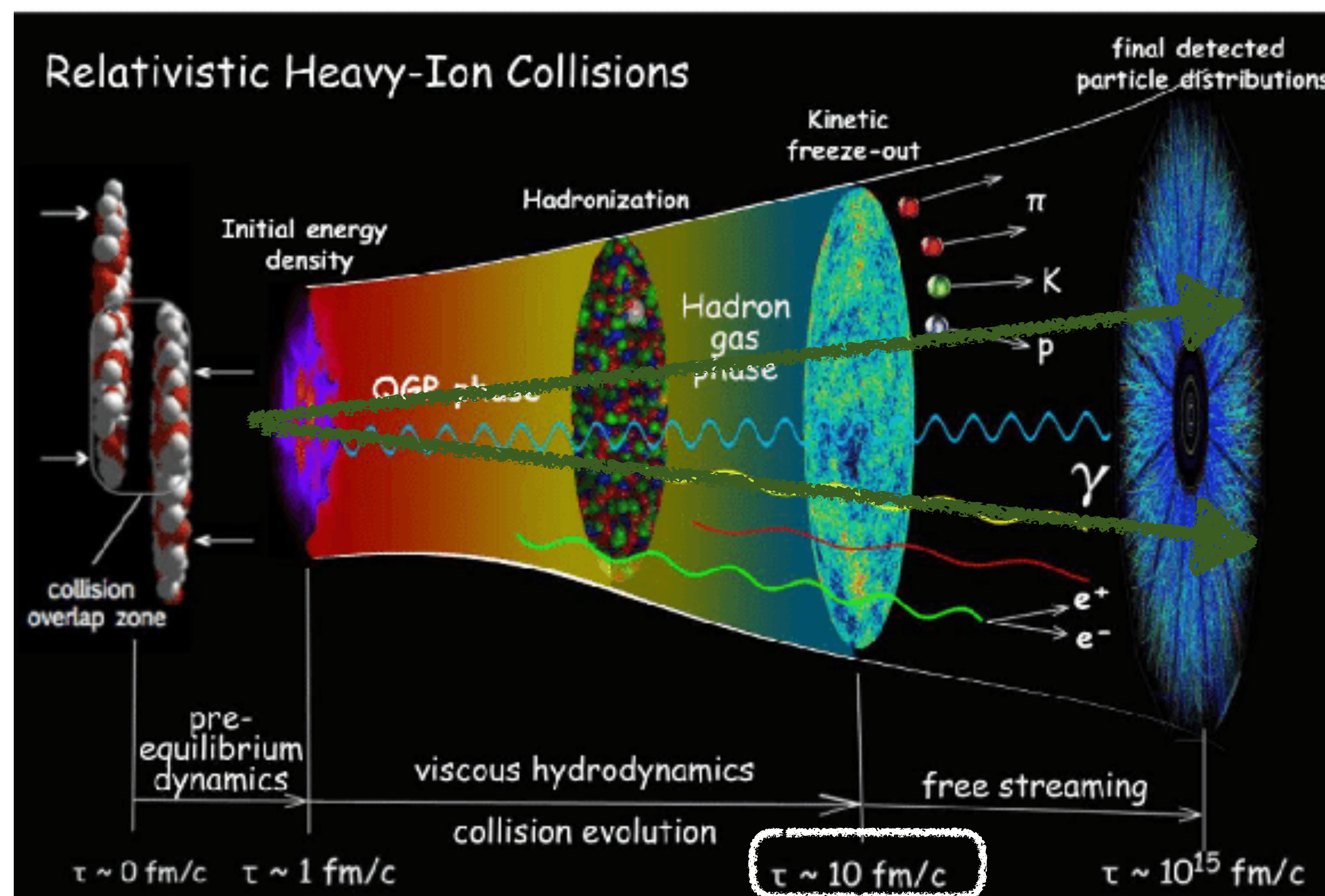
Soft  
probes  
non-pQCD

Caveat: need to rely on self-generated probes



# Probes of the QGP

- We can create it in the lab. But how to study it?



Soft probes  
non-pQCD

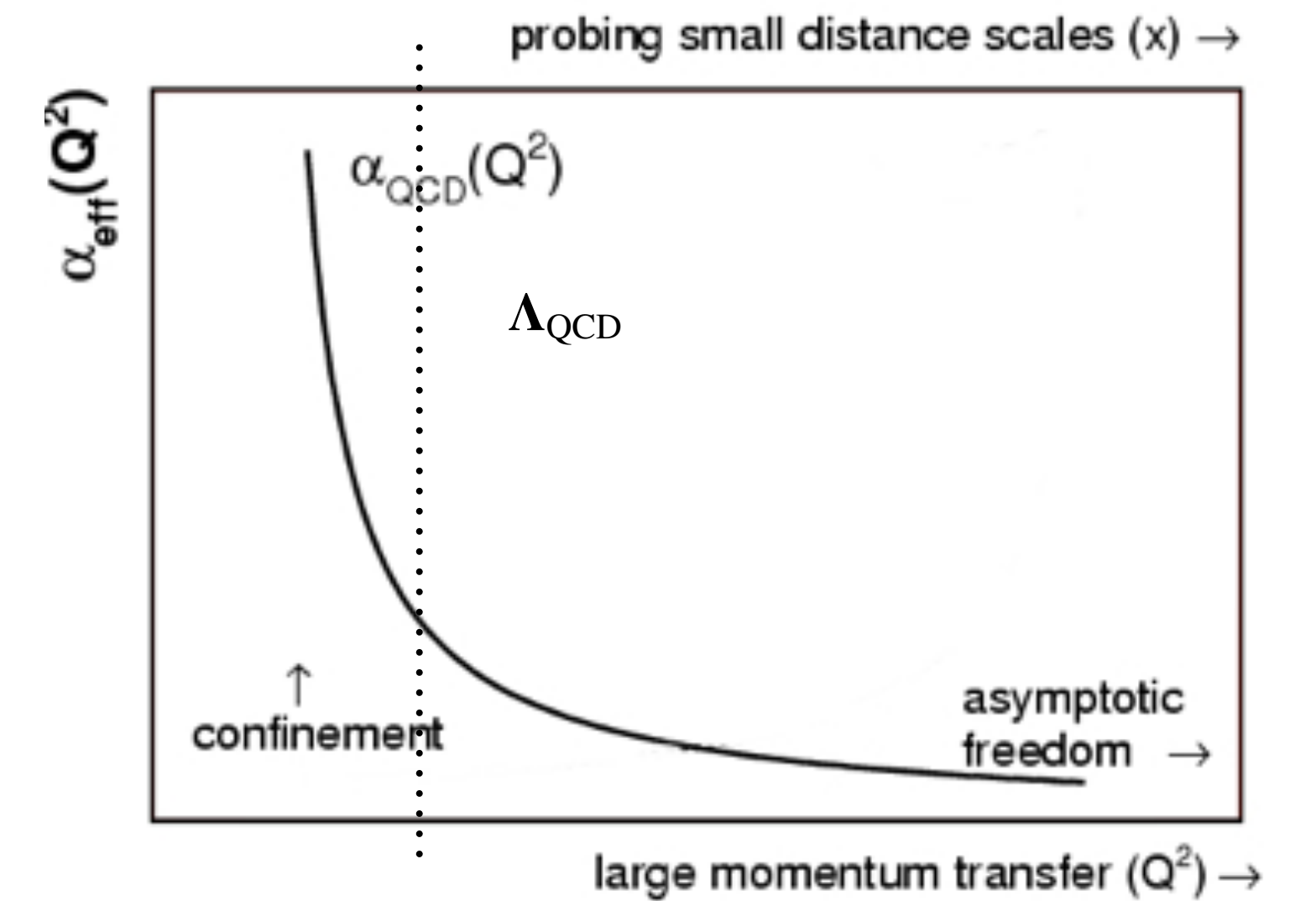
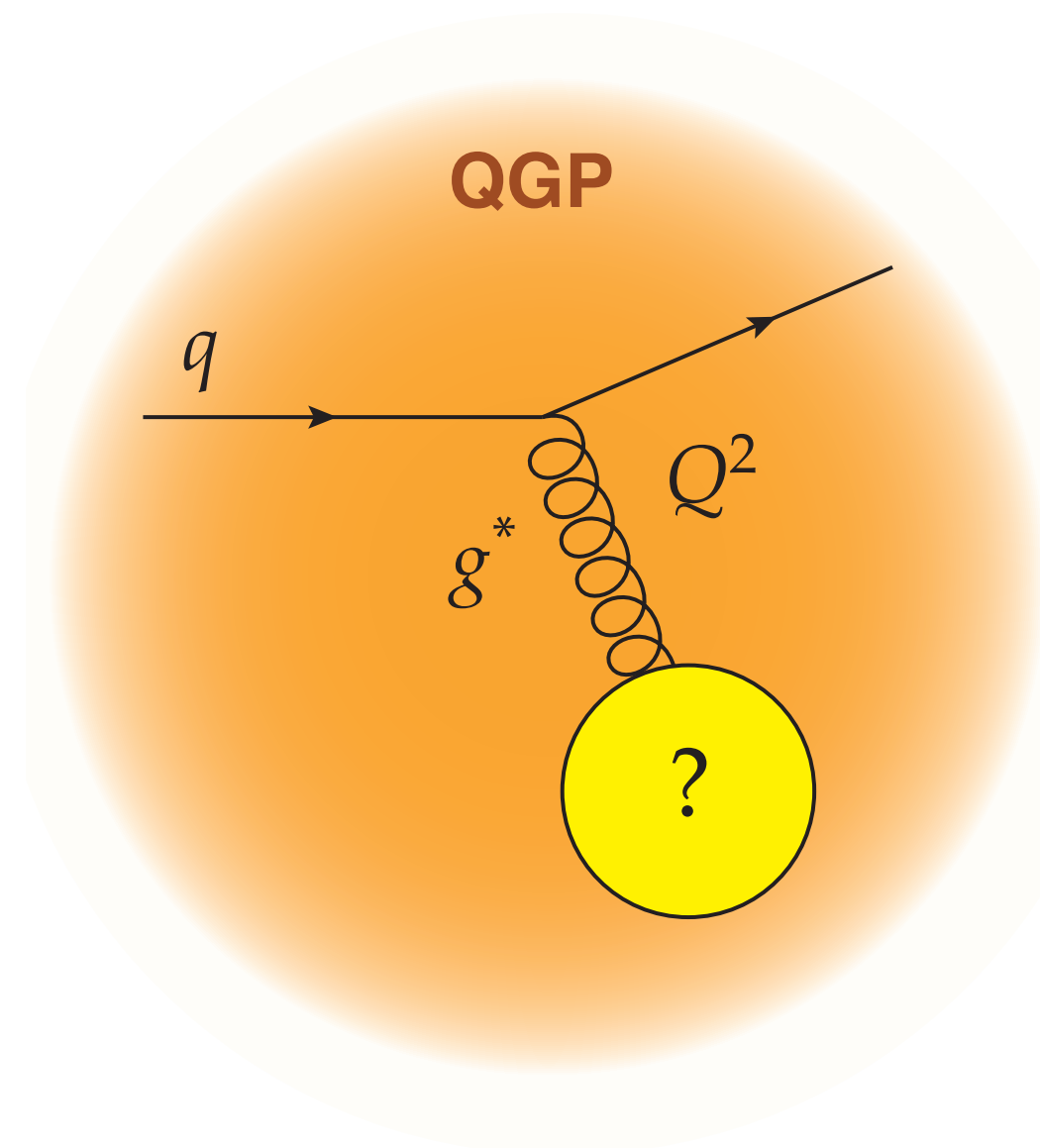
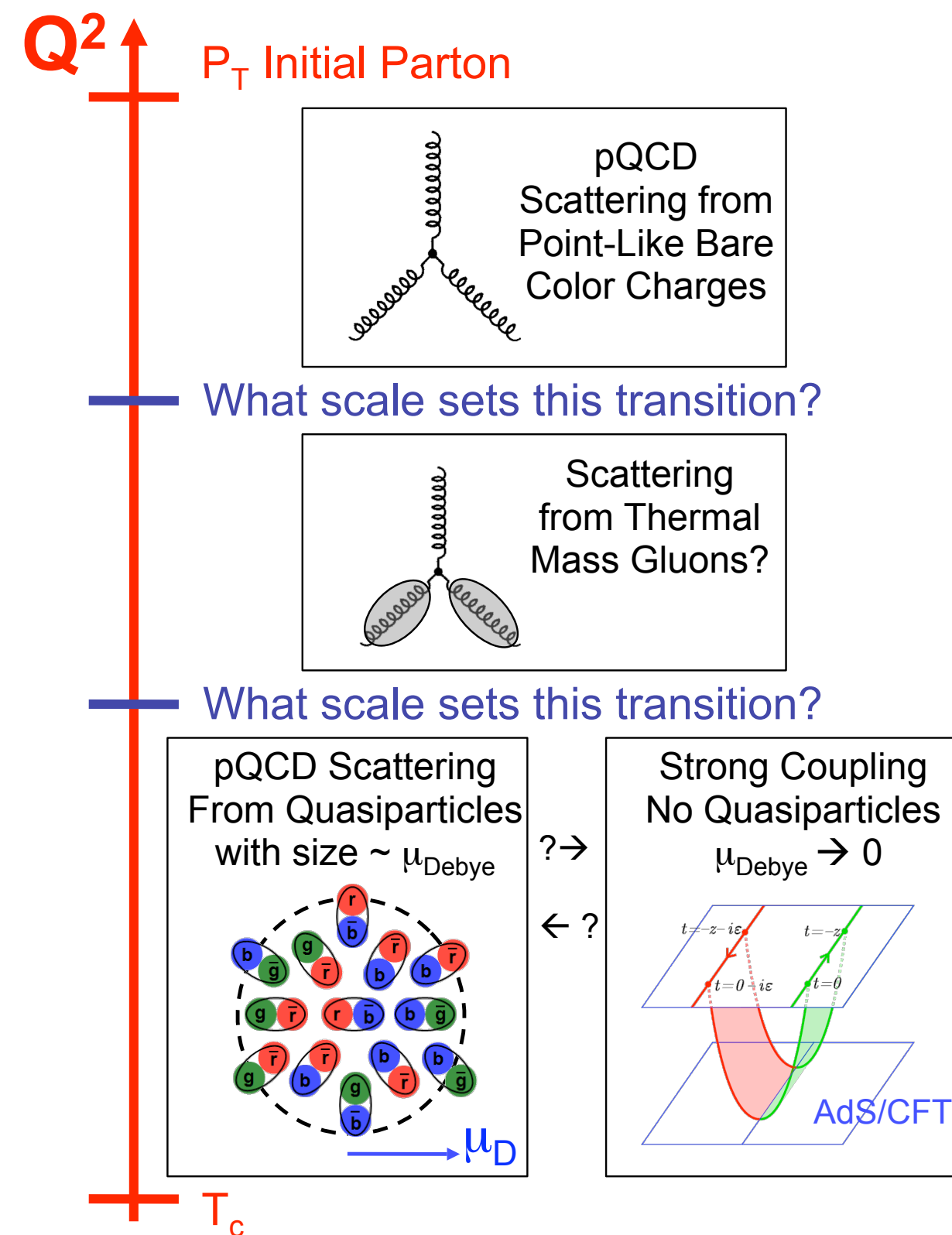
Hard probes  
pQCD (e.g: jets)

Caveat: need to rely on self-generated probes



# Hard probes

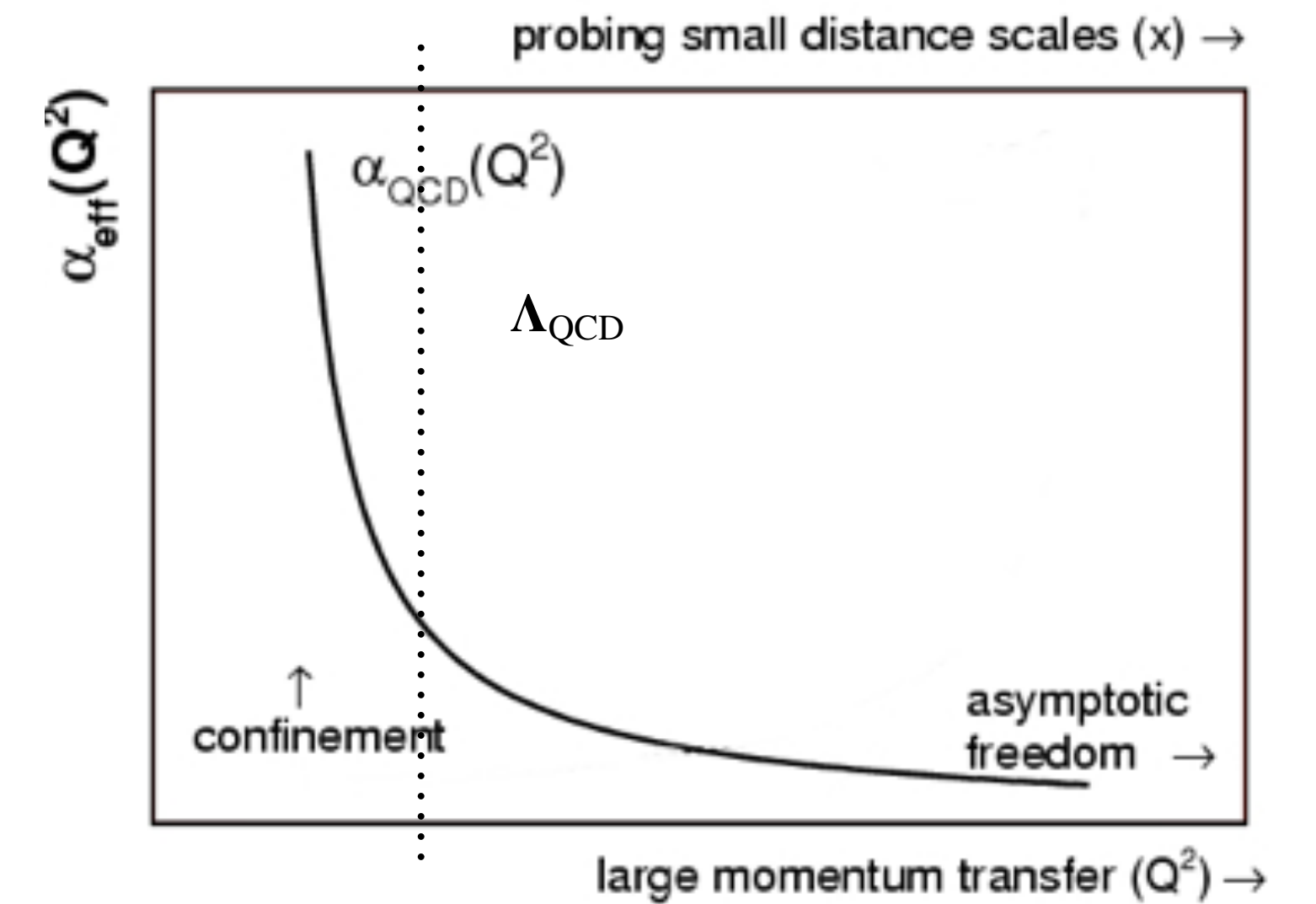
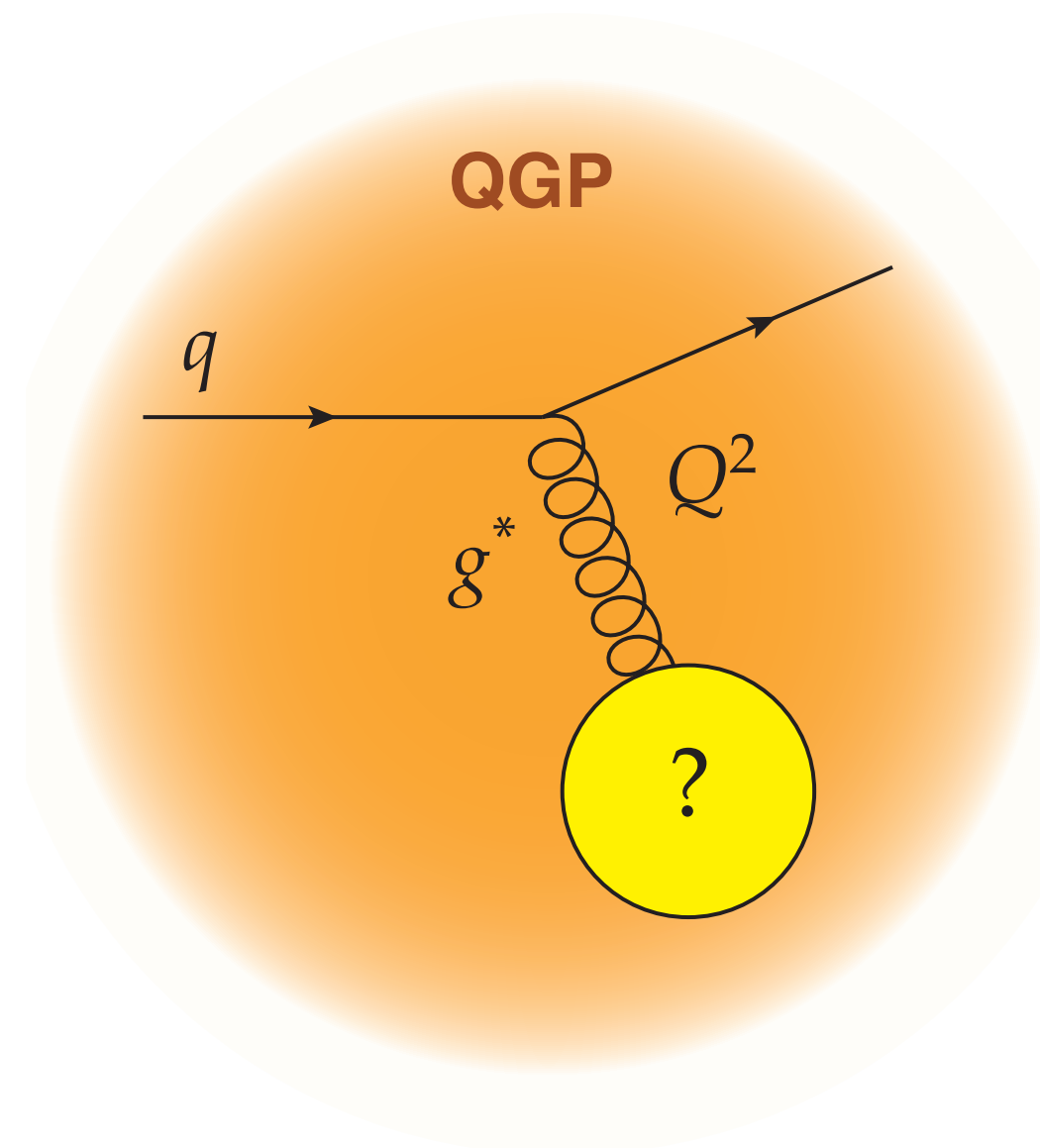
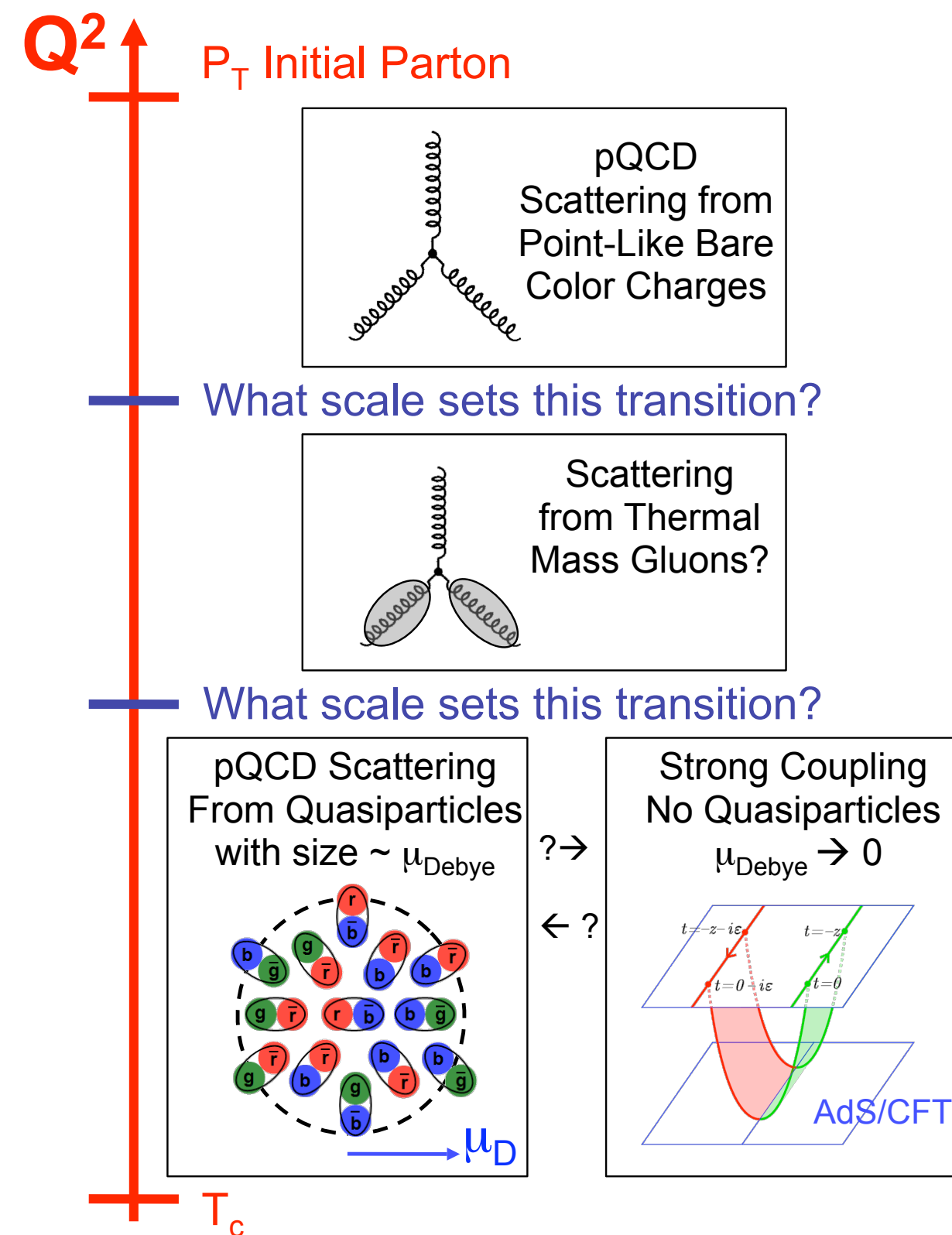
- What is the QGP?





# Hard probes

- What is the QGP?

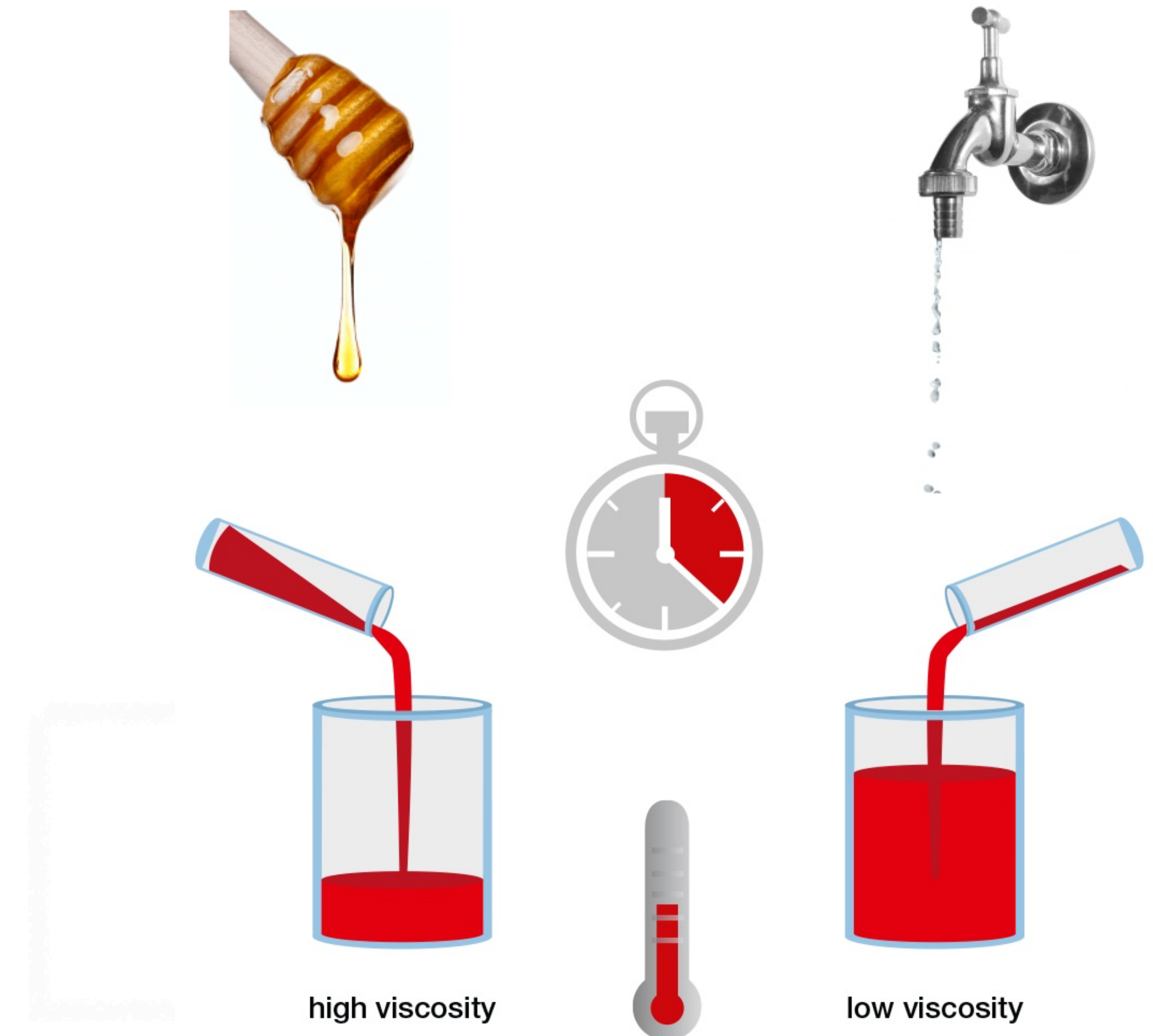
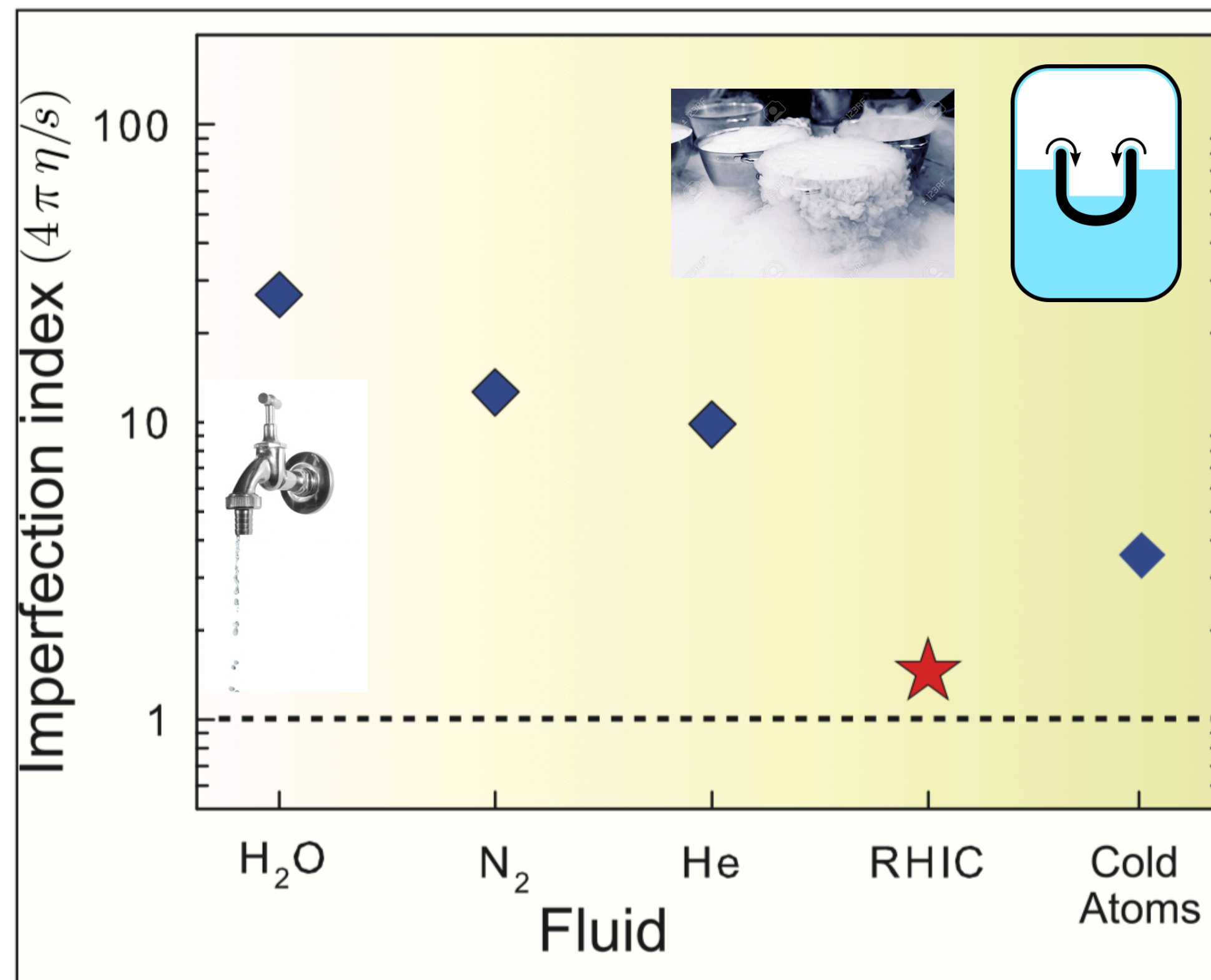


*One possible solution:  
use something that we do know!*



# Soft probes

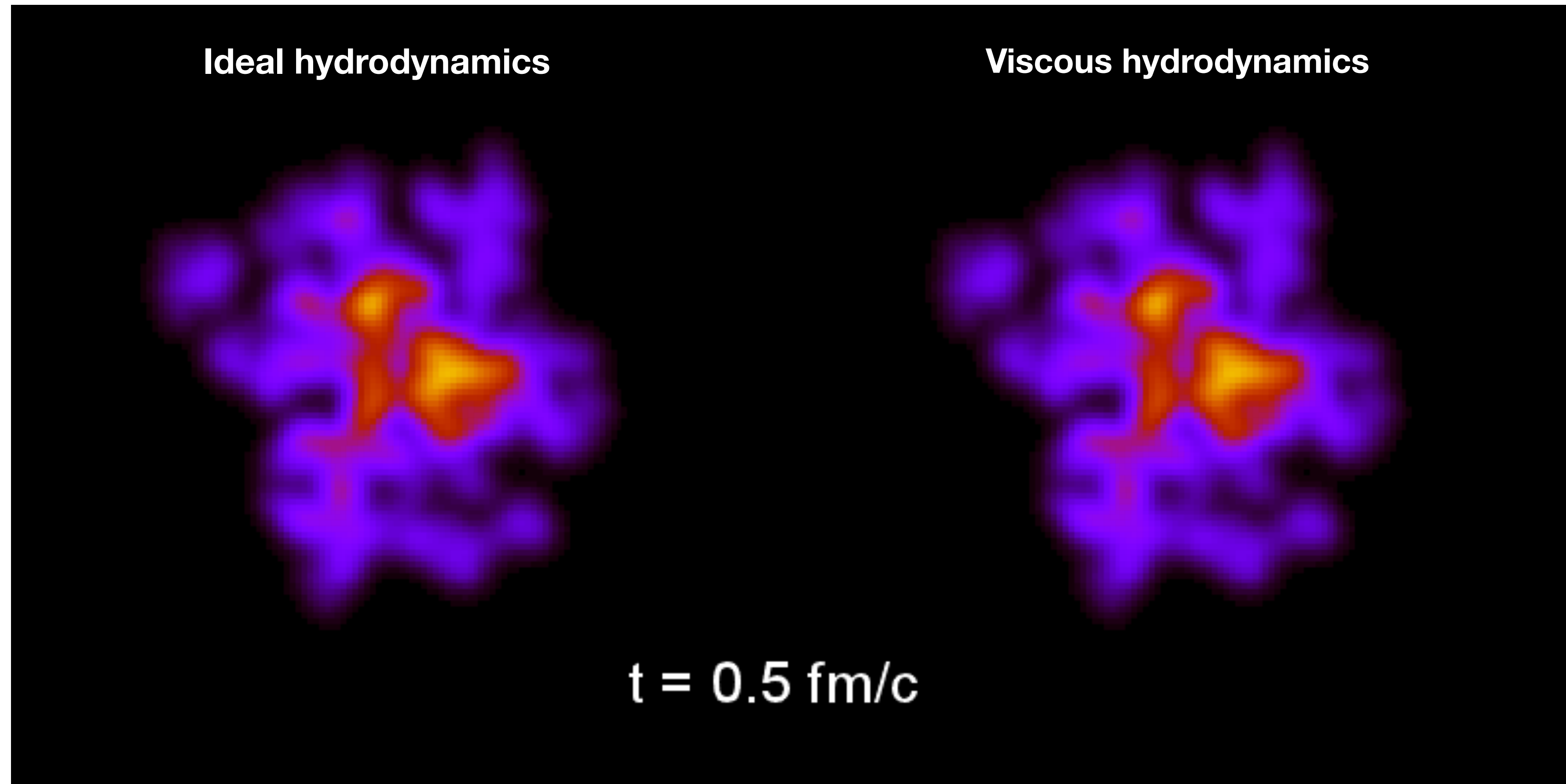
- QGP is not a hot gas of quarks and gluons... is a fluid! Measuring the imperfection factor (viscosity)....





# QGP: an almost perfect liquid

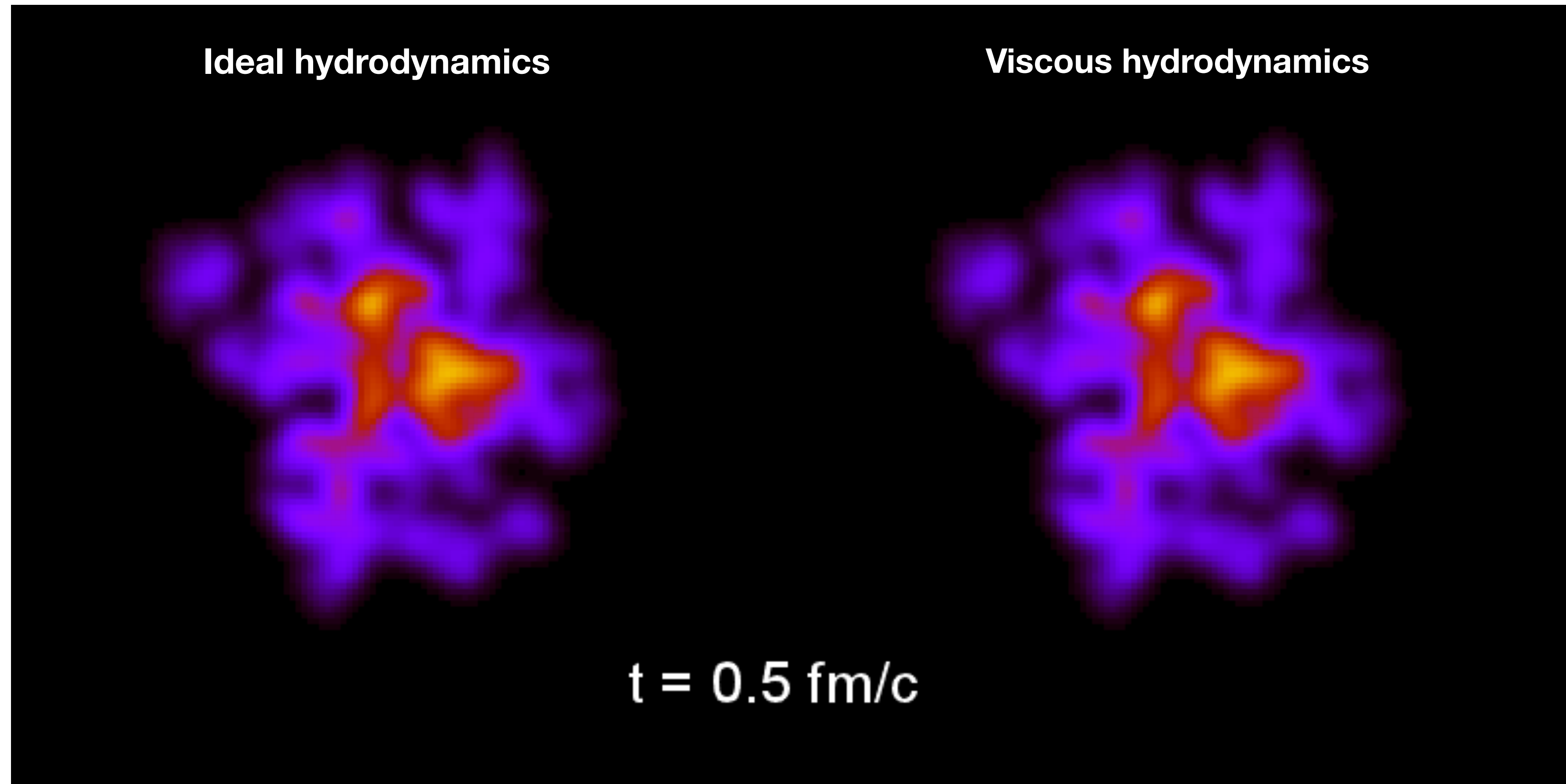
- Viscosity





# QGP: an almost perfect liquid

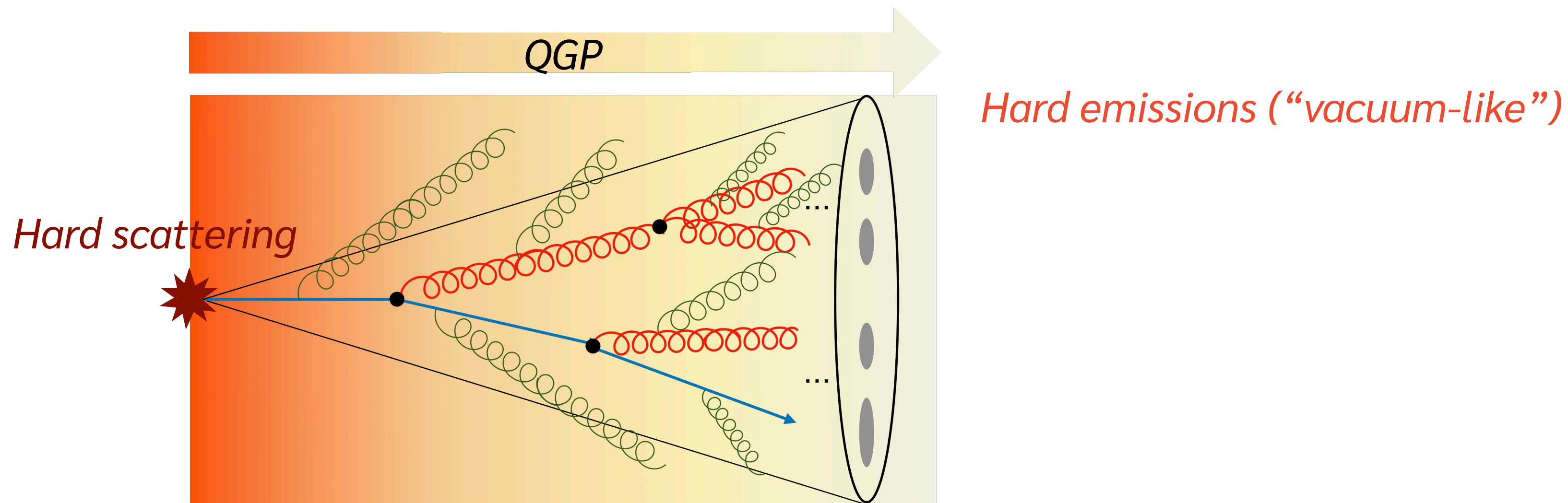
- Viscosity





# Jet Quenching Monte Carlo

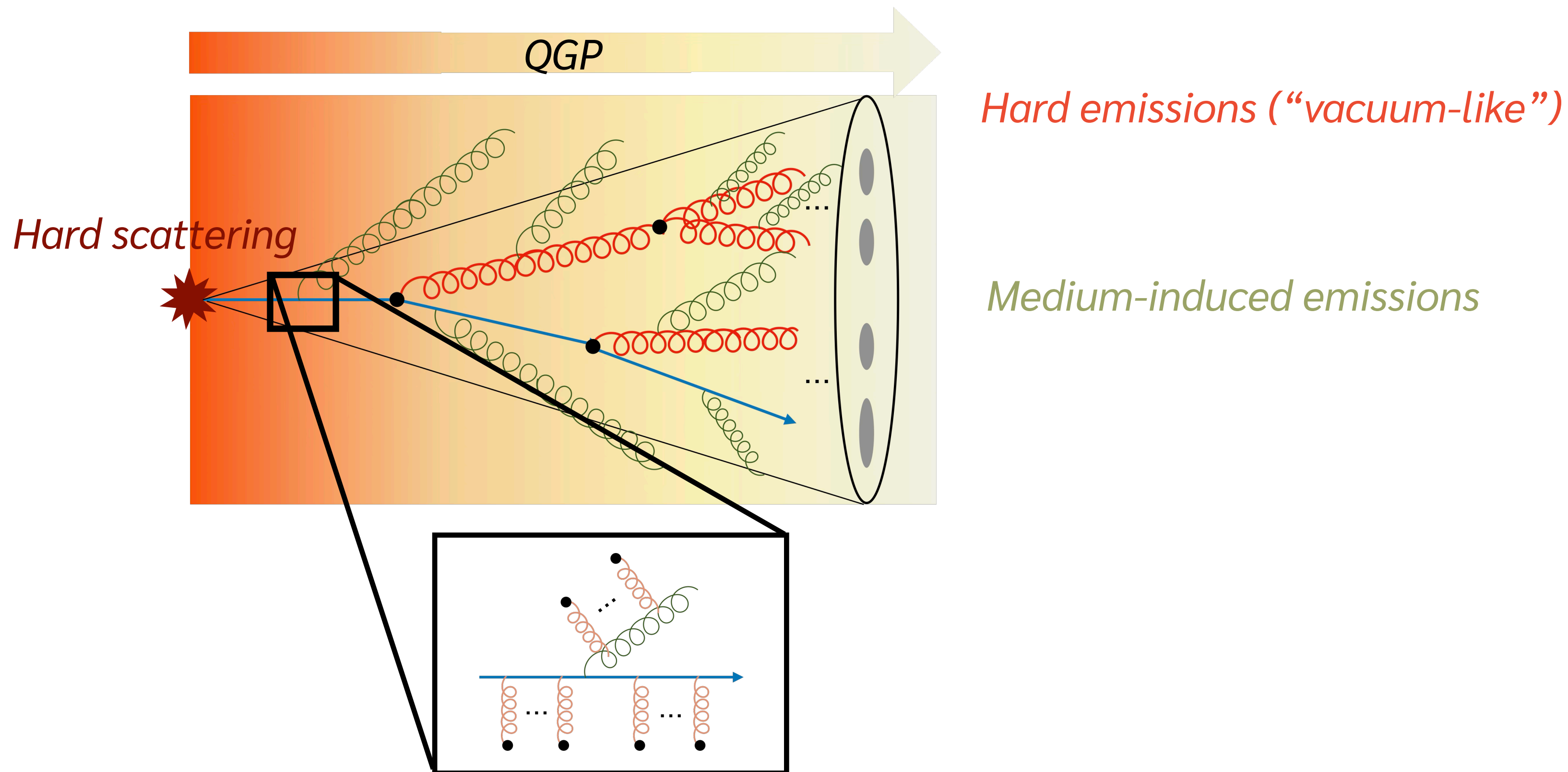
- Simulation of a heavy-ion event implies **medium-induced modifications** to a **vacuum reference without considering the QGP itself**





# Jet Quenching Monte Carlo

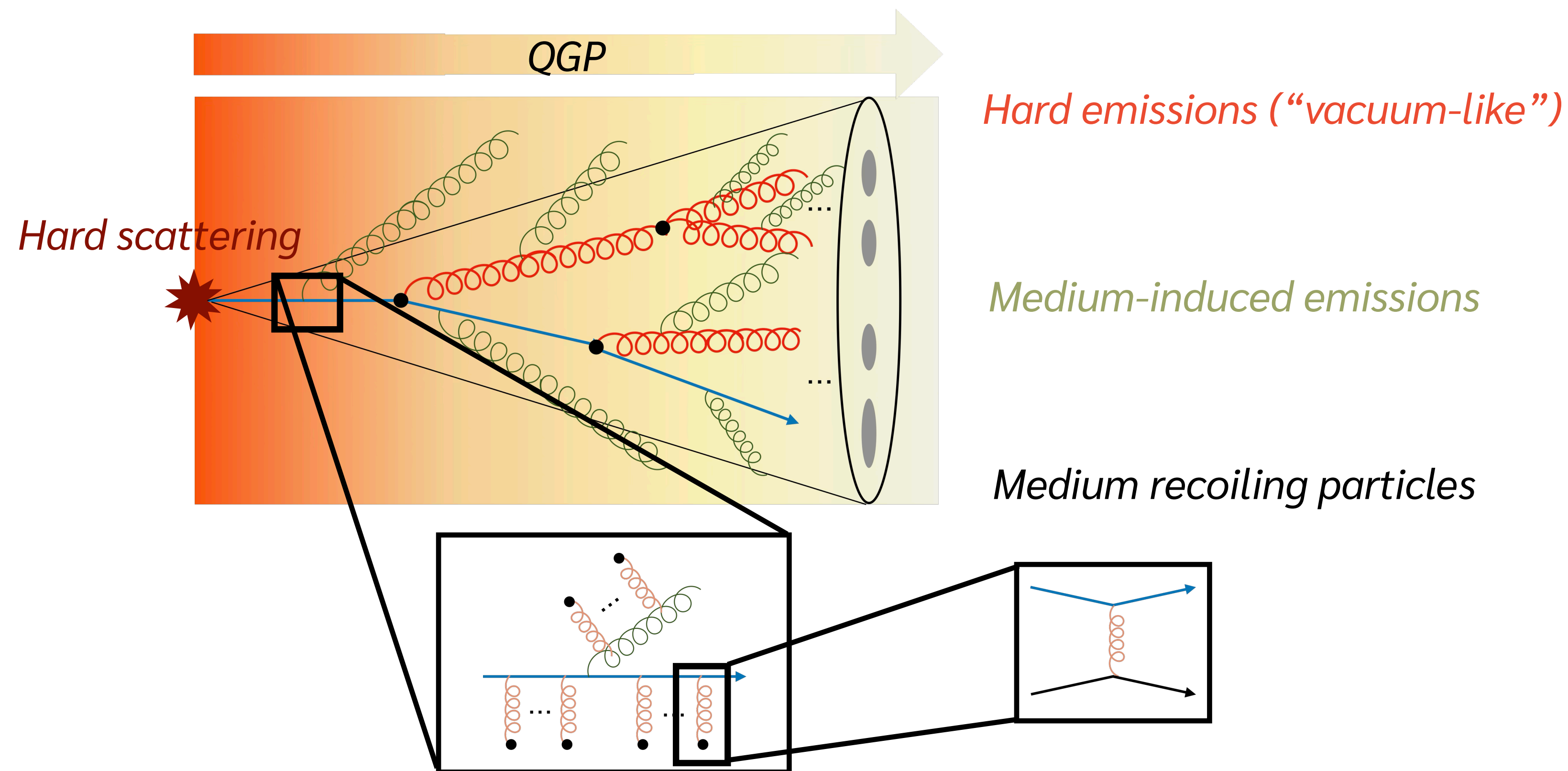
- Simulation of a heavy-ion event implies **medium-induced modifications** to a **vacuum reference without considering the QGP itself**





# Jet Quenching Monte Carlo

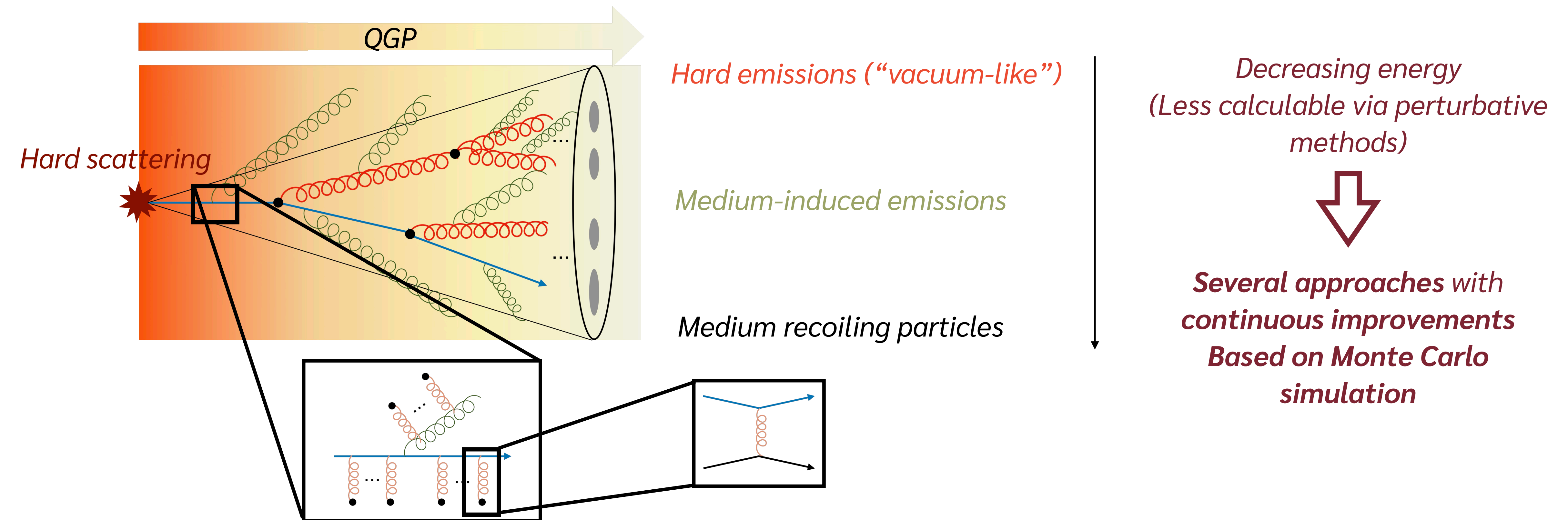
- Simulation of a heavy-ion event implies **medium-induced modifications** to a **vacuum reference without considering the QGP itself**





# Jet Quenching Monte Carlo

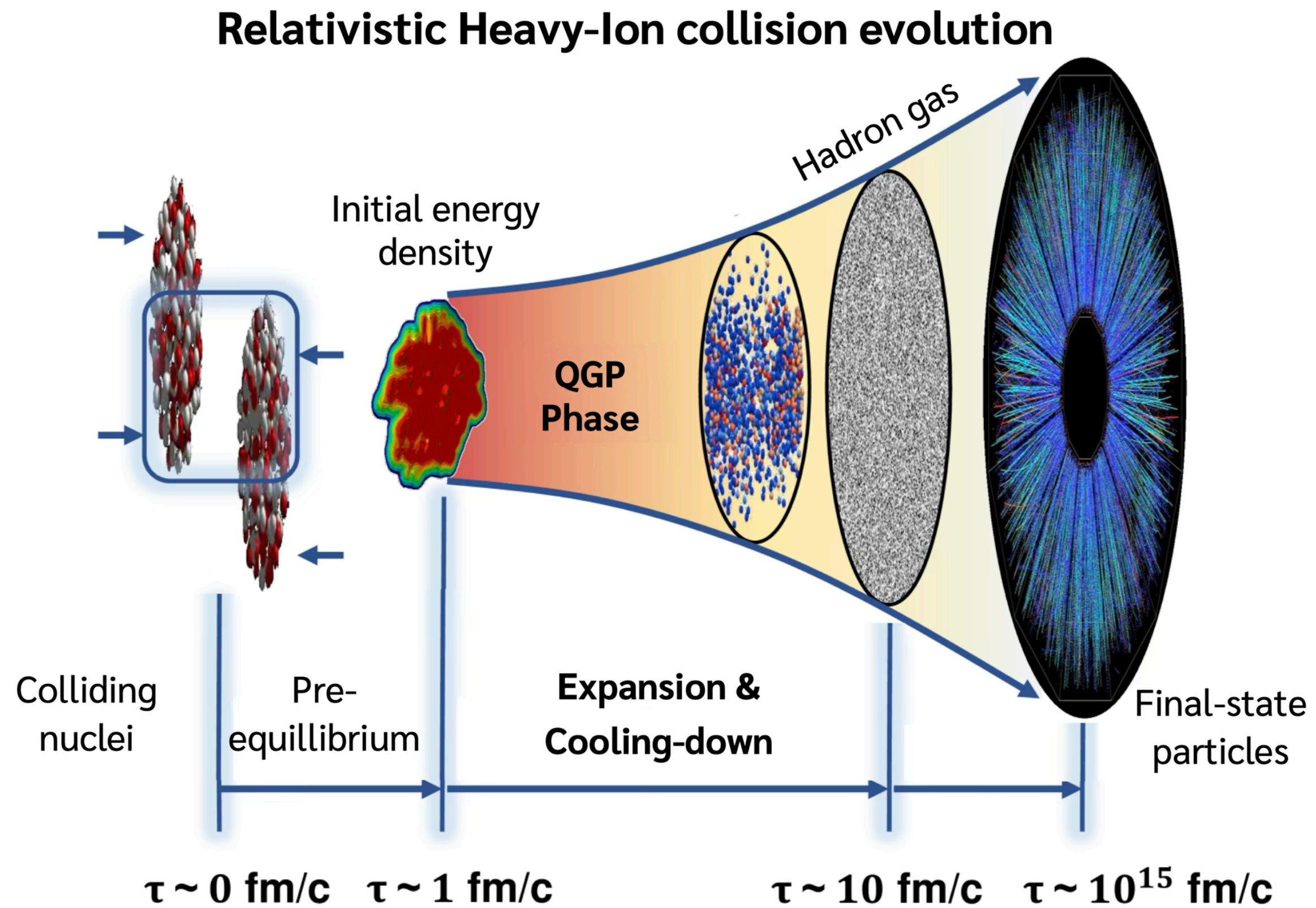
- Simulation of a heavy-ion event implies **medium-induced modifications** to a **vacuum reference without considering the QGP itself**





# The Ridge

- Global event from a heavy-ion collision hints at a **fluid-like** behaviour: **ridge presence**

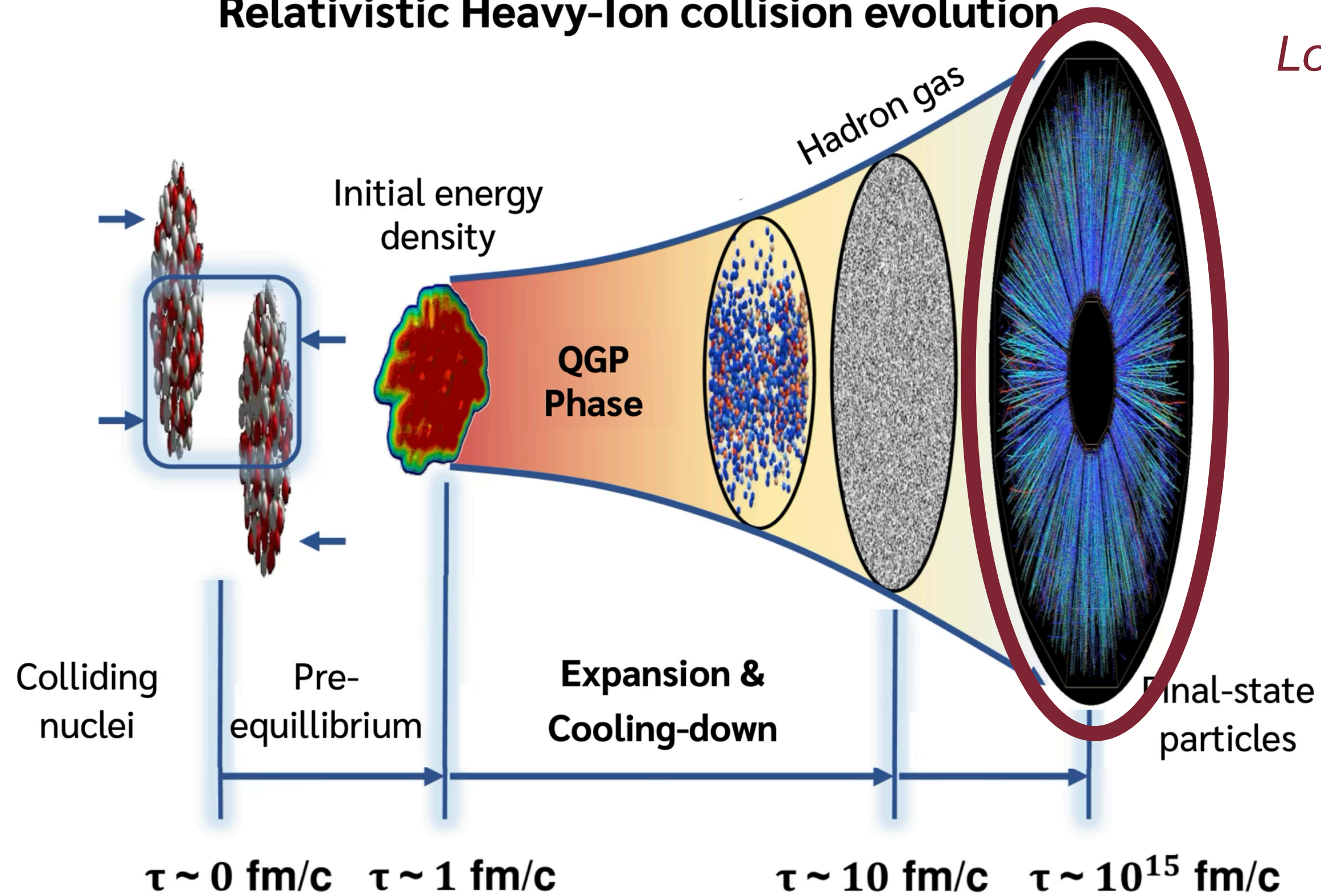




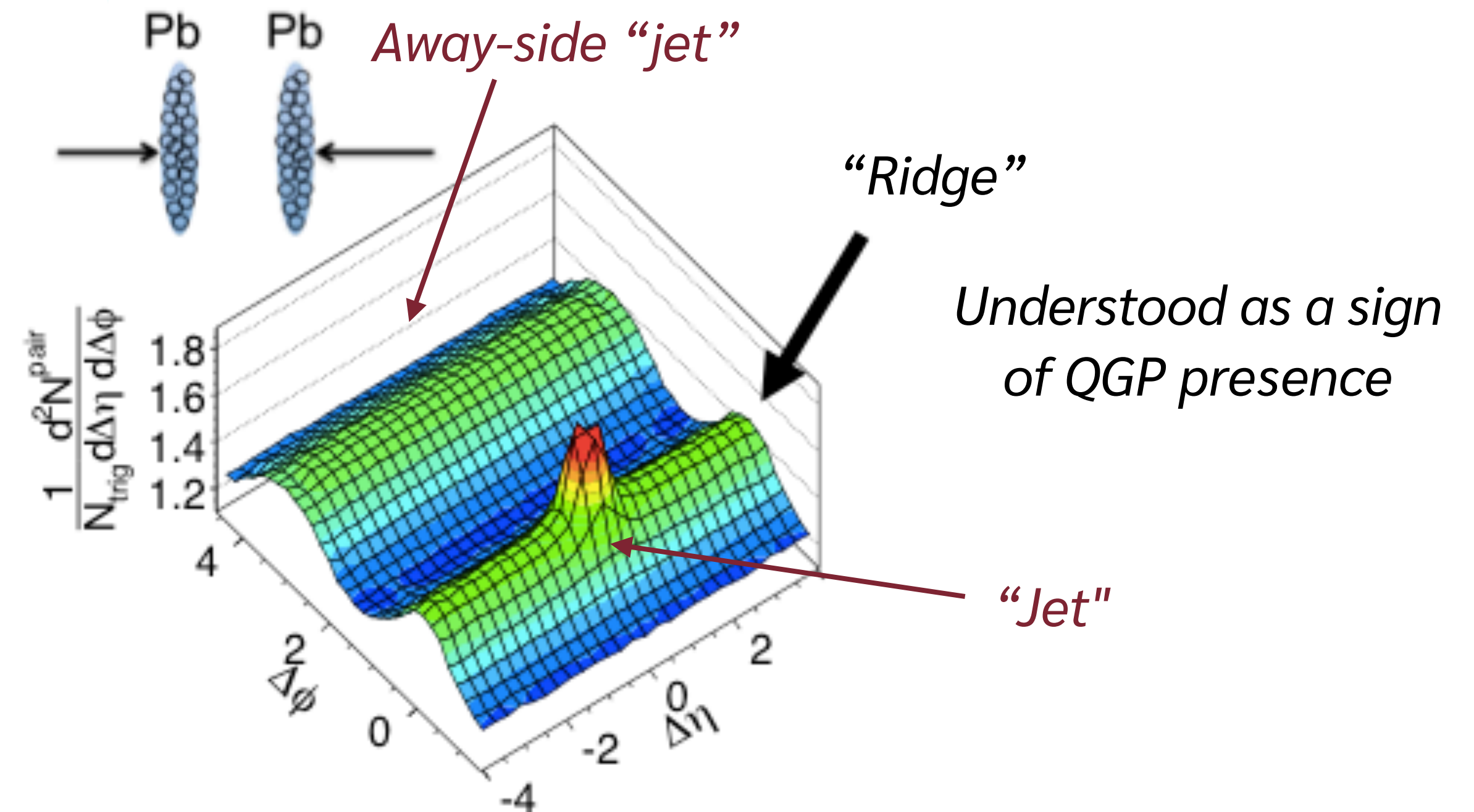
# The Ridge

- Global event from a heavy-ion collision hints at a **fluid-like** behaviour: **ridge presence**

## Relativistic Heavy-Ion collision evolution



*Look to the 2-particle correlation of a heavy-ion event*

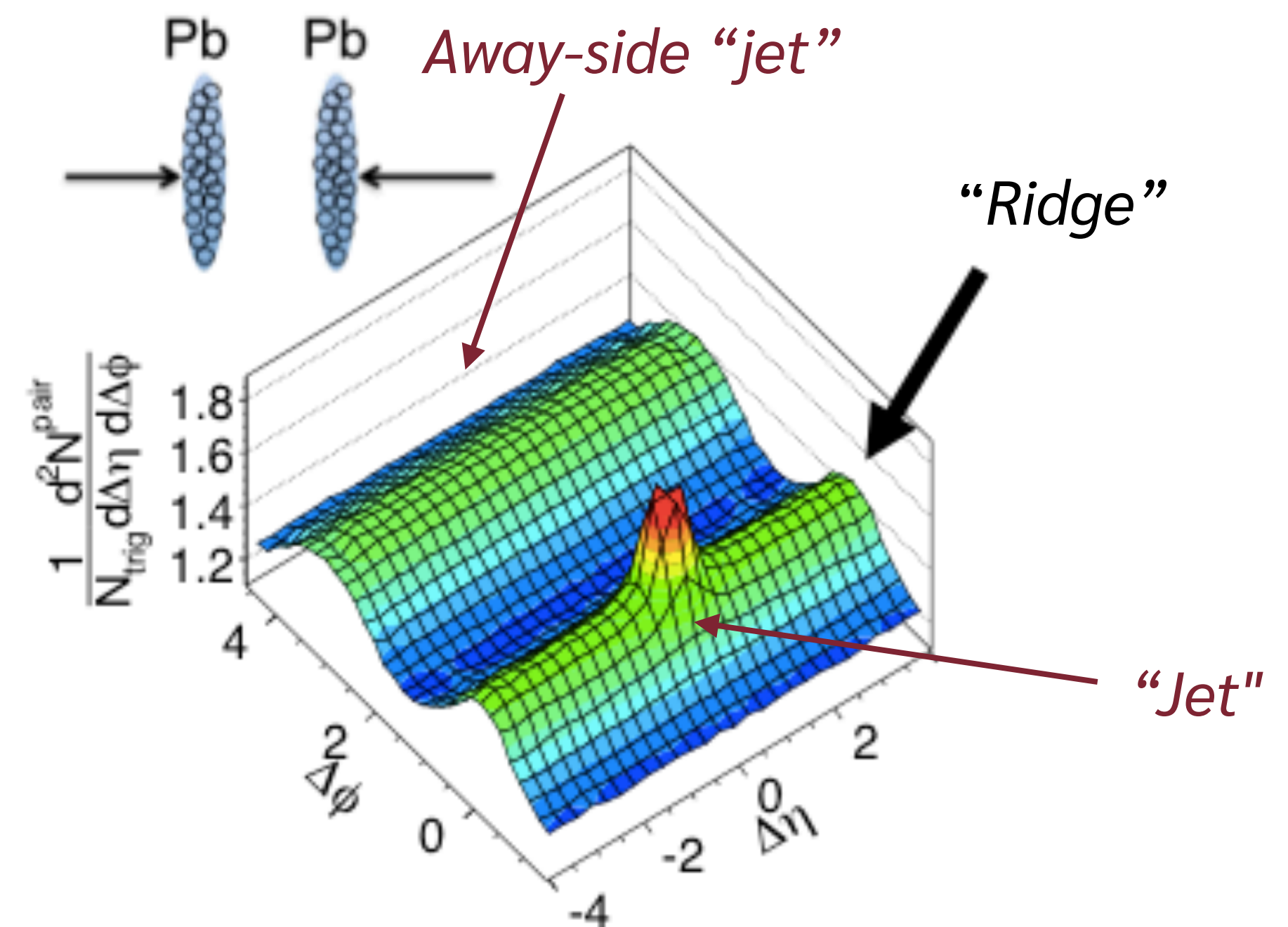
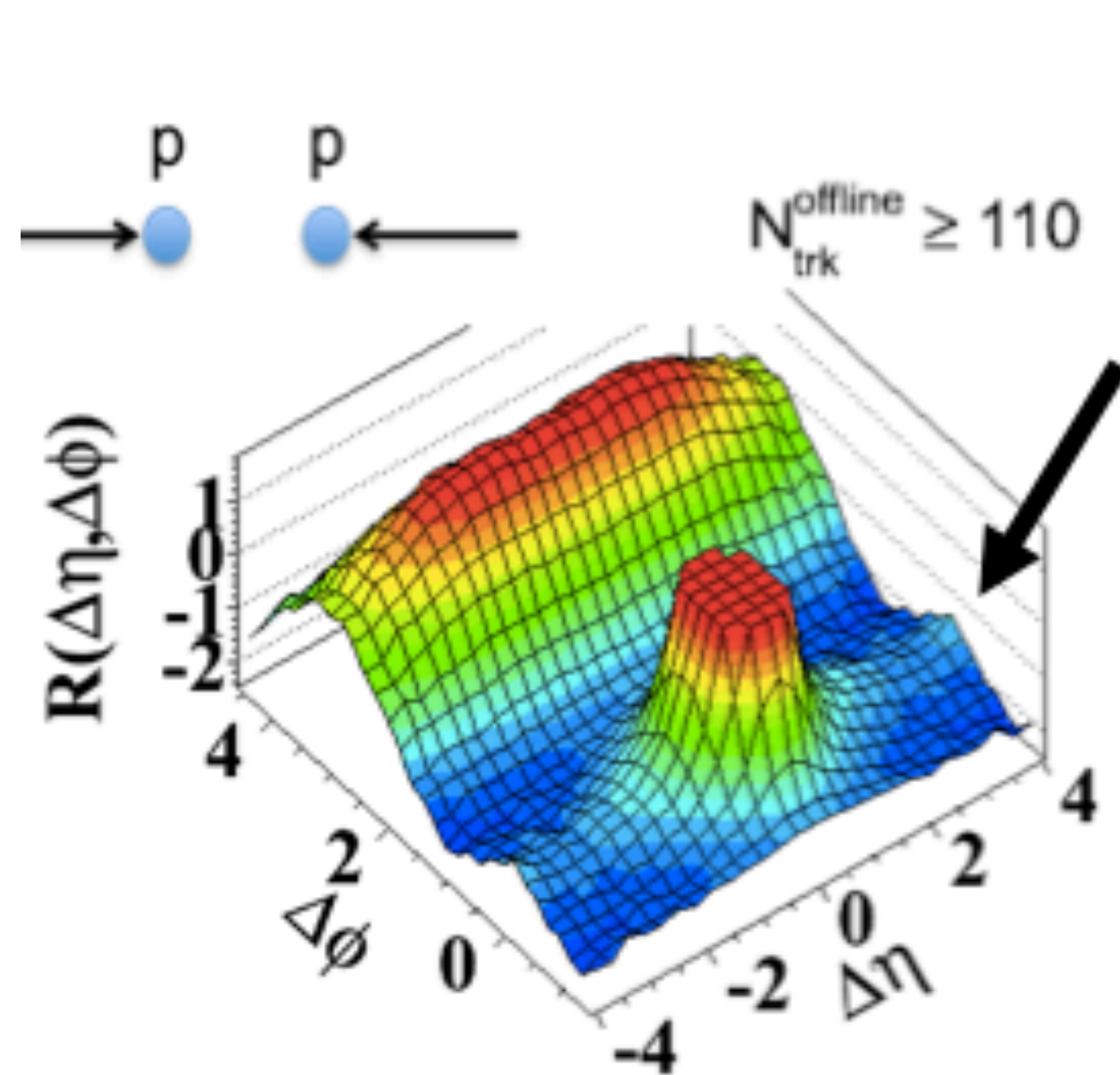




# The Ridge

- Also visible in small systems, where QGP formation not expected

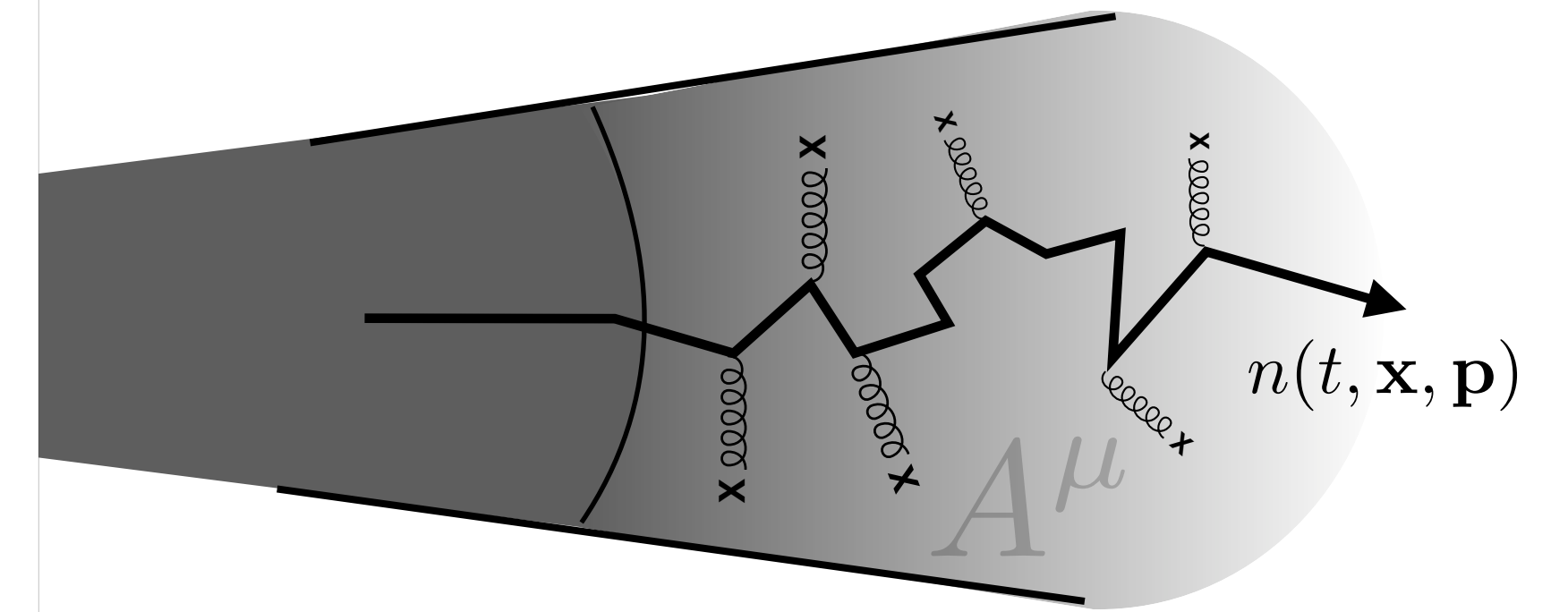
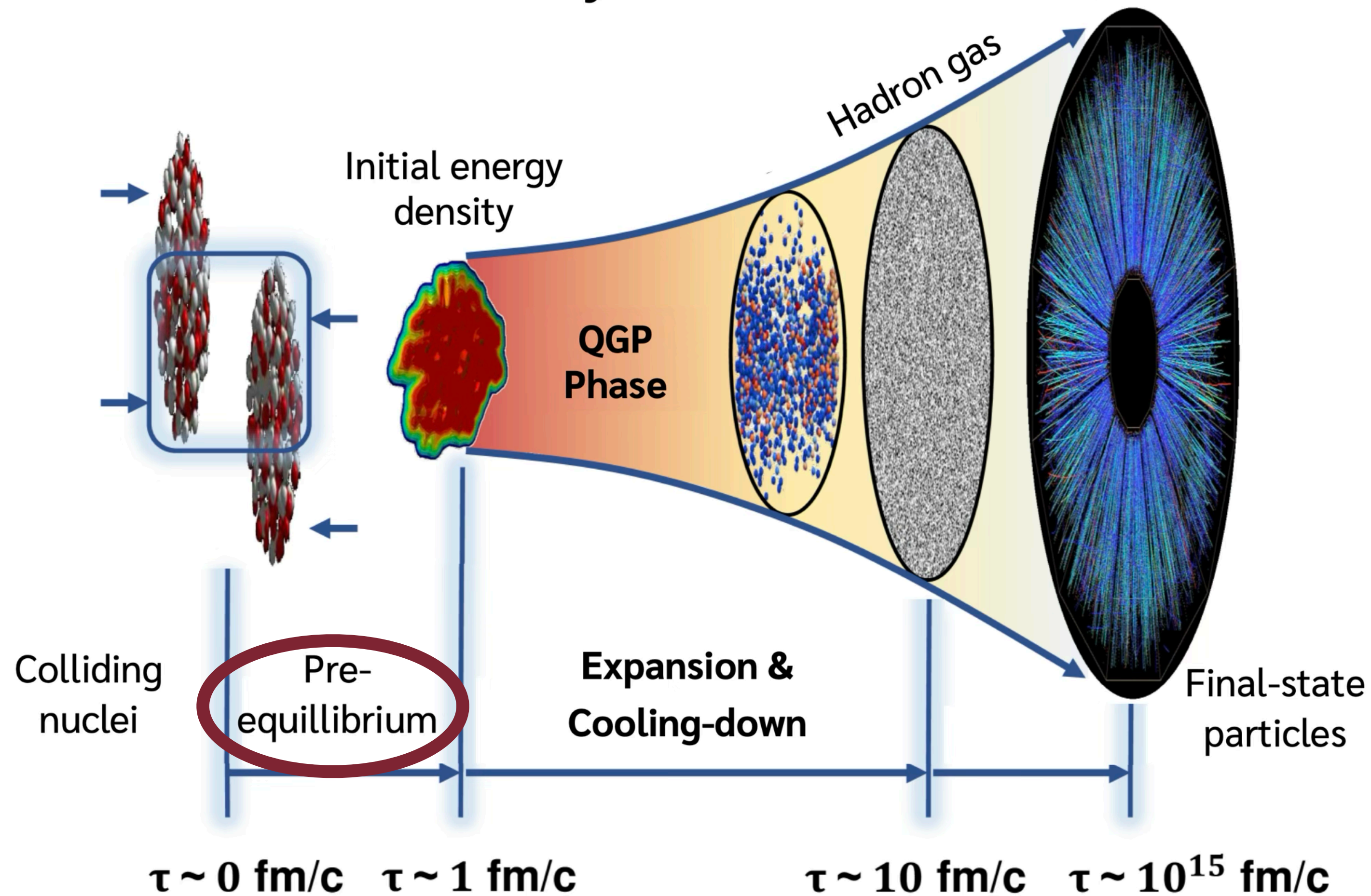
*High-multiplicity proton-proton event also display QGP-like features??*





# Pre-QGP

## Relativistic Heavy-Ion collision evolution



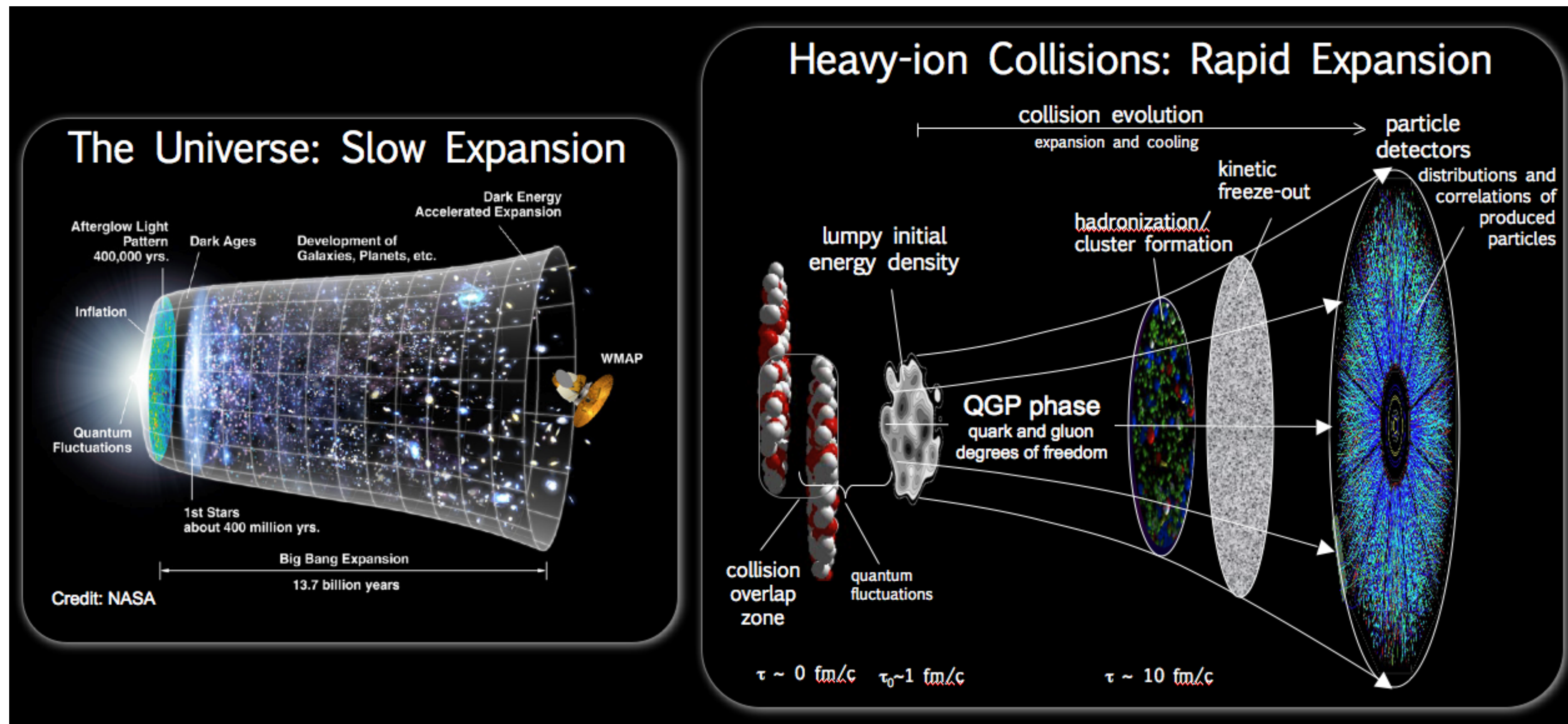
The dynamics of the **pre-equilibrium** phase of Heavy Ion Collisions can have a **significant effect** in jet observables.

This extremely brief phase of the collision, called "**GLASMA**", is amenable to a description in terms of classical fields.



# QGP: Universe to the Laboratory

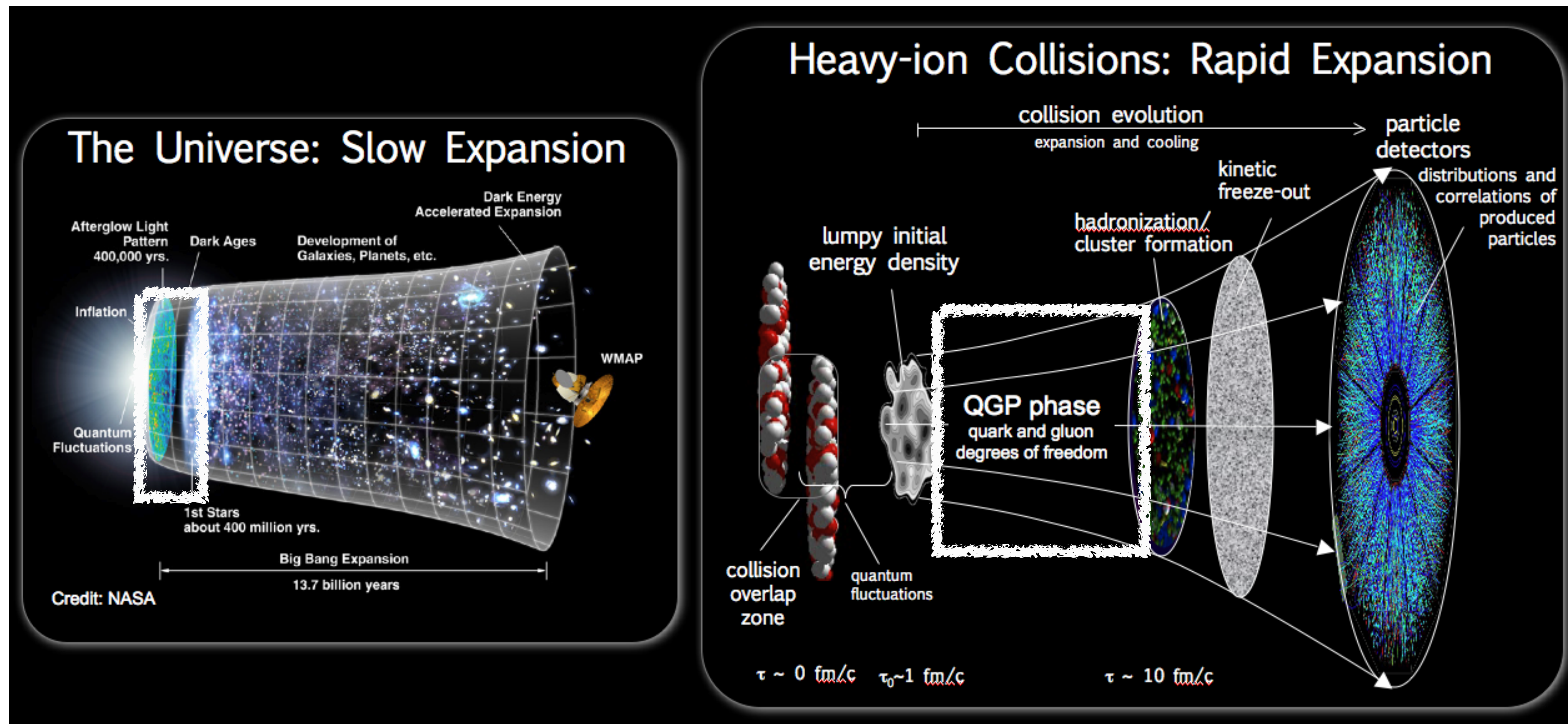
- QGP Phase was also the primordial state of our Universe





# QGP: Universe to the Laboratory

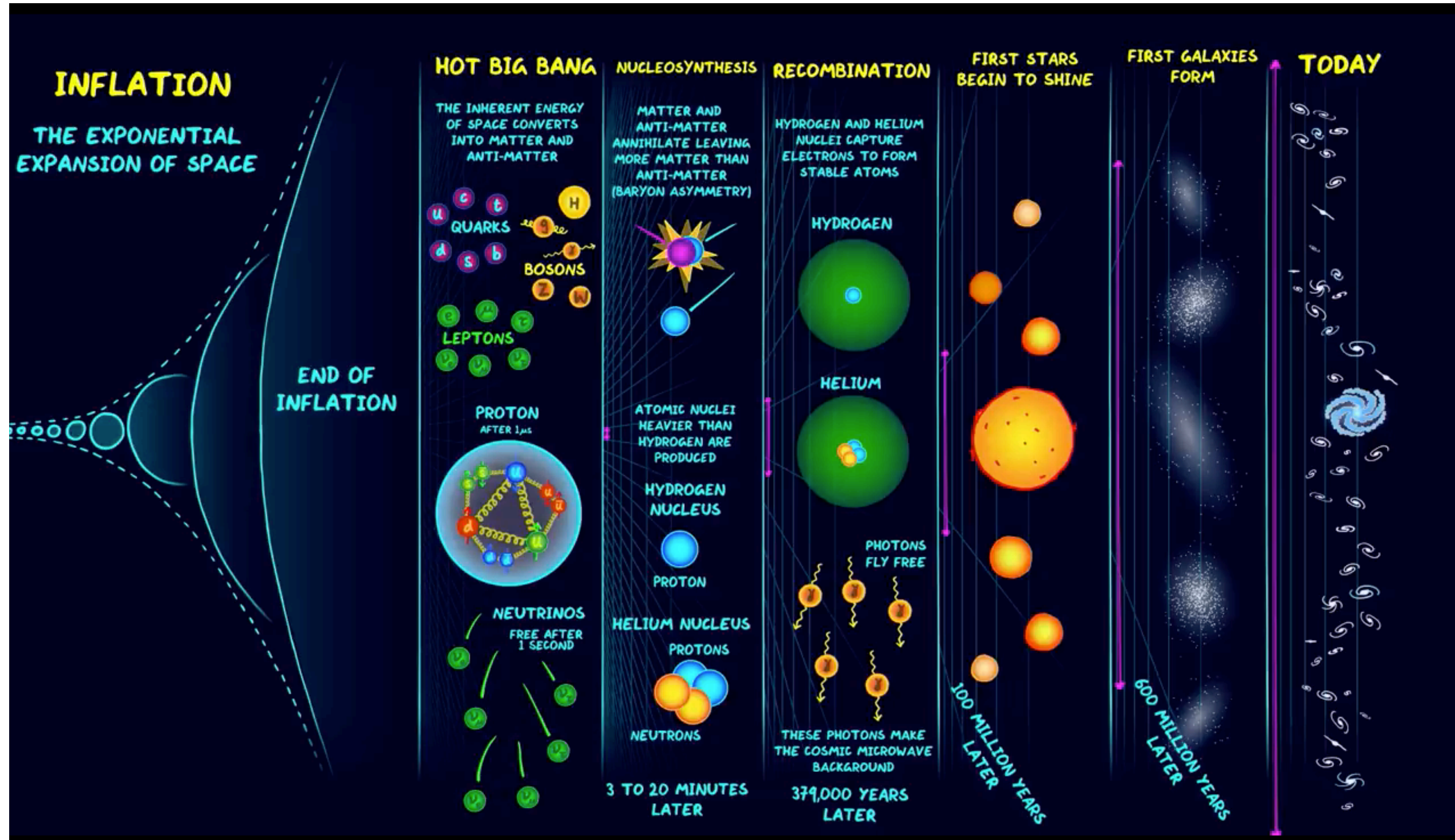
- QGP Phase was also the primordial state of our Universe





# Cosmo Evolution

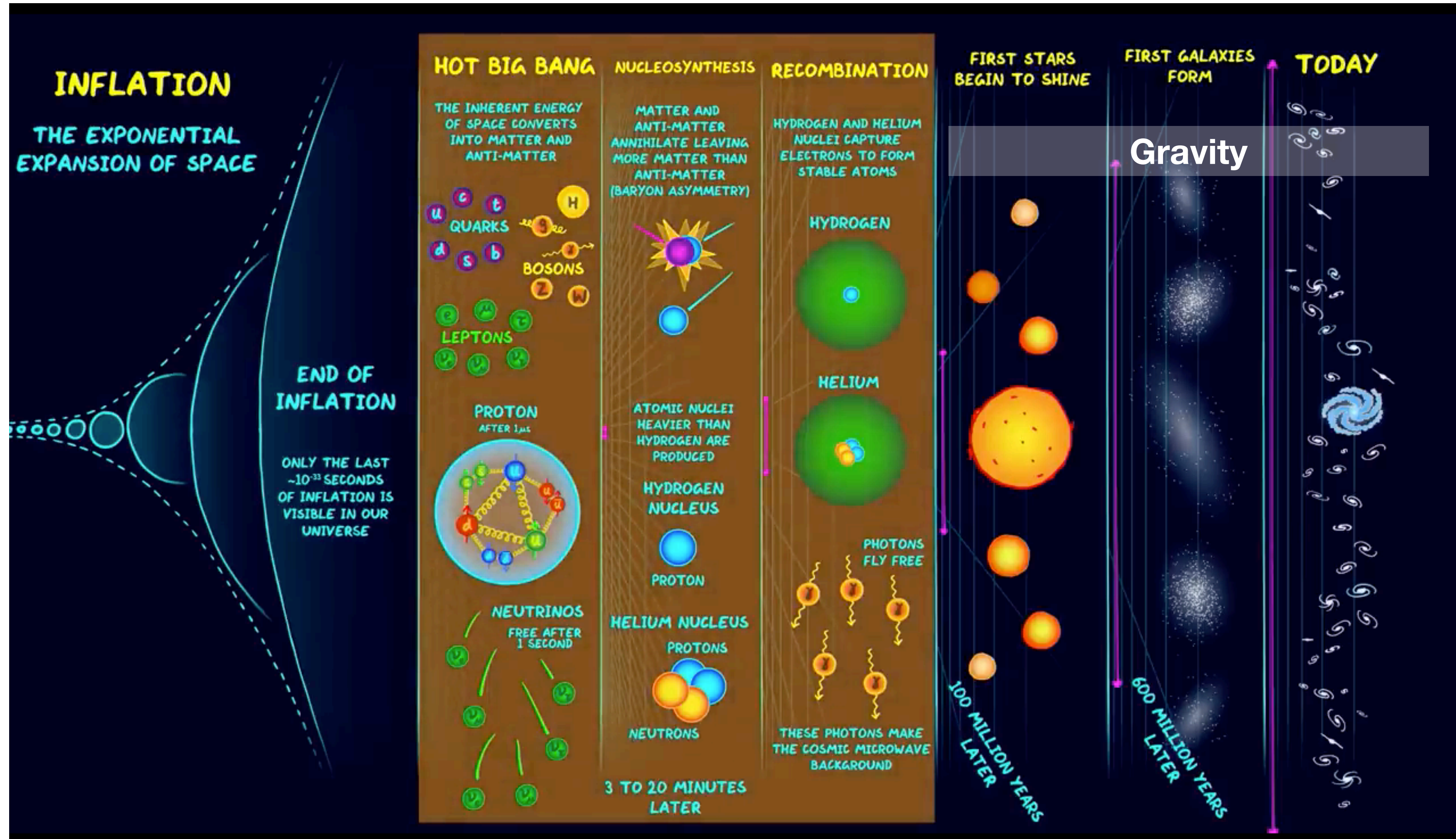
?





# Cosmo Evolution

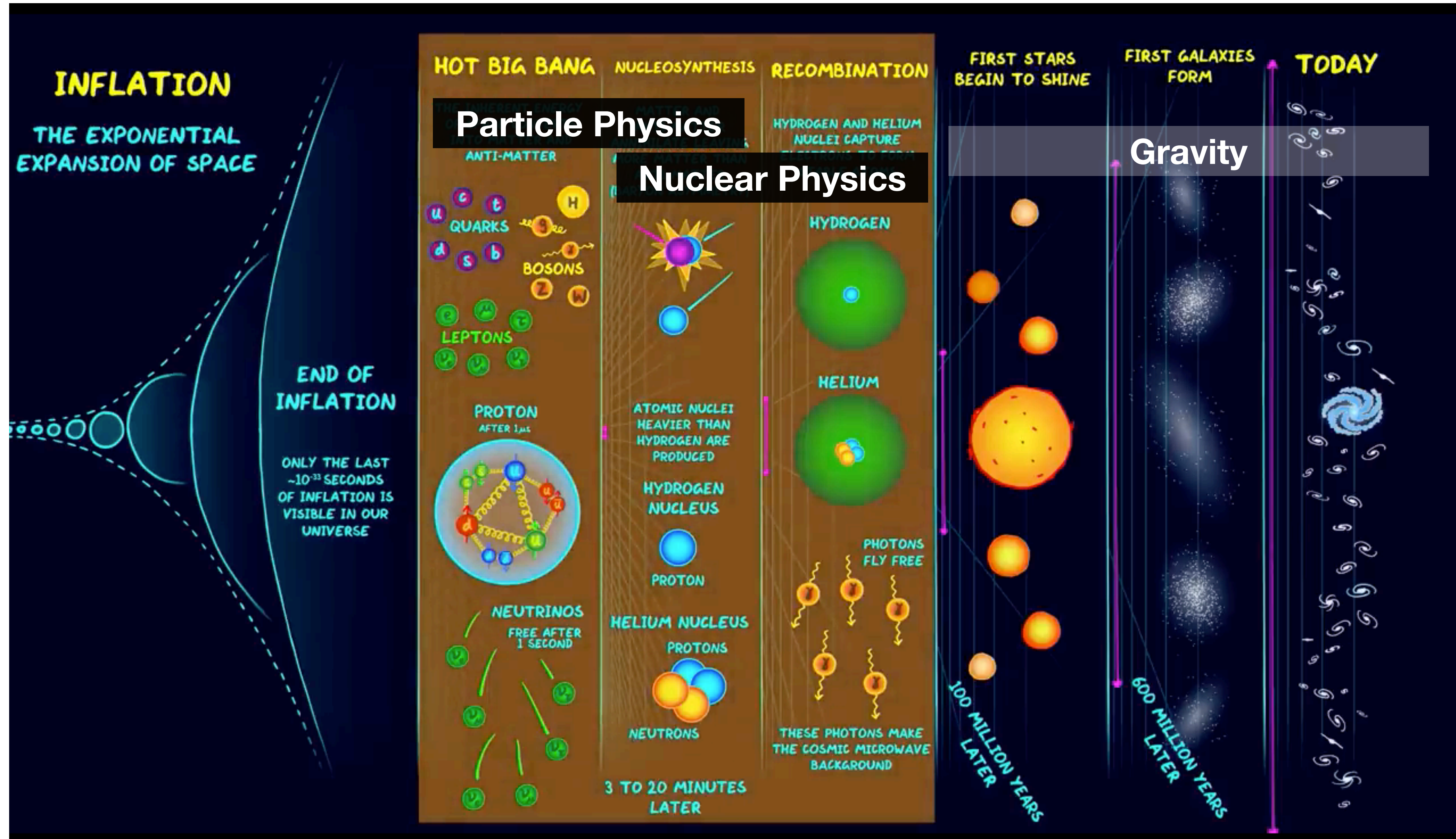
?





# Cosmo Evolution

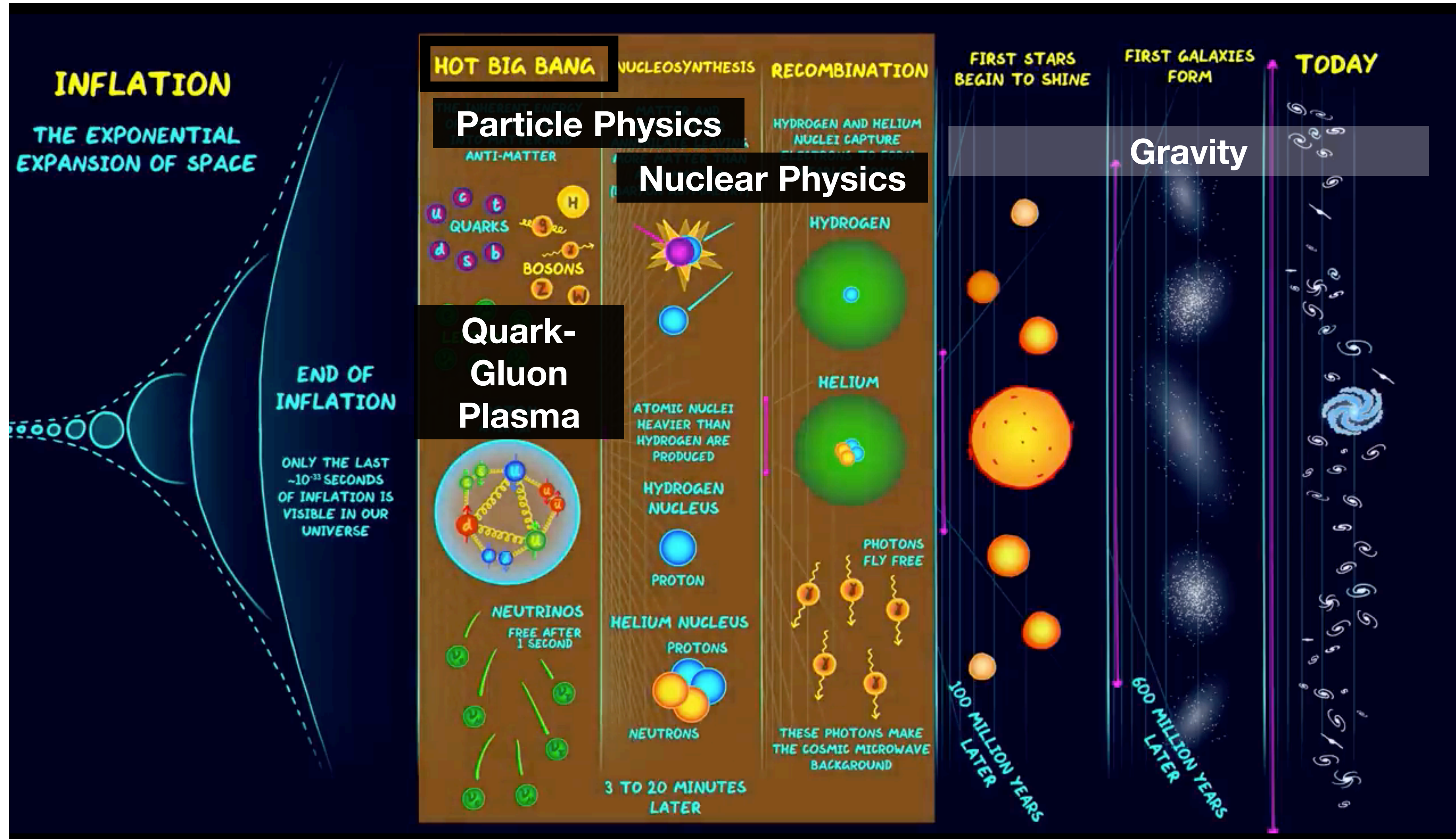
?





# Cosmo Evolution

?





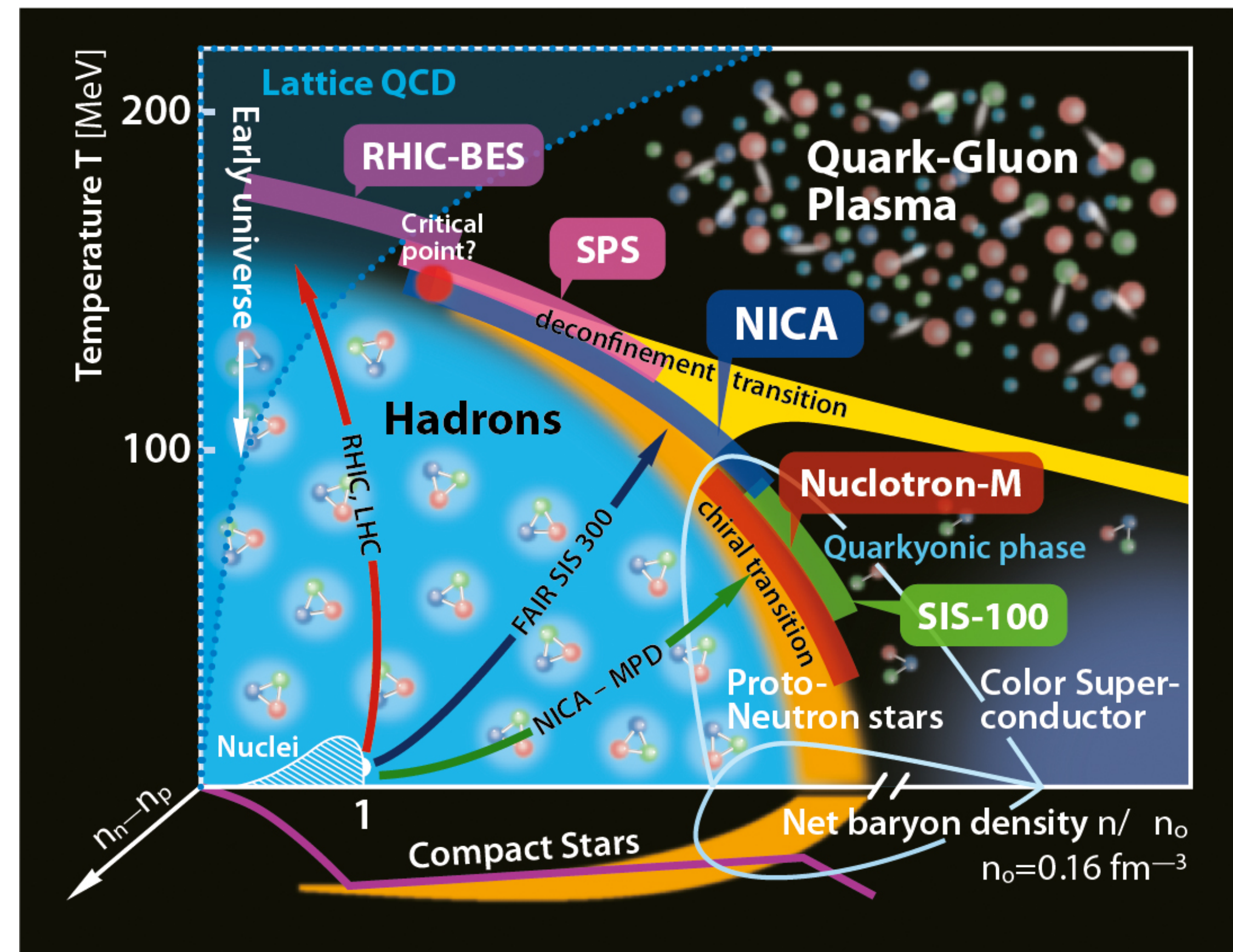
# QCD high density

- Exploring the different QCD phase diagram corner

Early Universe  $\longleftrightarrow$  LHC

Critical point searches  $\longleftrightarrow$  BES (RHIC)

Neutron stars  $\longleftrightarrow$  FAIR/NICA





# Compact stars

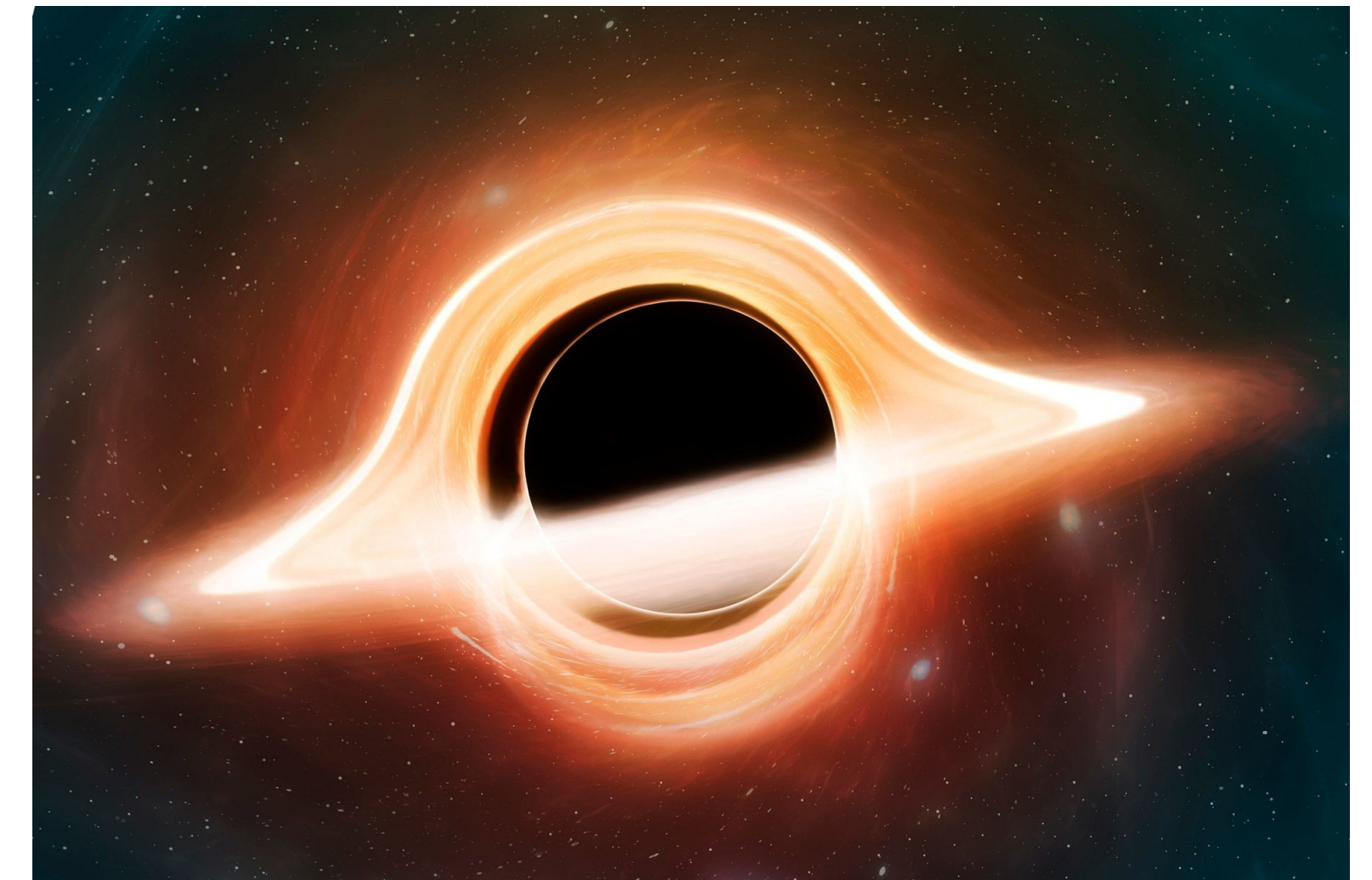
- Astrophysics distinguish between 3 types of compact stars



**White Dwarf**  
(Collapse of low mass stars)  
e.g: our Sun



**Neutron Stars**  
(Collapse of massive stars)



**Black Holes**  
(Catastrophic collapse of massive stars)



# Compact stars

- Astrophysics distinguish between 3 types of compact stars

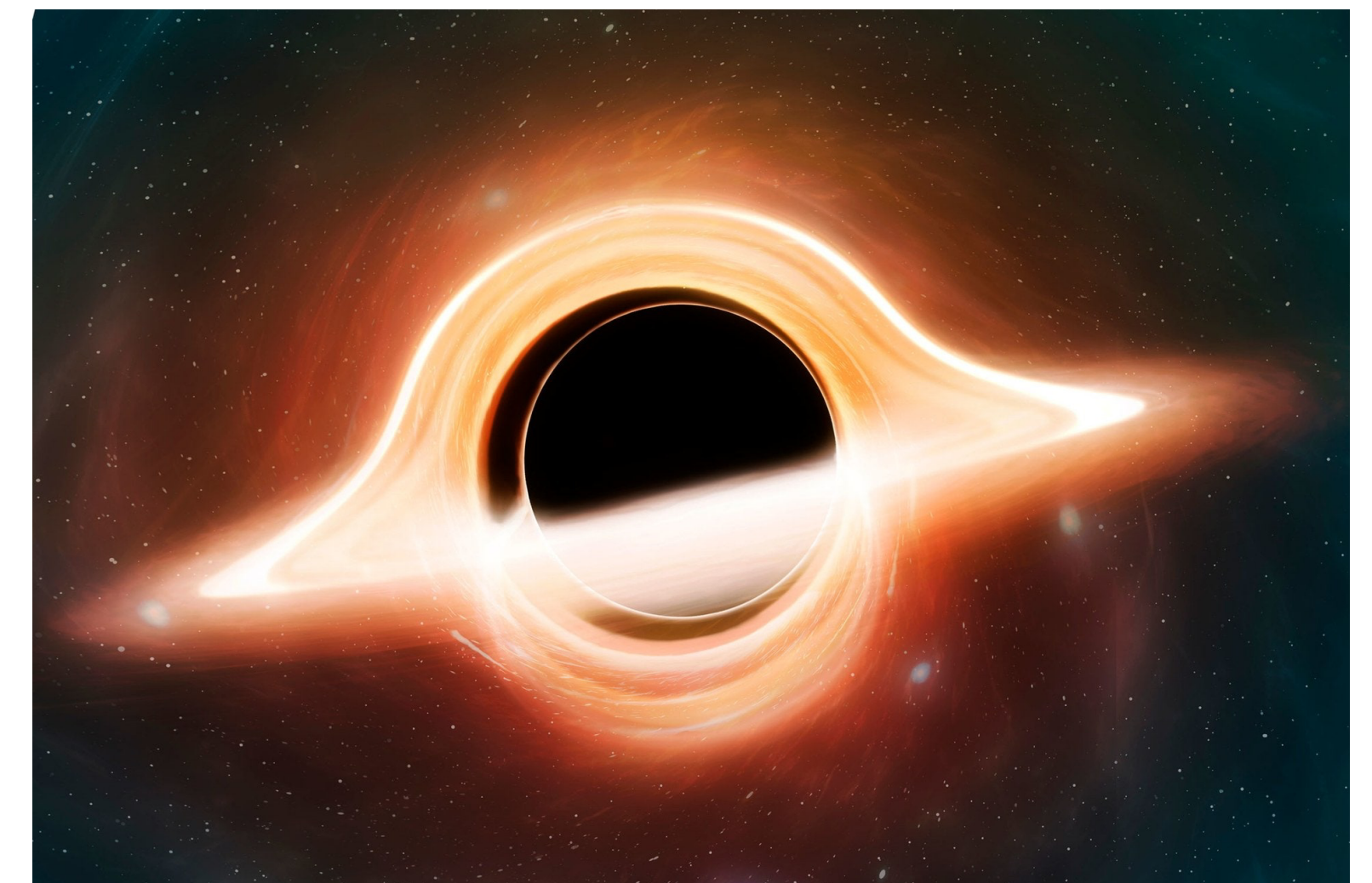


**White Dwarf**  
(Collapse of low mass stars)  
e.g: our Sun



**Neutron Stars**  
(Collapse of massive stars)

Particularly interesting for QCD



**Black Holes**  
(Catastrophic collapse of massive stars)

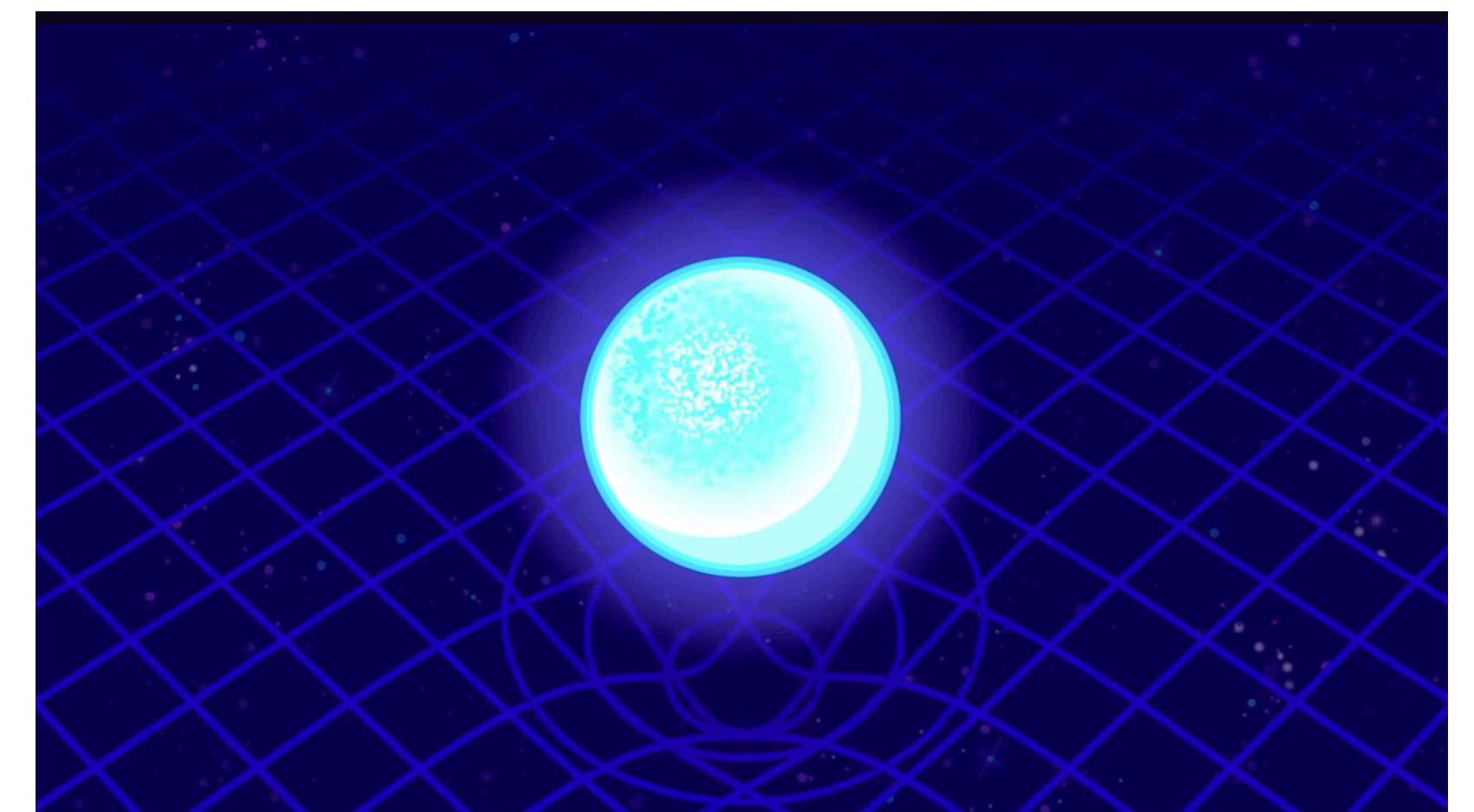
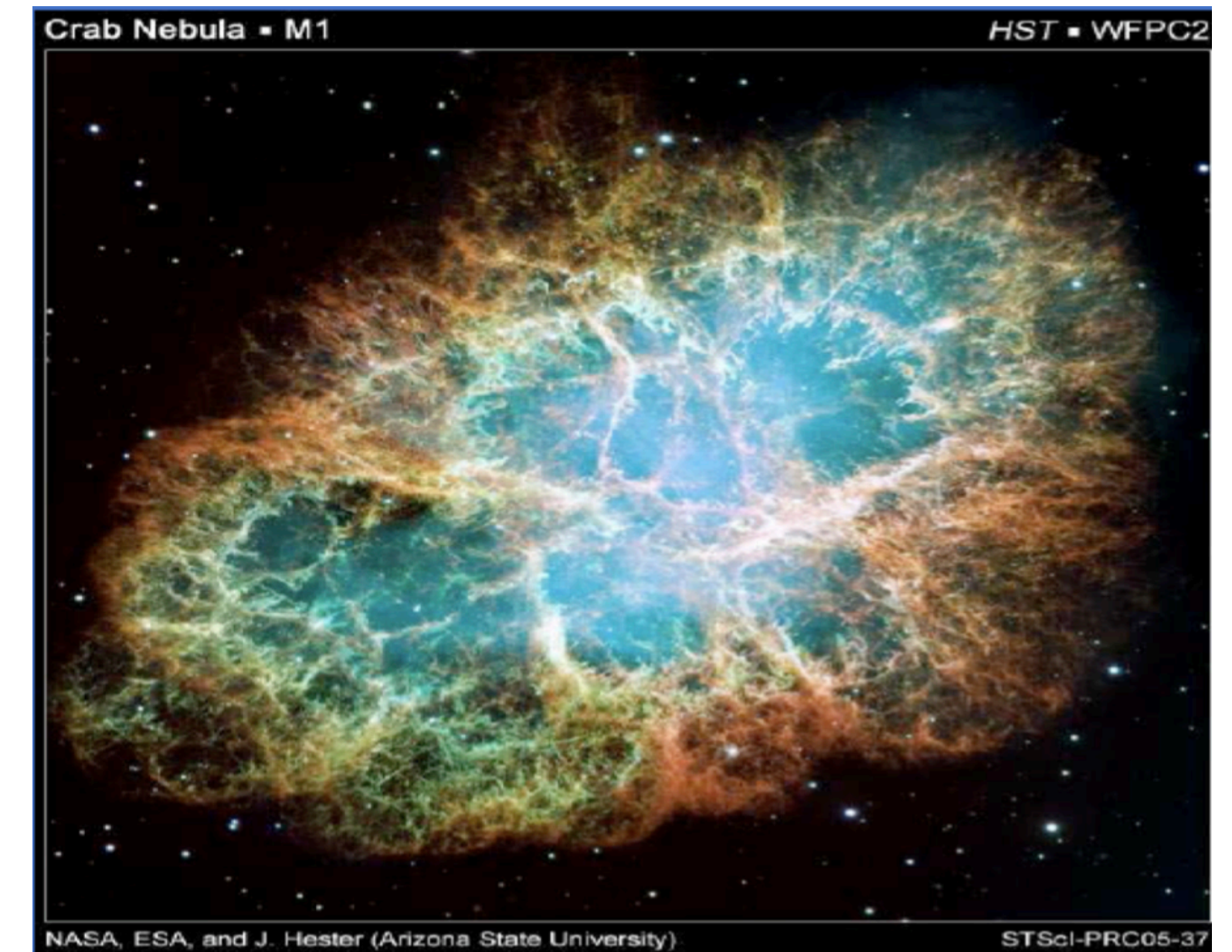


# Neutron Stars

- When fusion of the stars ends (production of iron), gravitational collapse pushes electrons to fuse with protons
- Result: super nova explosion
- Remnant: Neutron star

**$M \sim 1-2 M_{\text{sun}}, R \sim 10 \text{ Km}$**

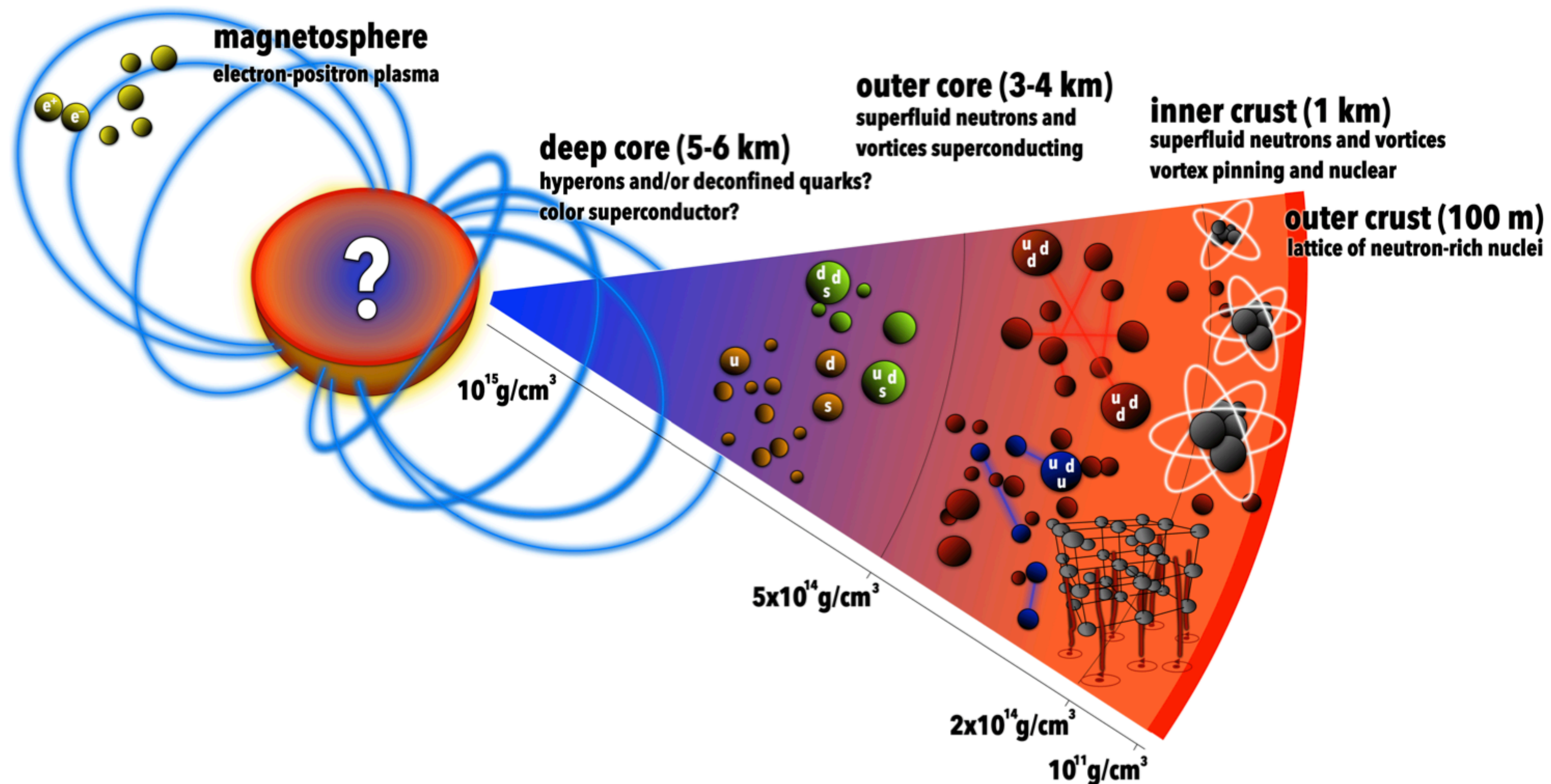
**Strongest gravitational field  
(next to black holes)**





# Neutron Stars

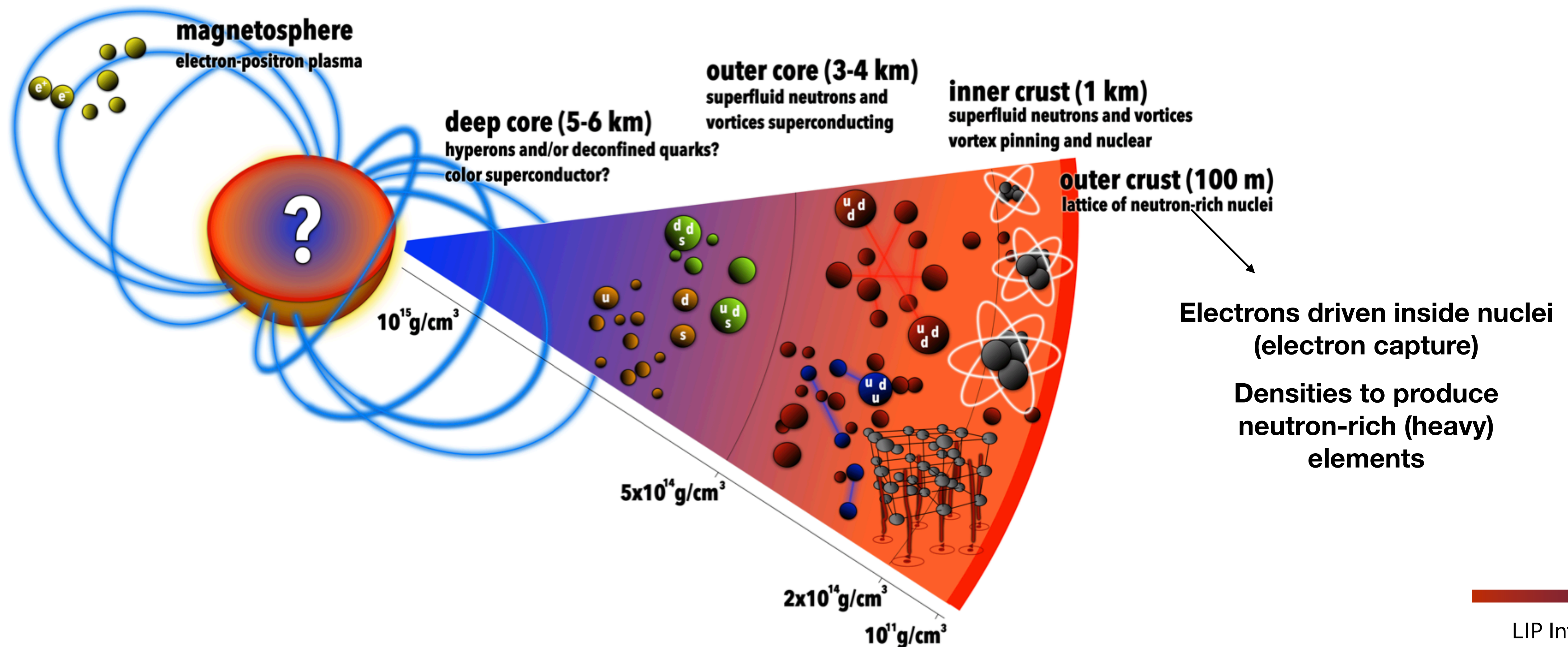
- Internal structure and composition





# Neutron Stars

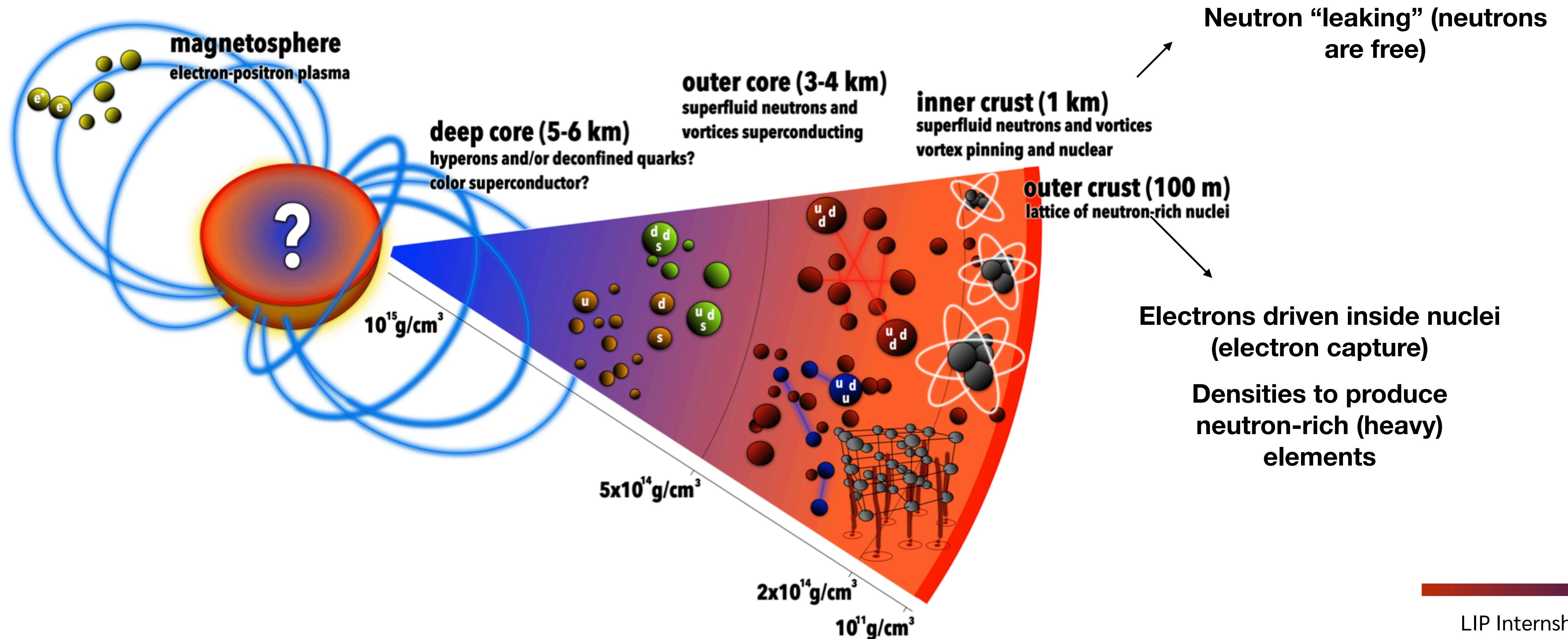
- Internal structure and composition





# Neutron Stars

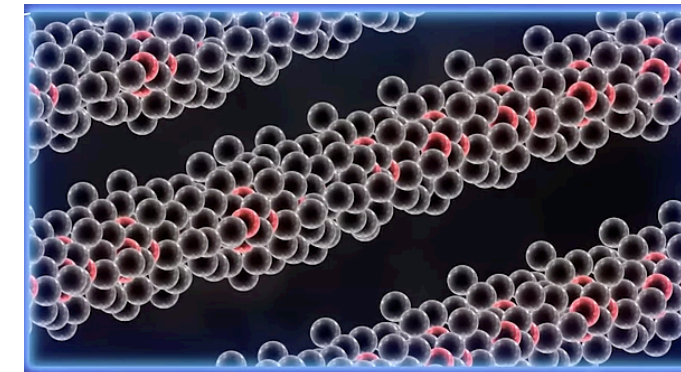
- Internal structure and composition



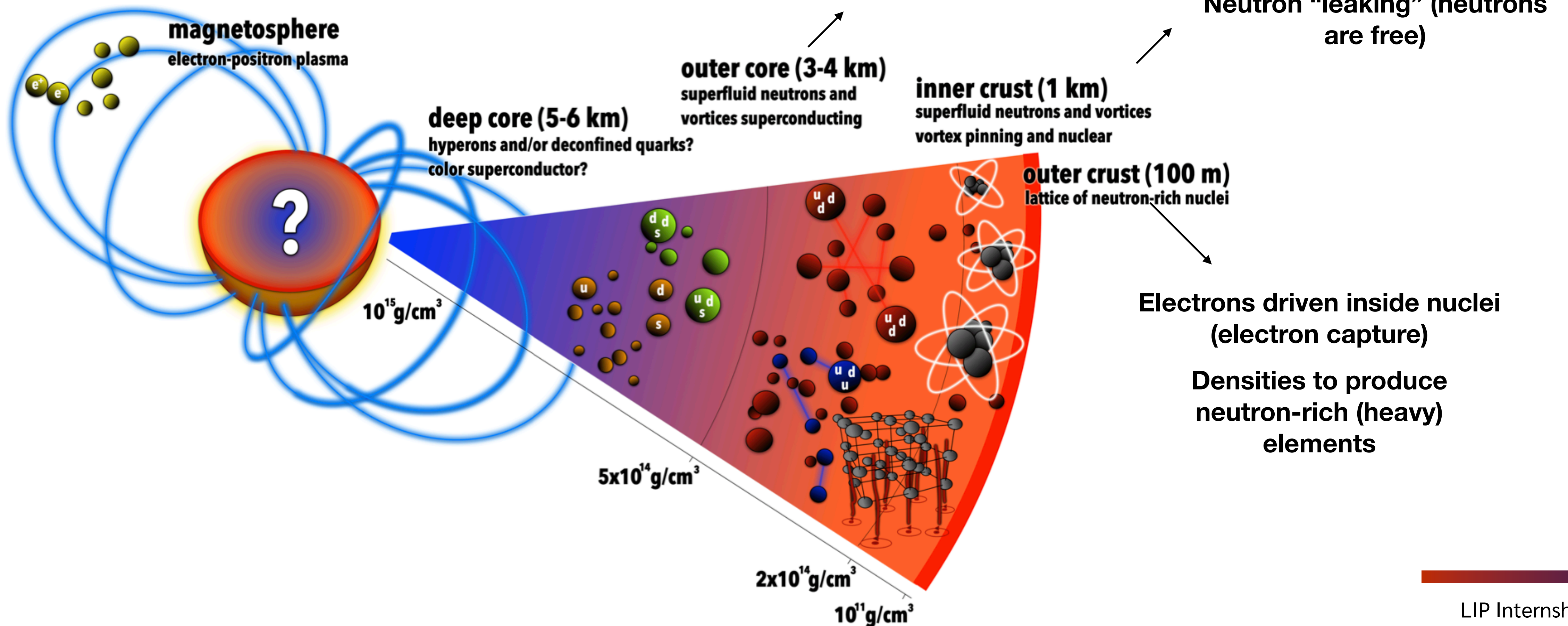


# Neutron Stars

- Internal structure and composition



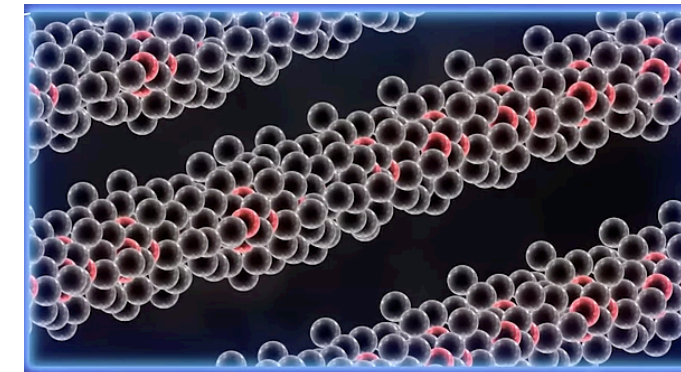
Protons outnumbered by neutrons: nuclear pasta



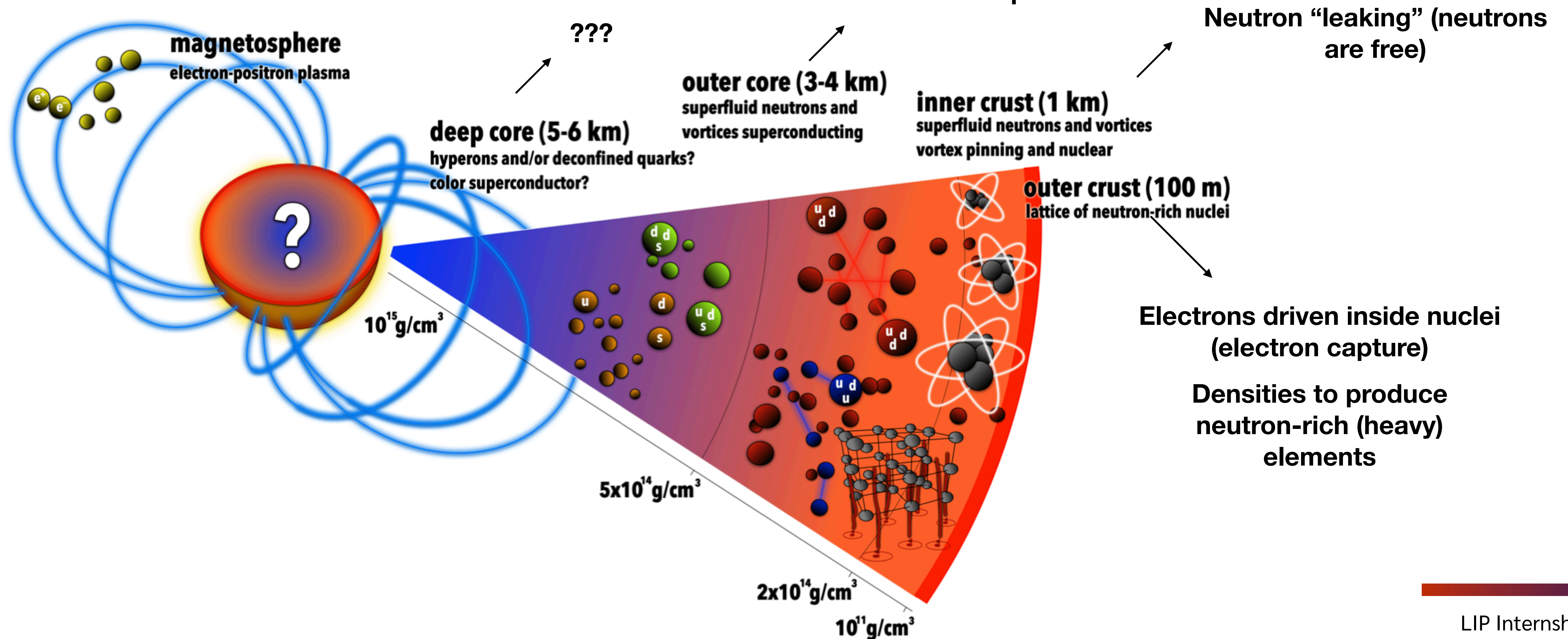


# Neutron Stars

- Internal structure and composition



Protons outnumbered by neutrons: nuclear pasta





# Neutron Stars

- Internal structure and composition
- Inner core is unknown (hadronic, exotic or deconfined matter?)

(Kurkela, Fraga, et al, *Astrophys.J.* 789 (2014) 127)

