# QCD and Heavy-Ion Physics

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LIP

TÉCNICO LISBOA

June 2025

LIP Internships

# What is this talk about?

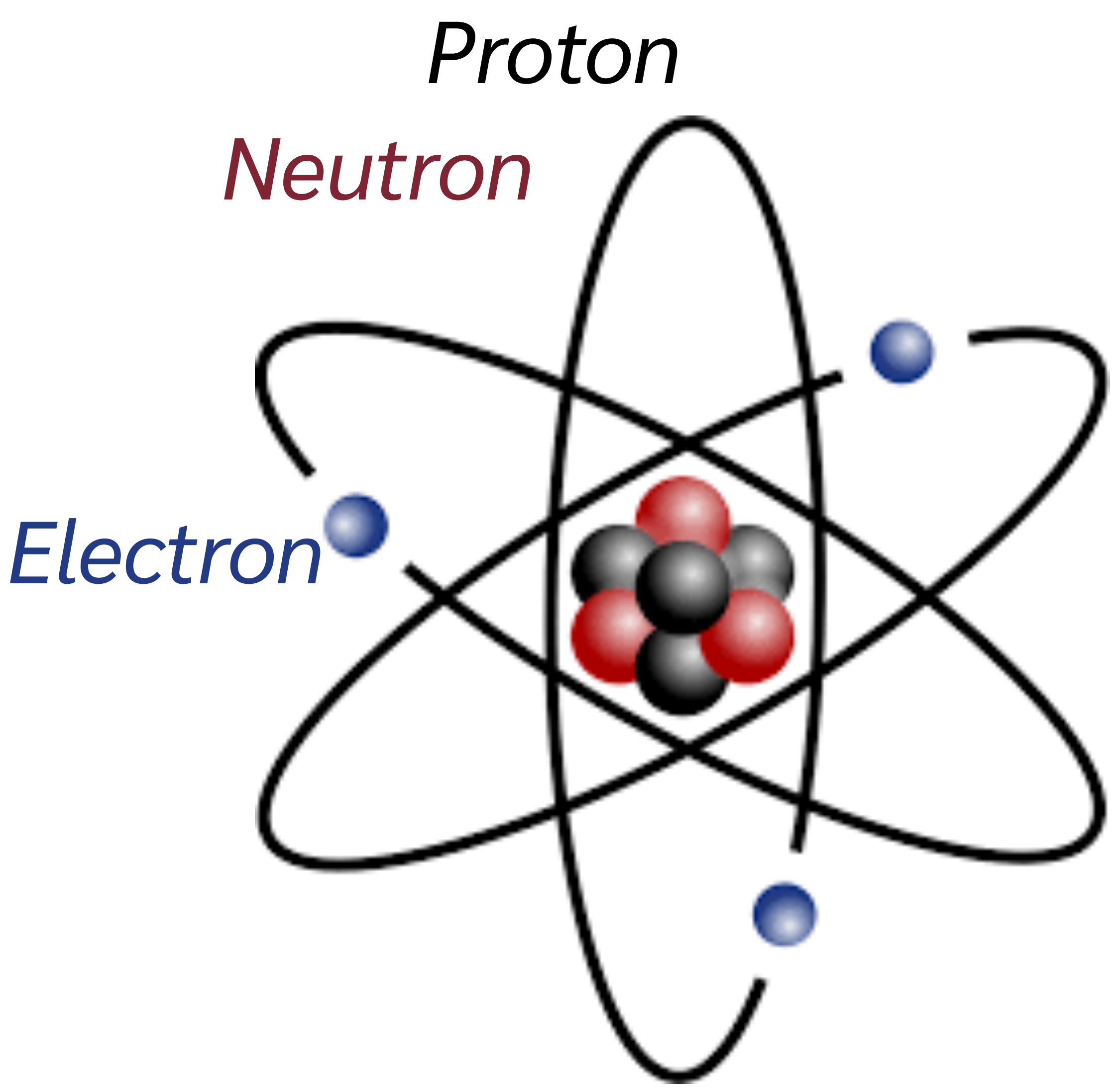
- QCD is more than protons and neutrons
  - Understanding the strong force means exploring new forms of matter.
- Heavy-ion collisions as a QCD laboratory
  - We use energetic ion collisions to create and study extreme QCD environments.
- How do we study a plasma of quarks and gluons?
  - From collective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

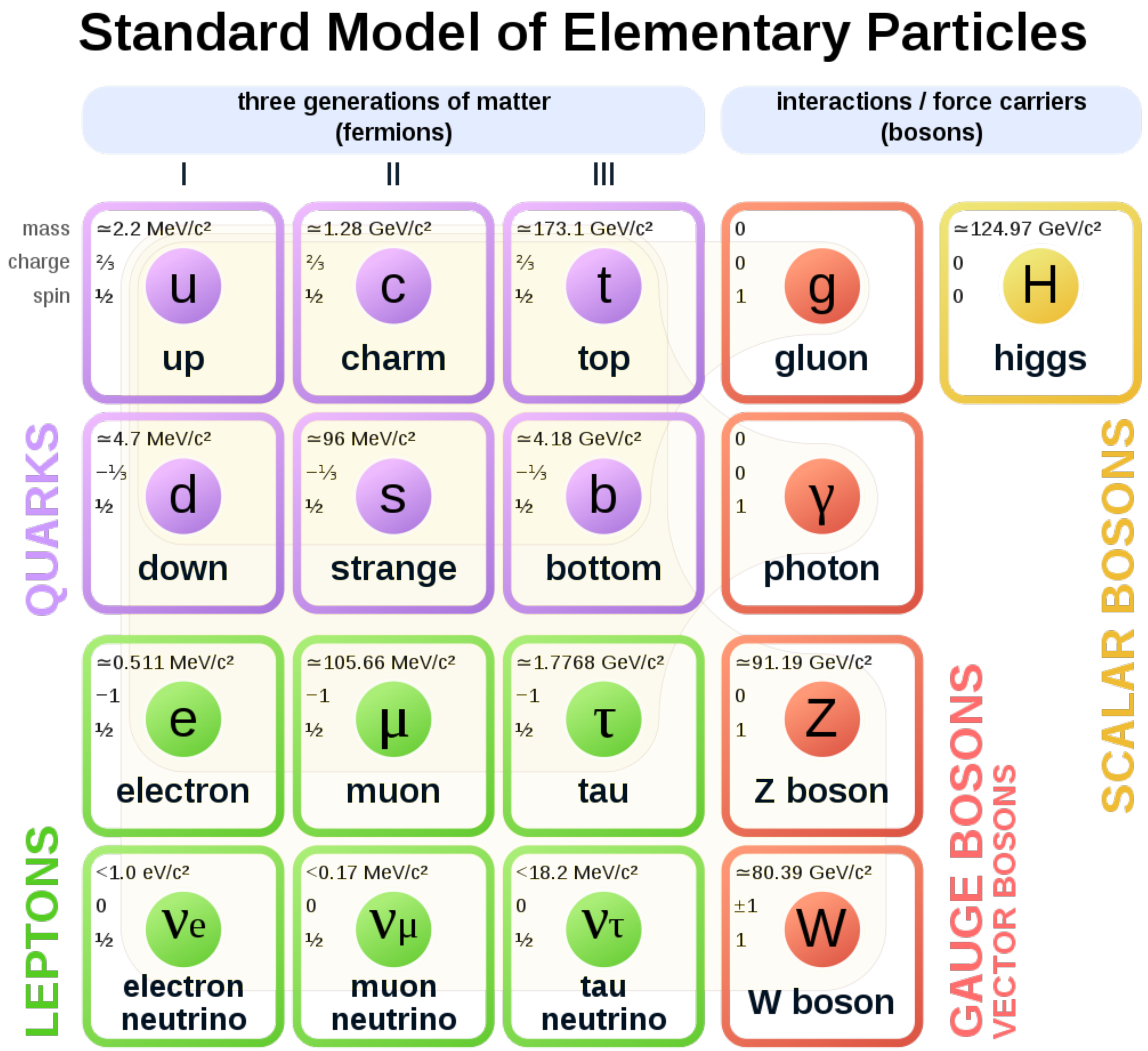
# QCD & The Standard Model

*See J. Varela, June 4th*

# Standard Model

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

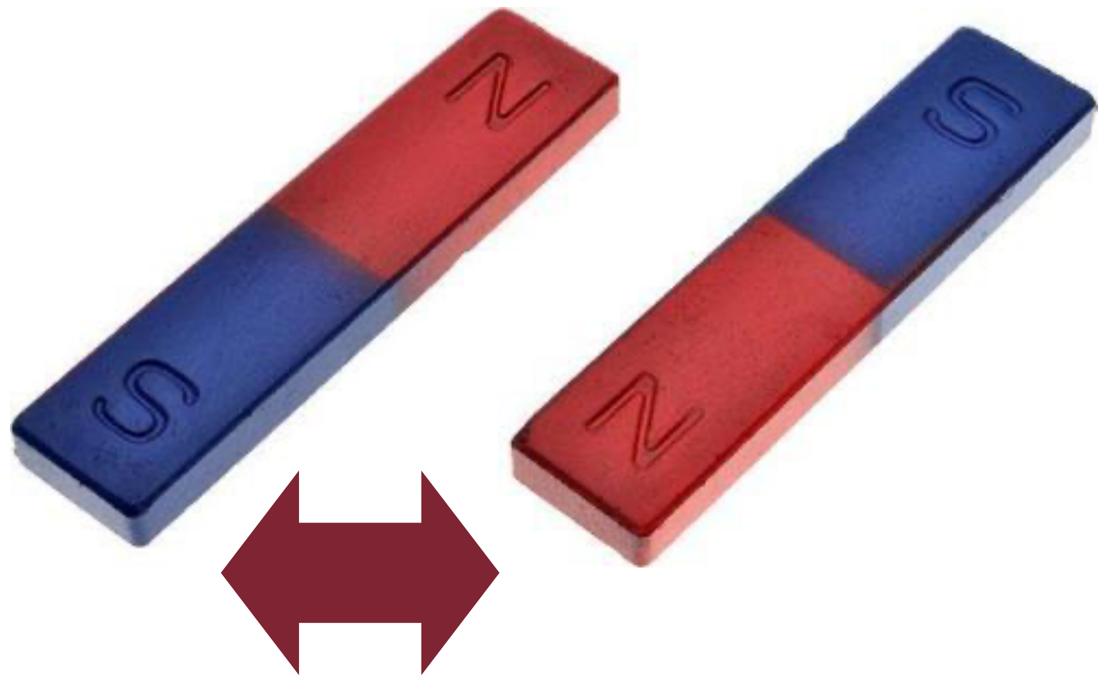


# Standard Model Sectors

- Quantum Electrodynamics

*Increasing "force"*



*Decreasing "force"*

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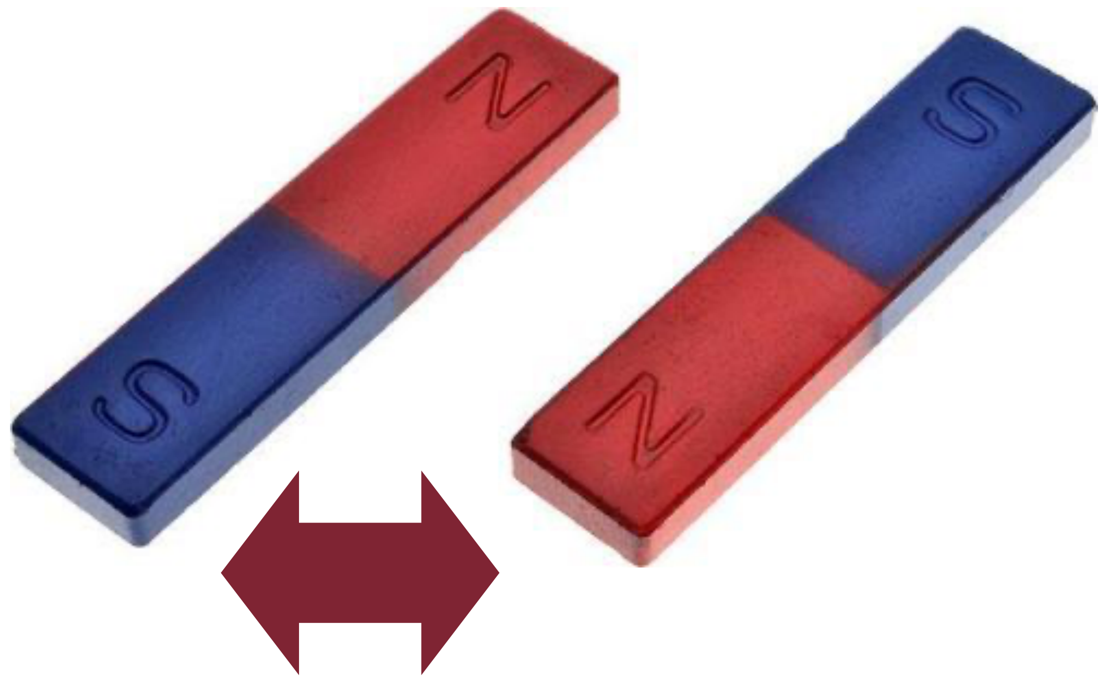
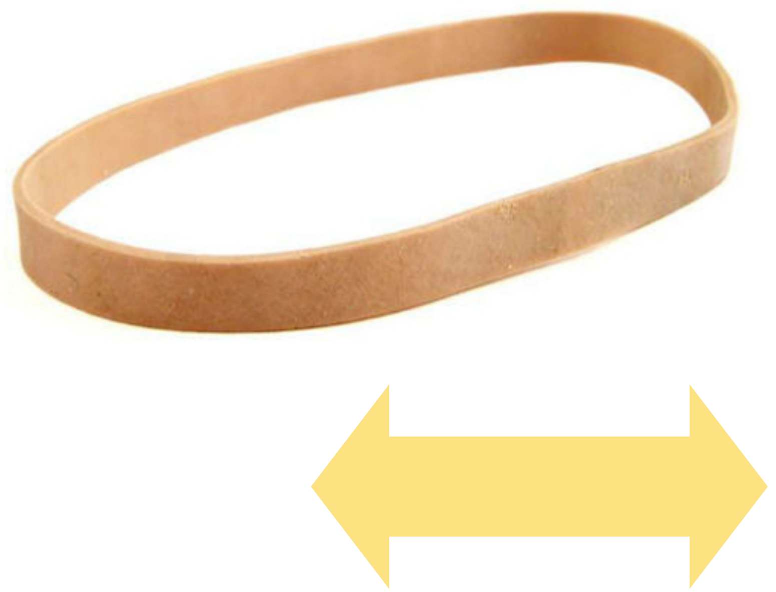



*Decreasing "force"*


- **Quantum Chromodynamics**

*Decreasing "force"*



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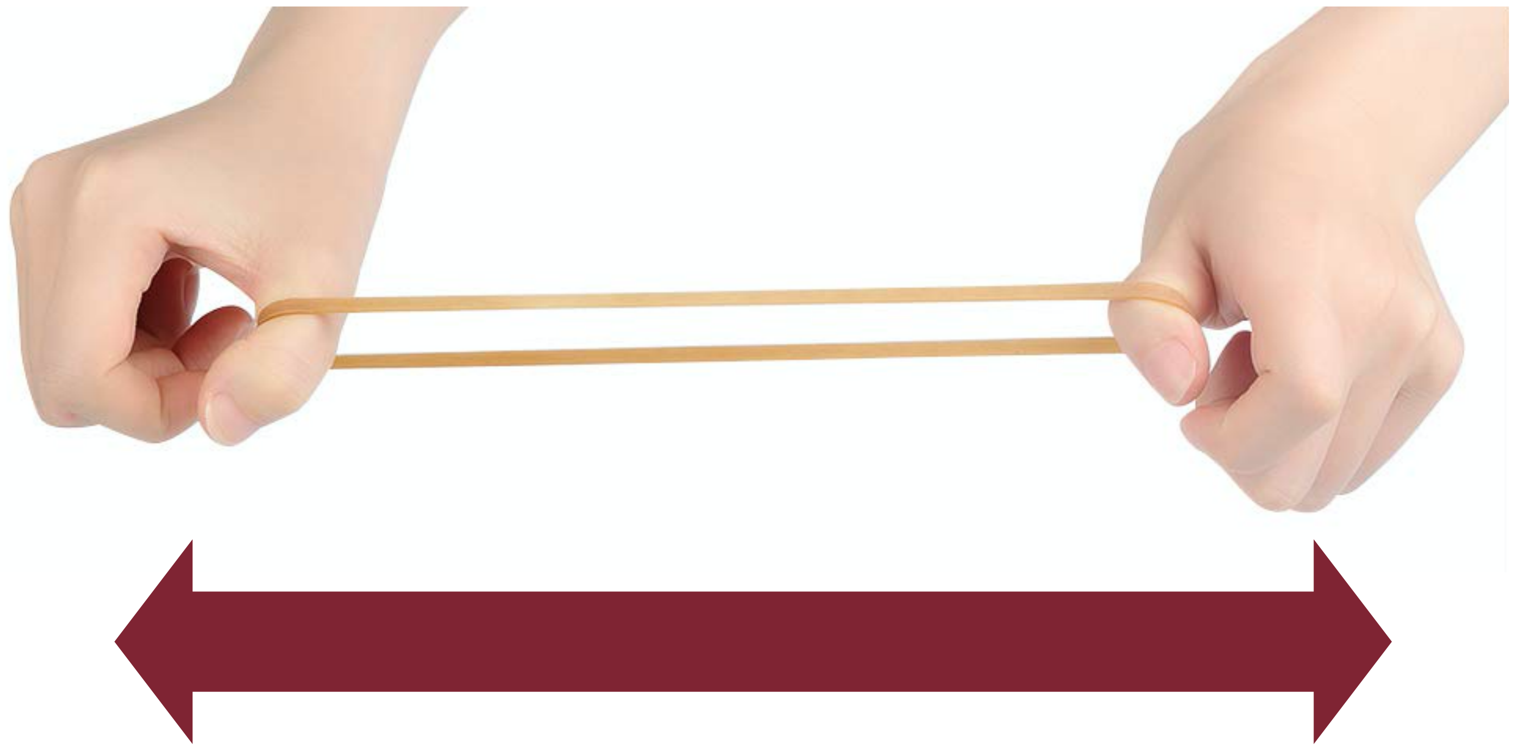
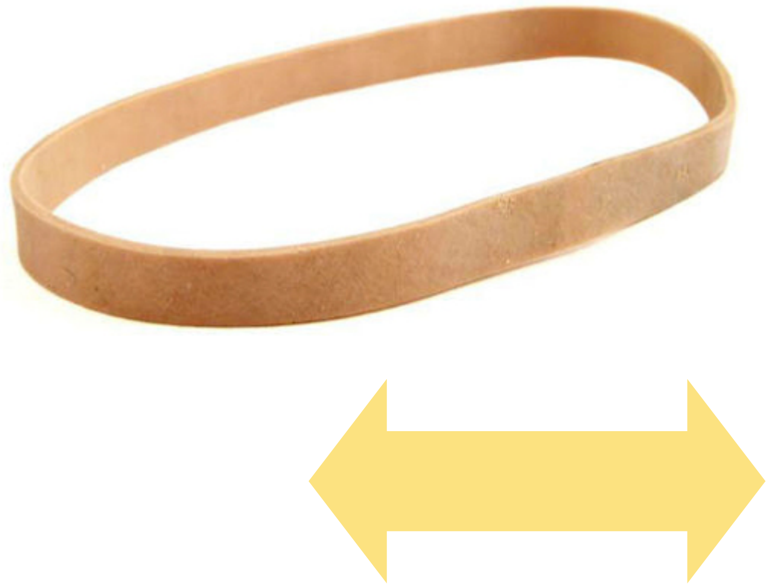


See E. Biernat, June 11th

# Confinement

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

*Decreasing "force"*



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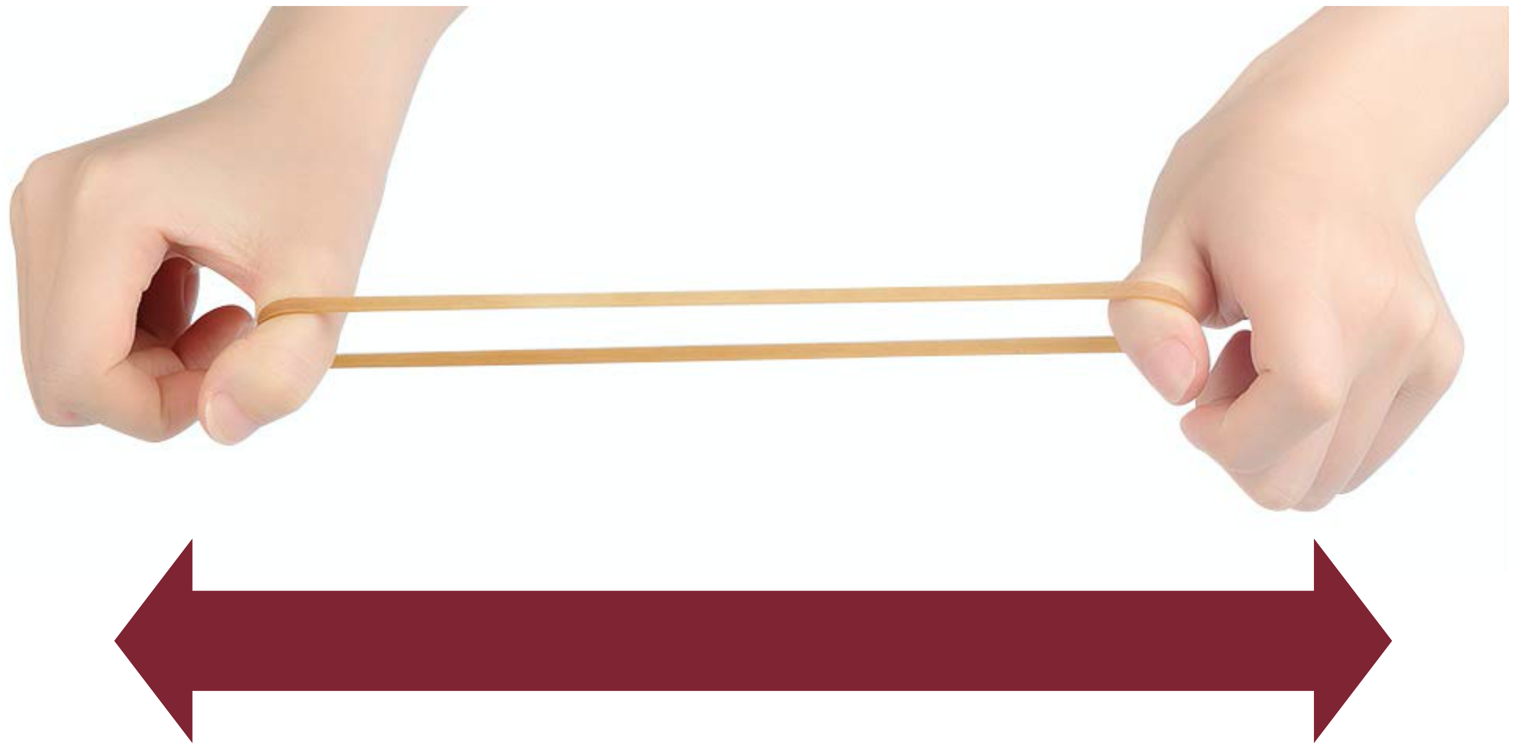
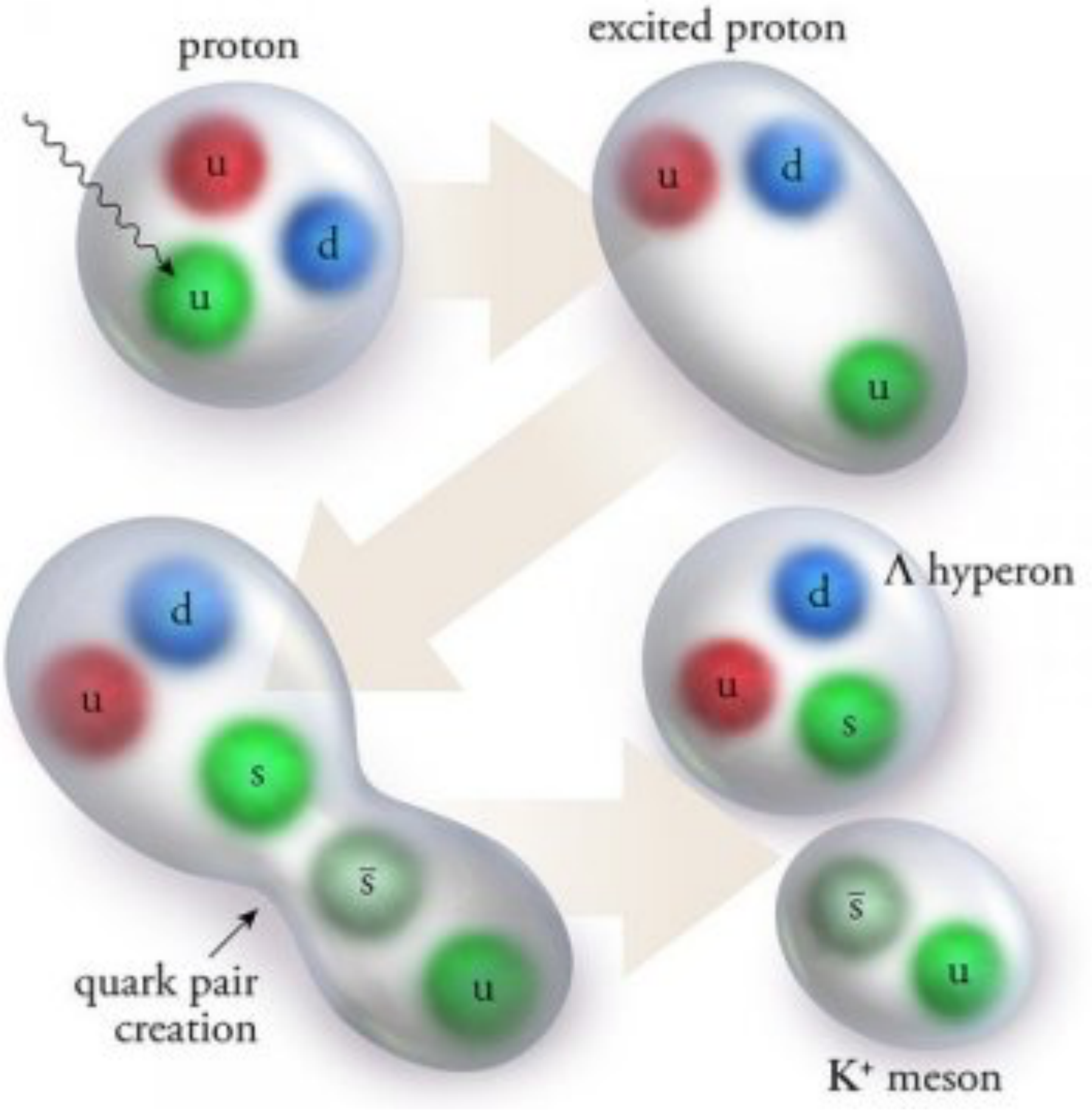
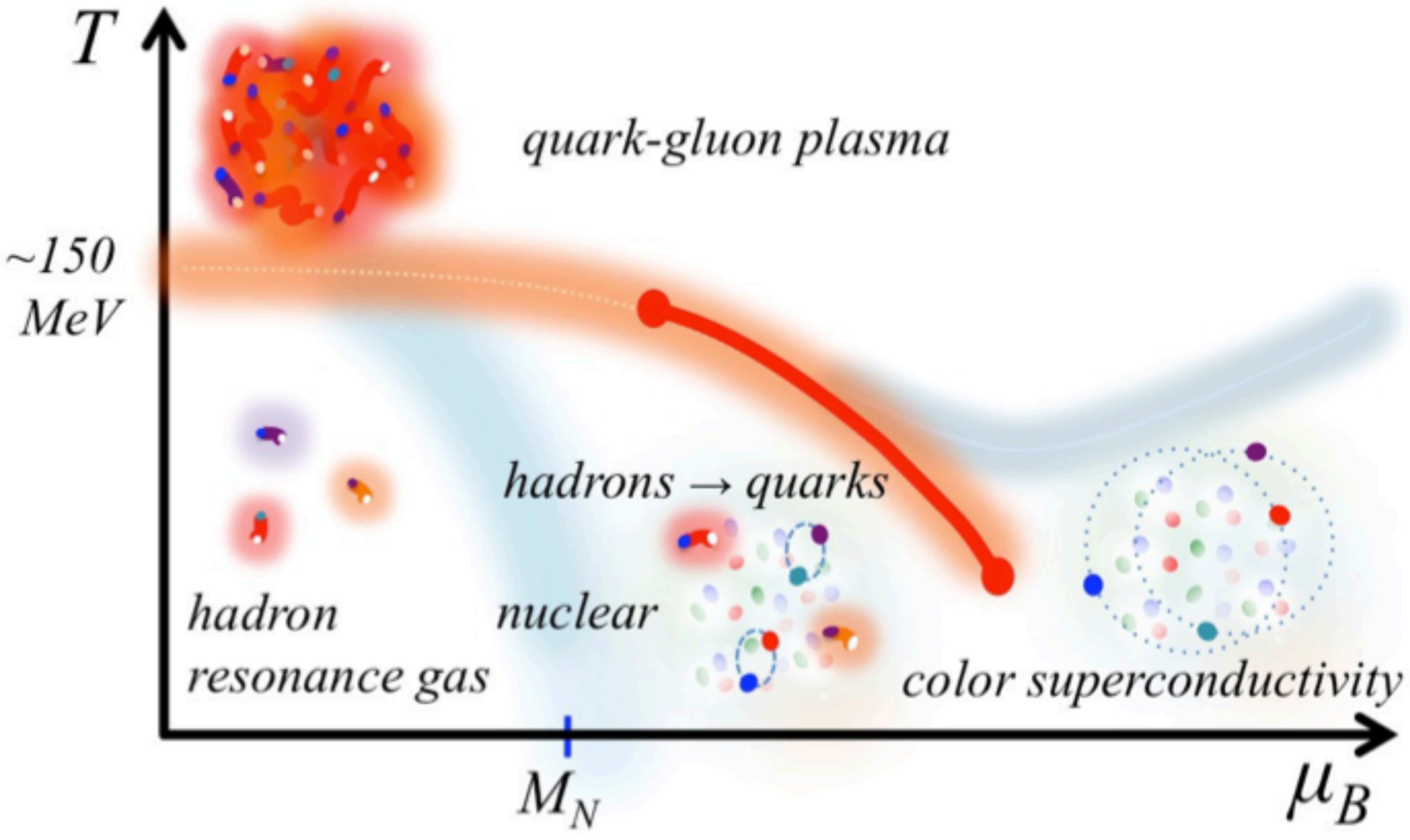




# QCD Phase Space

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



# How to reach other states of matter?

# Heavy-Ion Collisions

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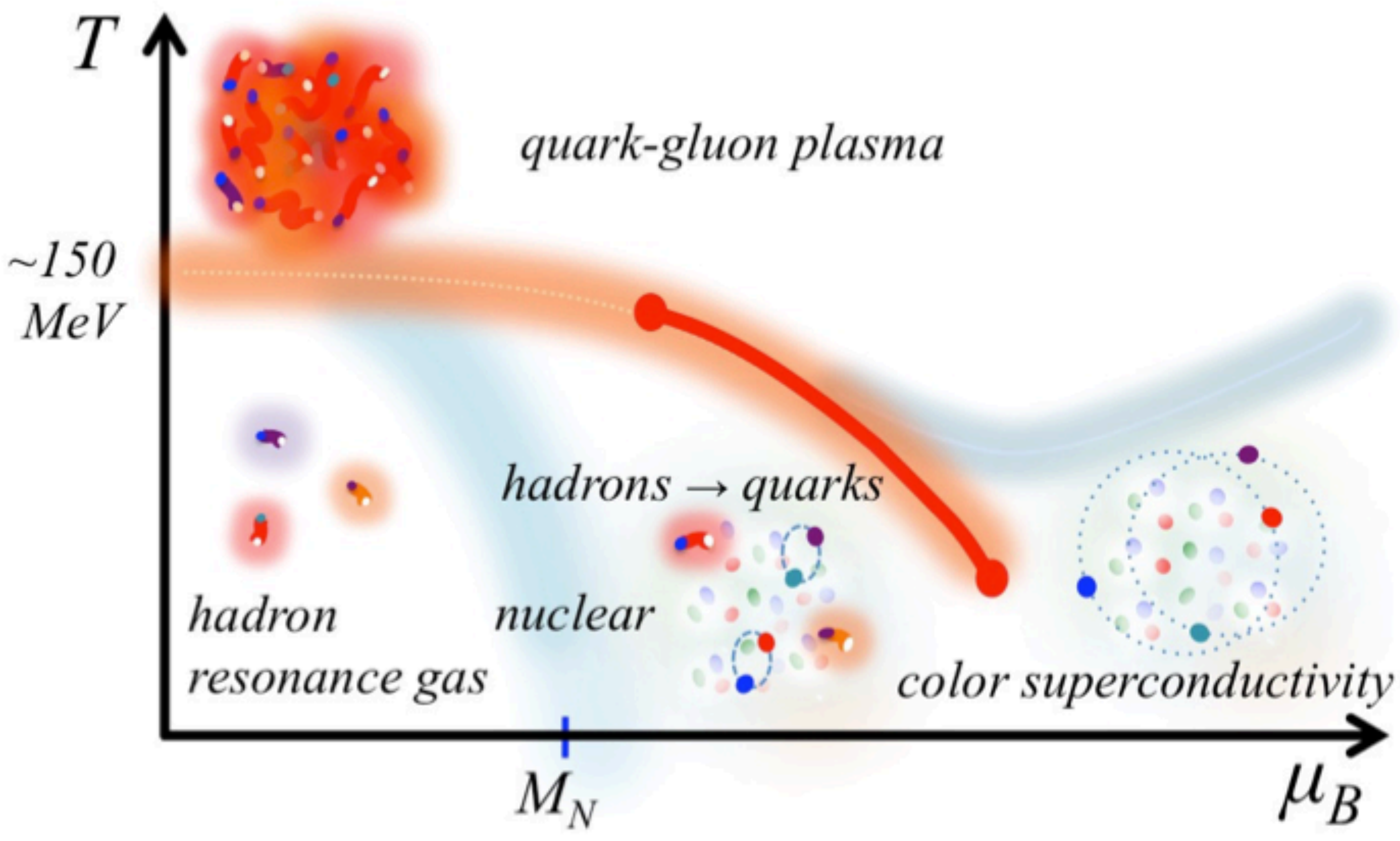
- Heavy-Ion Collisions allow to probe, in a controlled way, the QCD Phase Space



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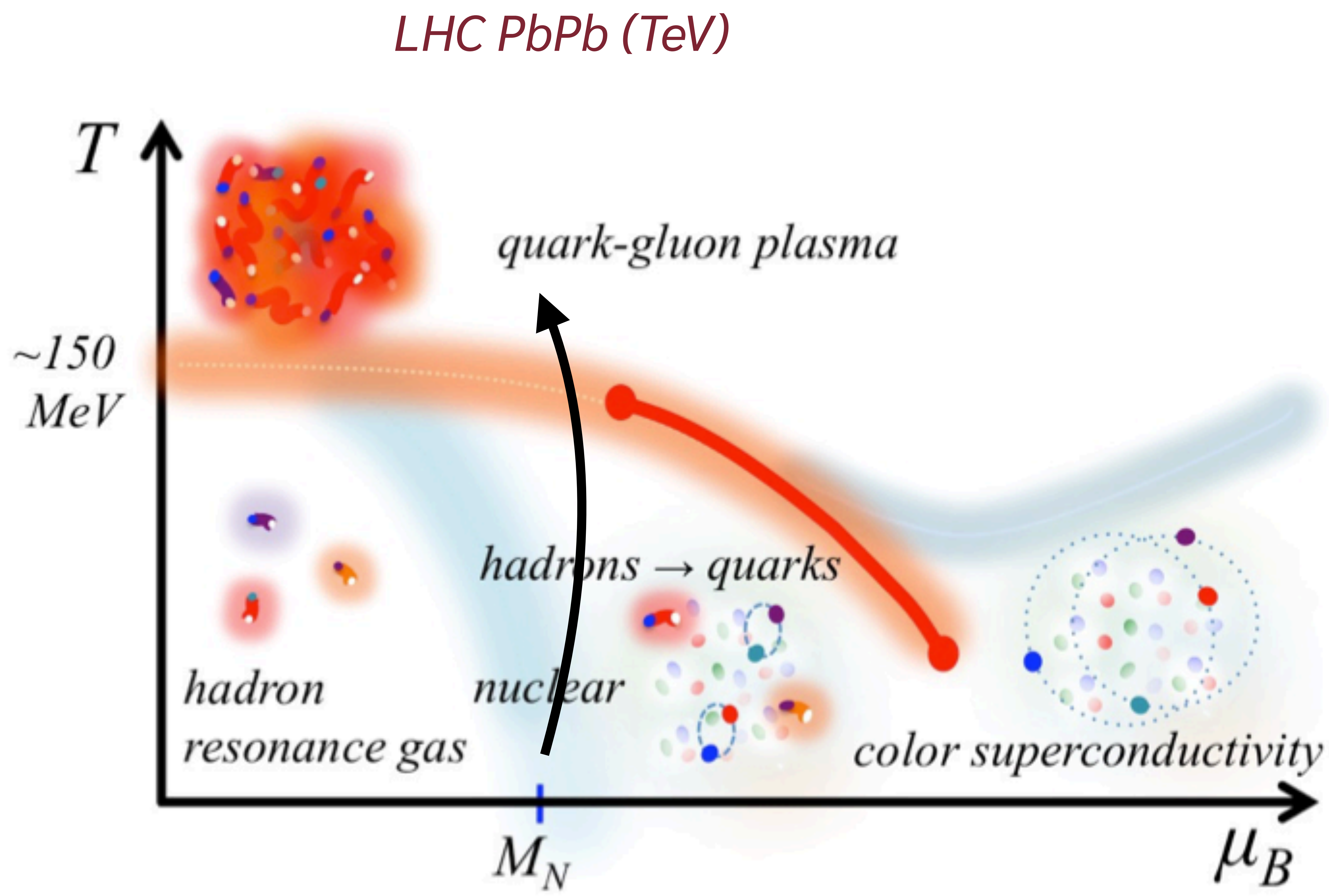


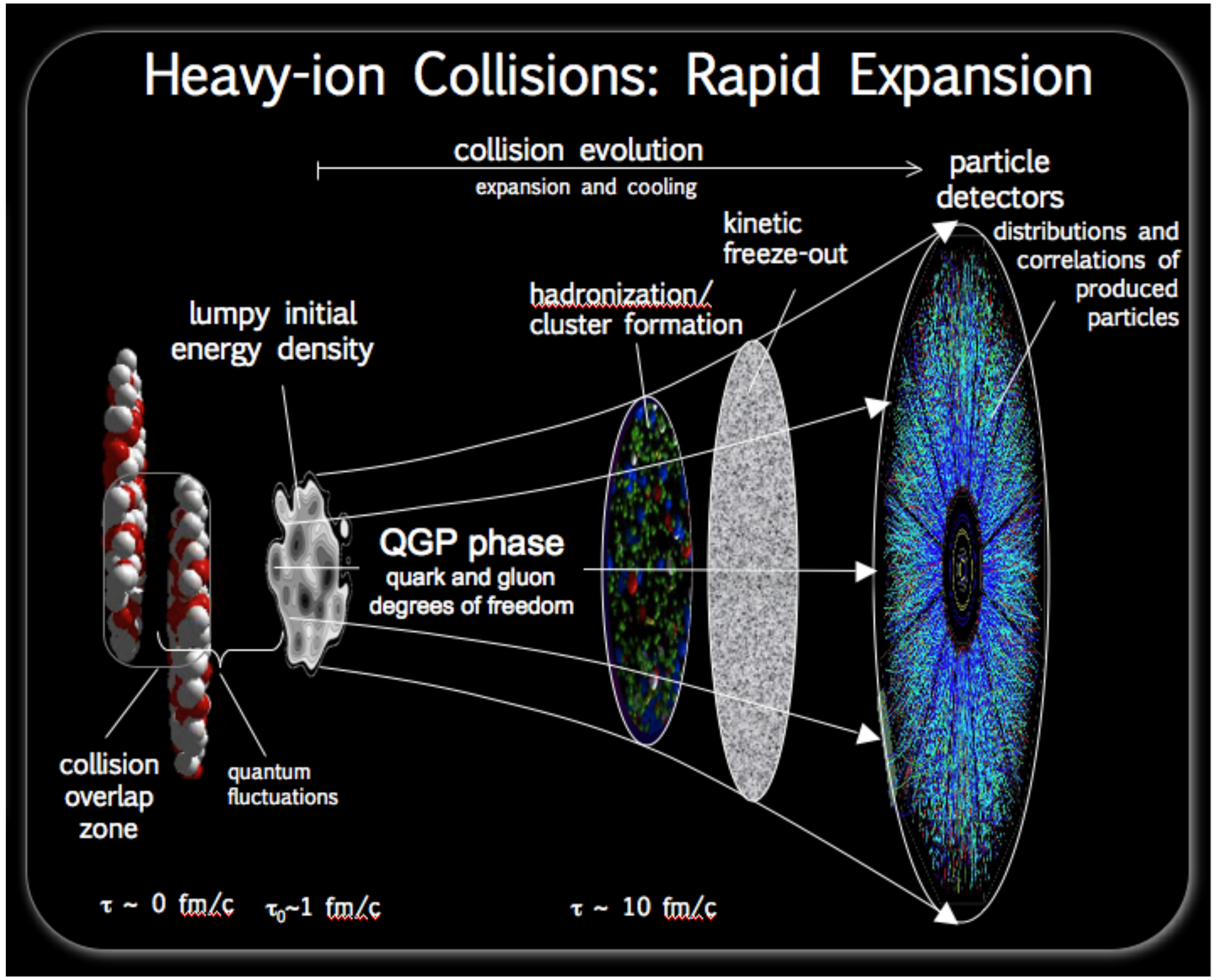

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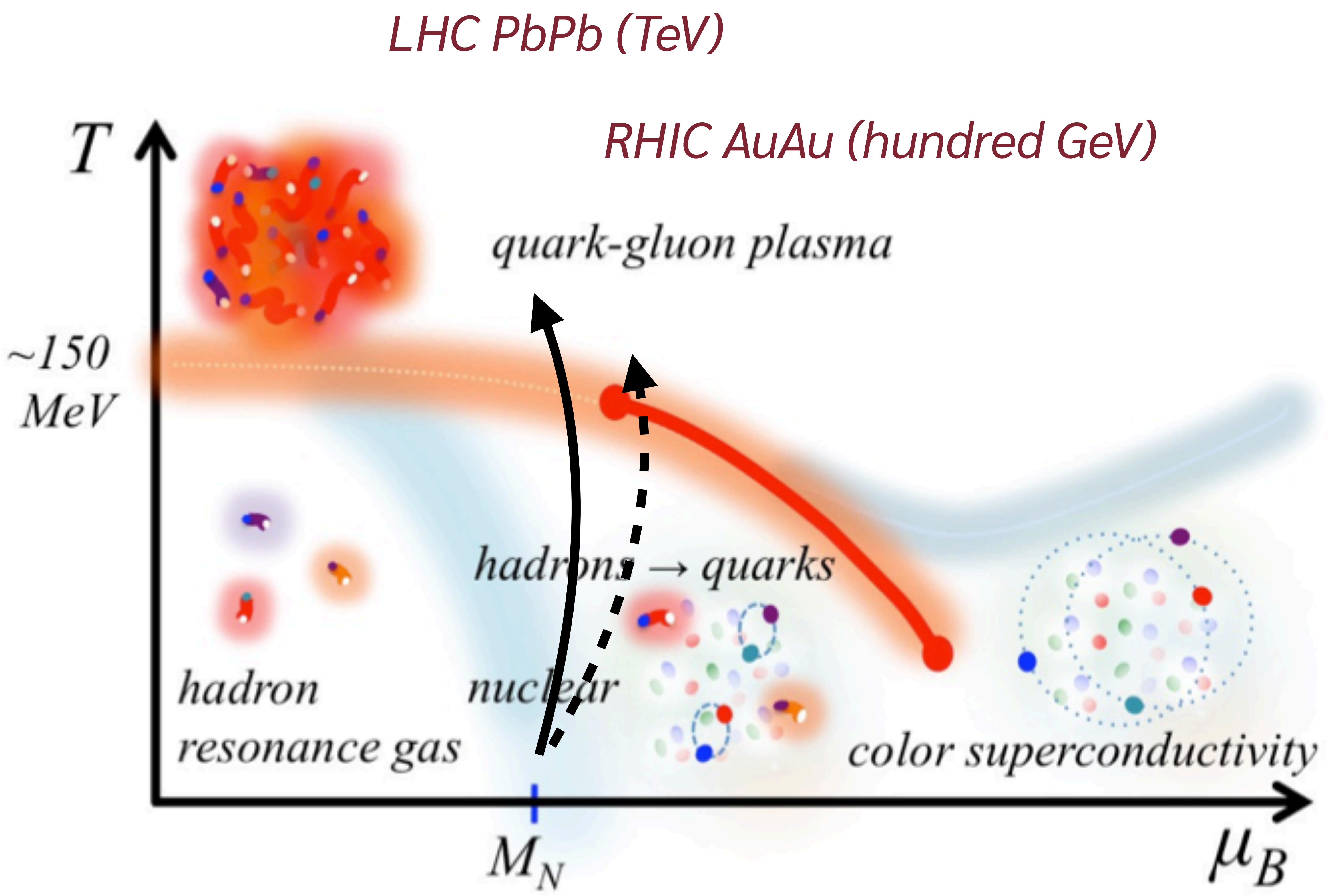


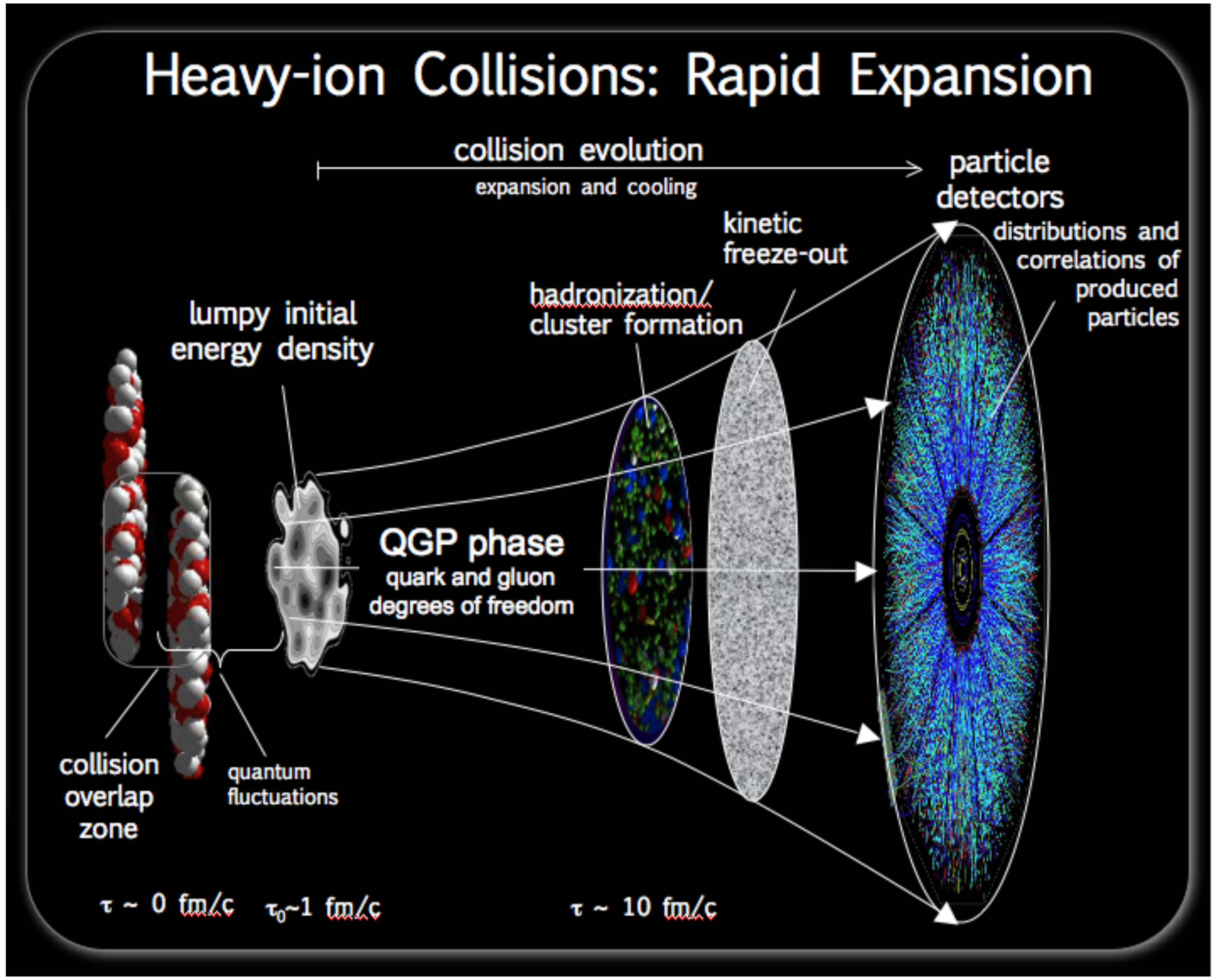

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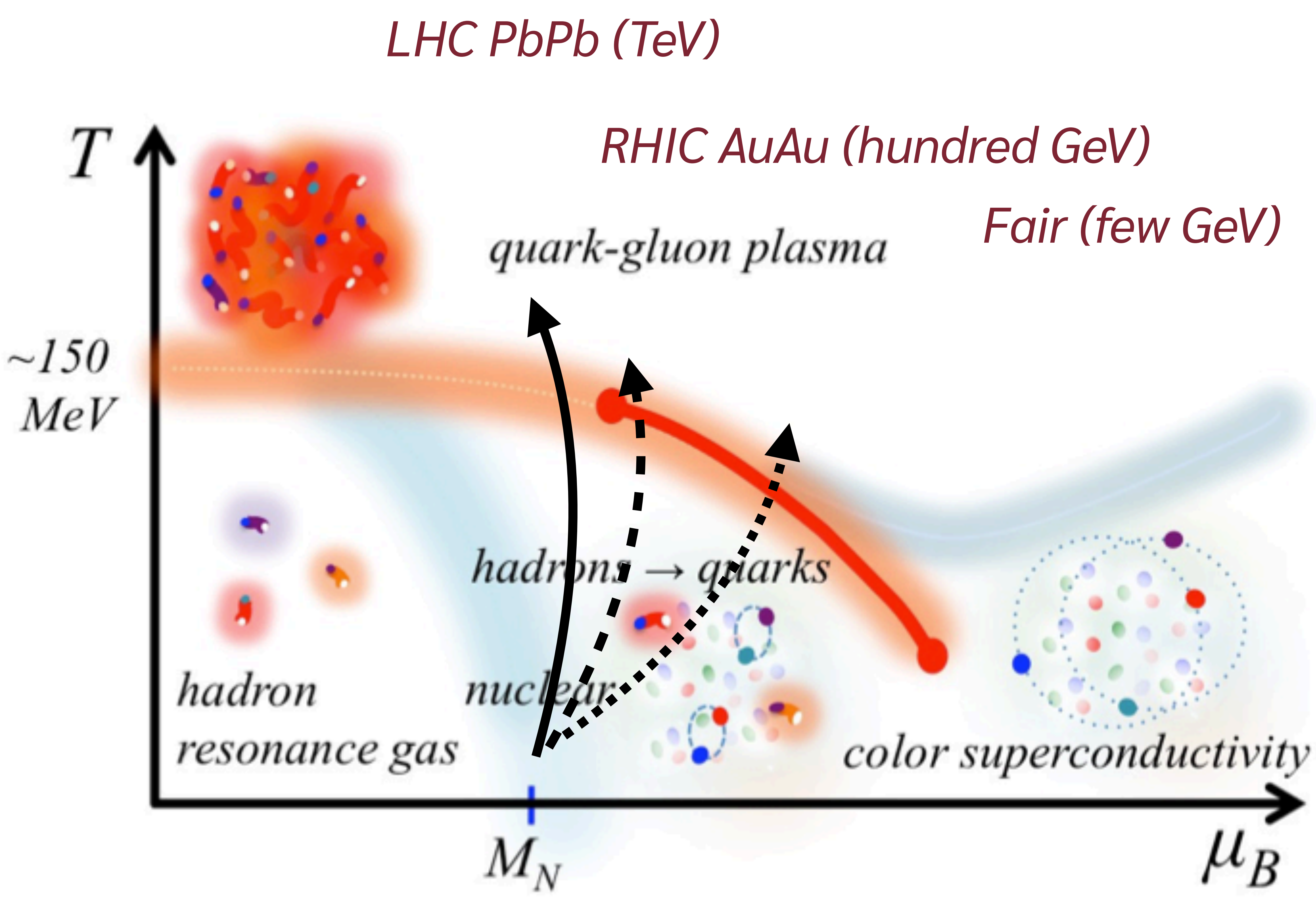


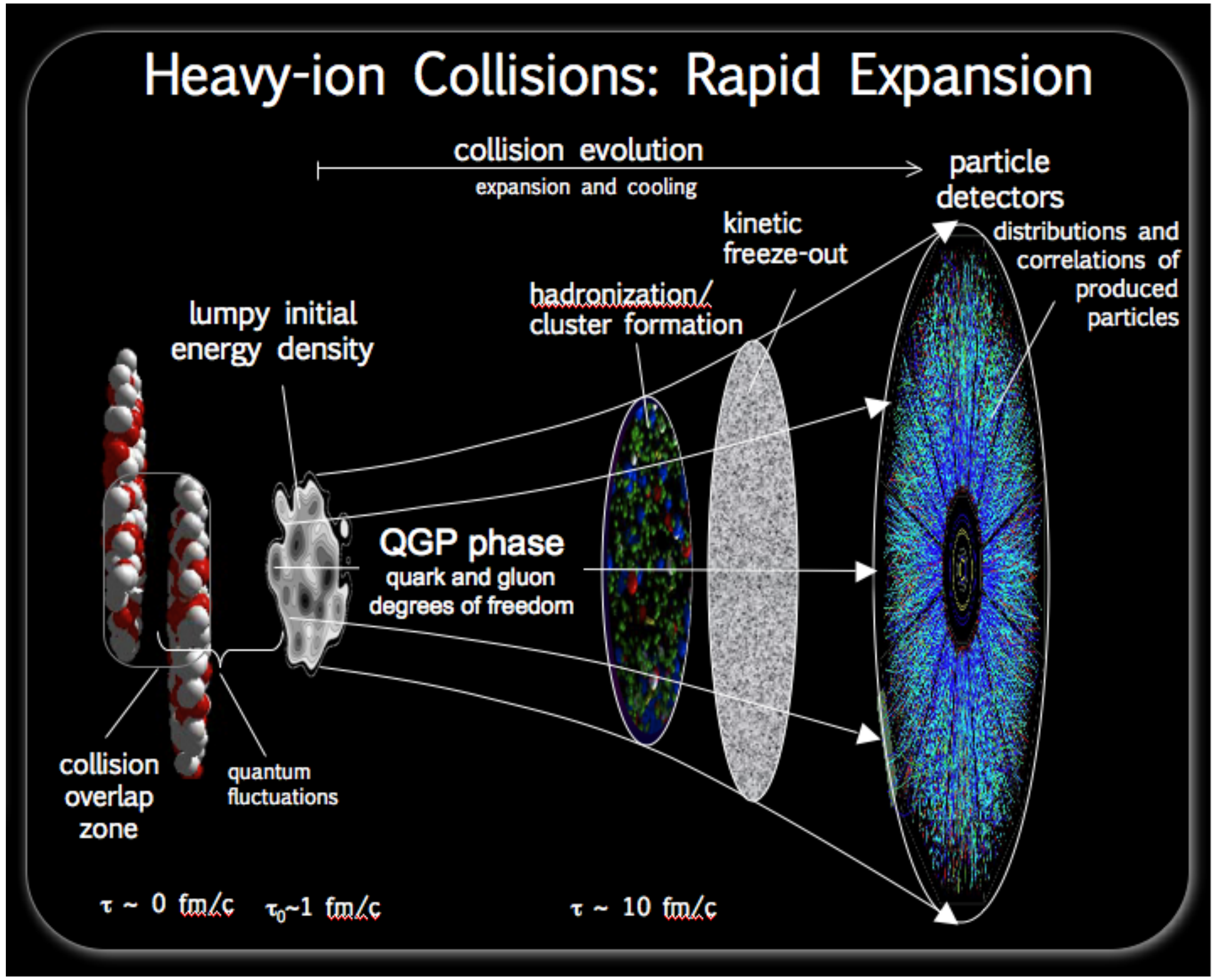

# Current Colliders

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

*CERN*
*Large Hadron Collider (LHC)*

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Perimeter: 3.8 km

*CERN*
*Large Hadron Collider (LHC)*

Perimeter: 27 km

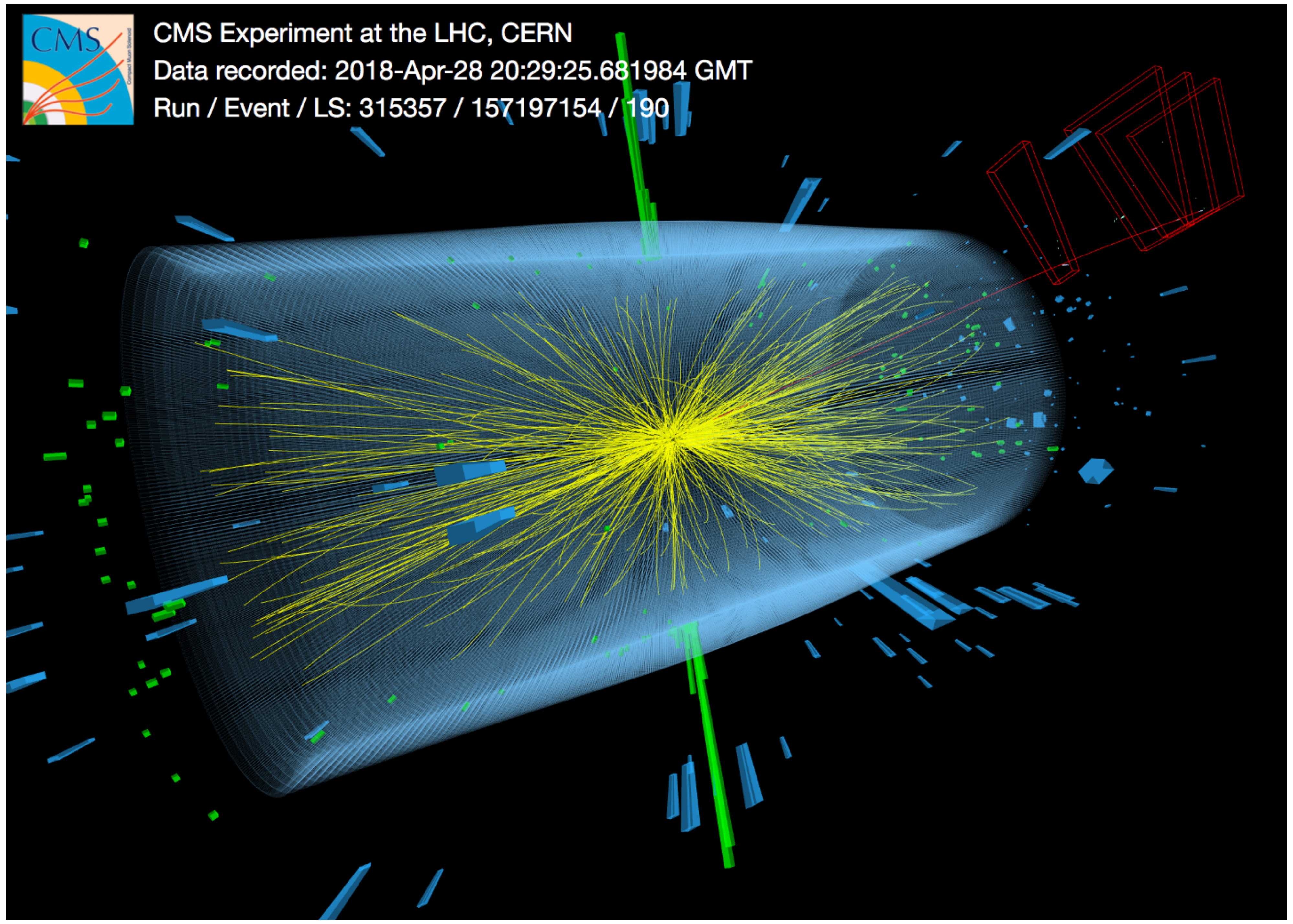
# The Quark-Gluon Plasma

## 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...)*

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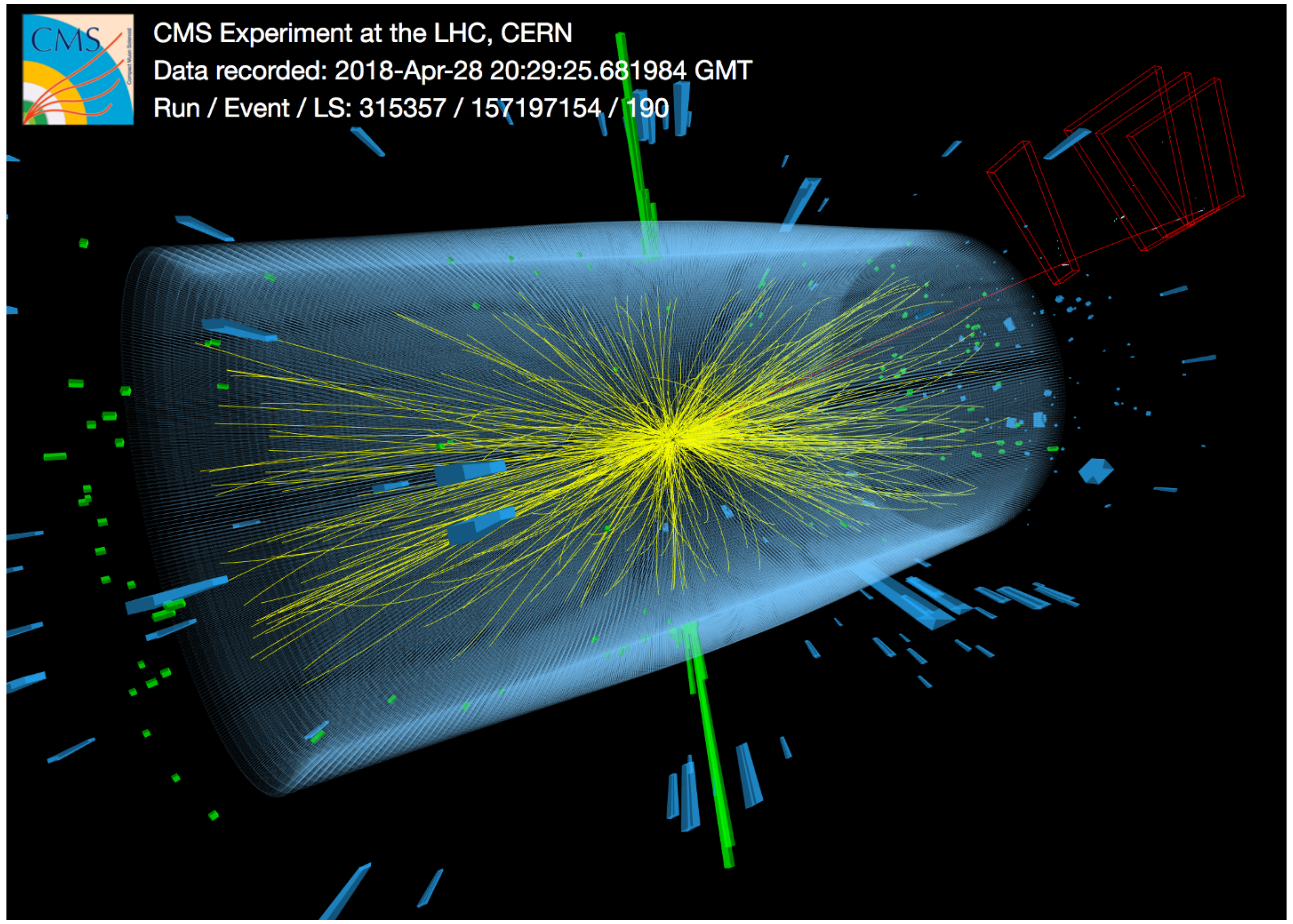


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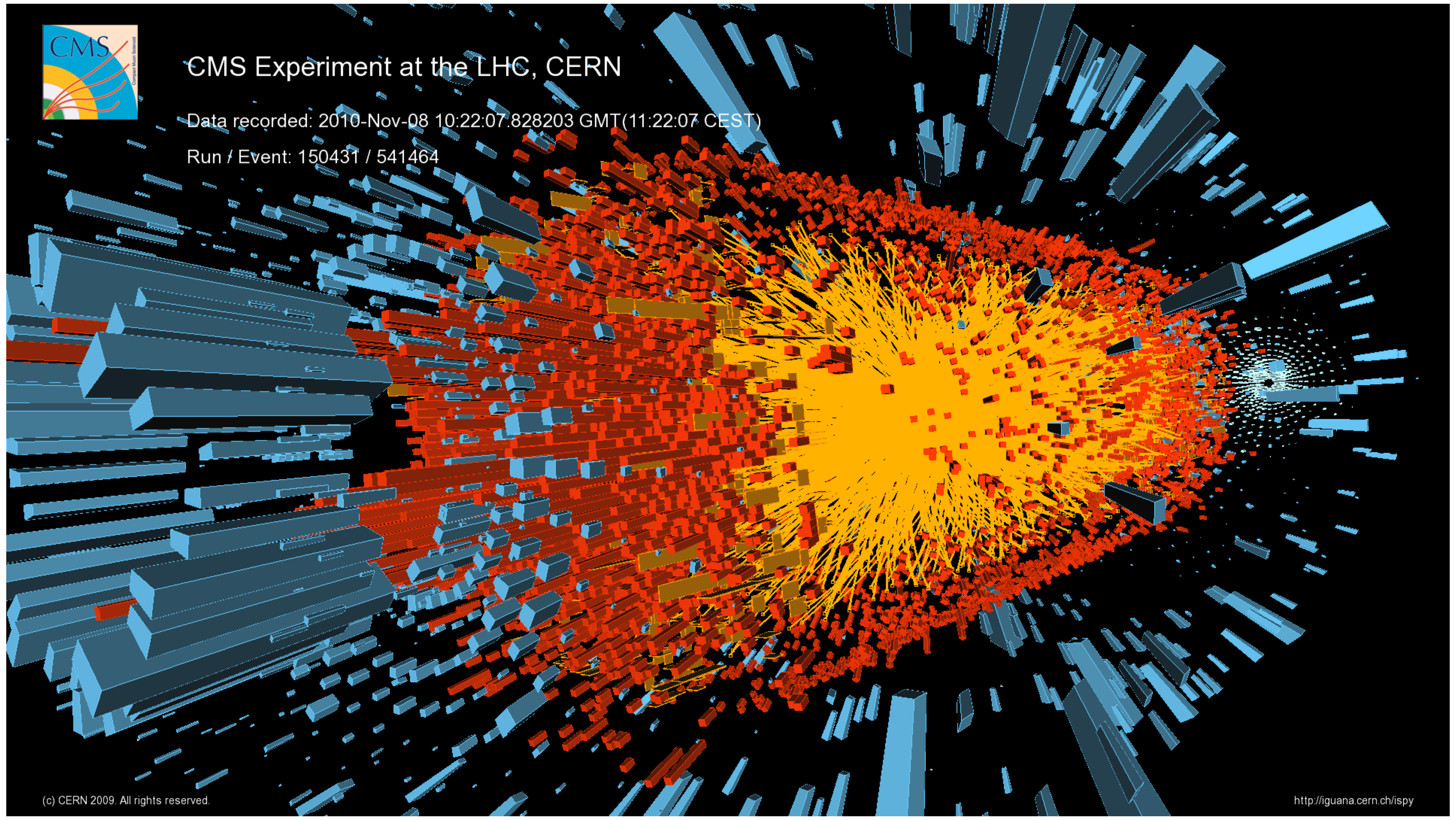
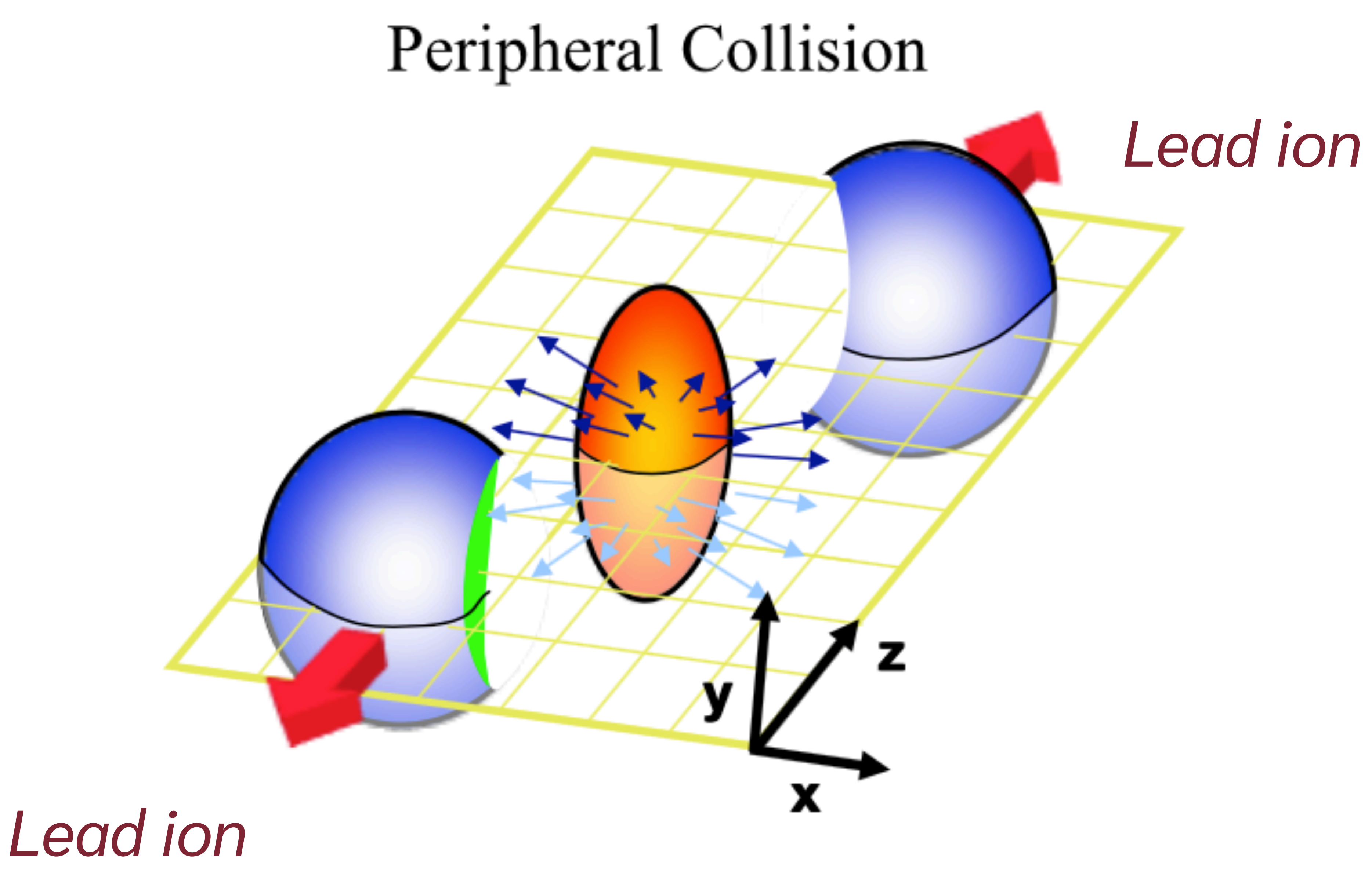
***Lead-Lead collisions***

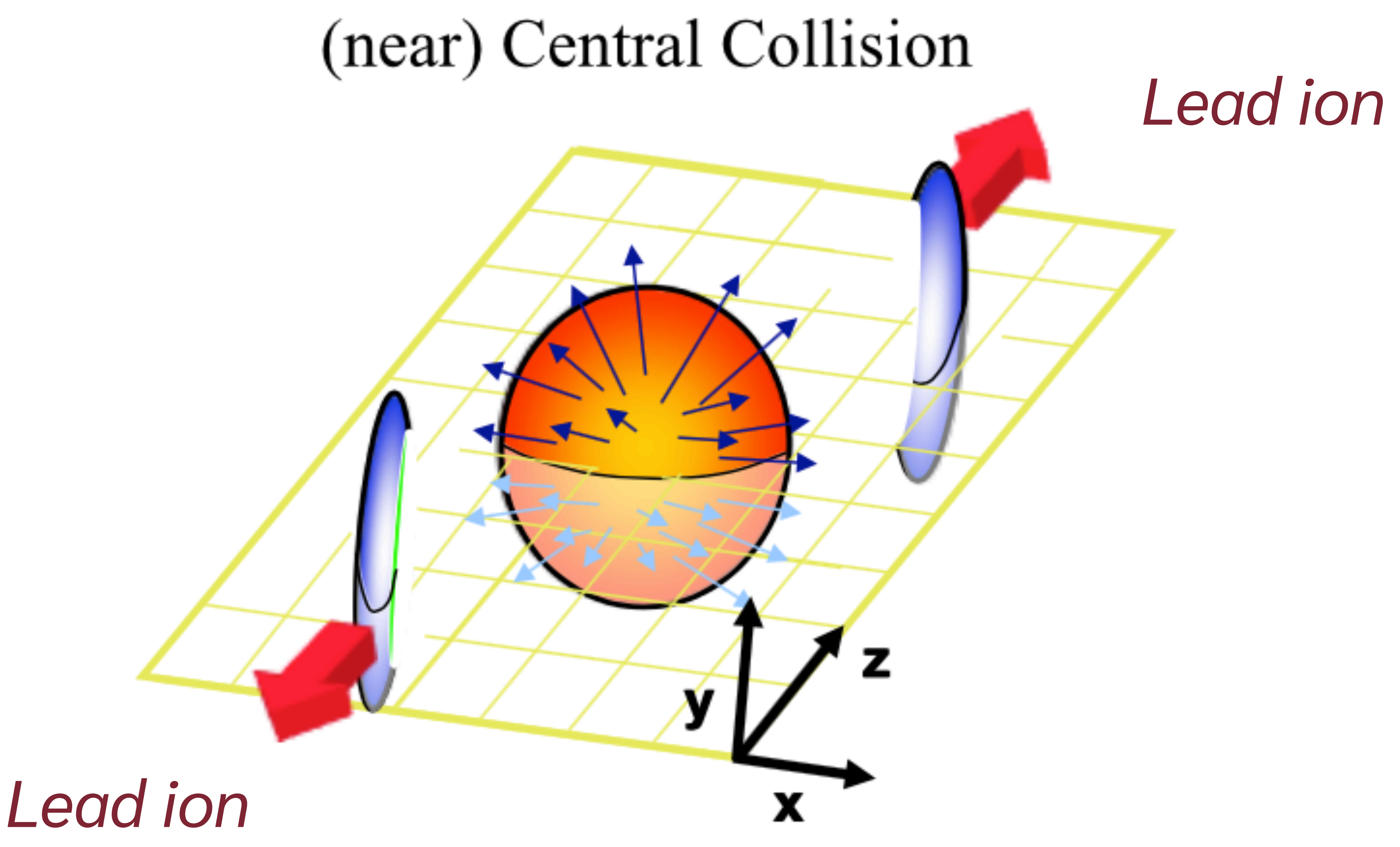



***High multiplicity event (many particles!)***
***Result of QGP formation***

# Centrality of the collision

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



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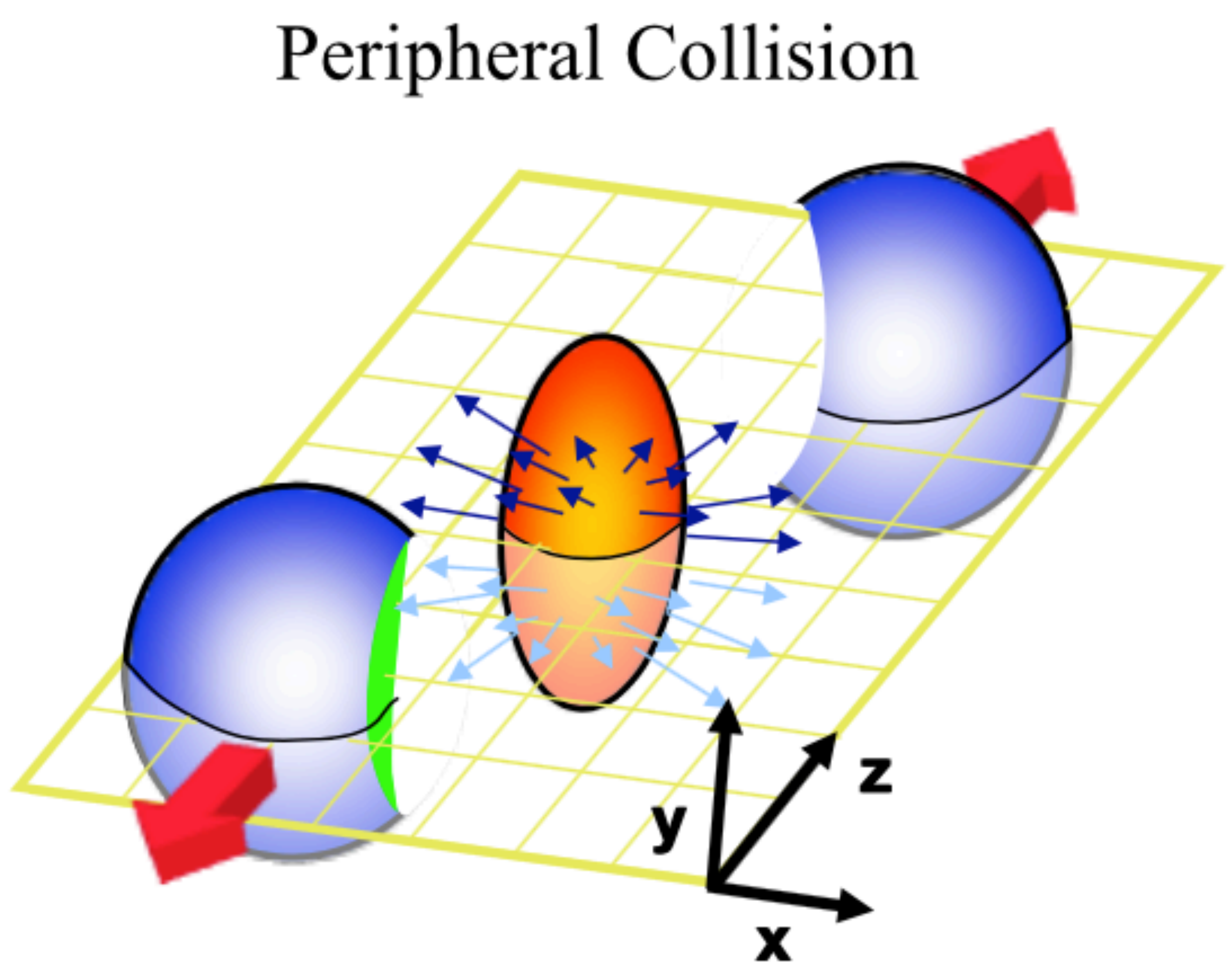

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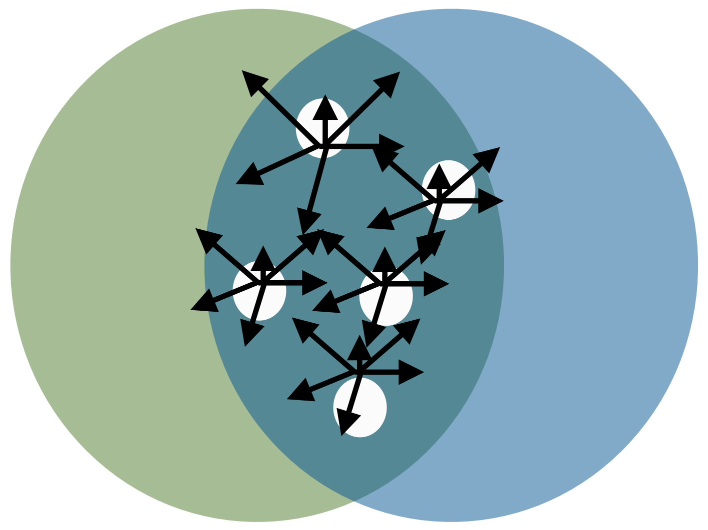
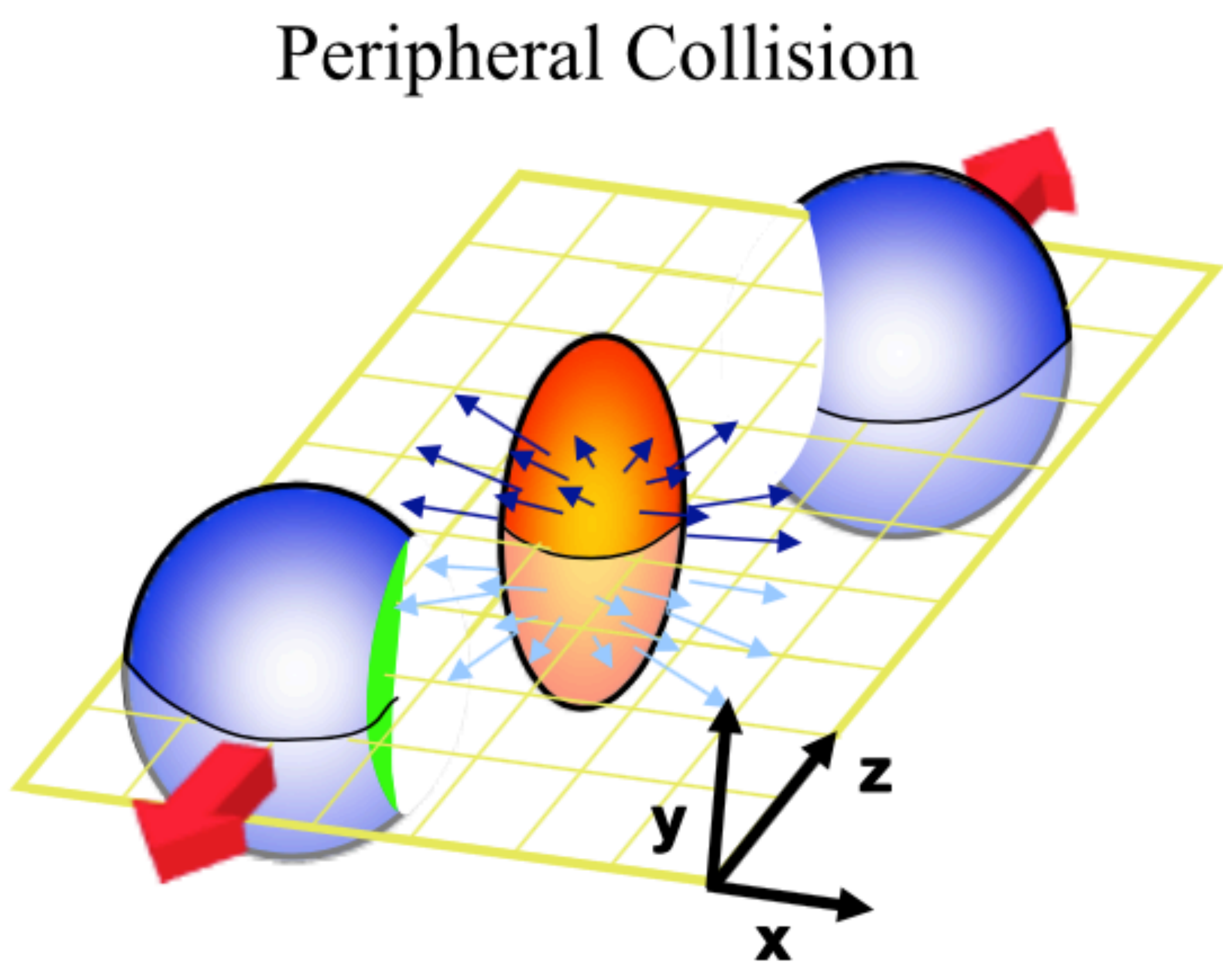
Superposition of multiple pp collisions





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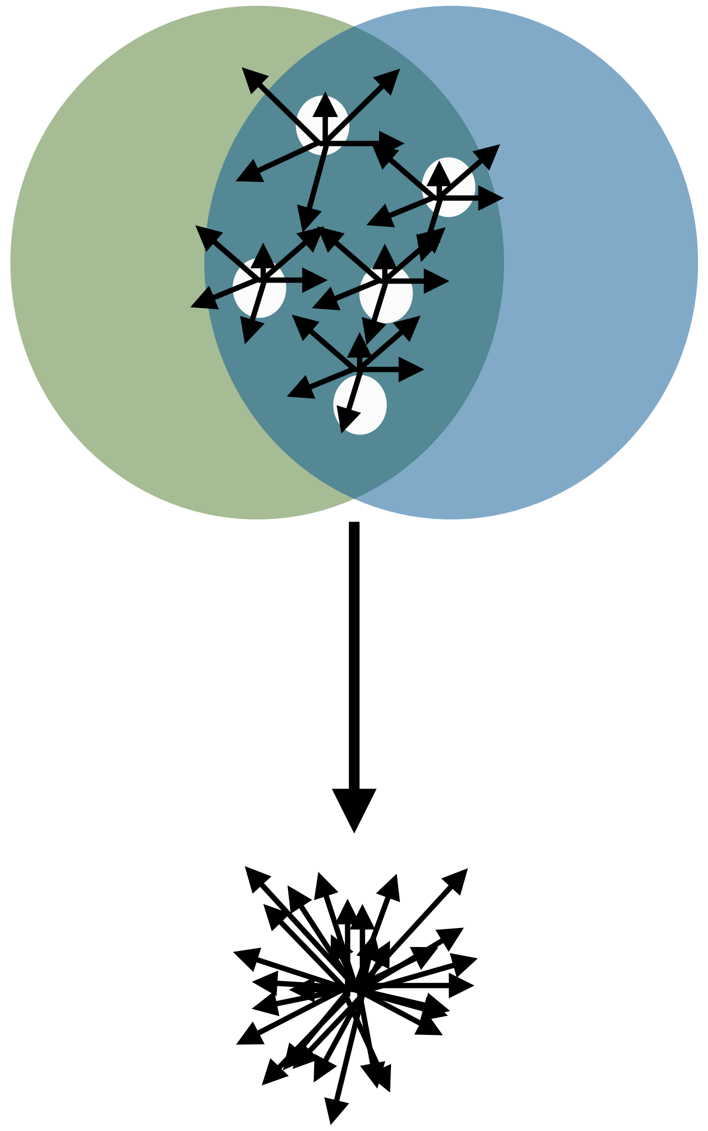

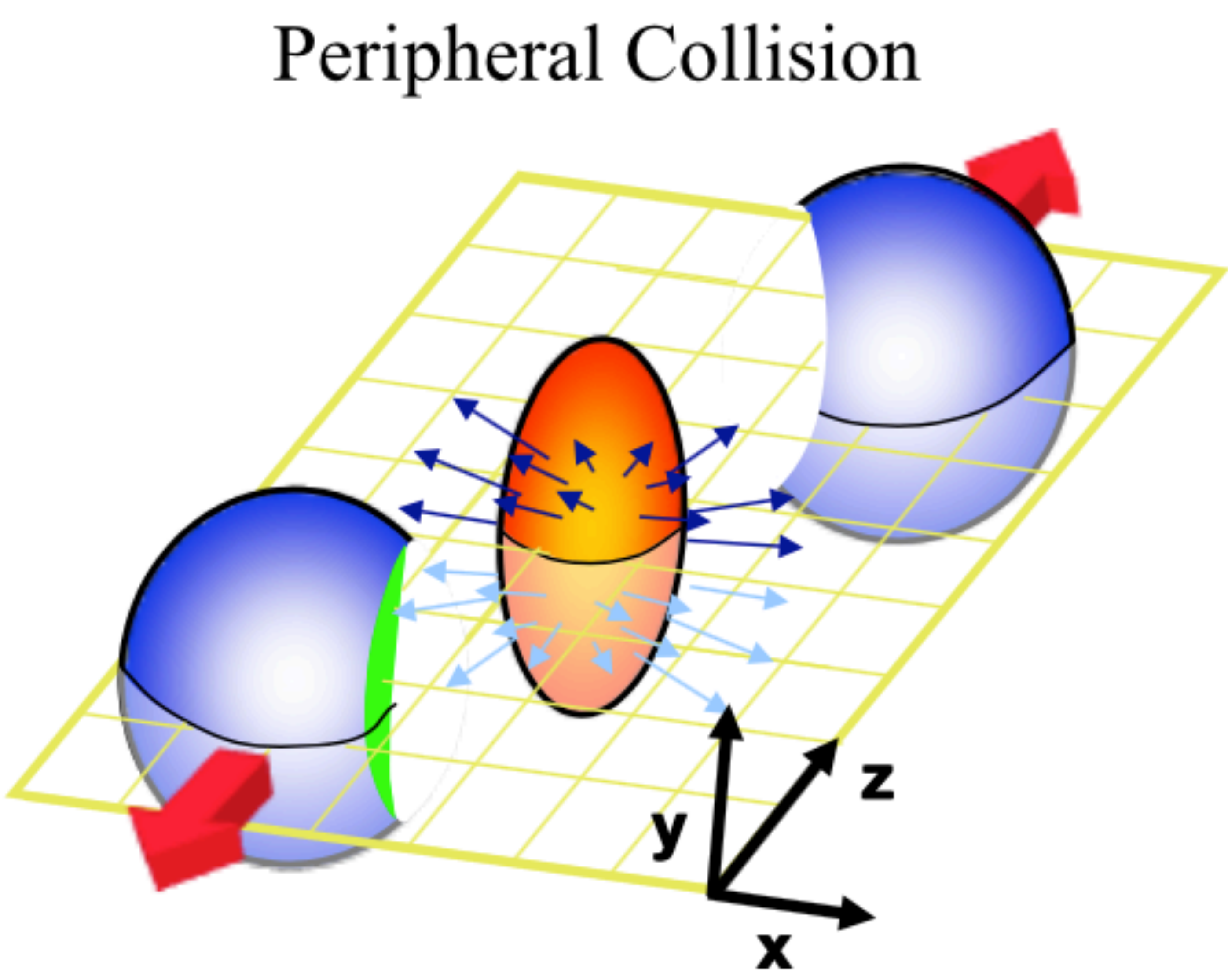

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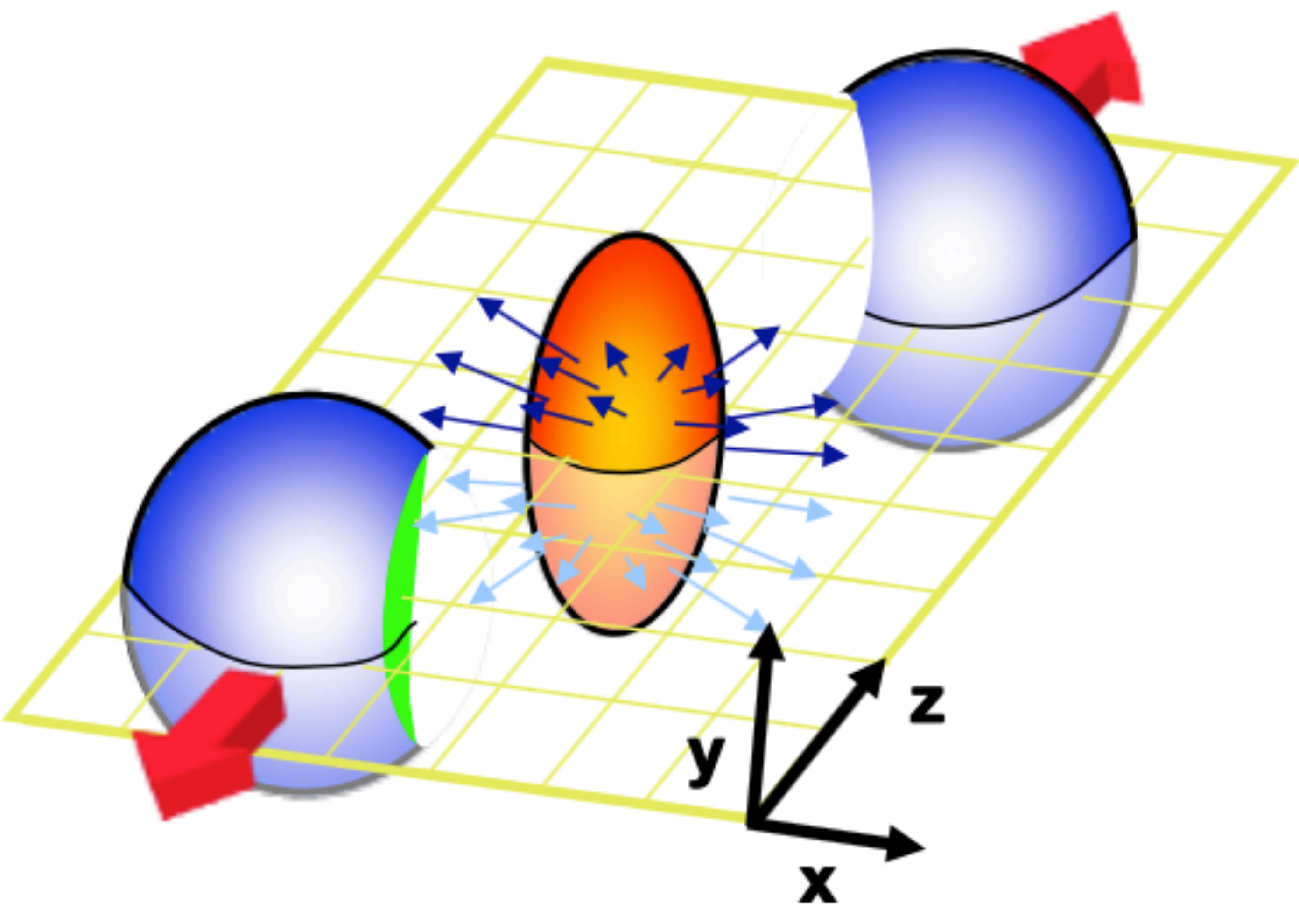
Peripheral Collision

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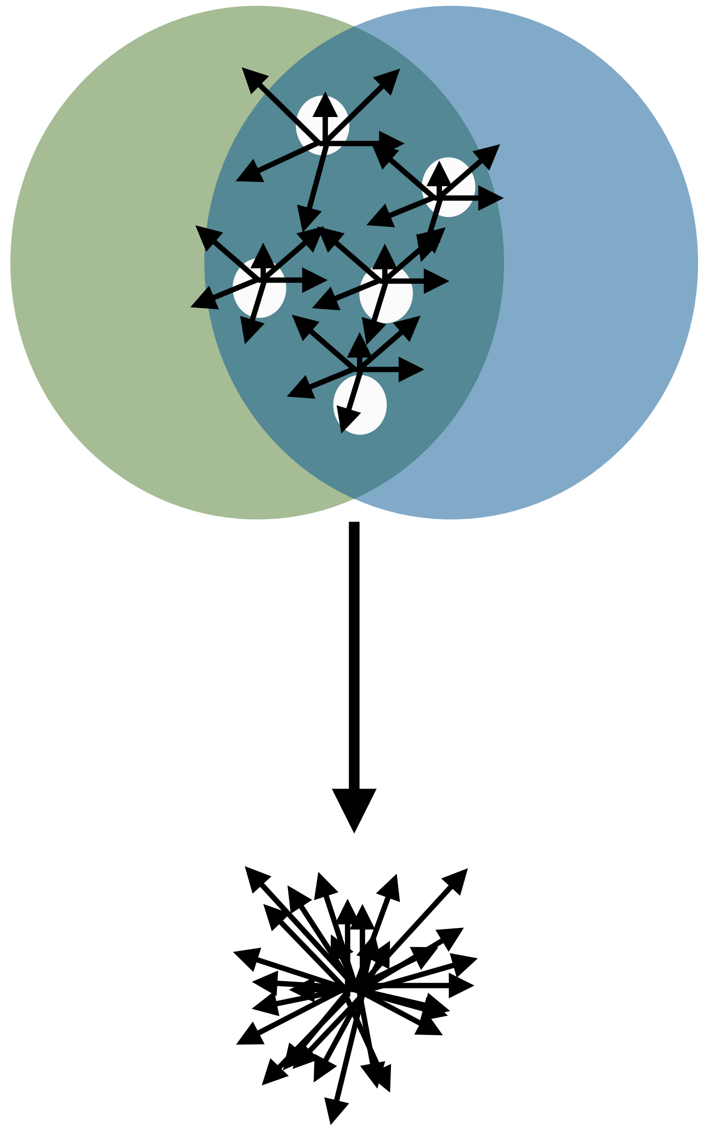

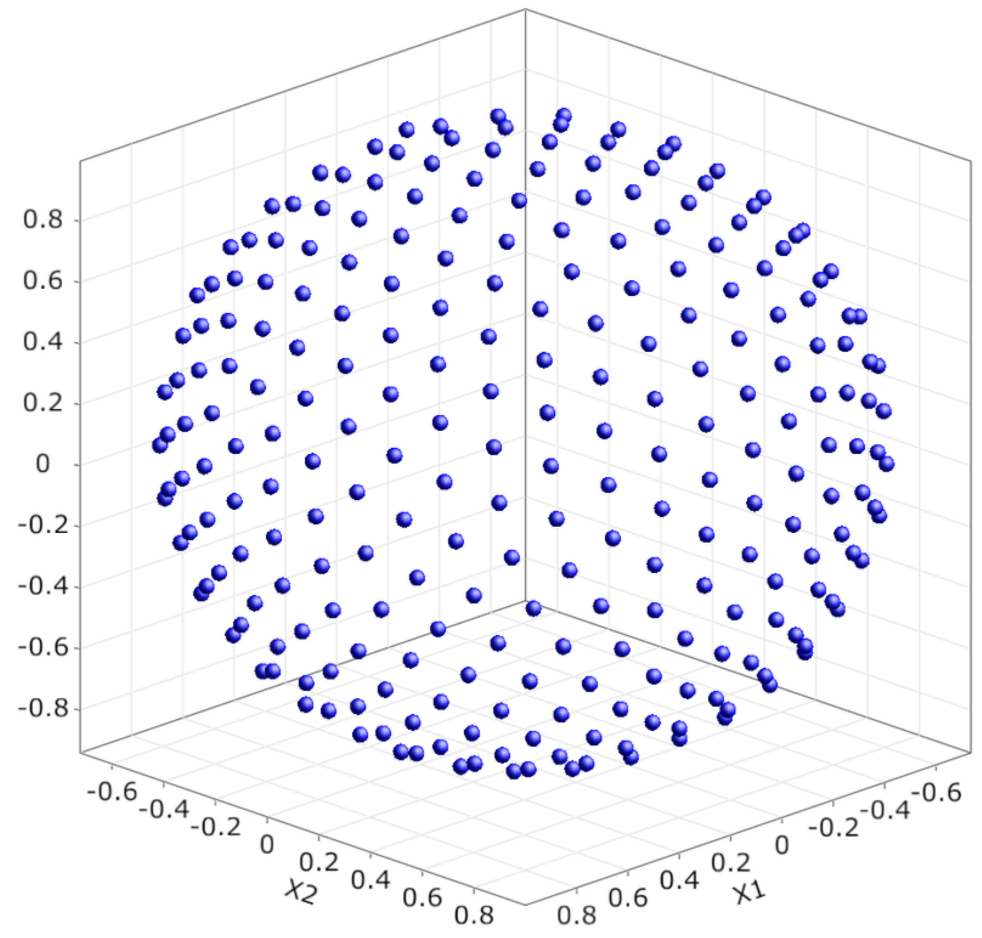


***Uniform distribution of final particles***

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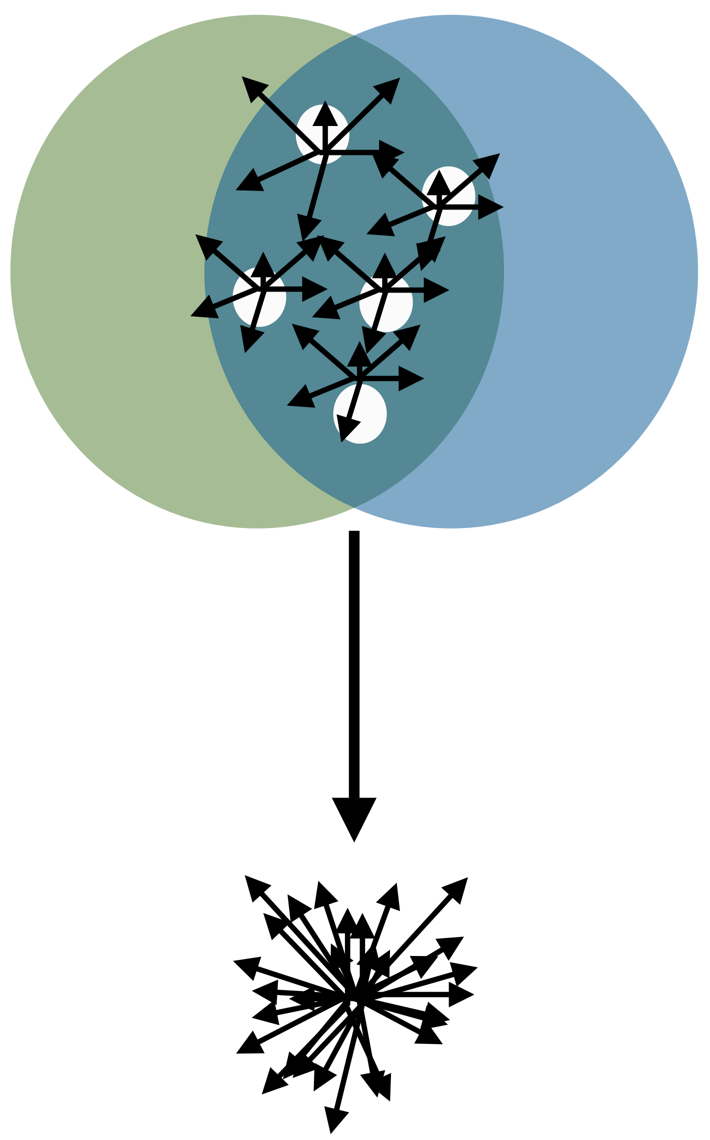
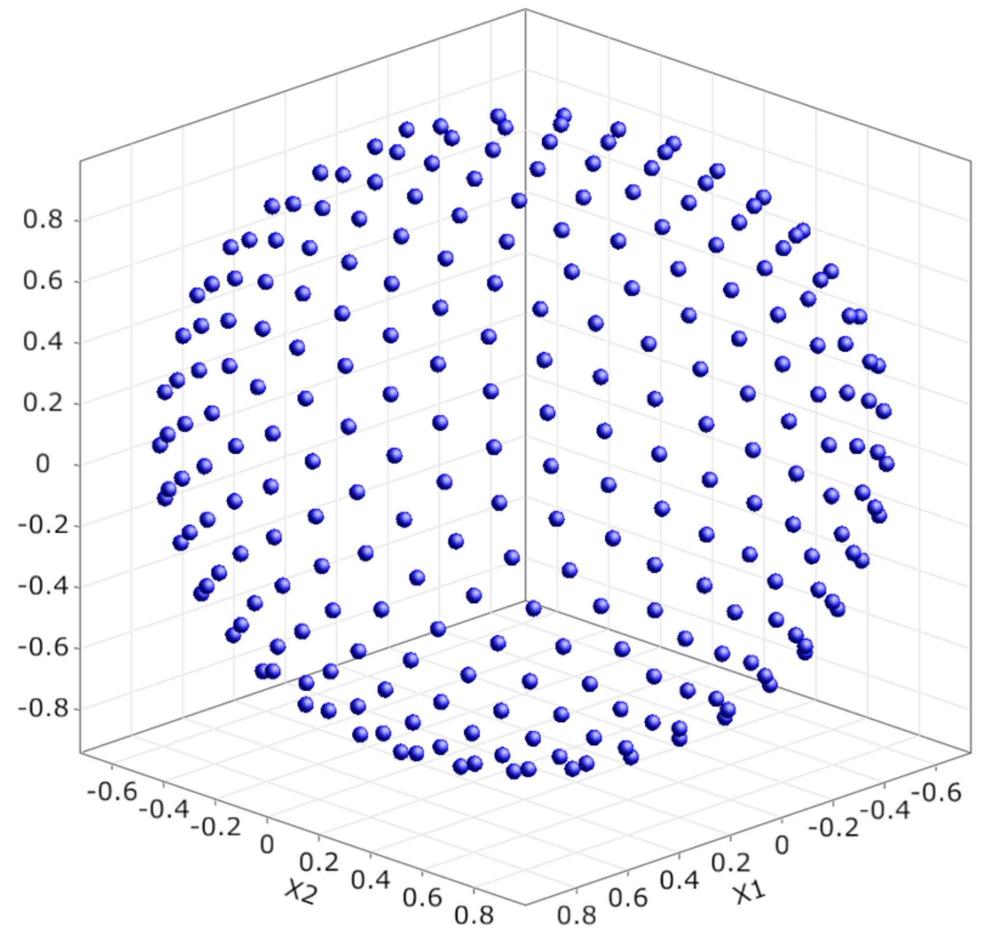
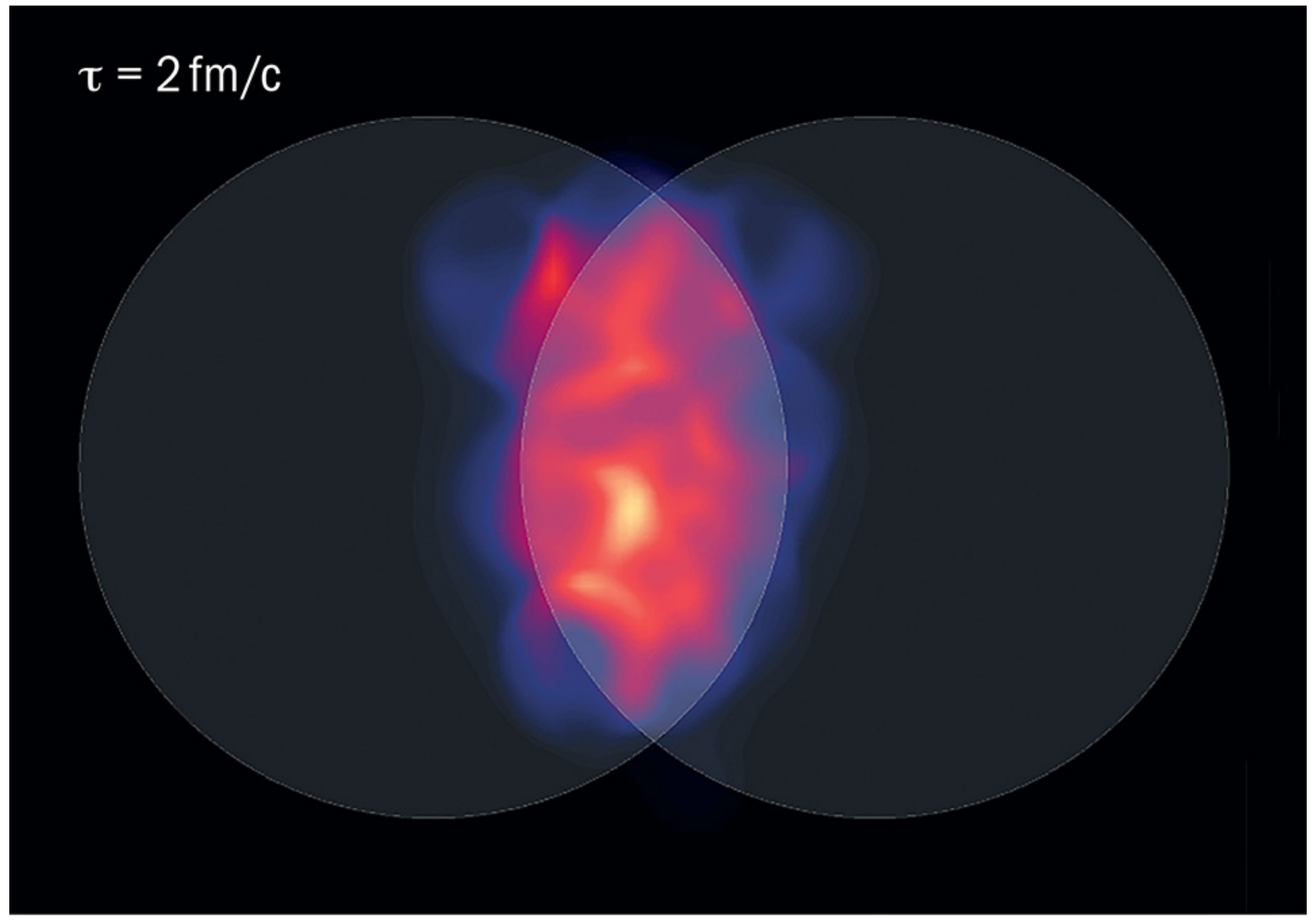
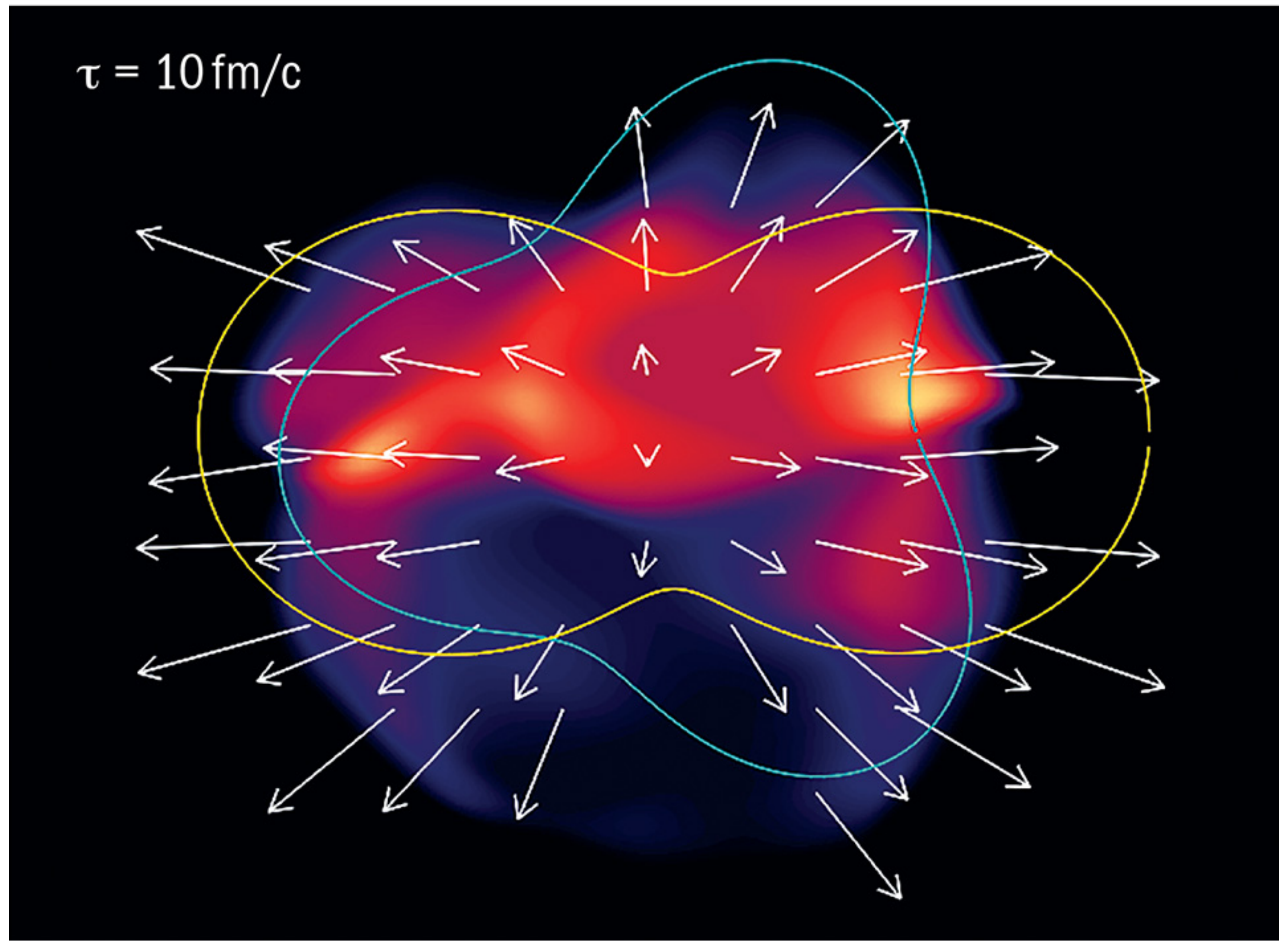





***Uniform distribution of final particles ??? Not quite...***



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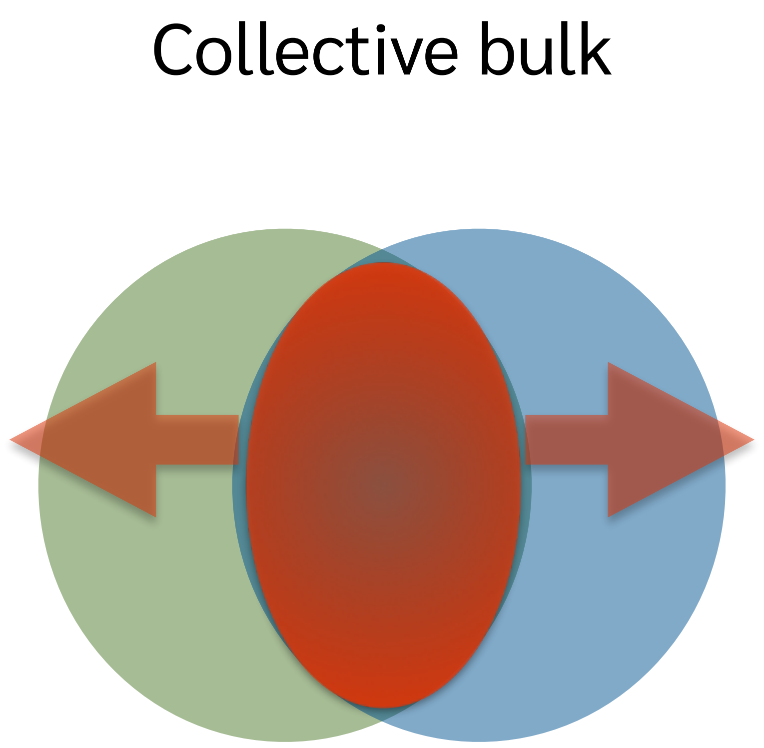


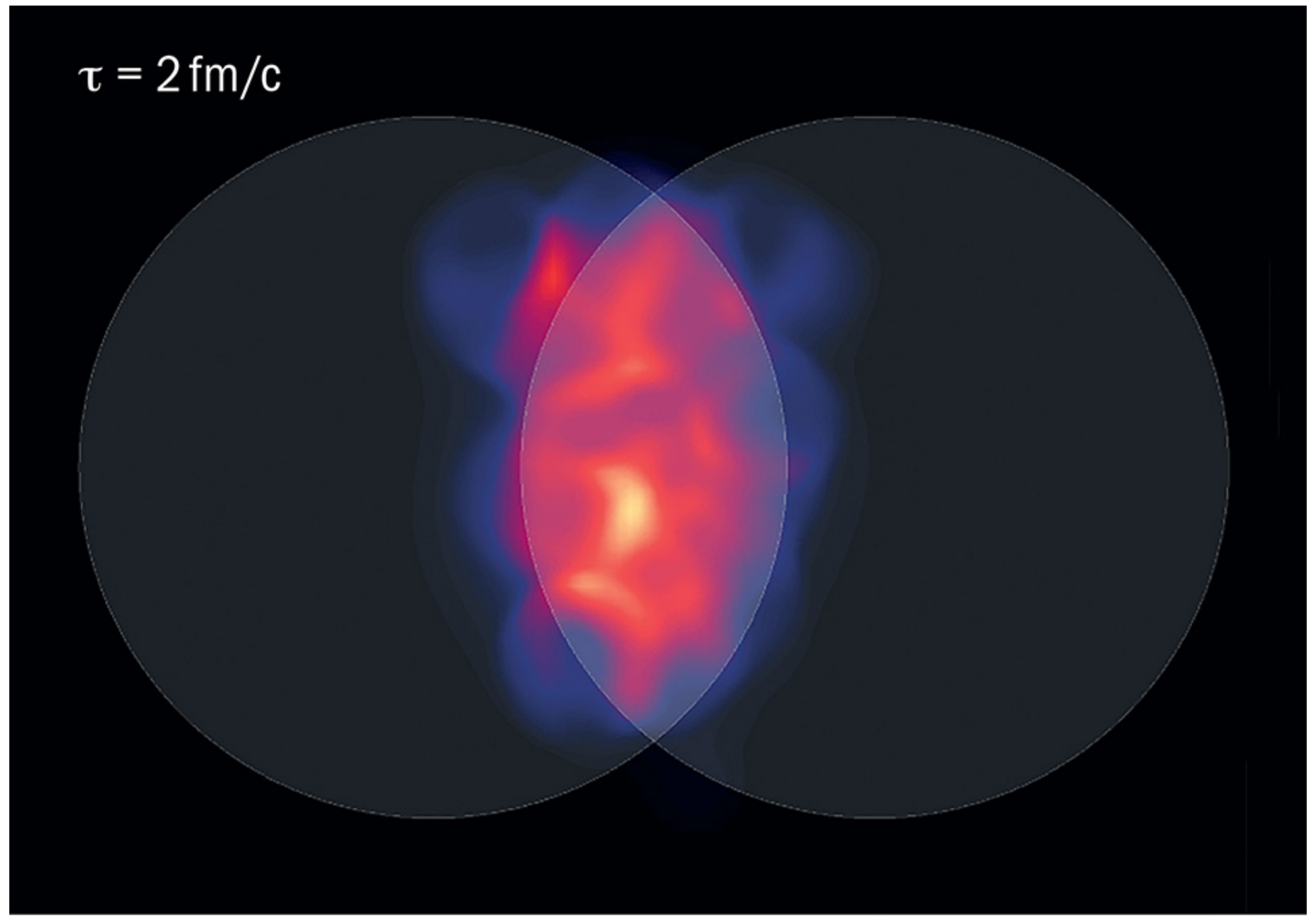


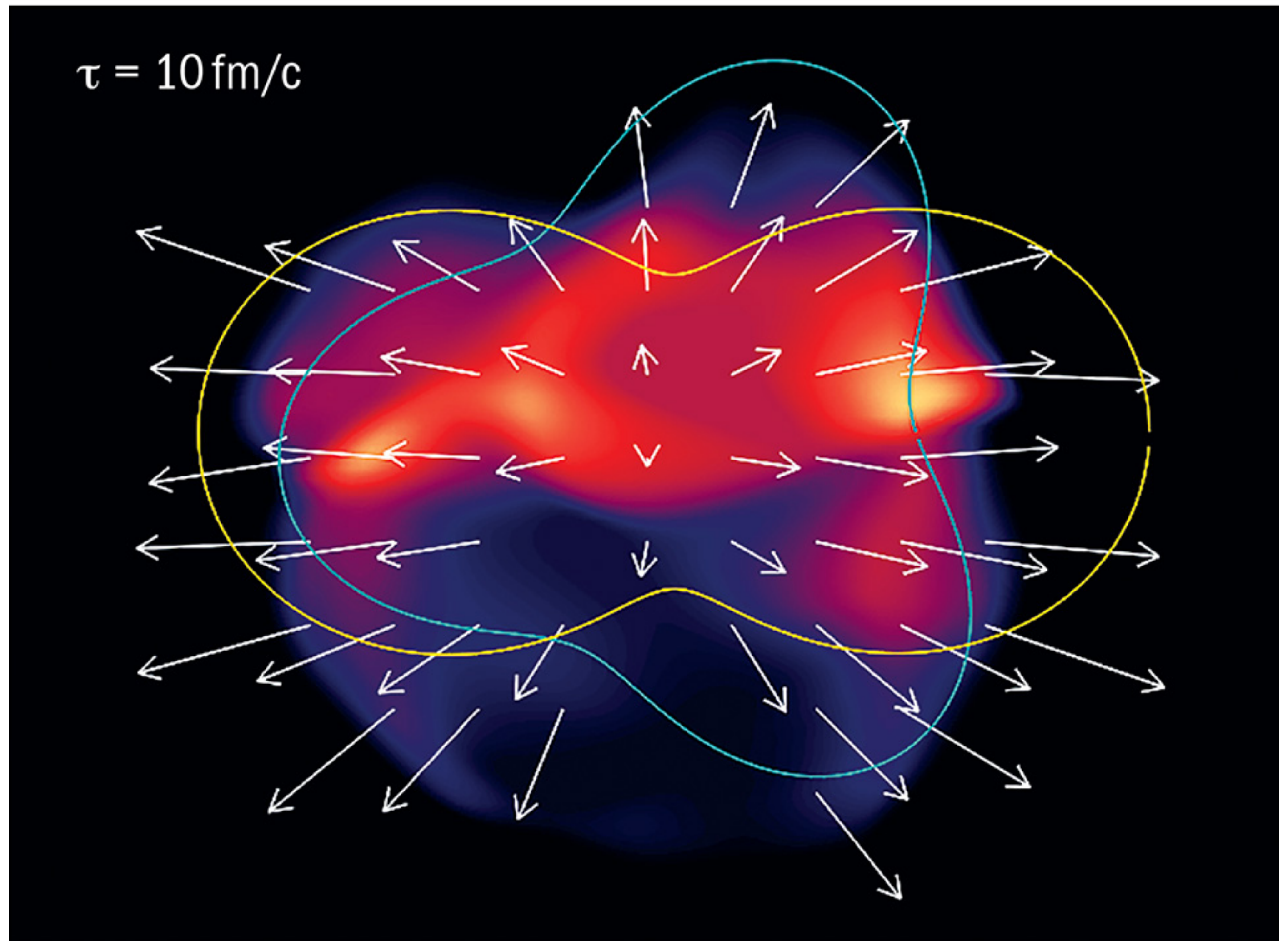

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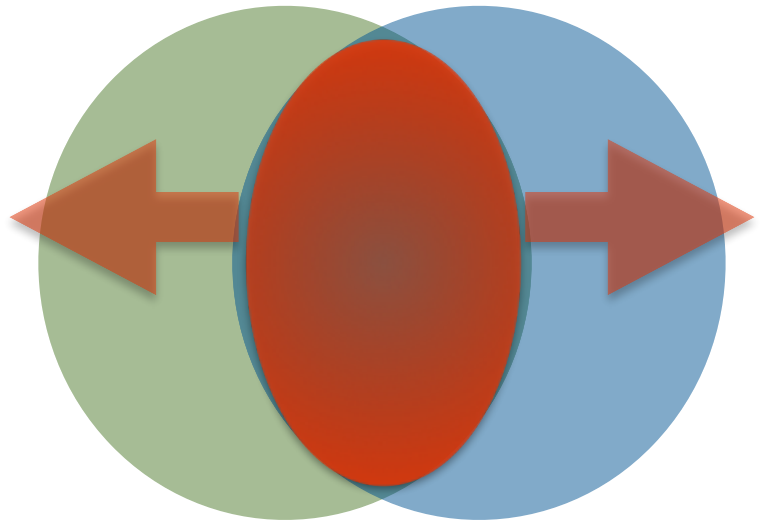
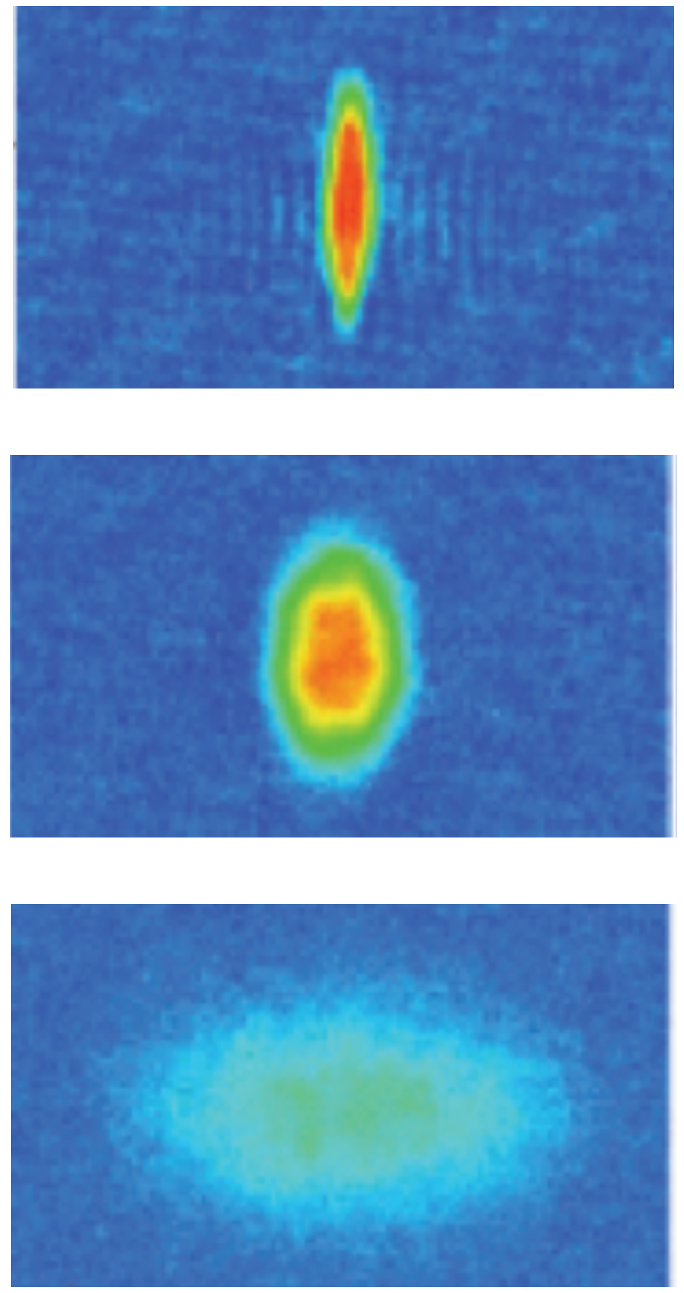
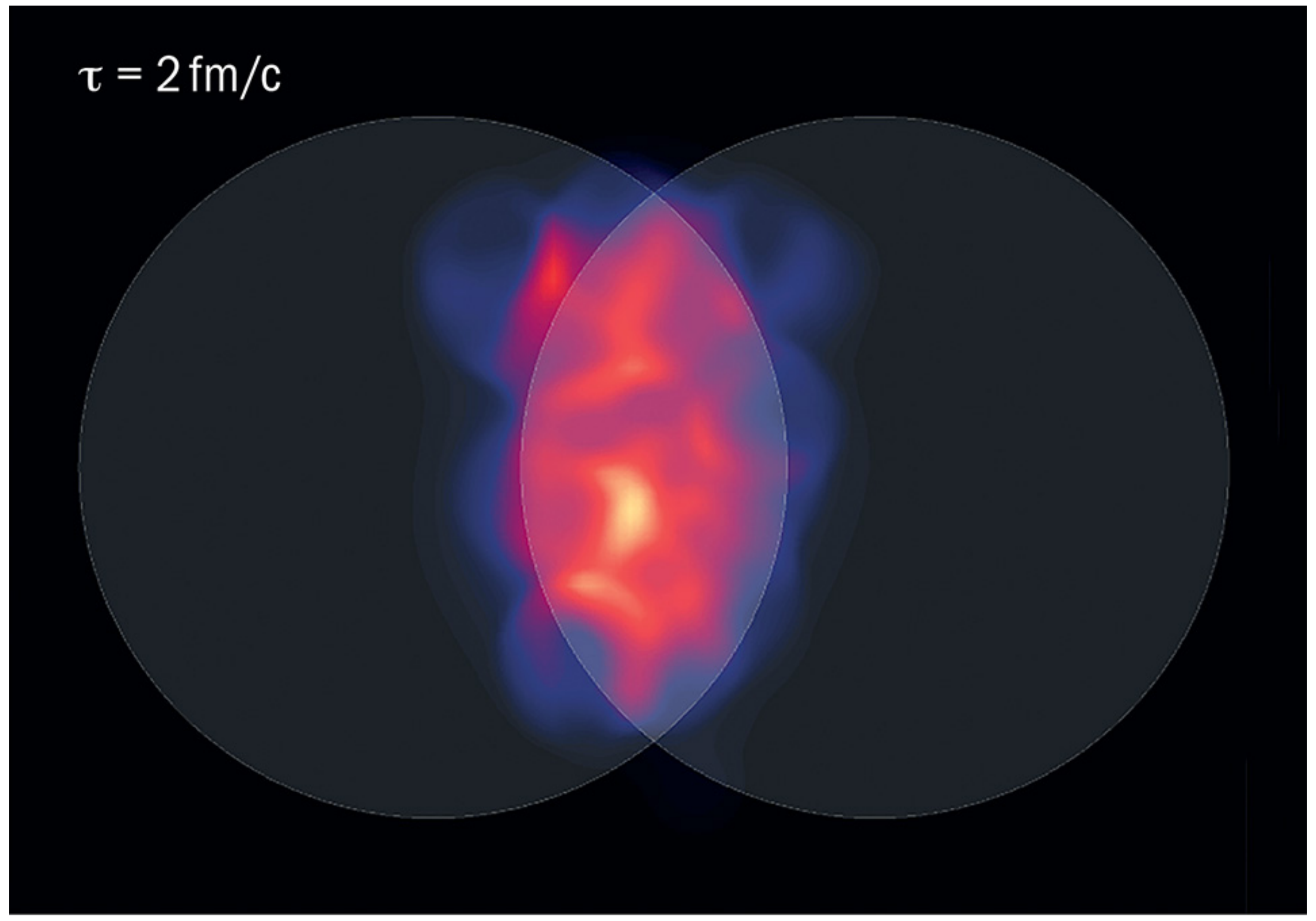
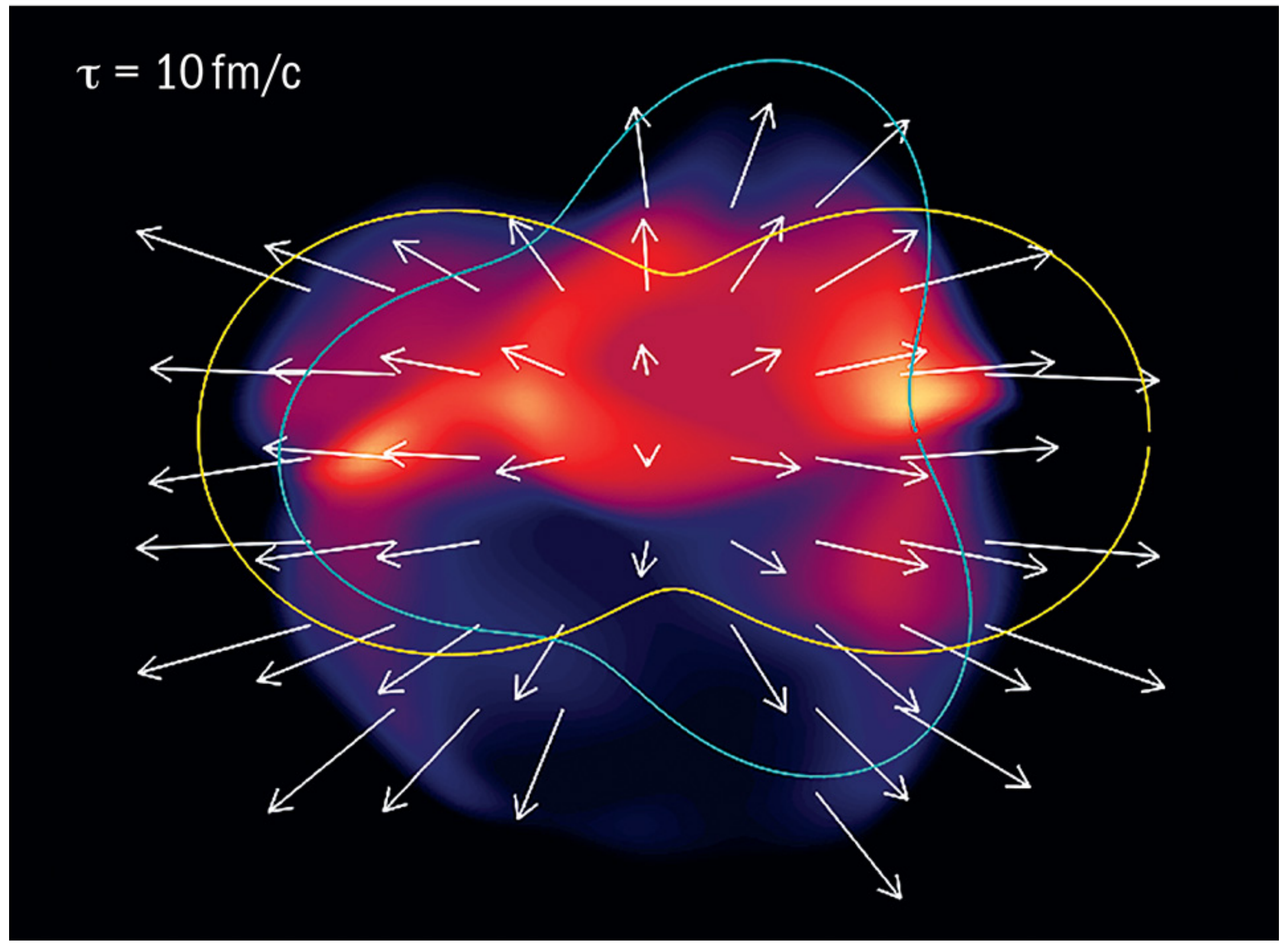
Collective bulk



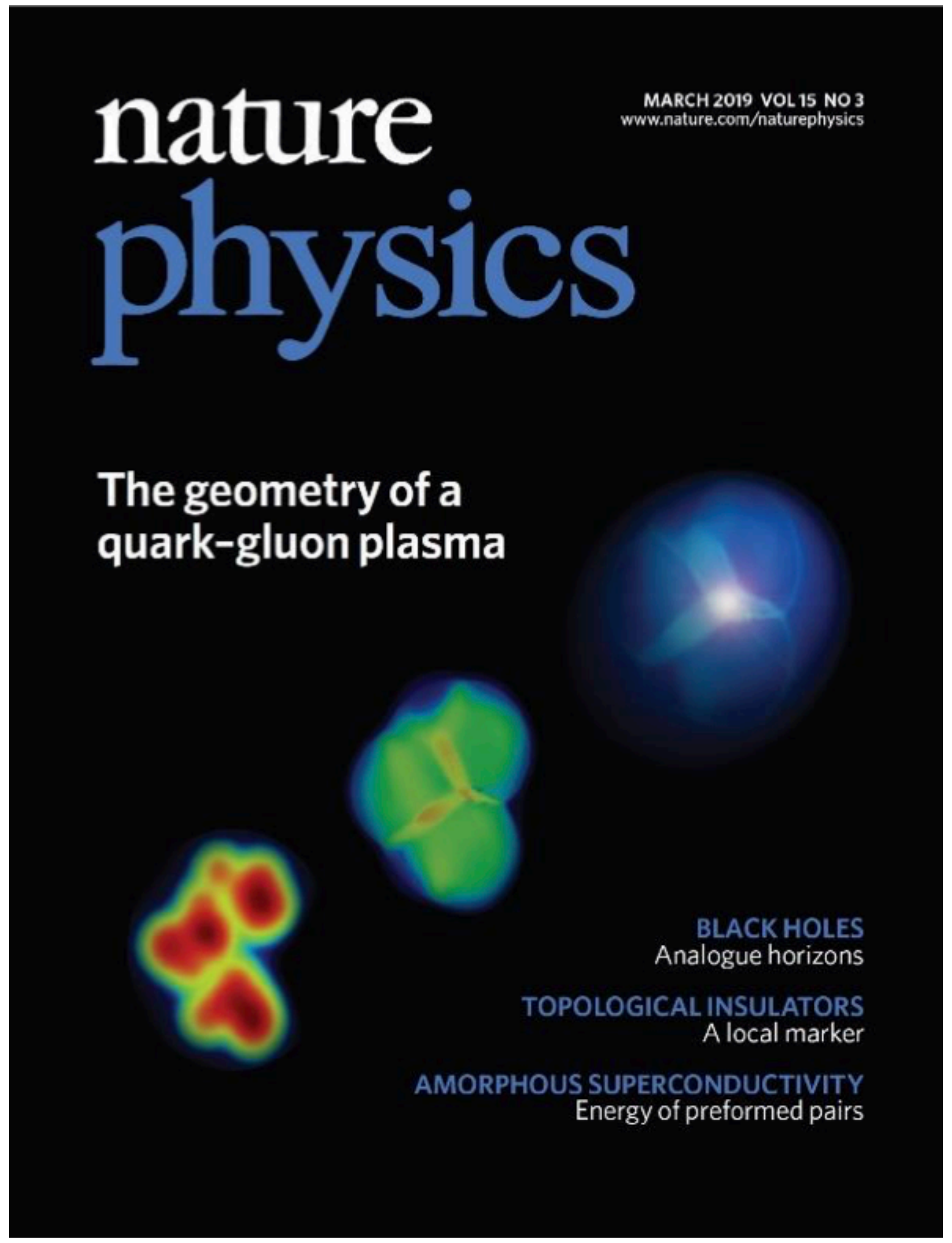
***Initial anisotropies propagate to the final state!***



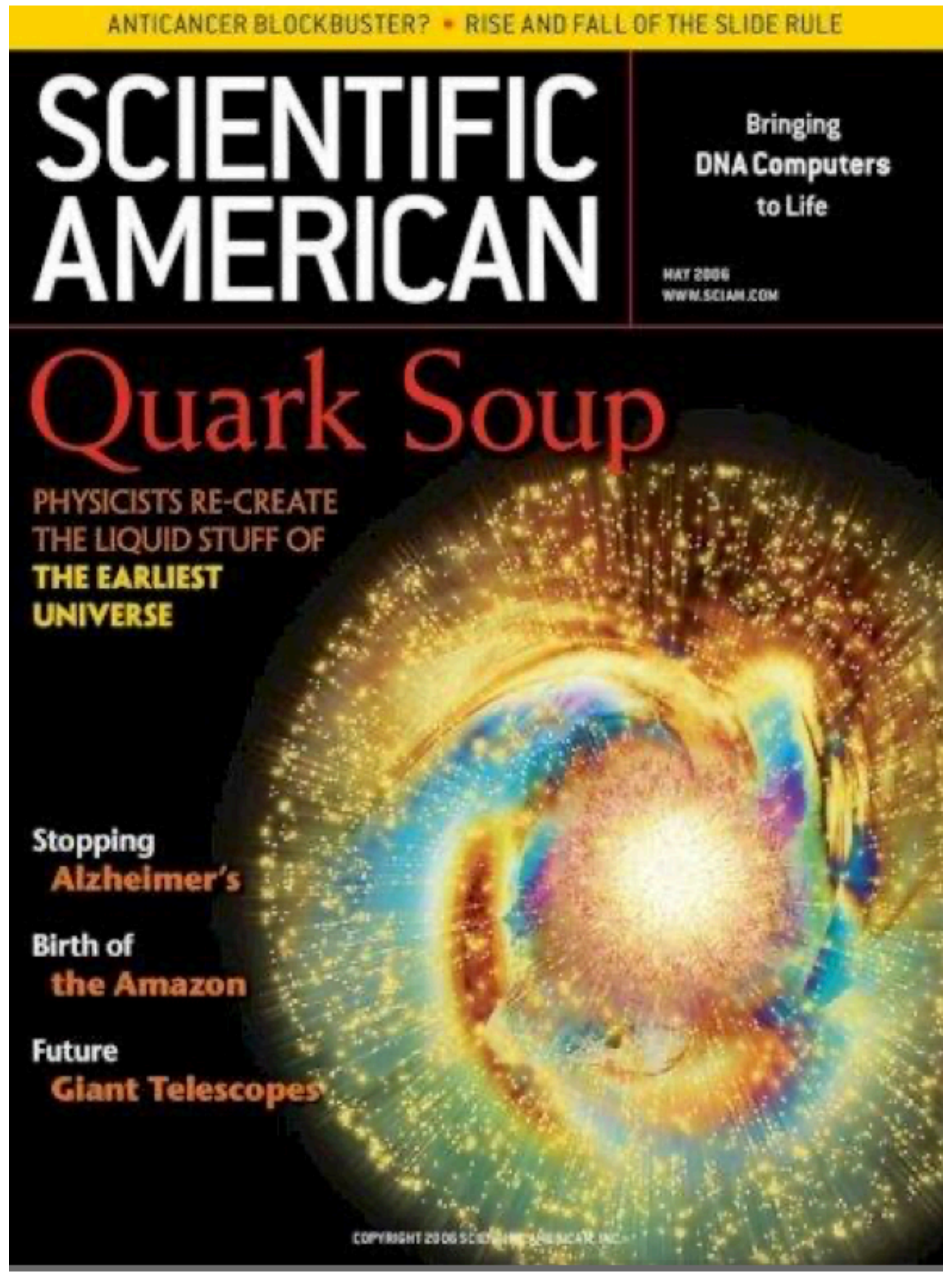


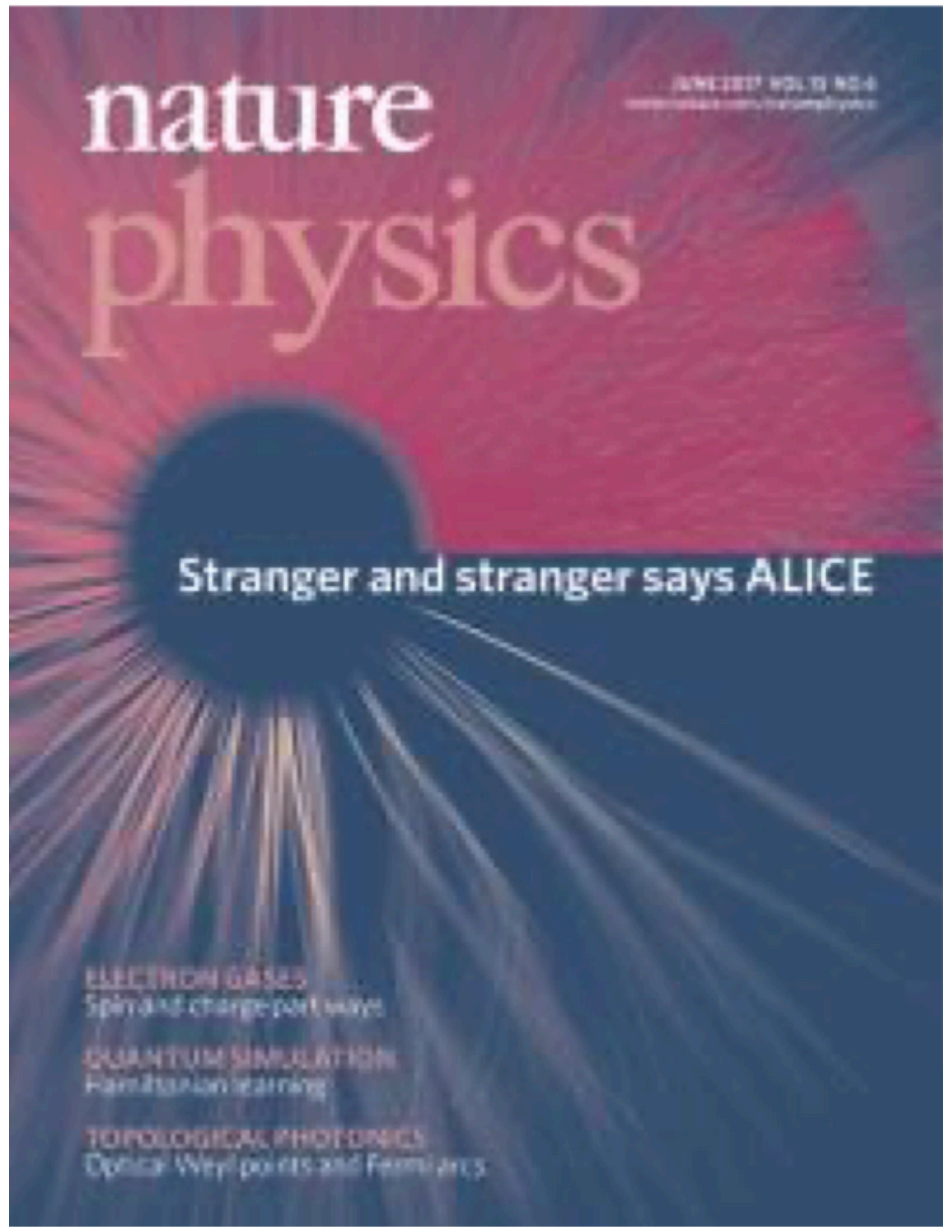
# What do we know so far?




(Almost) perfect fluid!




Temperatures higher than the Sun.




Fluid with strange particles…

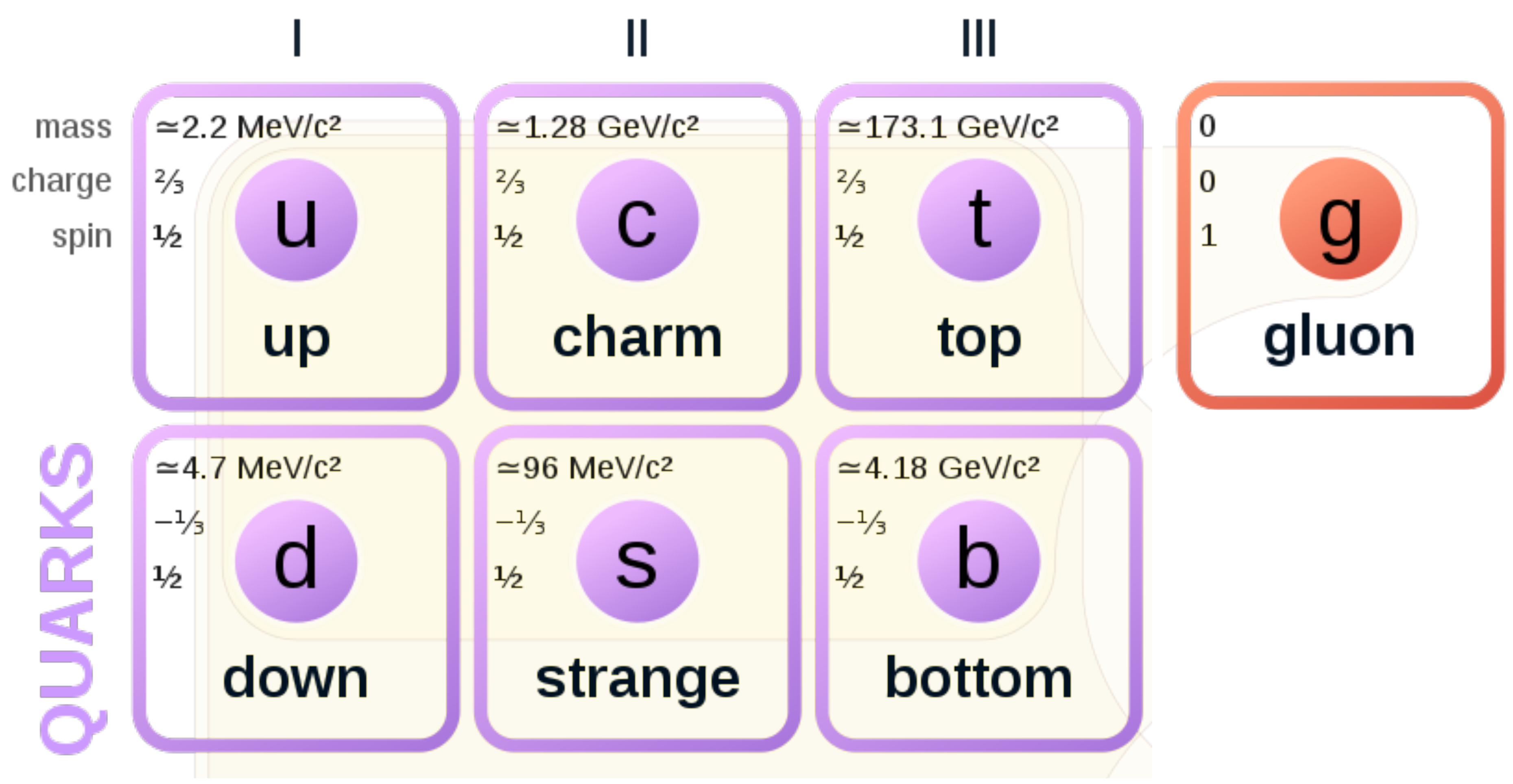

Higher vorticity then Jupiter?

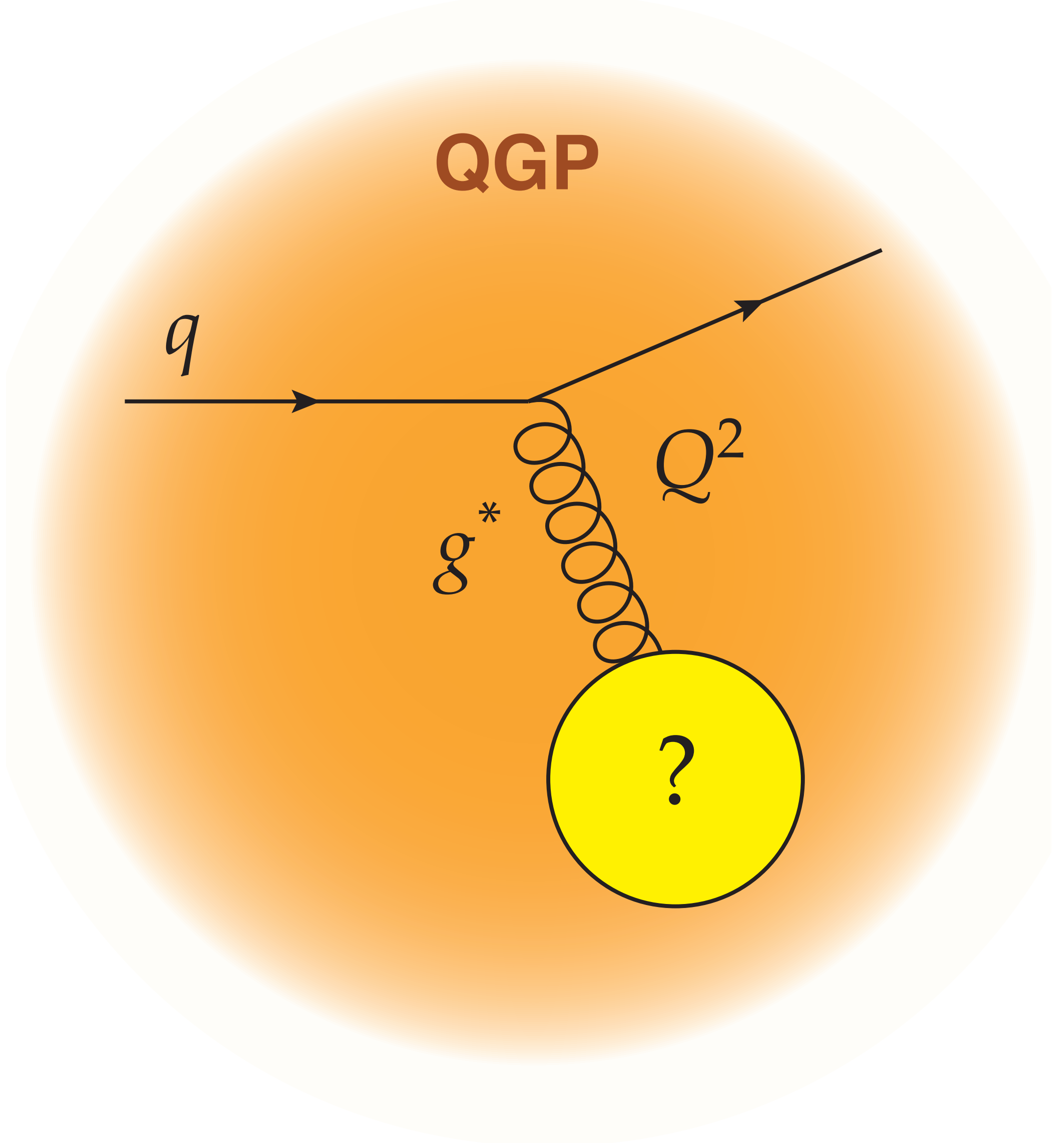
# The Quark-Gluon Plasma

# 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?



# Hard Probes of the QGP

- Use something we know to probe the unknown:

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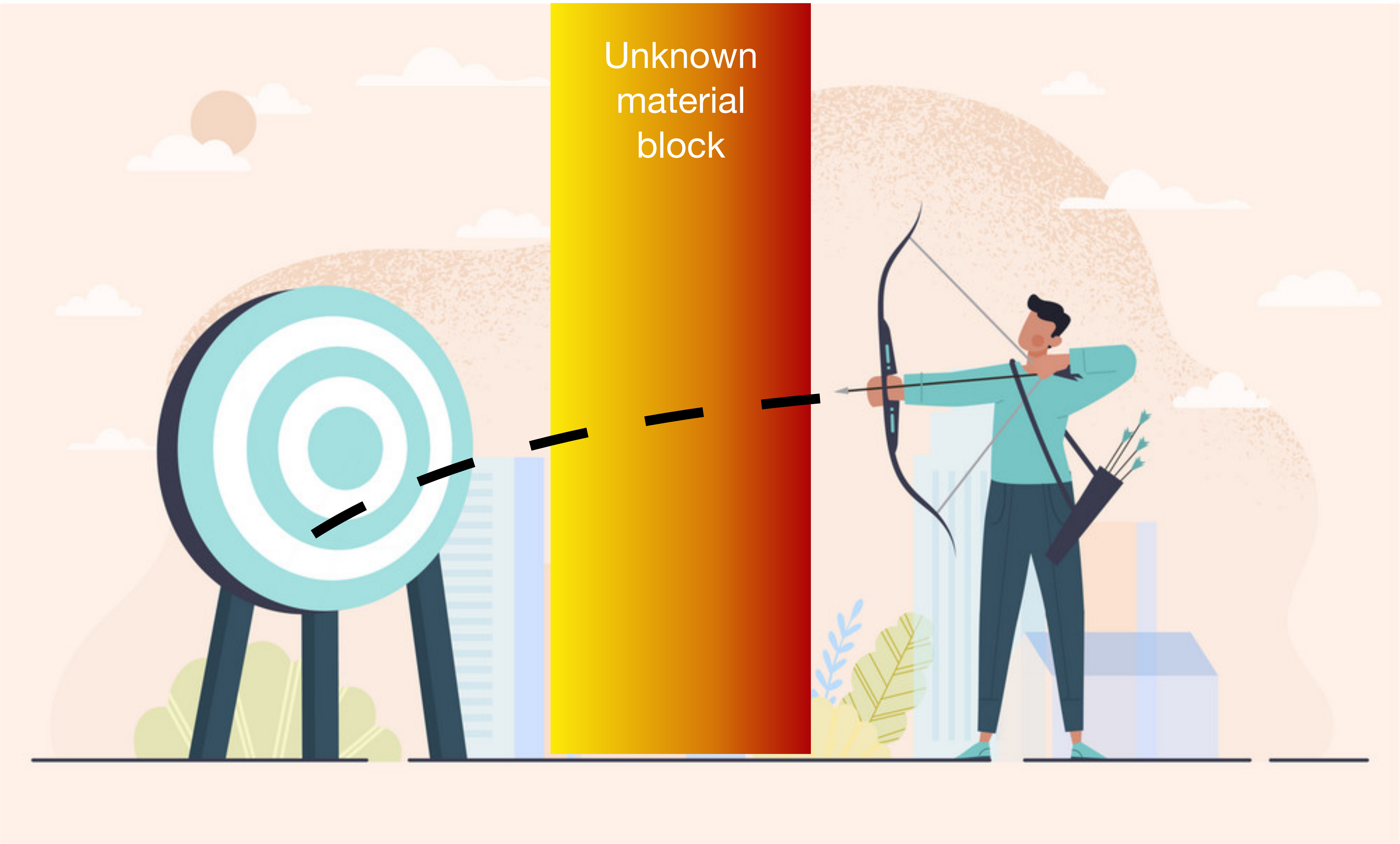
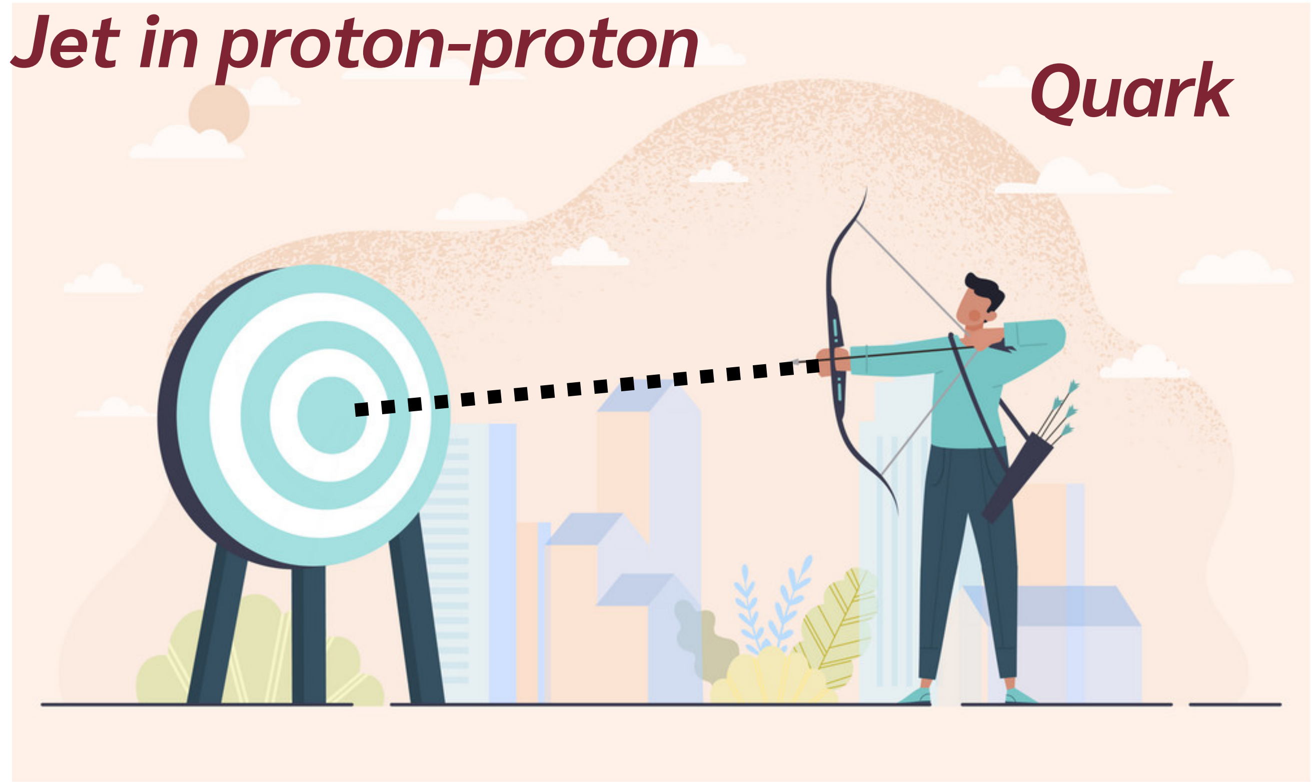
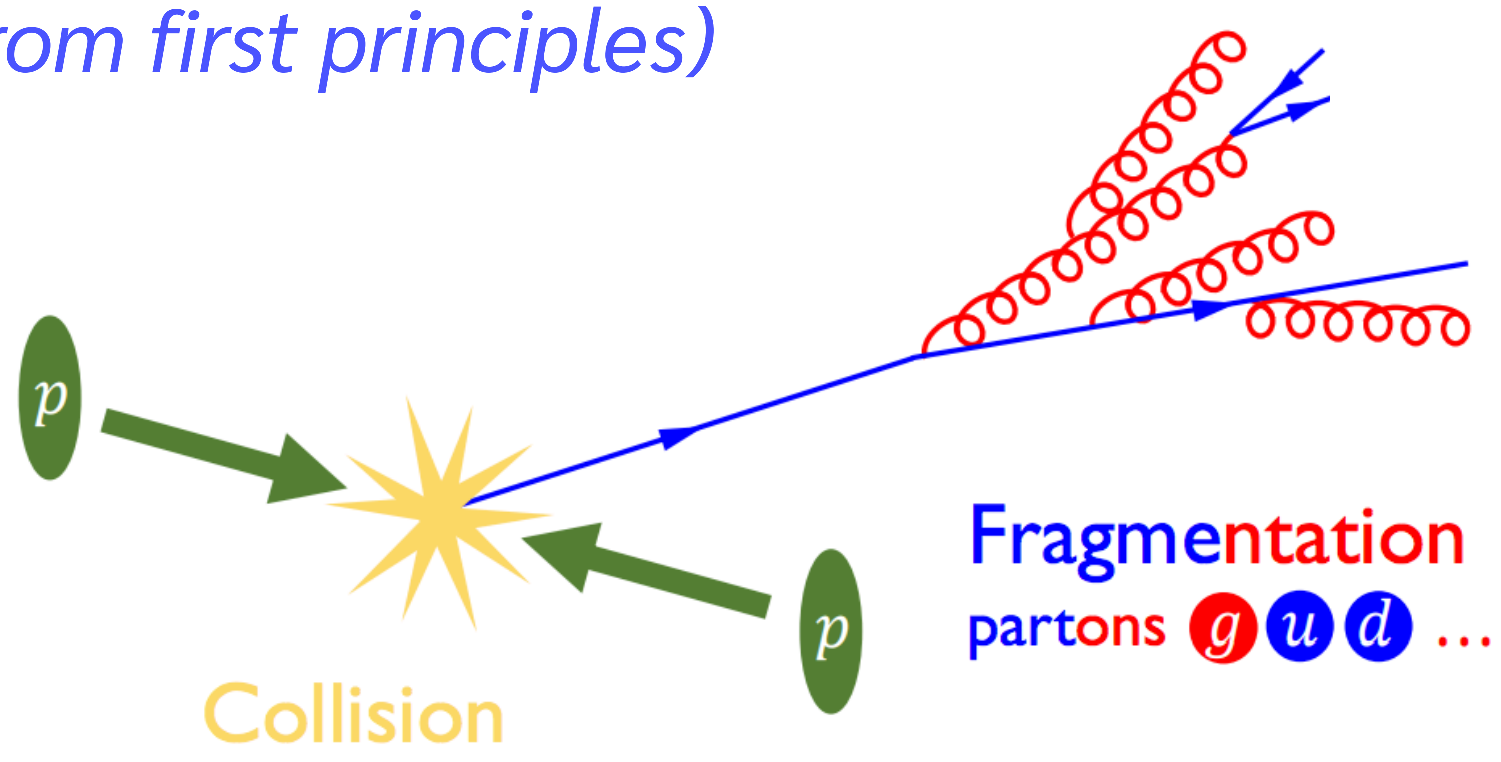


# Jets in Proton-Proton

- How quarks and gluons behave in "vacuum"?




*Small distance ("High-energy")*
=
*Can be described analytically*
*(From first principles)*



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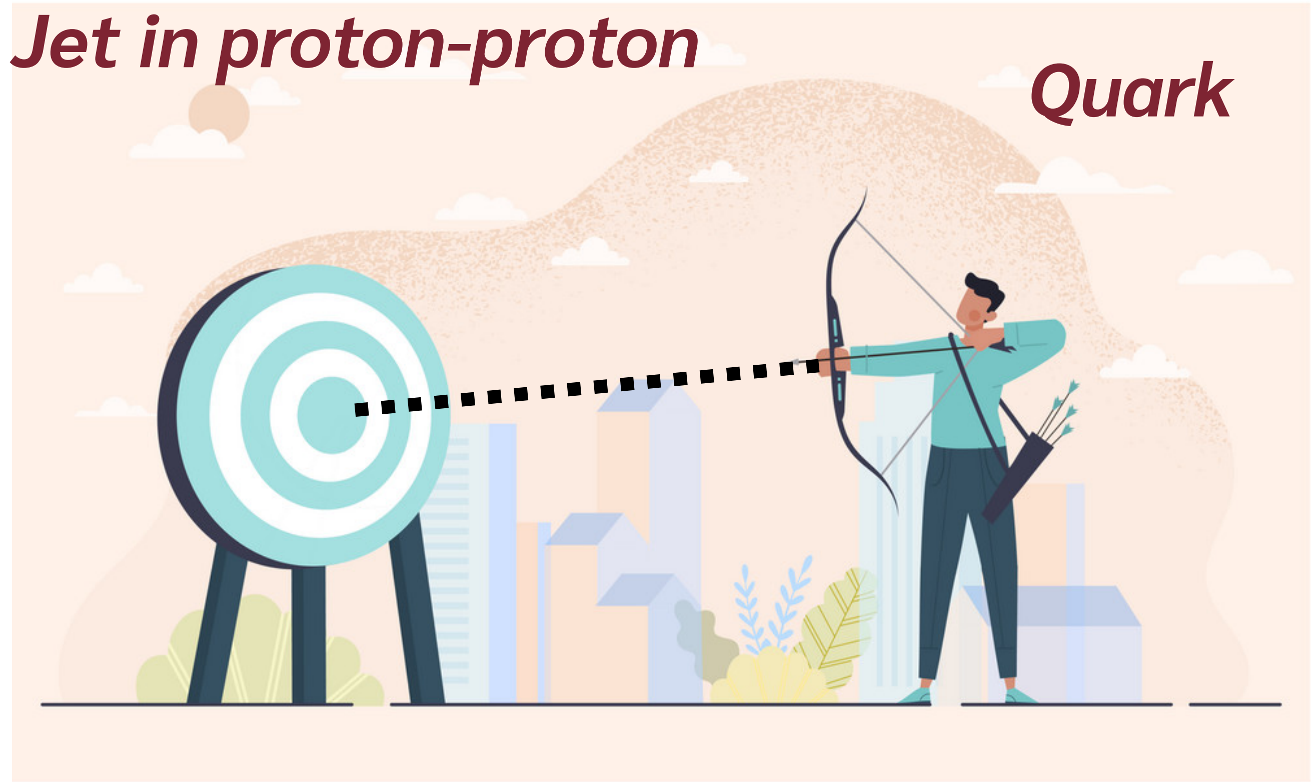


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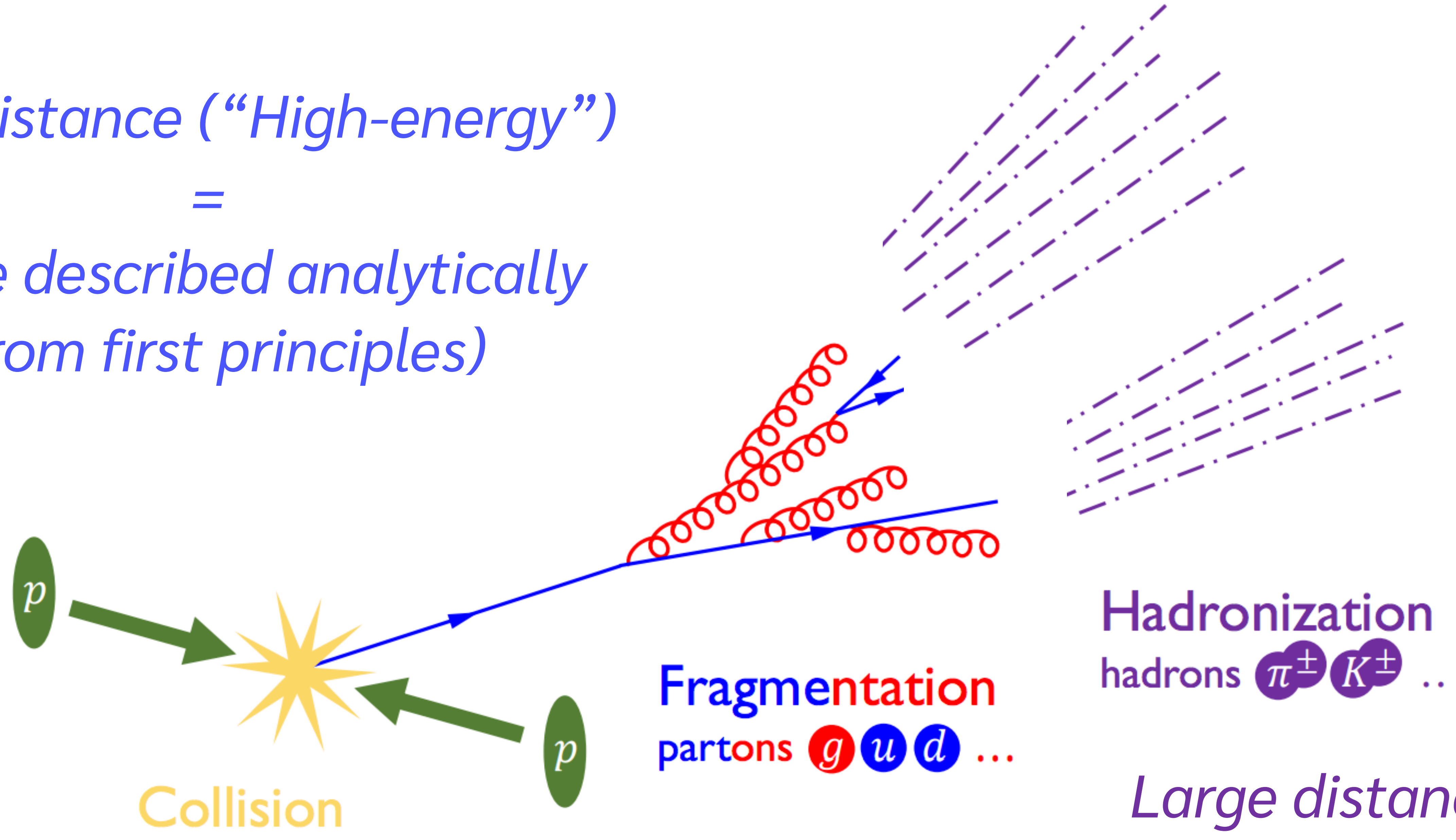


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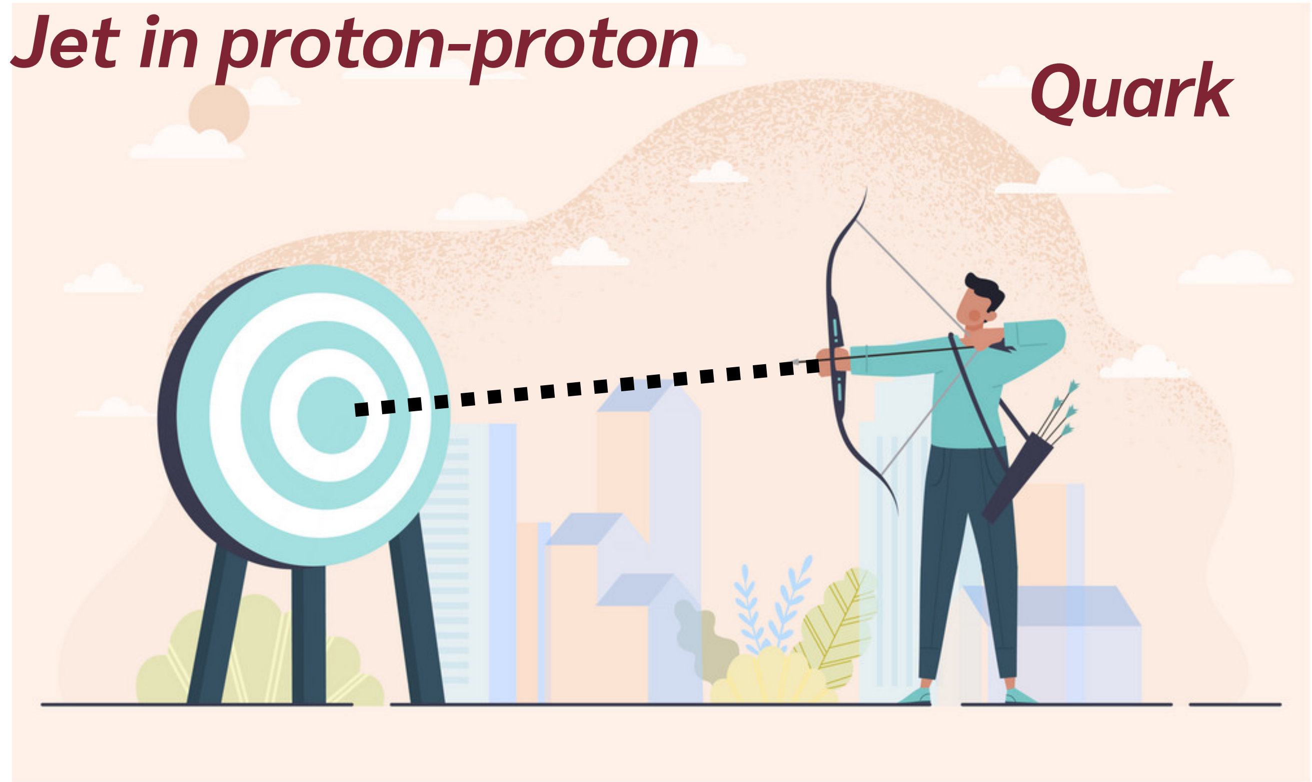


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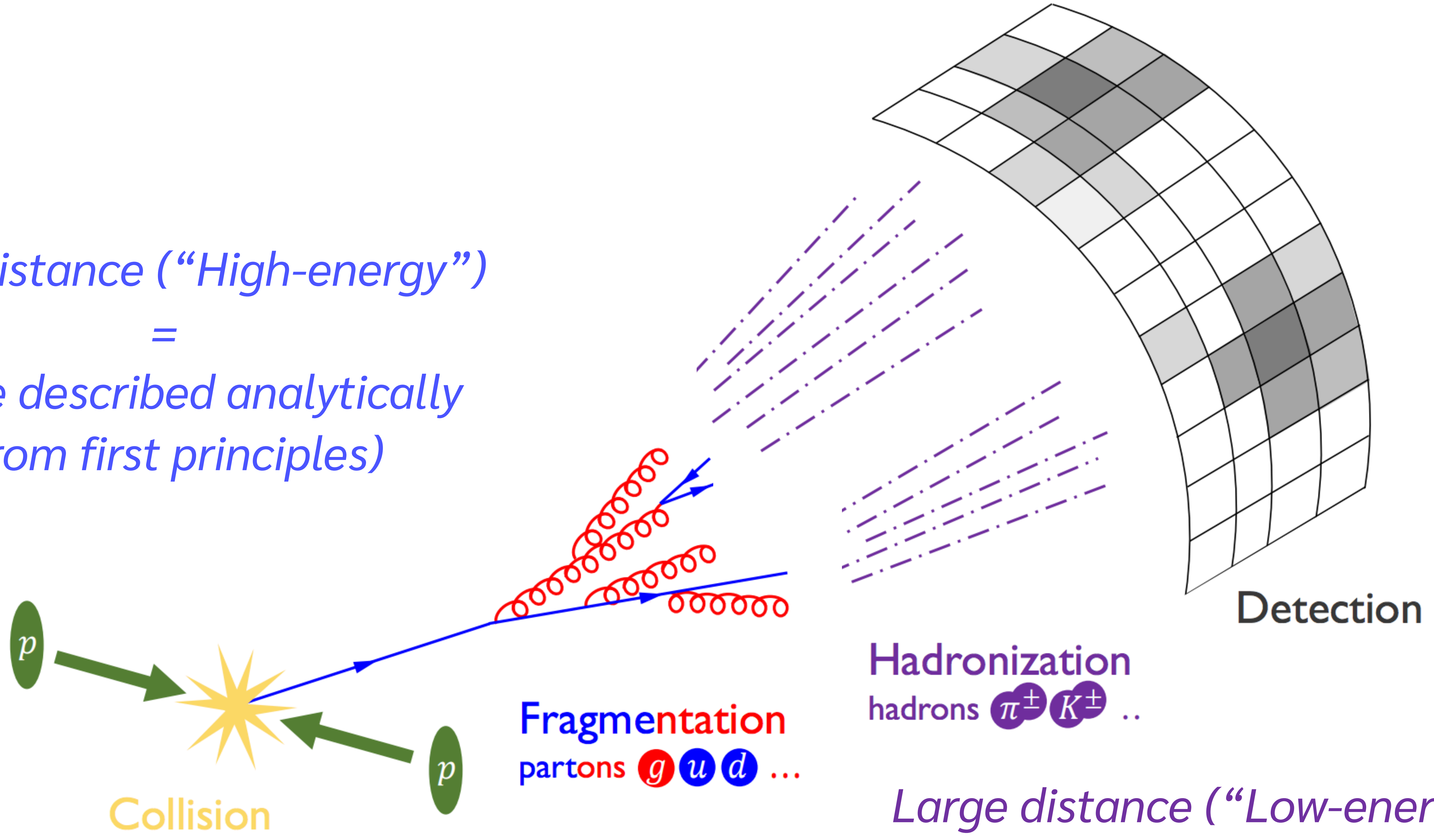


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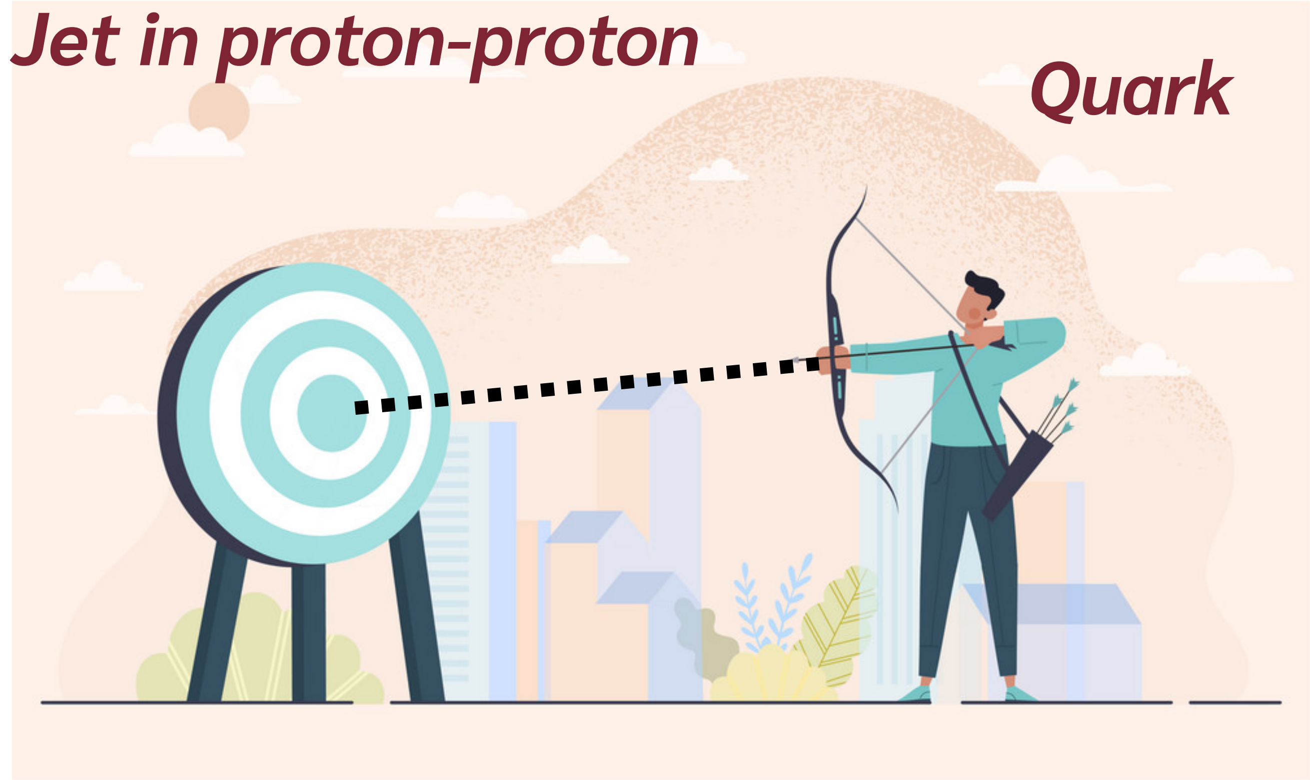


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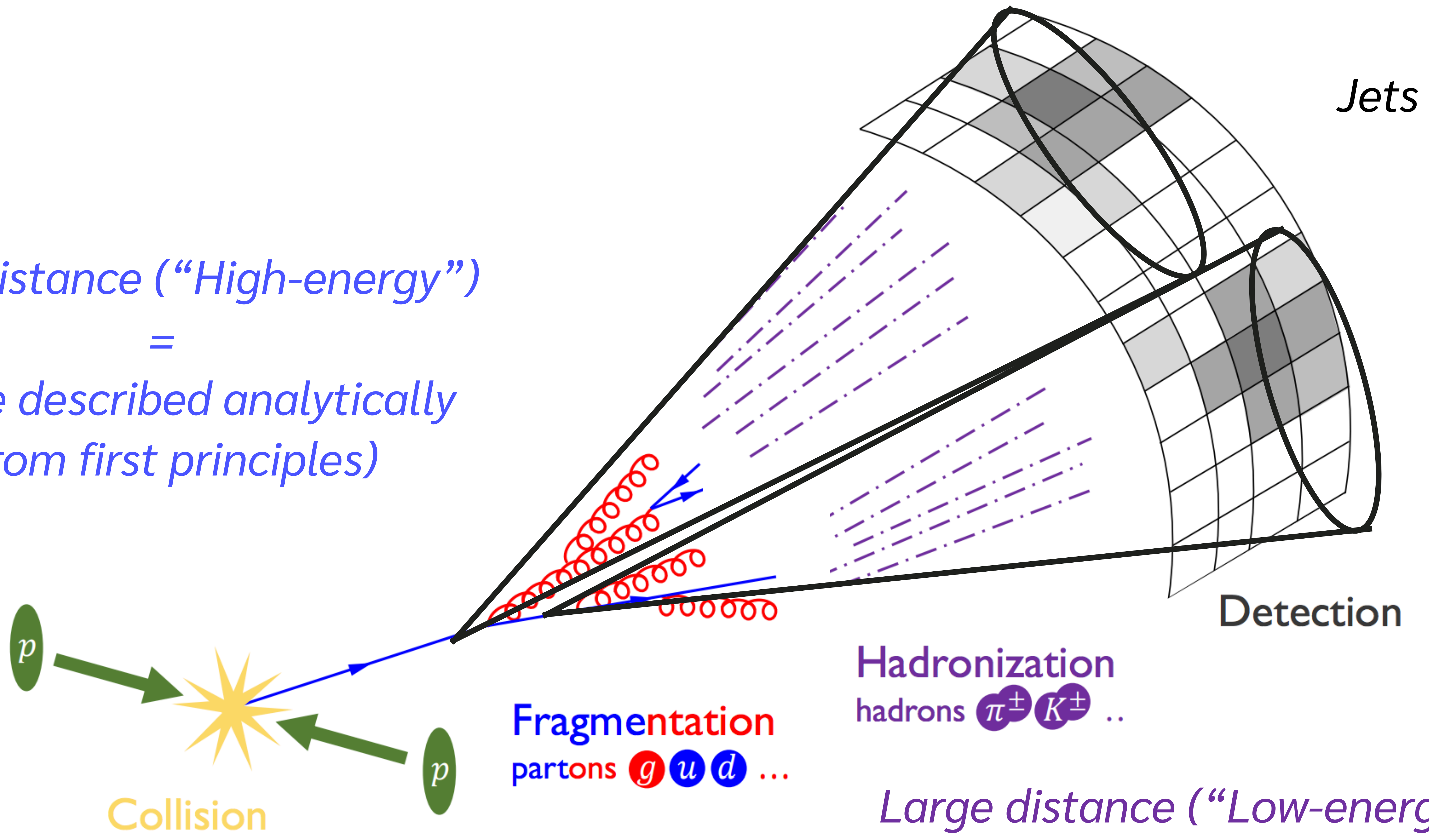


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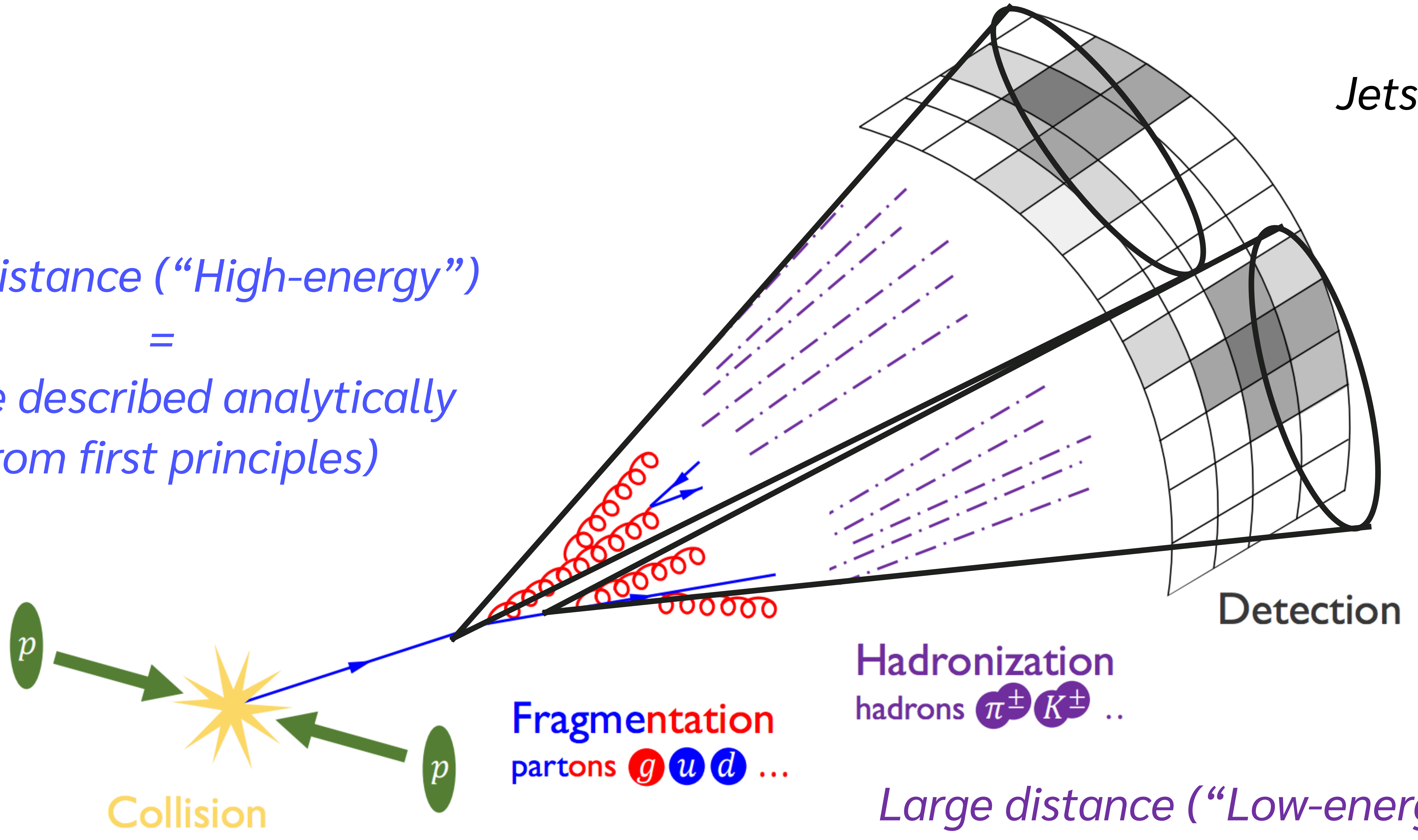


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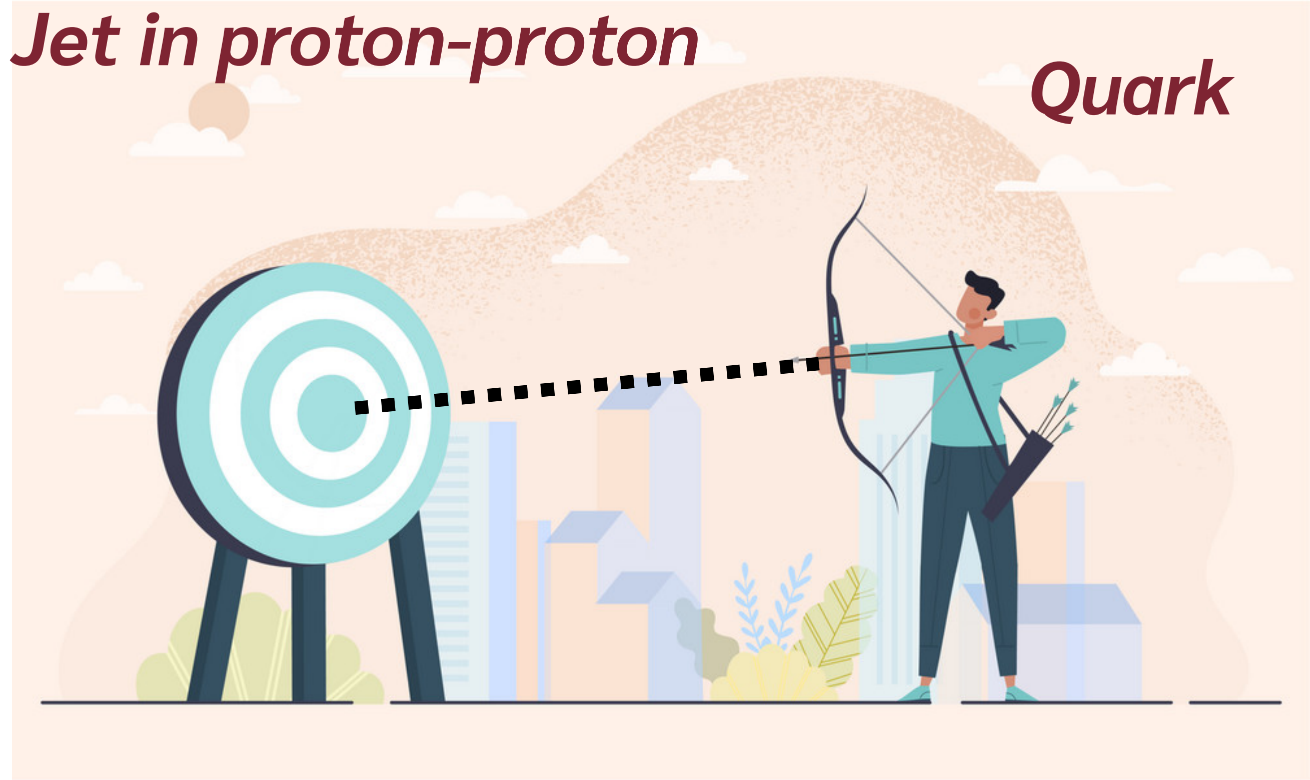


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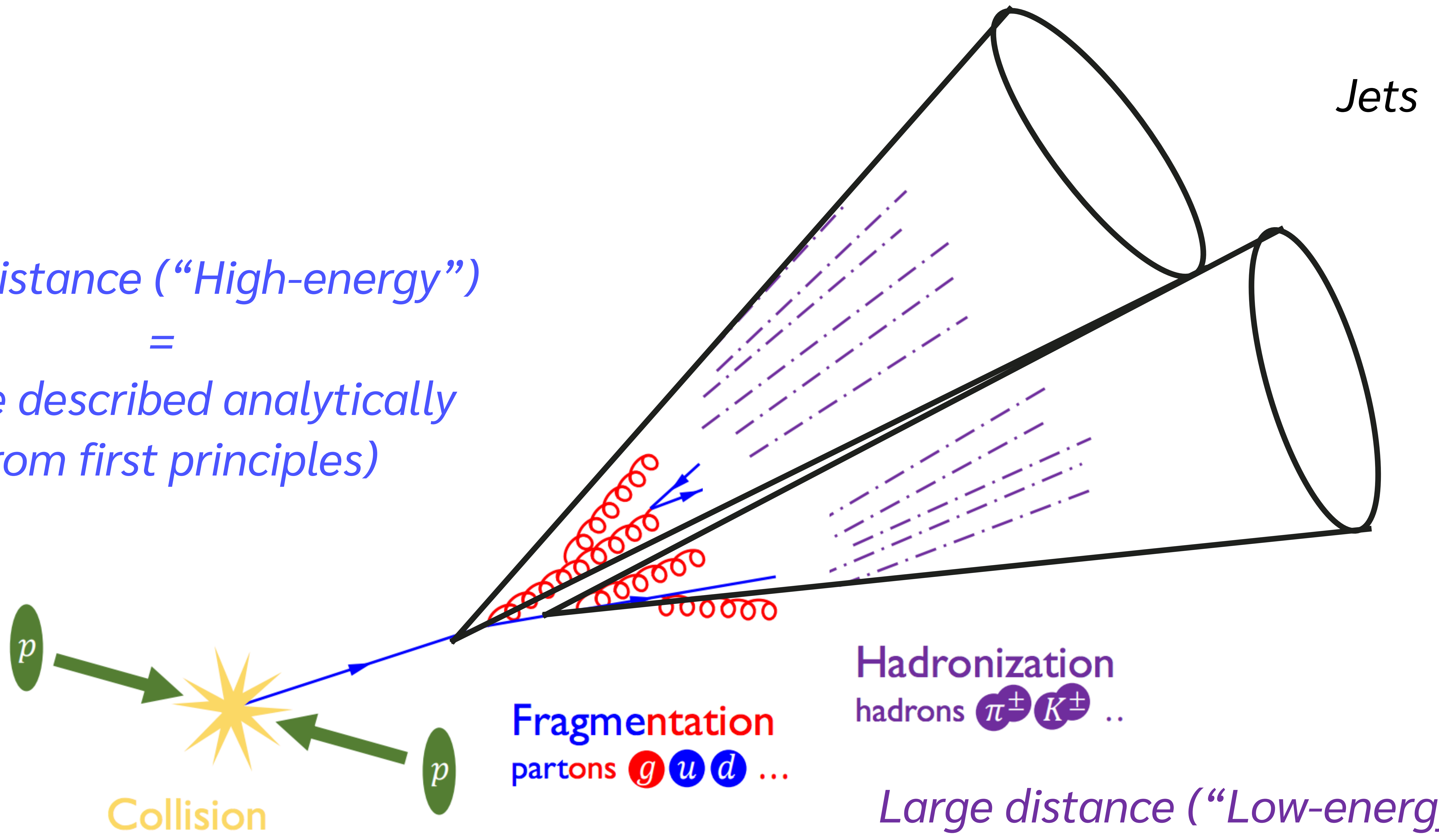


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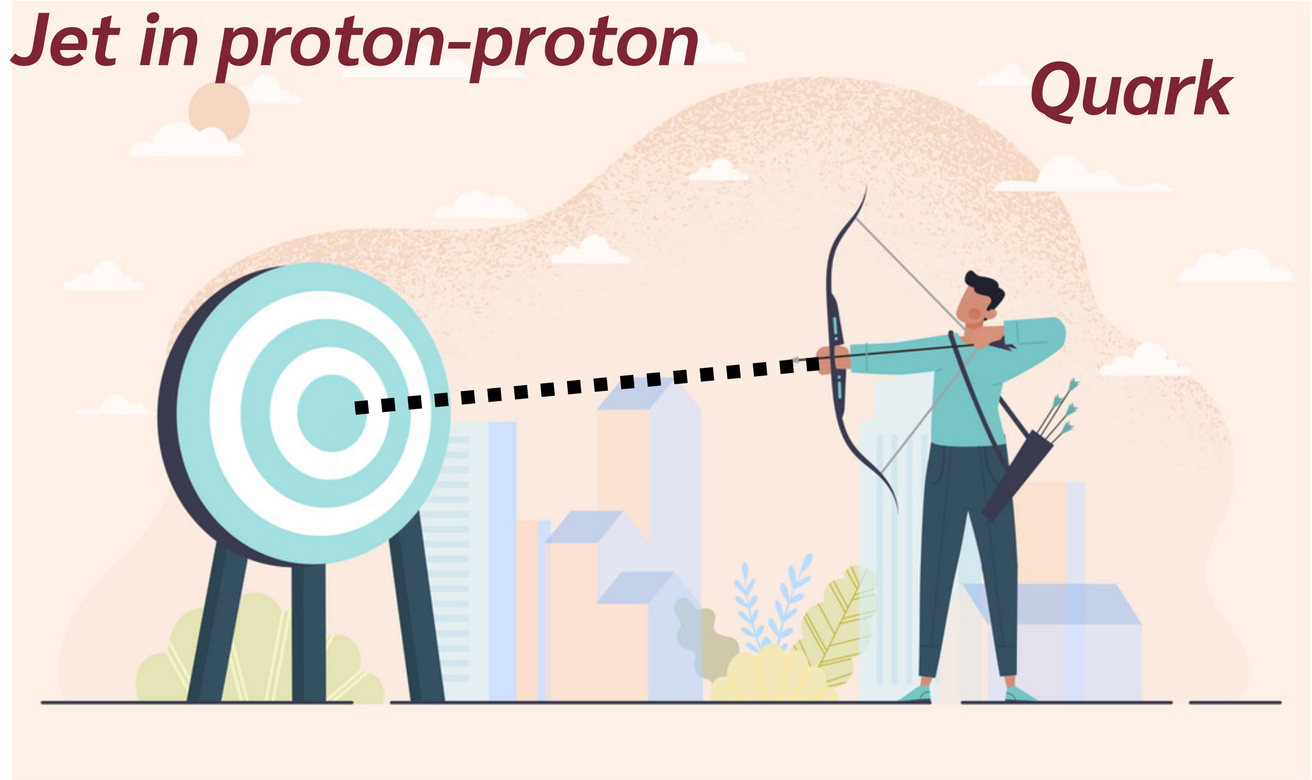


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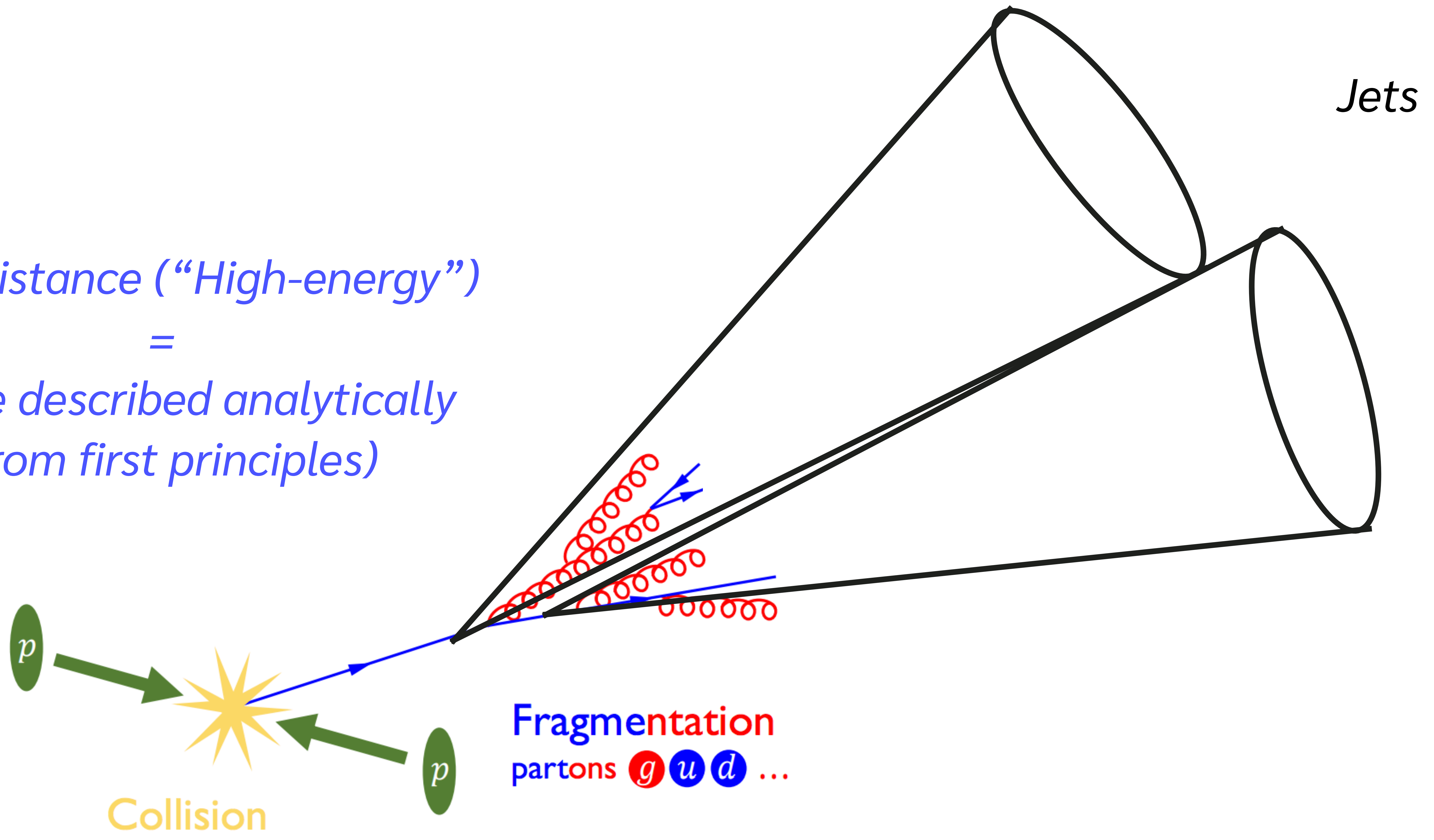
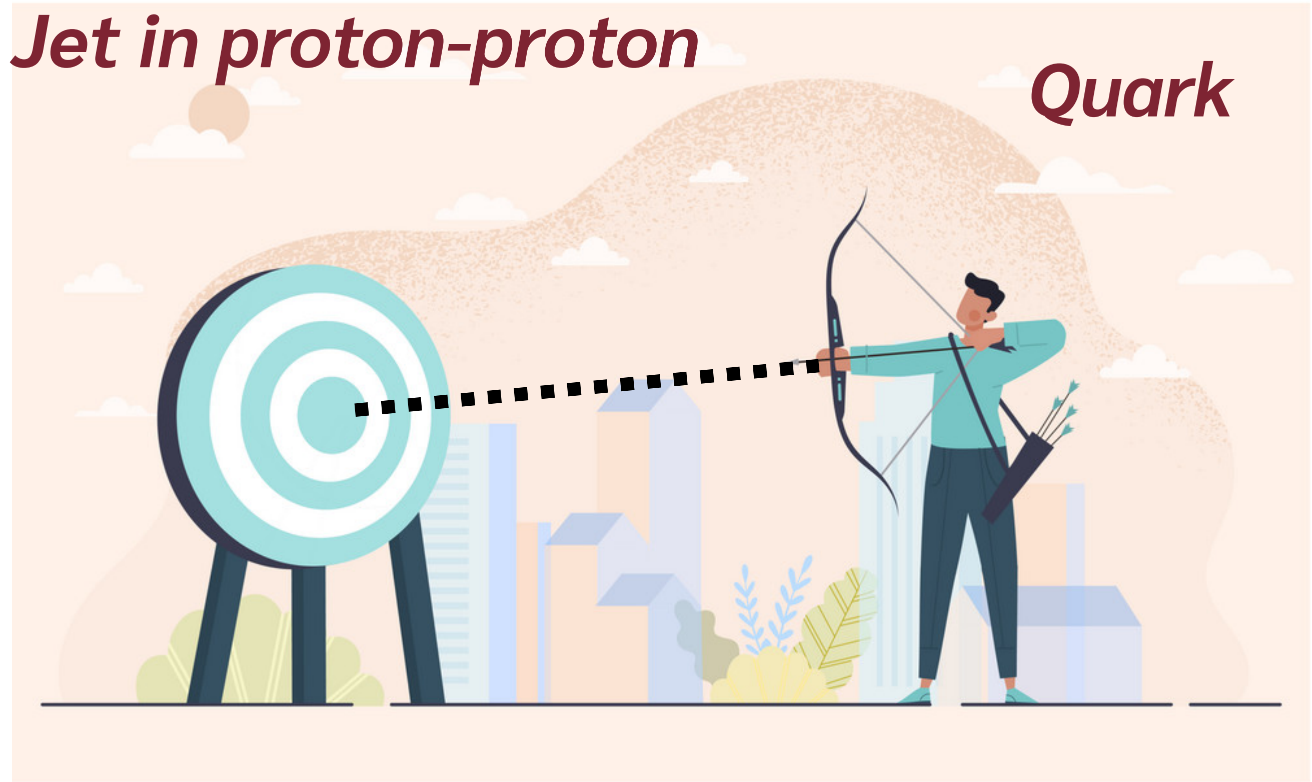


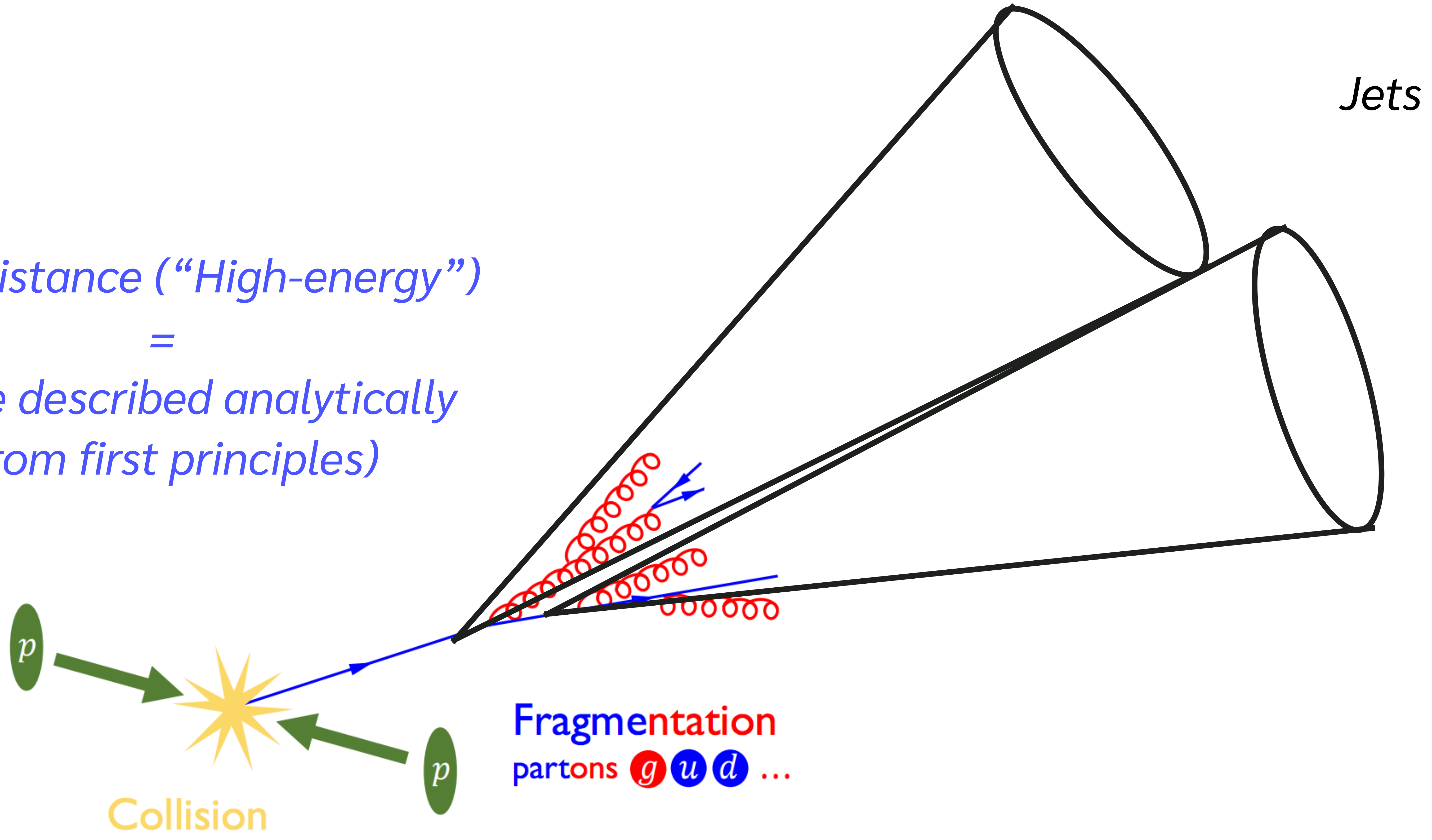



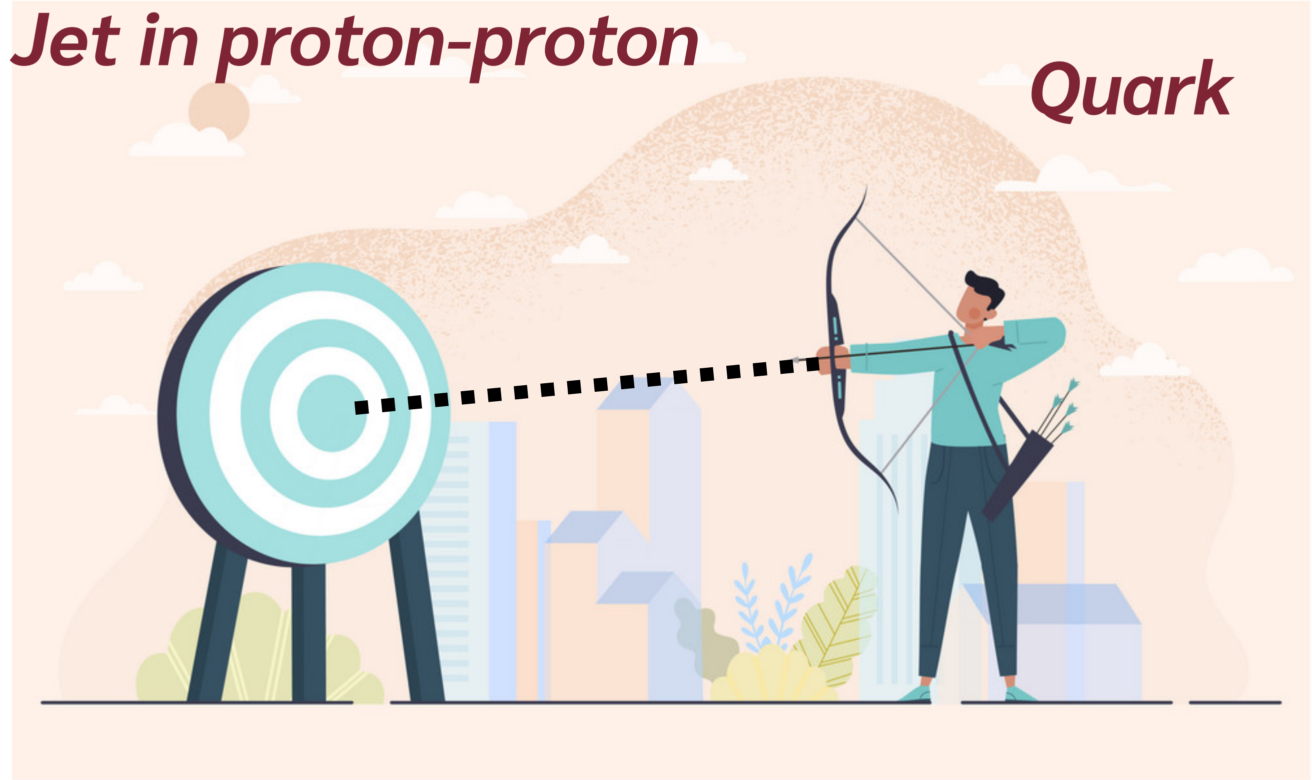

*QCD jets defined based on a set of rules: a **jet clustering algorithm***

# Jets in Proton-Proton

- How quarks and gluons behave in “vacuum”?

*Small distance (“High-energy”)*
=
*Can be described analytically*
*(From first principles)*



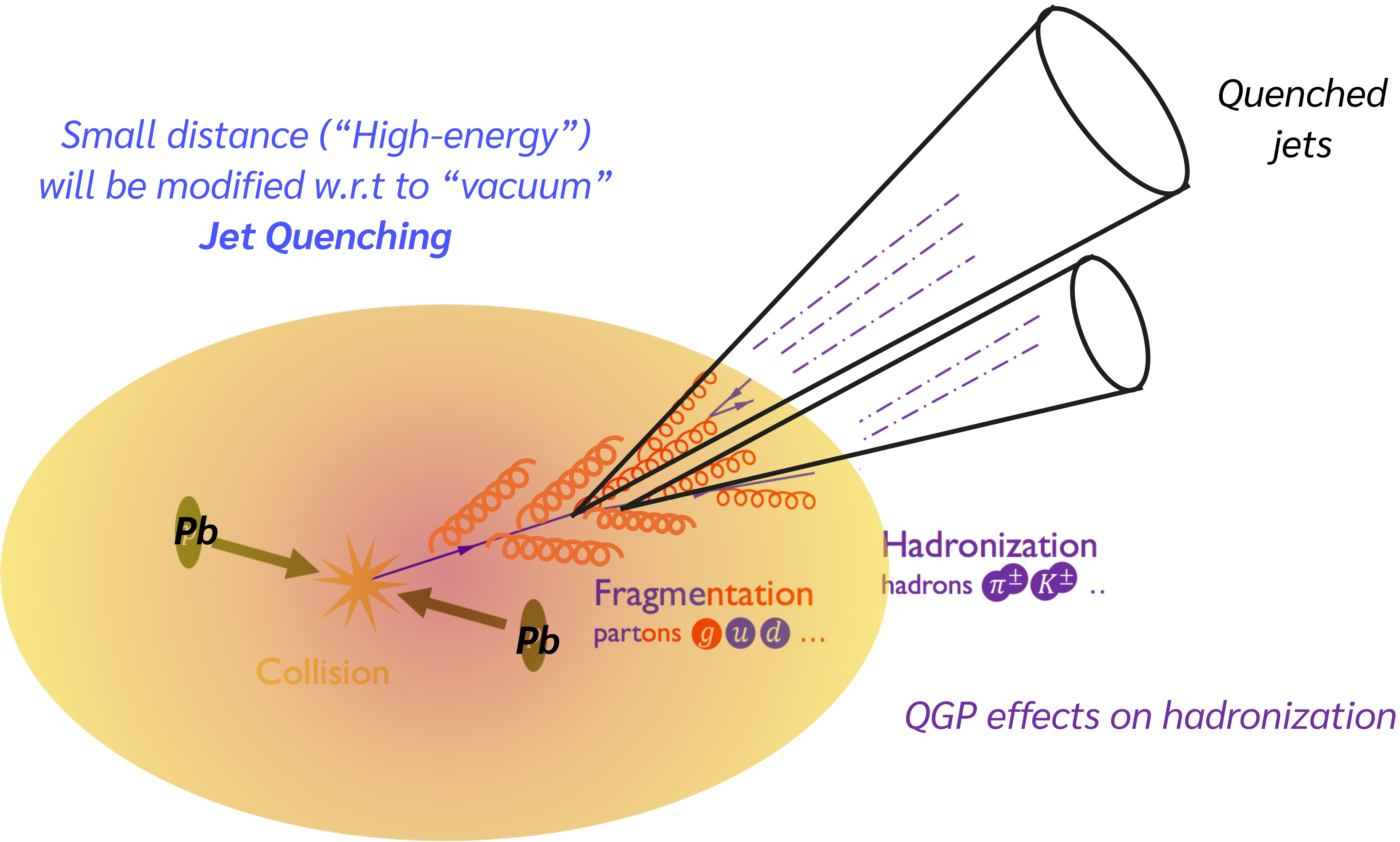

*QCD jets defined based on a set of rules: a **jet clustering algorithm***

*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***

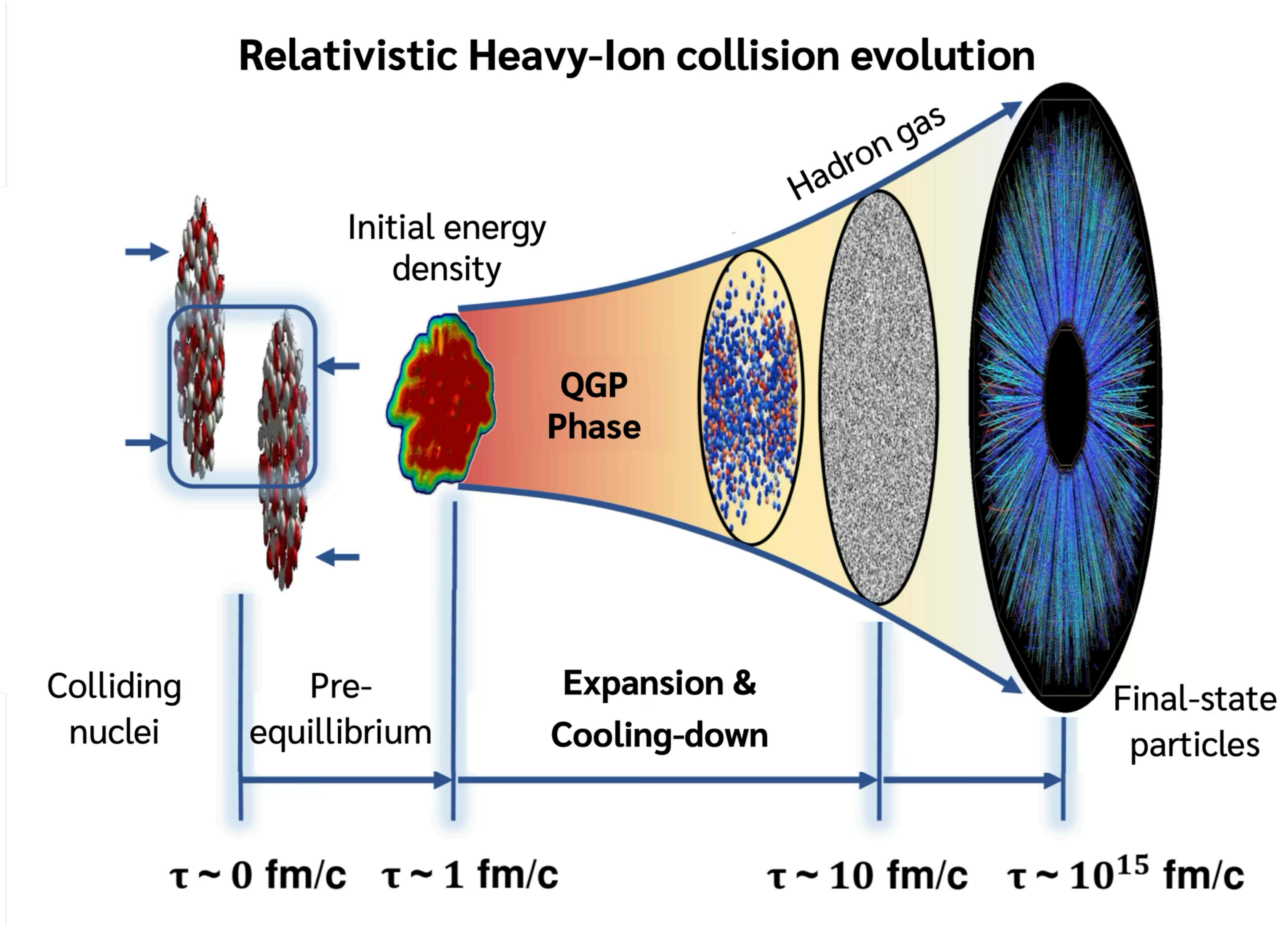



*QGP effects on hadronization?*


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

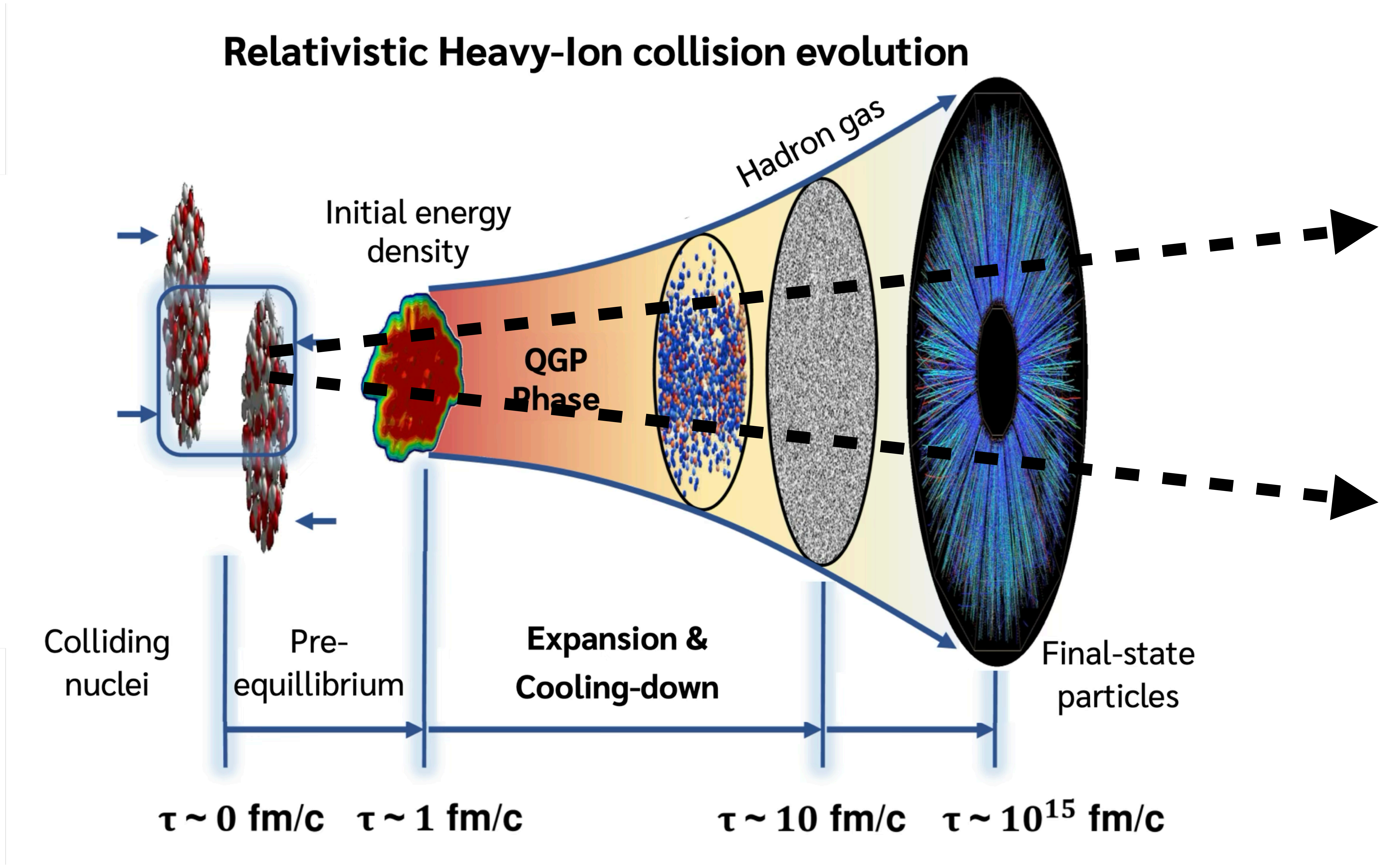
*They carry information about the QGP characteristics.*

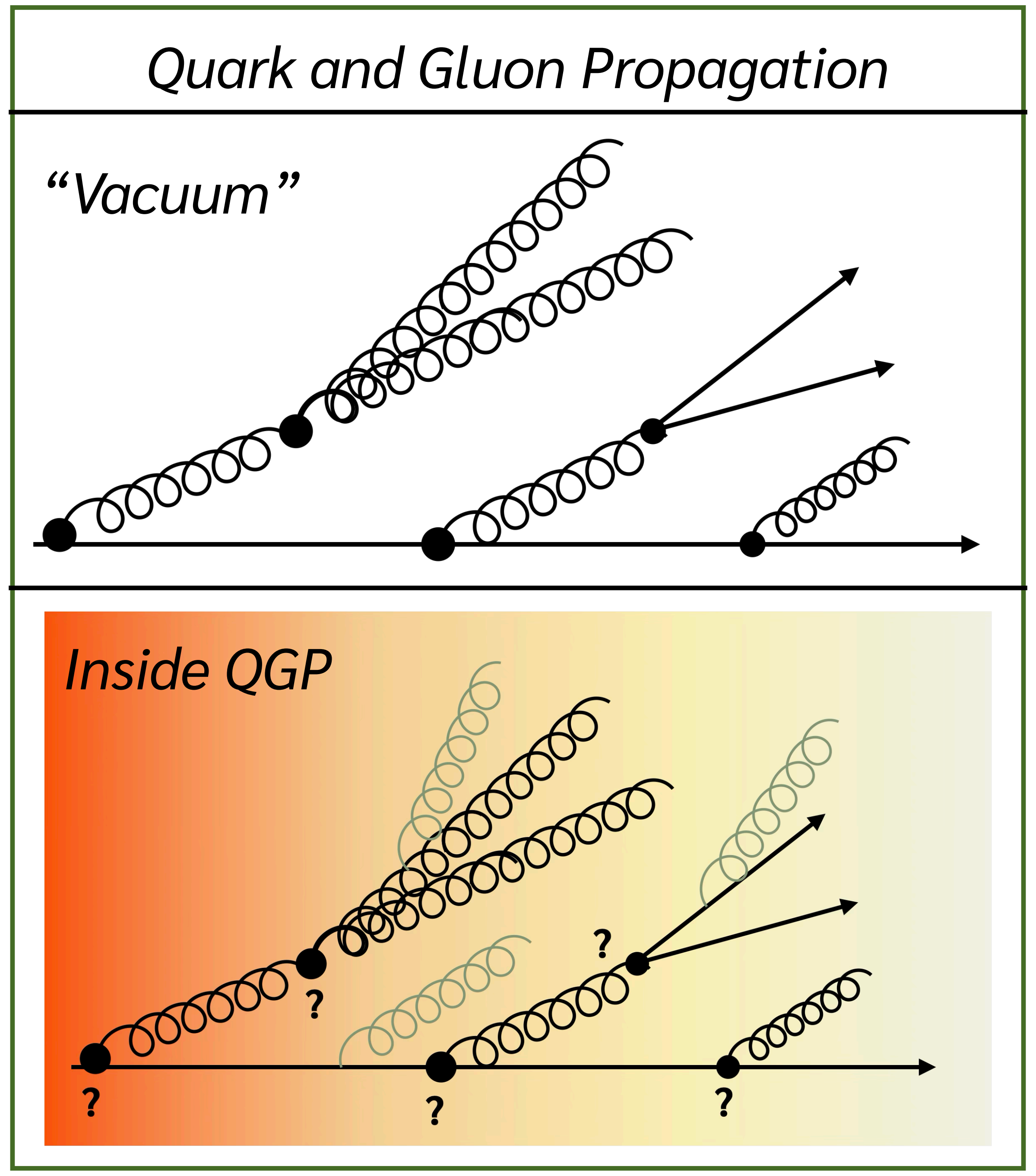
# On-going QGP studies




*What are the conditions to form a QGP? How does it evolve?*
*[E.g: Pheno projects, LHC (CMS) projects]*

# On-going QGP studies




*What are the conditions to form a QGP? How does it evolve?*
*[E.g: Pheno projects, LHC (CMS) projects]*

*What underlying mechanisms govern the interaction of the QGP with the propagating particles?*
*[E.g: Pheno projects]*

# 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

LIP

TÉCNICO LISBOA

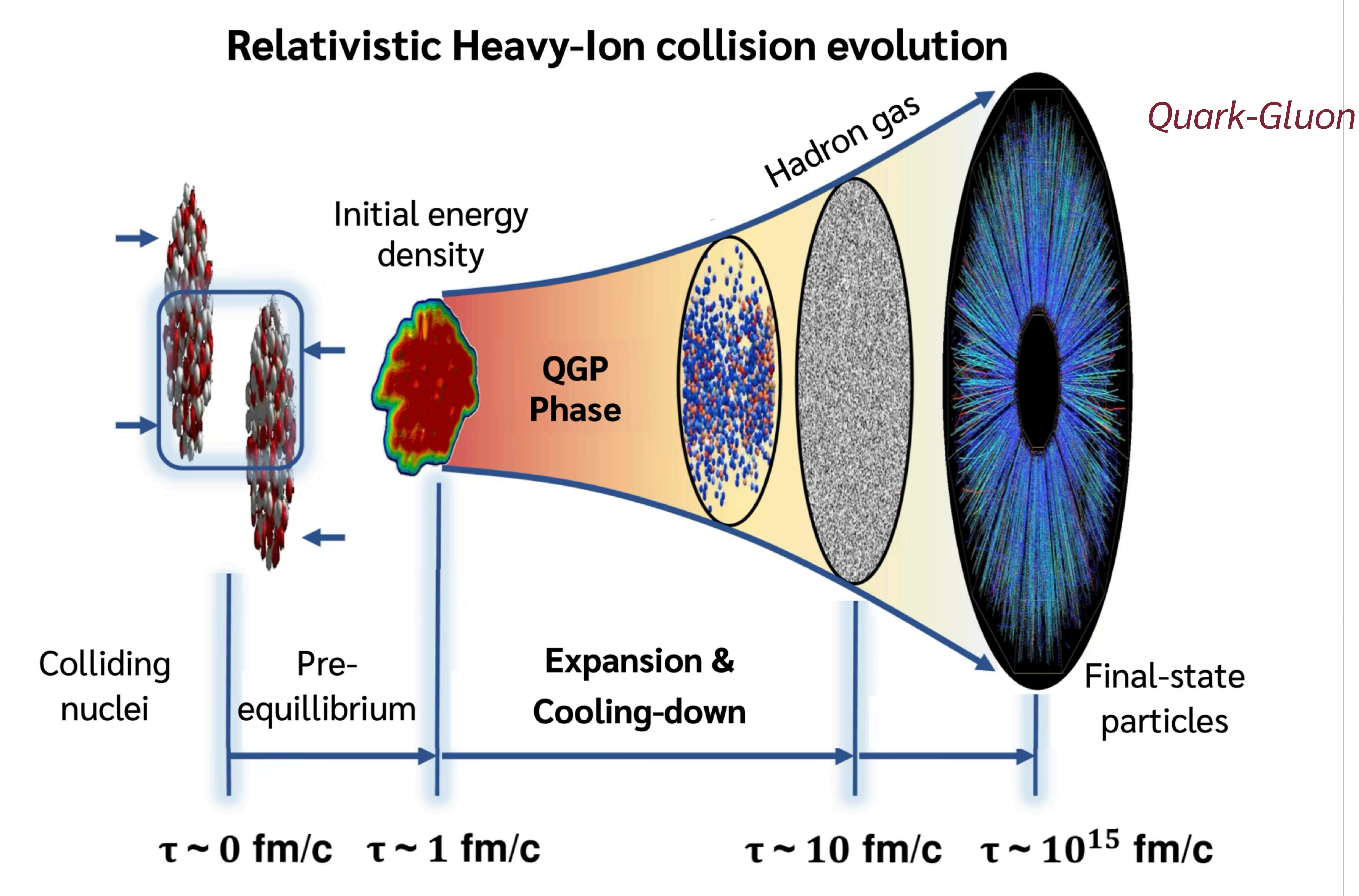
REPÚBLICA PORTUGUESA

fct

Fundação para a Ciência e a Tecnologia

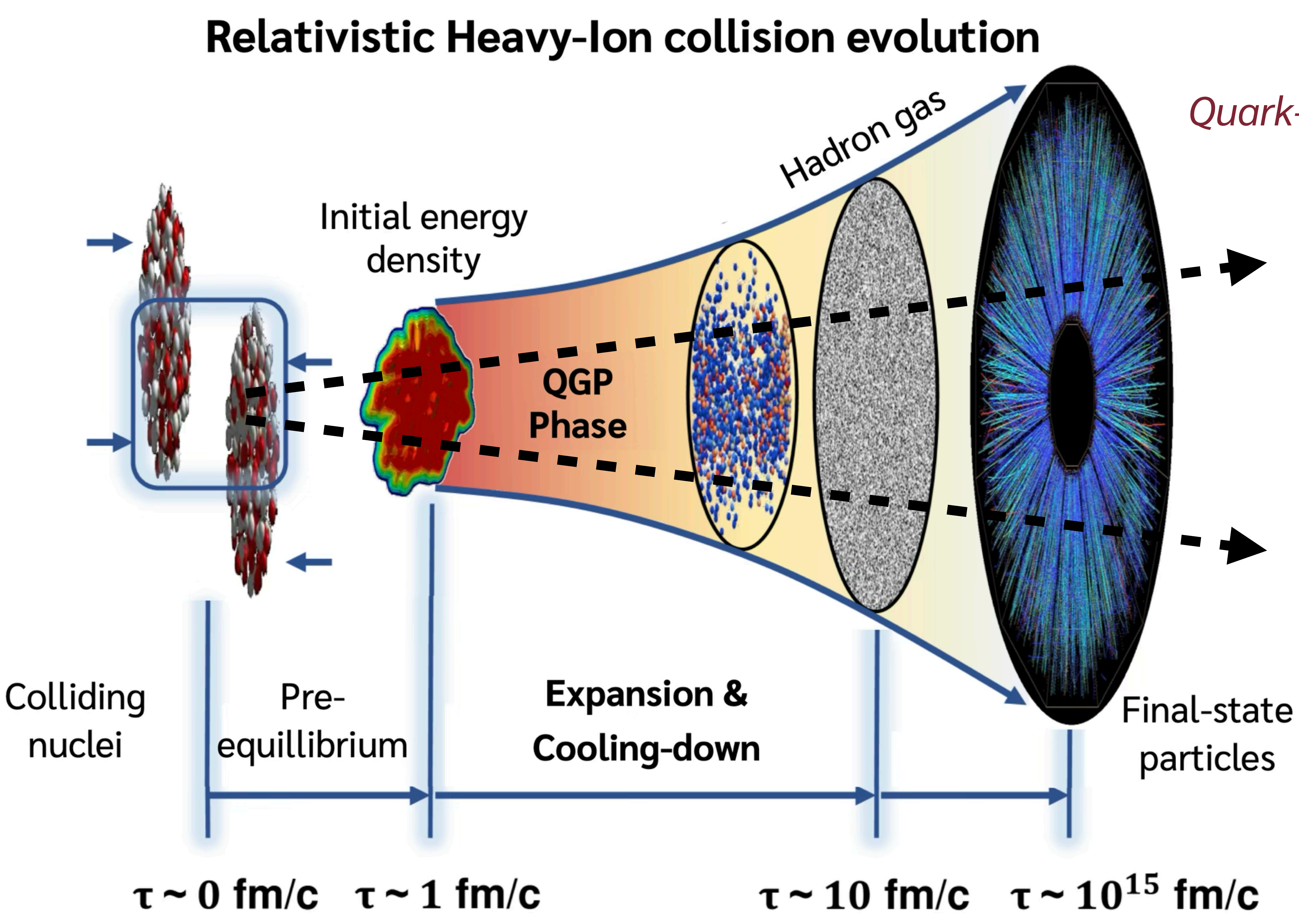
# Backup Slides

# Heavy-Ion Collisions



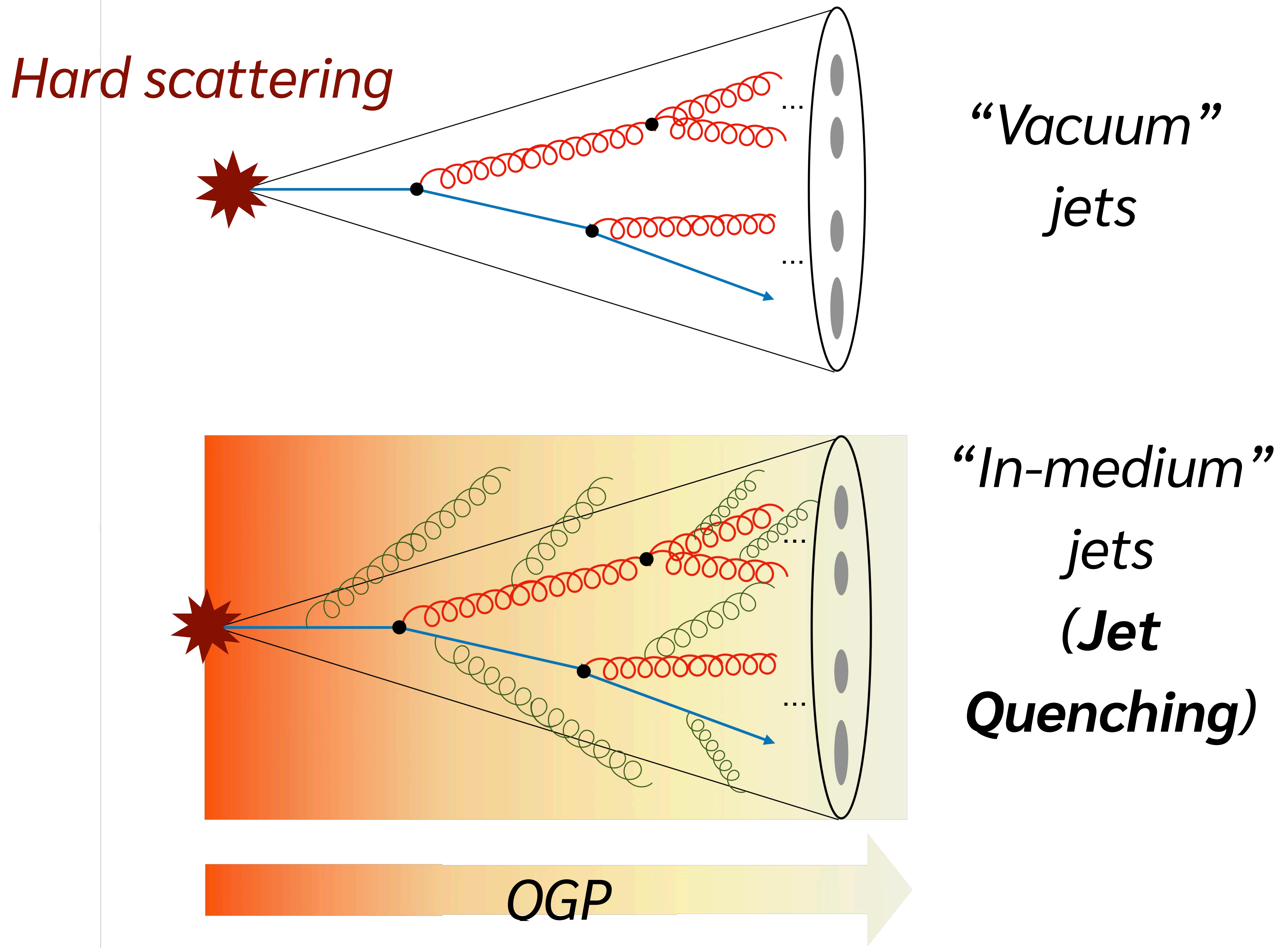

*Quark-Gluon Plasma (QGP) has an extremely short lifetime*

# Heavy-Ion Collisions



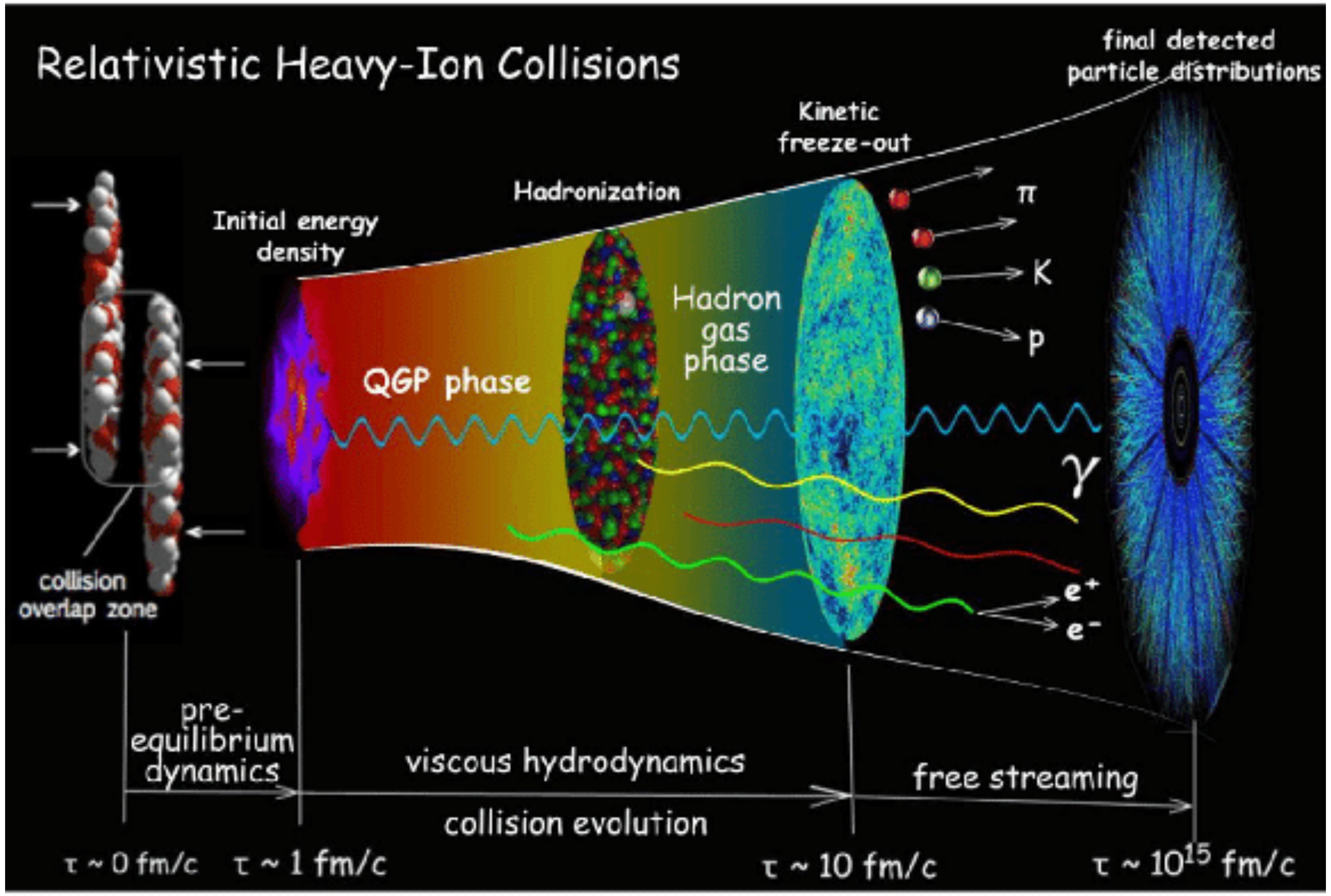

*Quark-Gluon Plasma (QGP) has an extremely short lifetime*

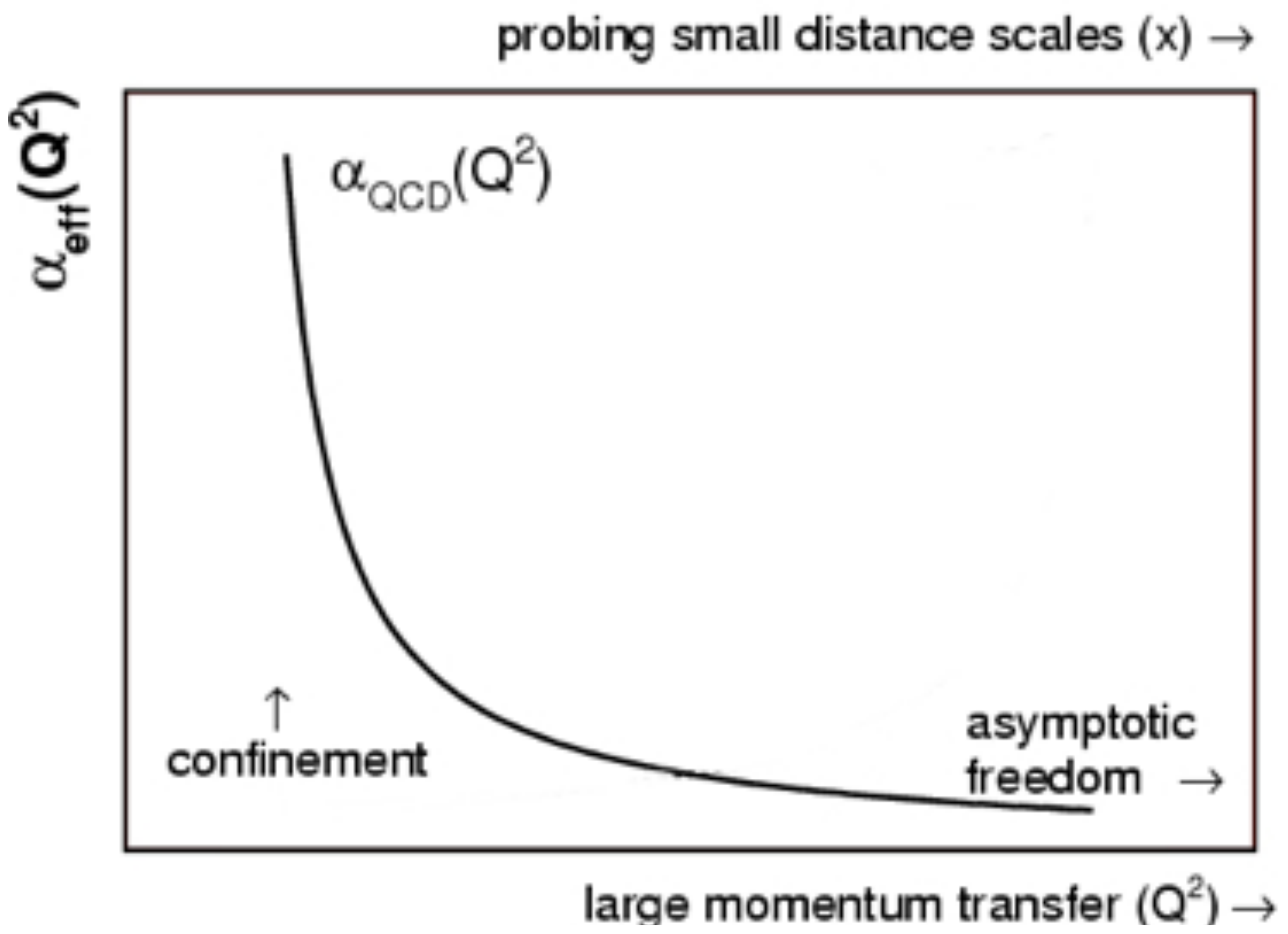
***Solution**: use jets as probing tool*



# Probes of the QGP

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



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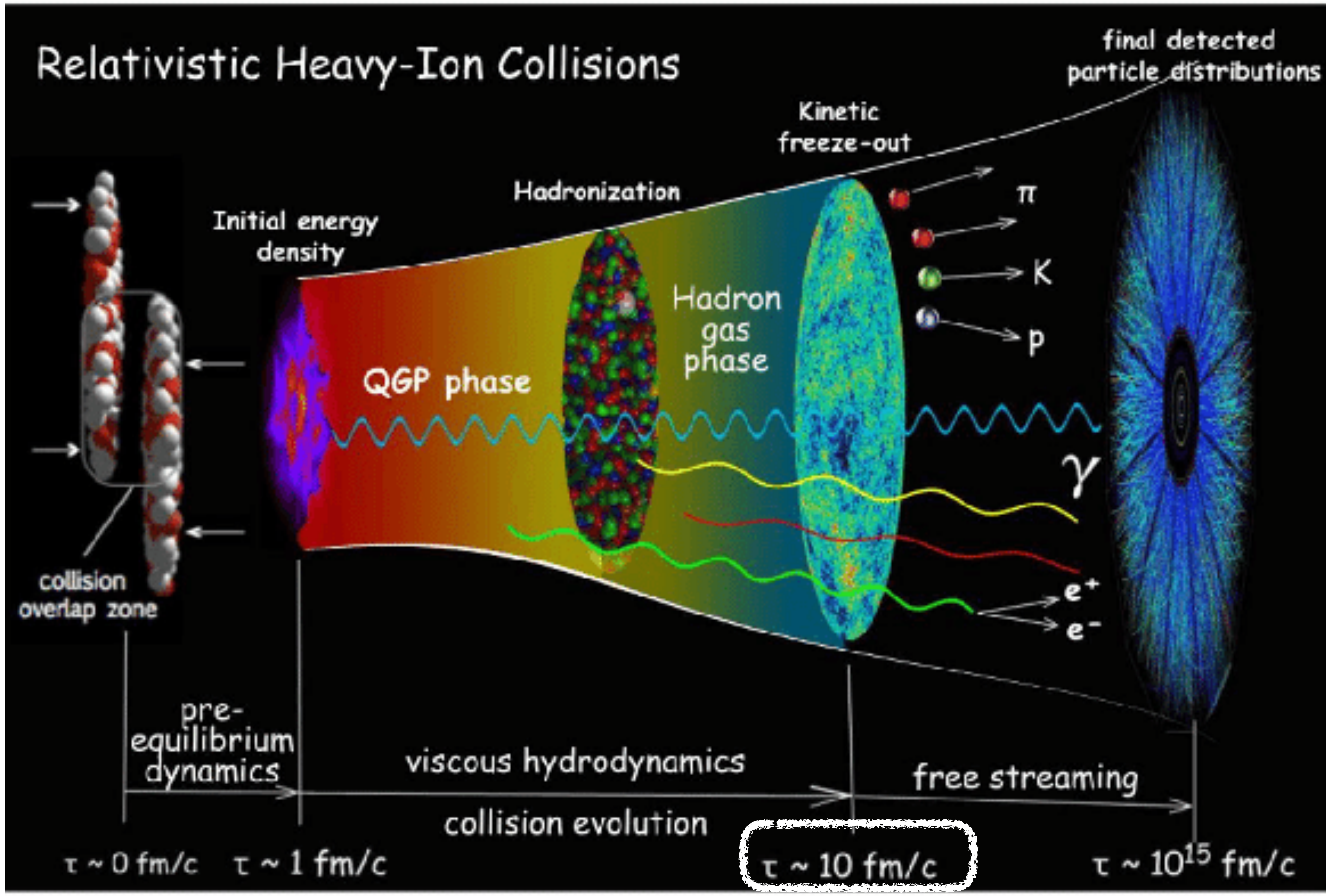


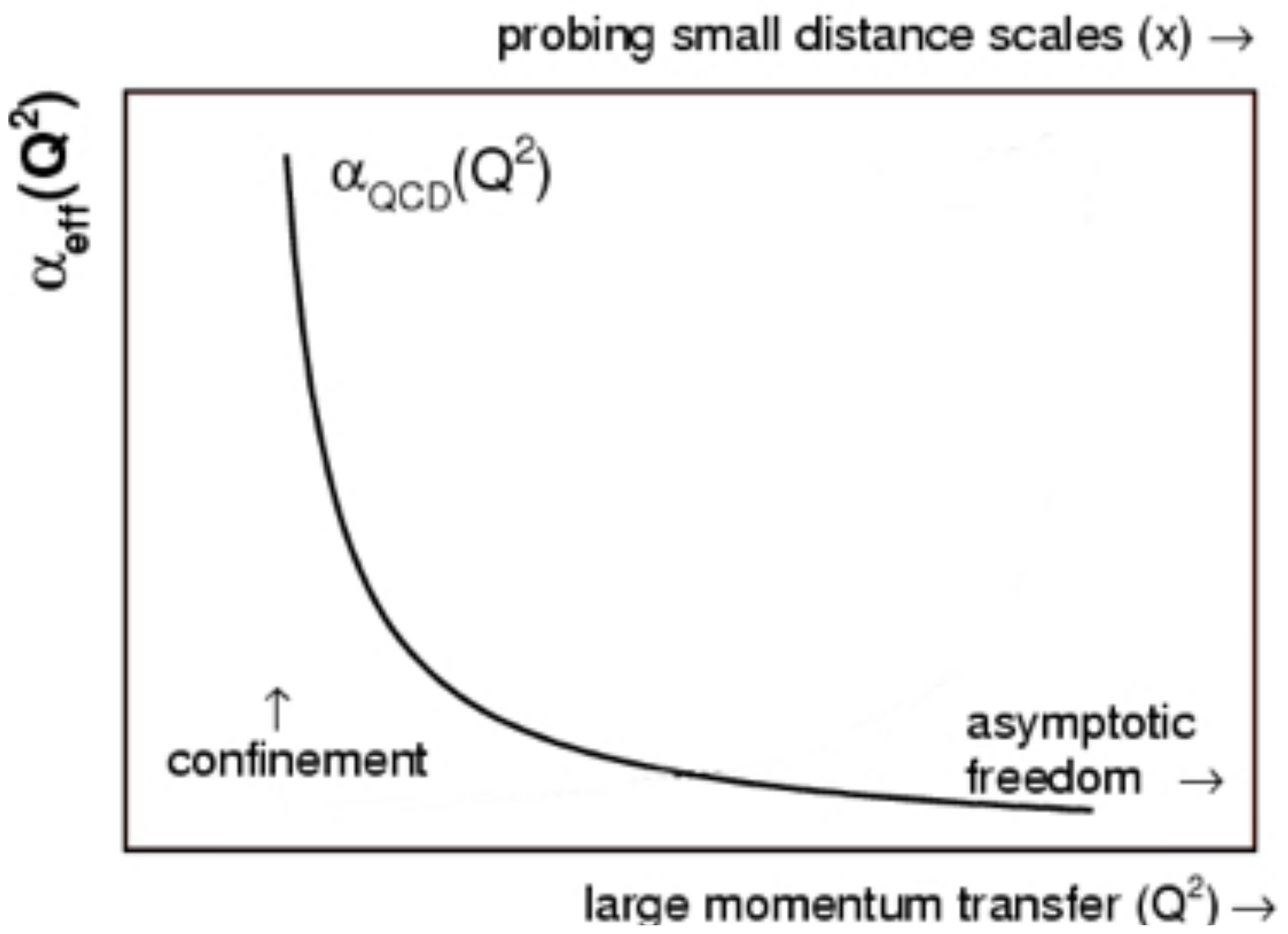


Caveat: need to rely on self-generated probes

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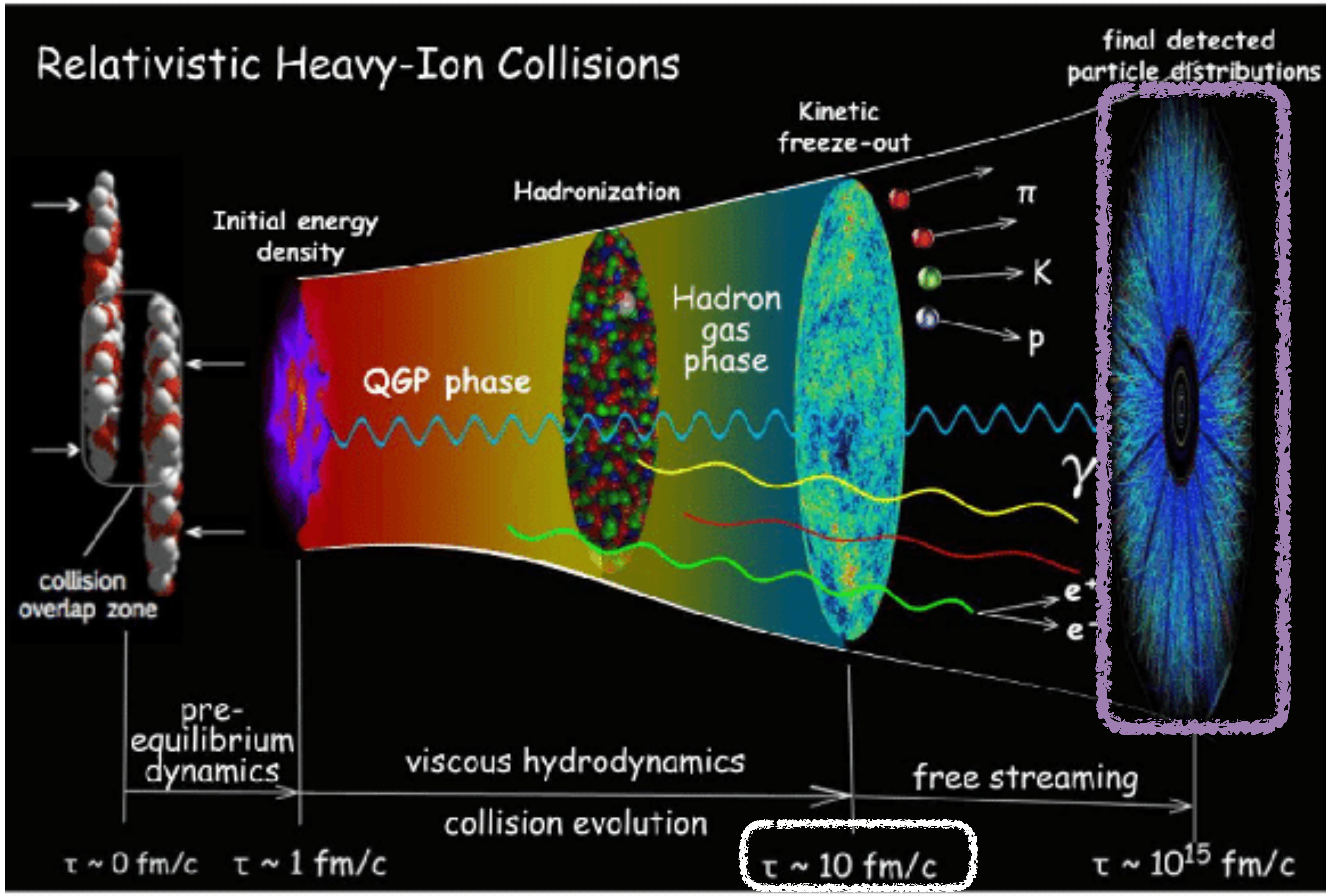


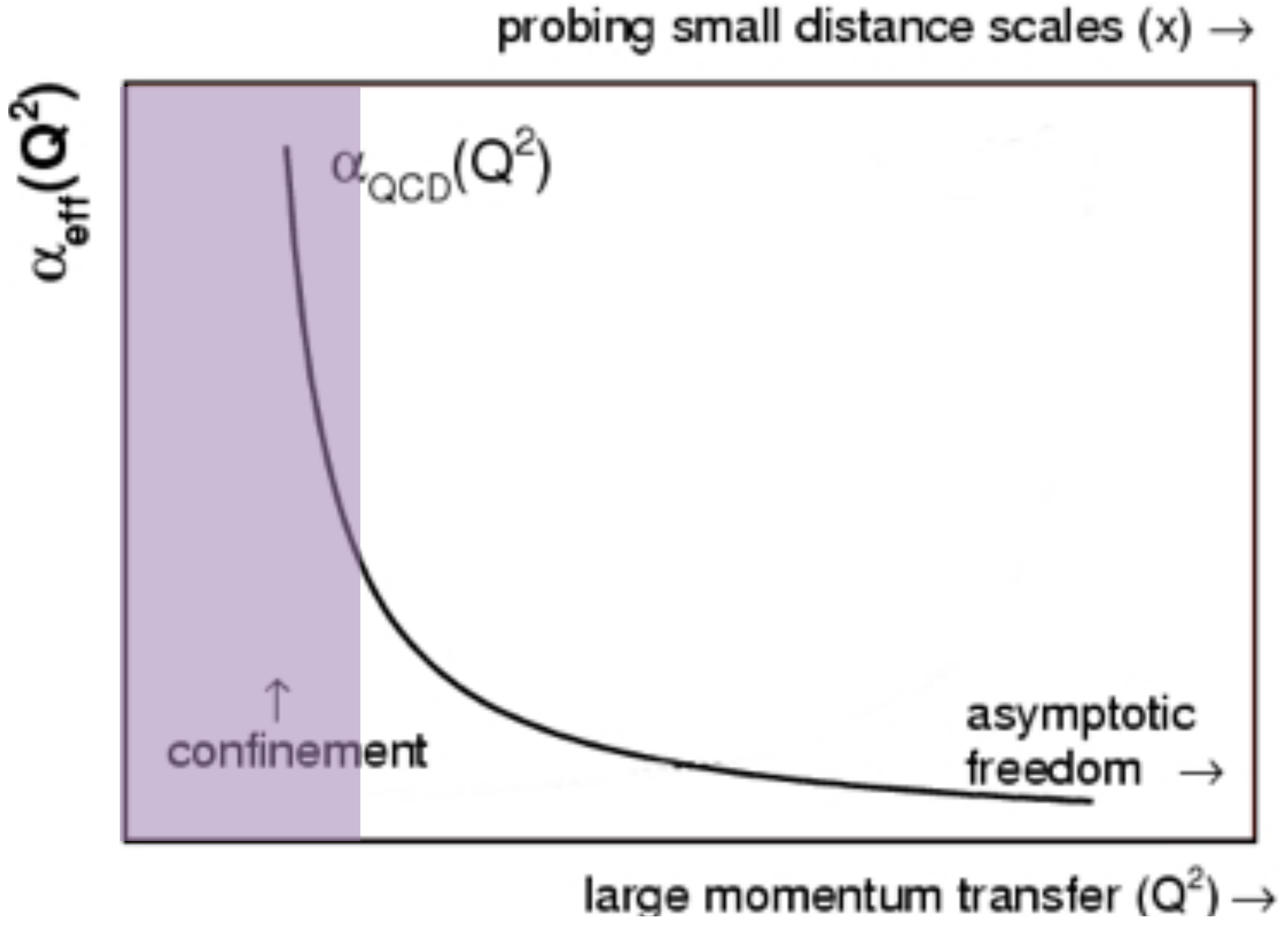


Soft probes

non-pQCD

Caveat: need to rely on self-generated probes

# Probes of the QGP

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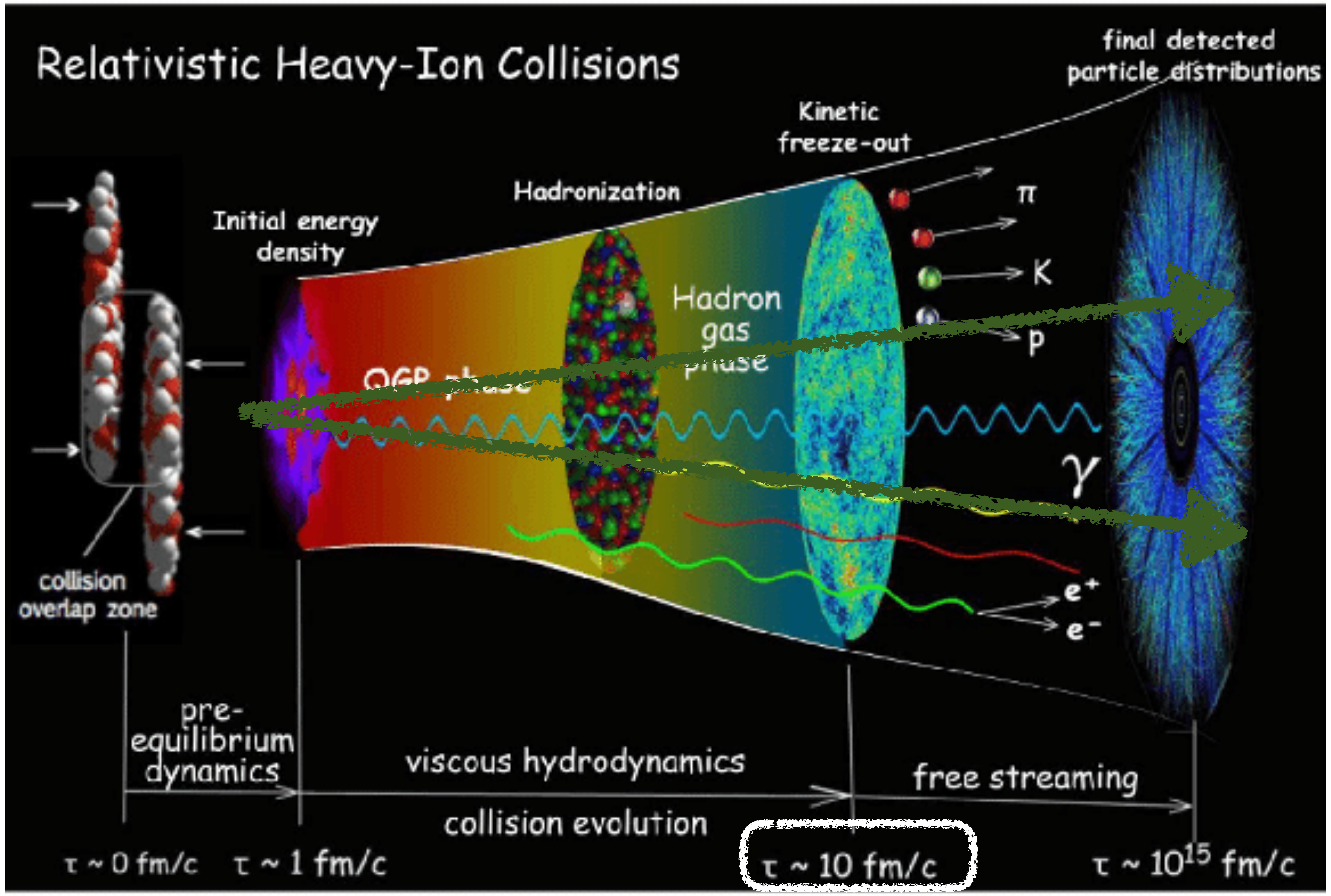
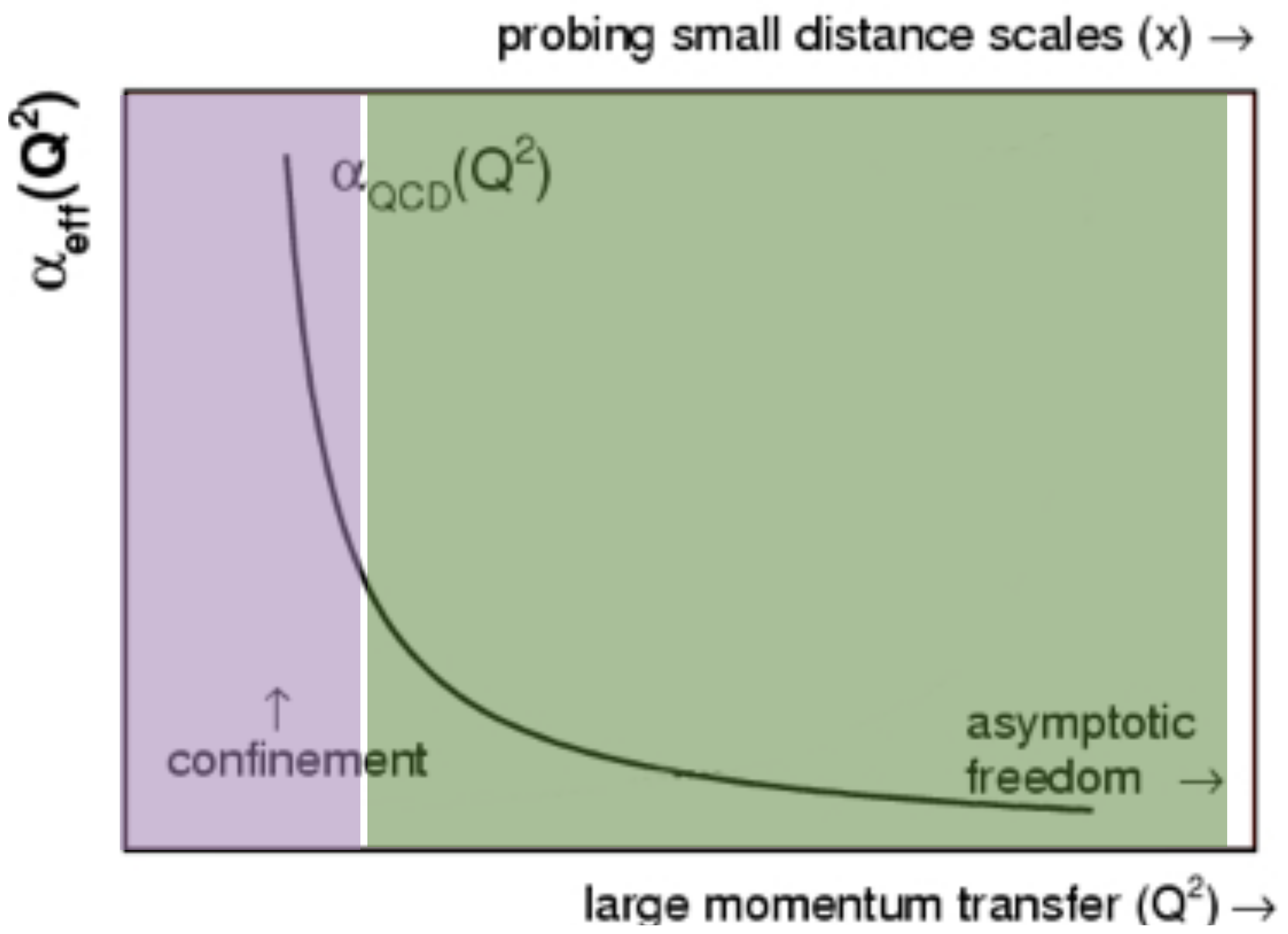



Soft probes

non-pQCD

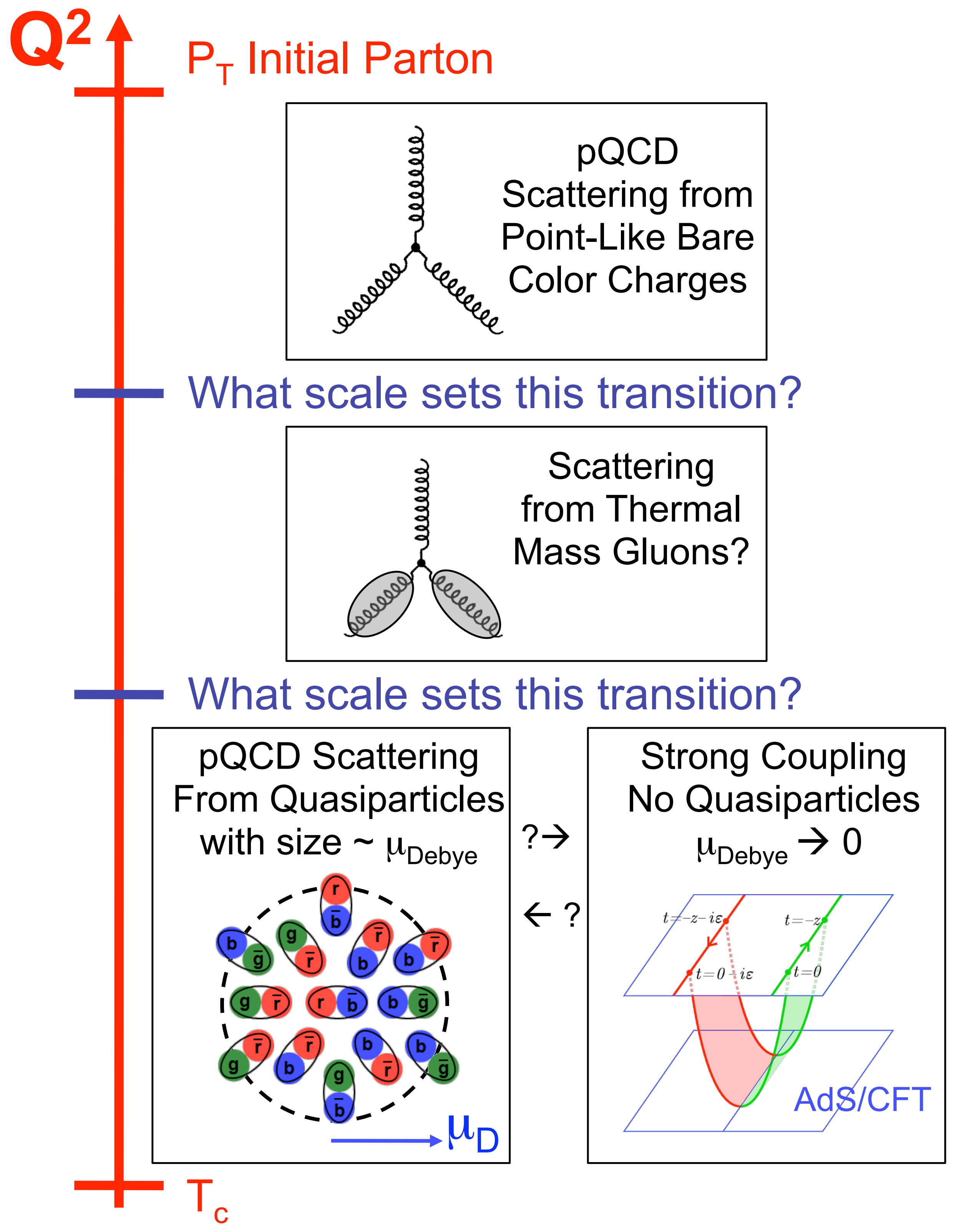
Hard probes

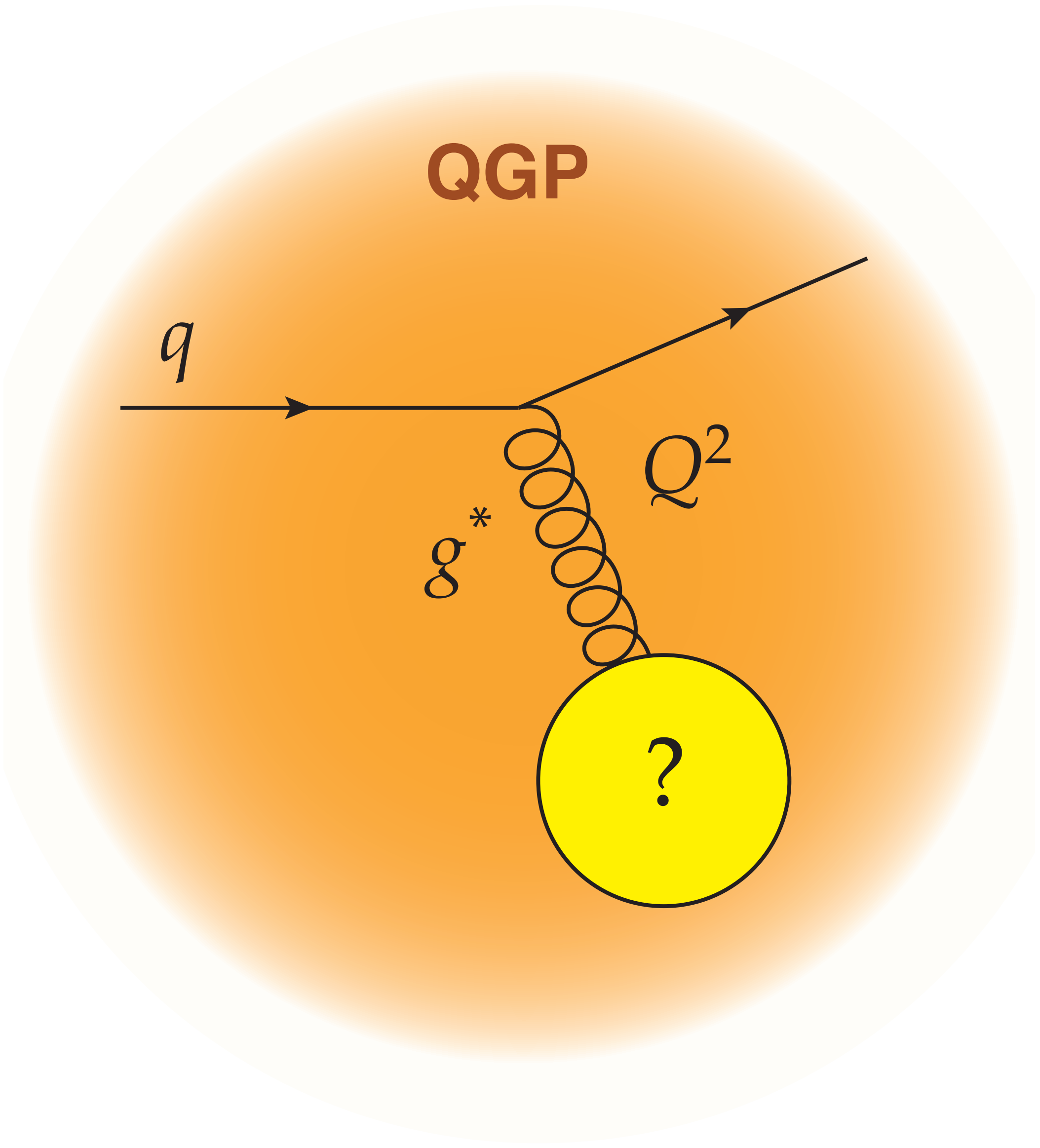
pQCD (e.g: jets)

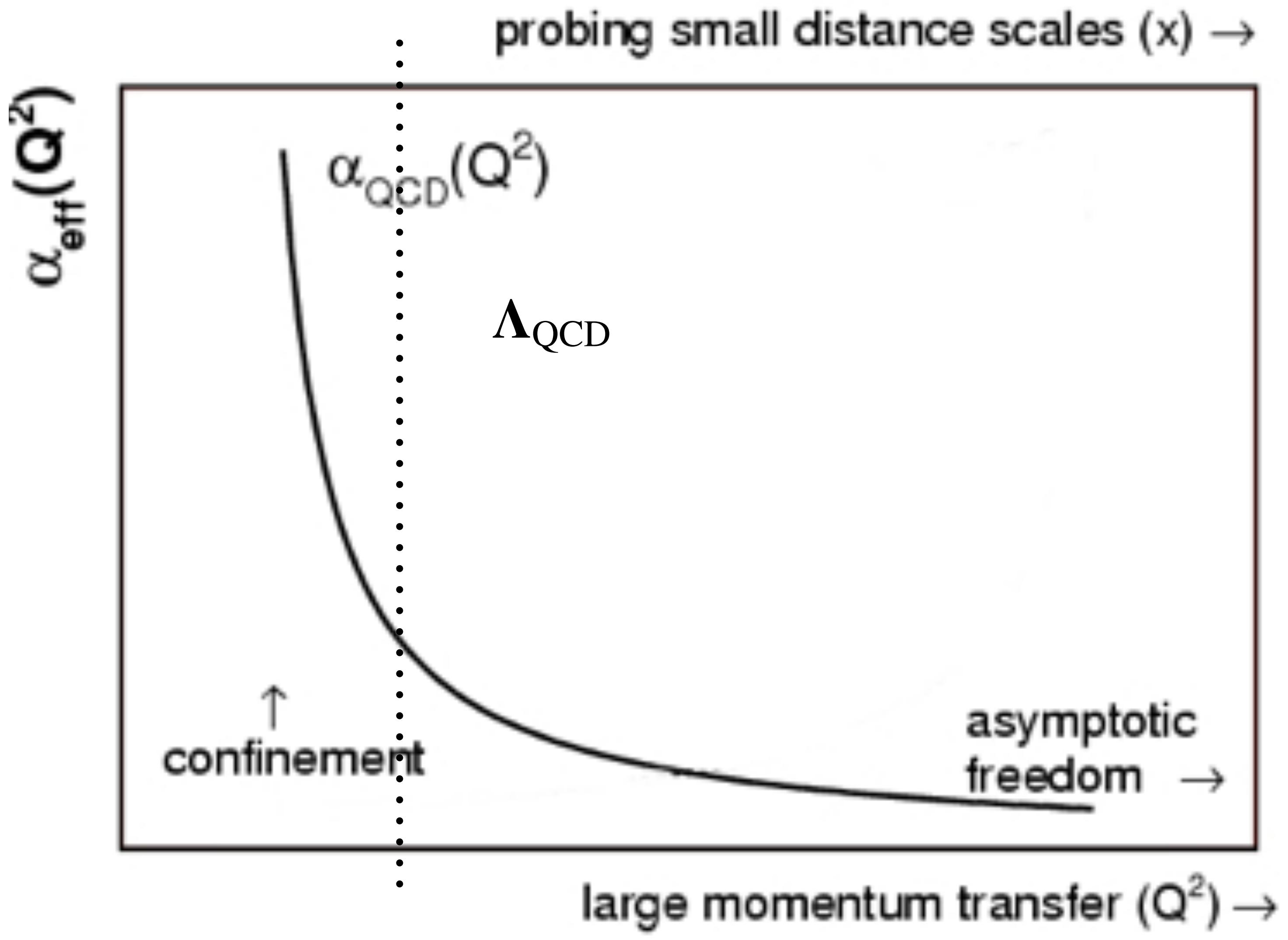
Caveat: need to rely on self-generated probes

# Hard probes

- What is the QGP?



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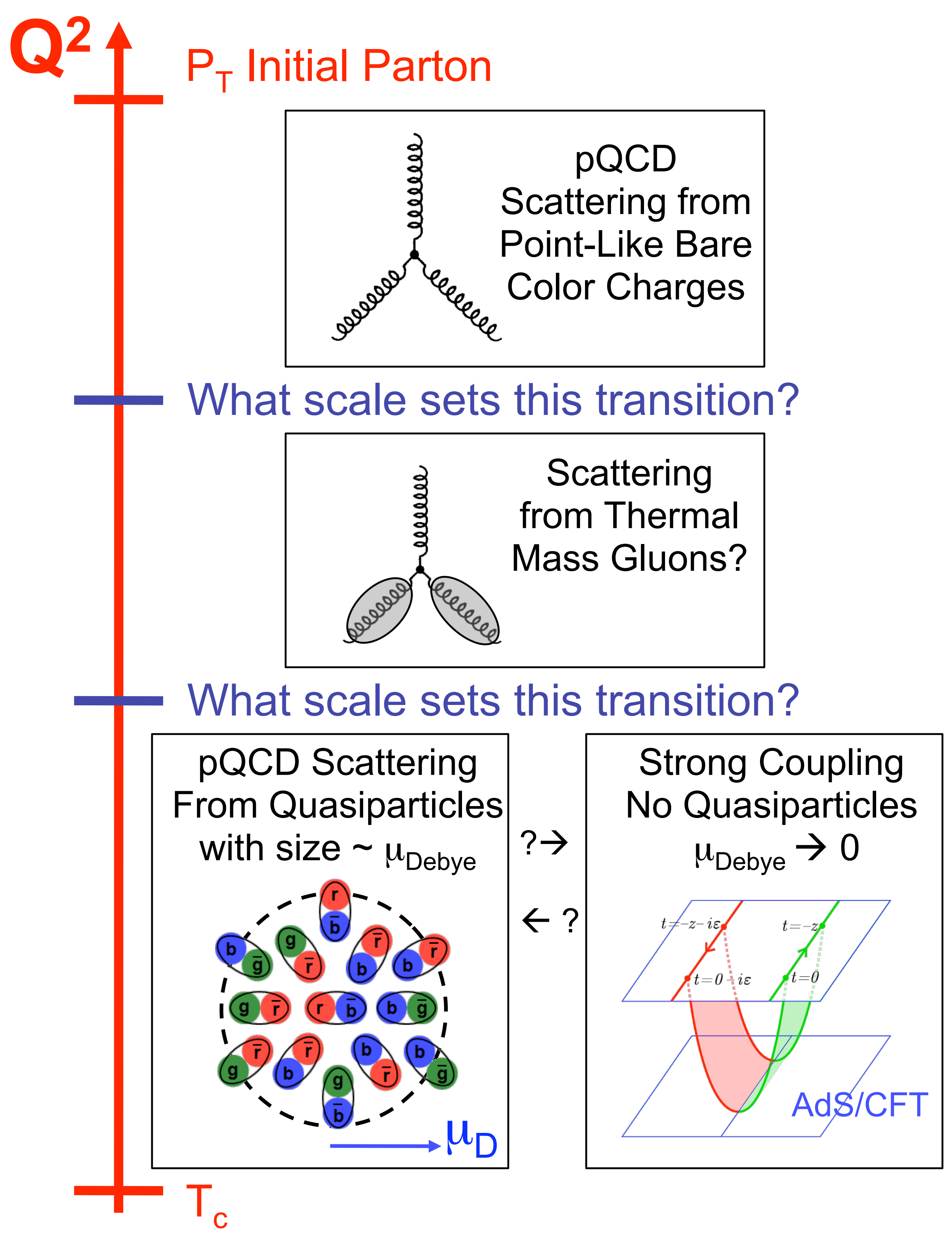
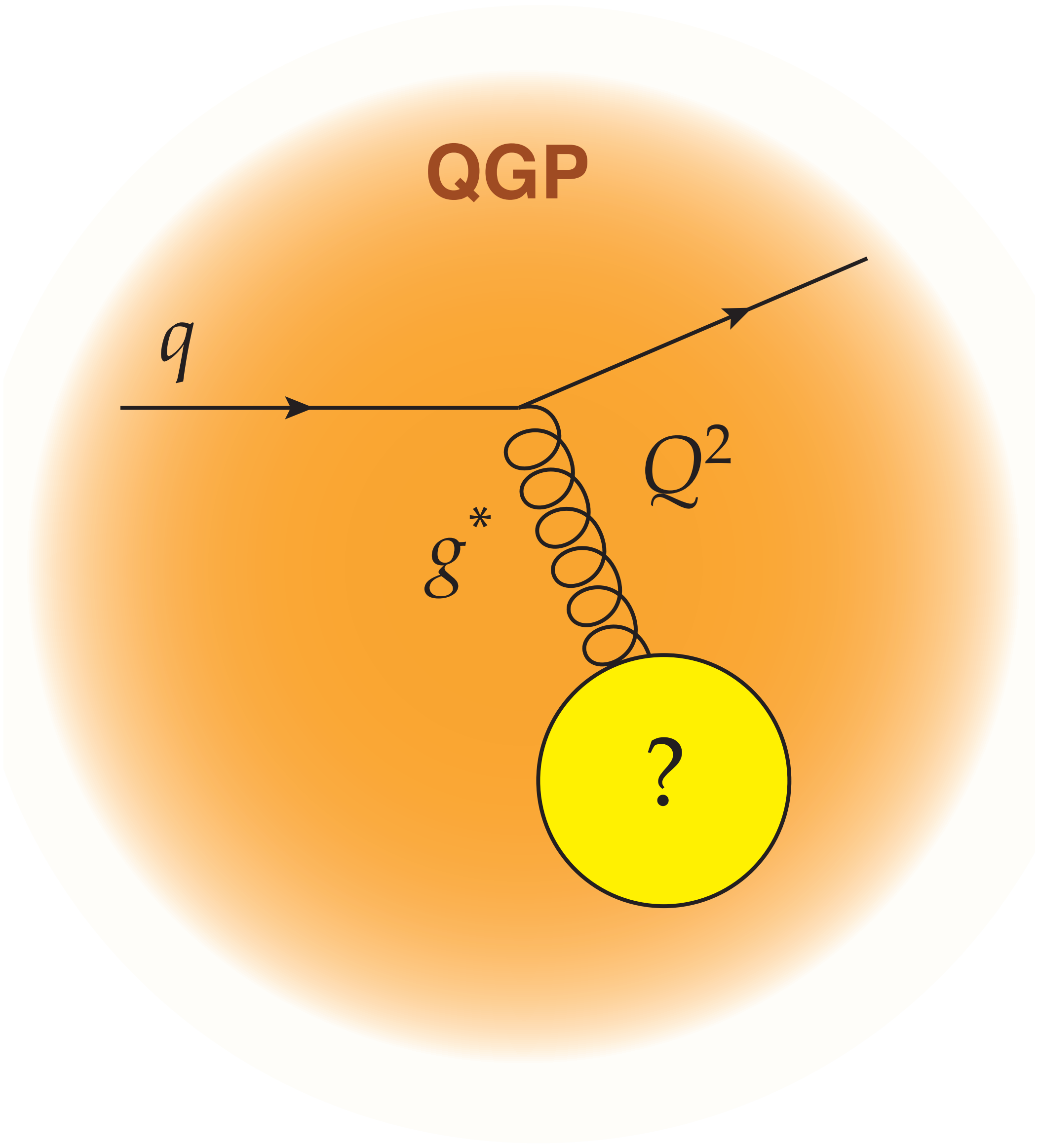
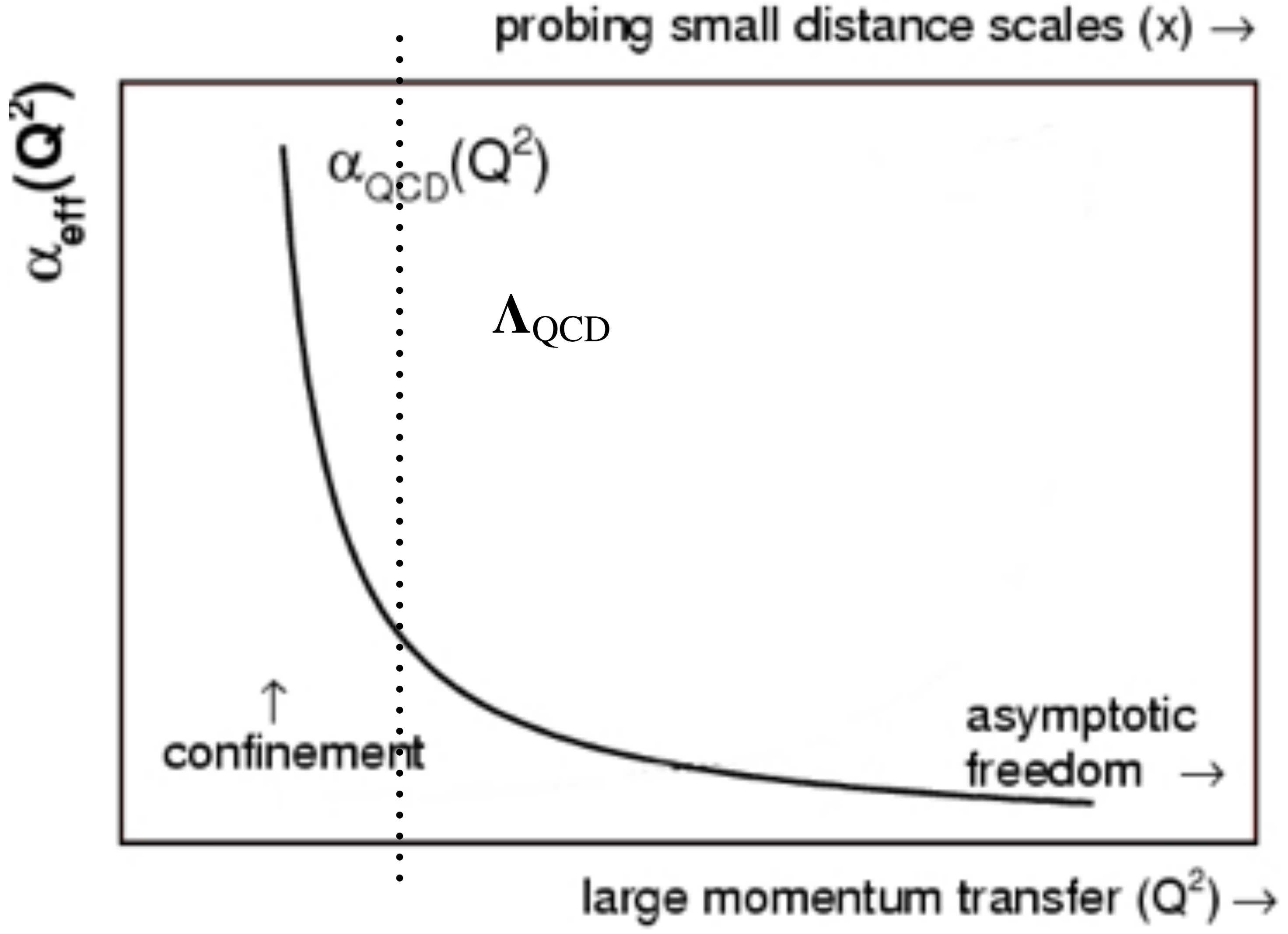


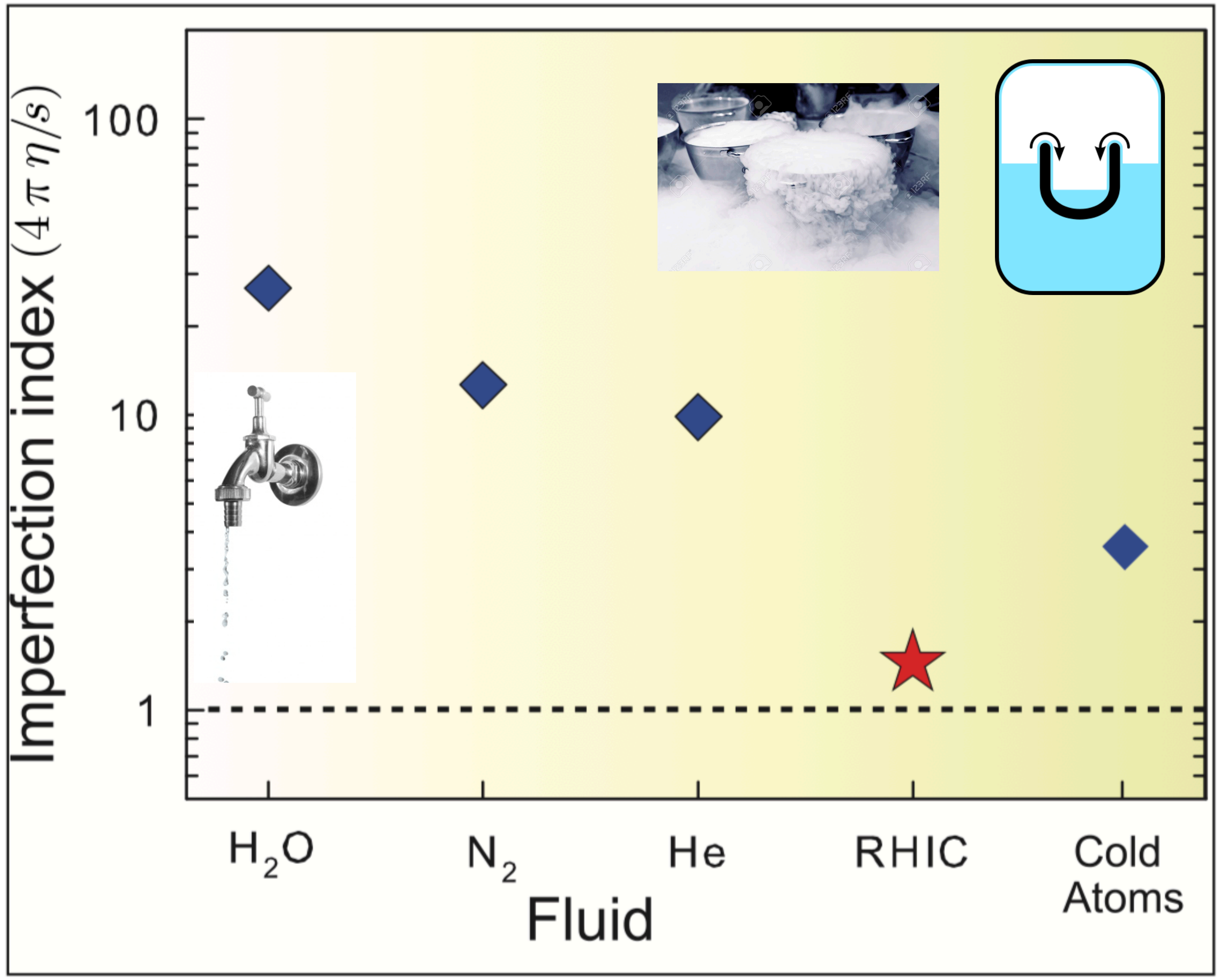



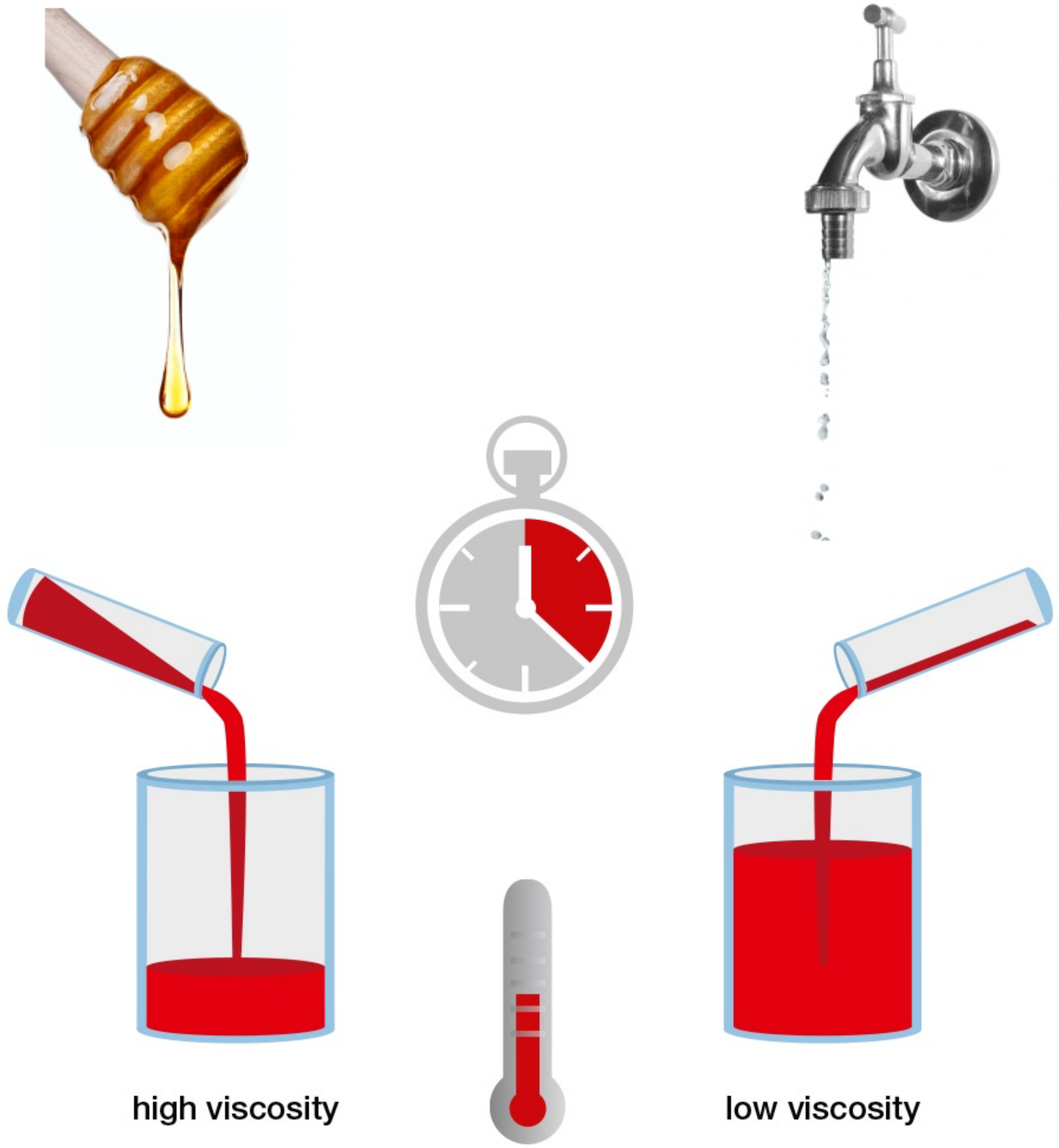




*One possible solution:*
*use something that we do know!*

# Soft probes

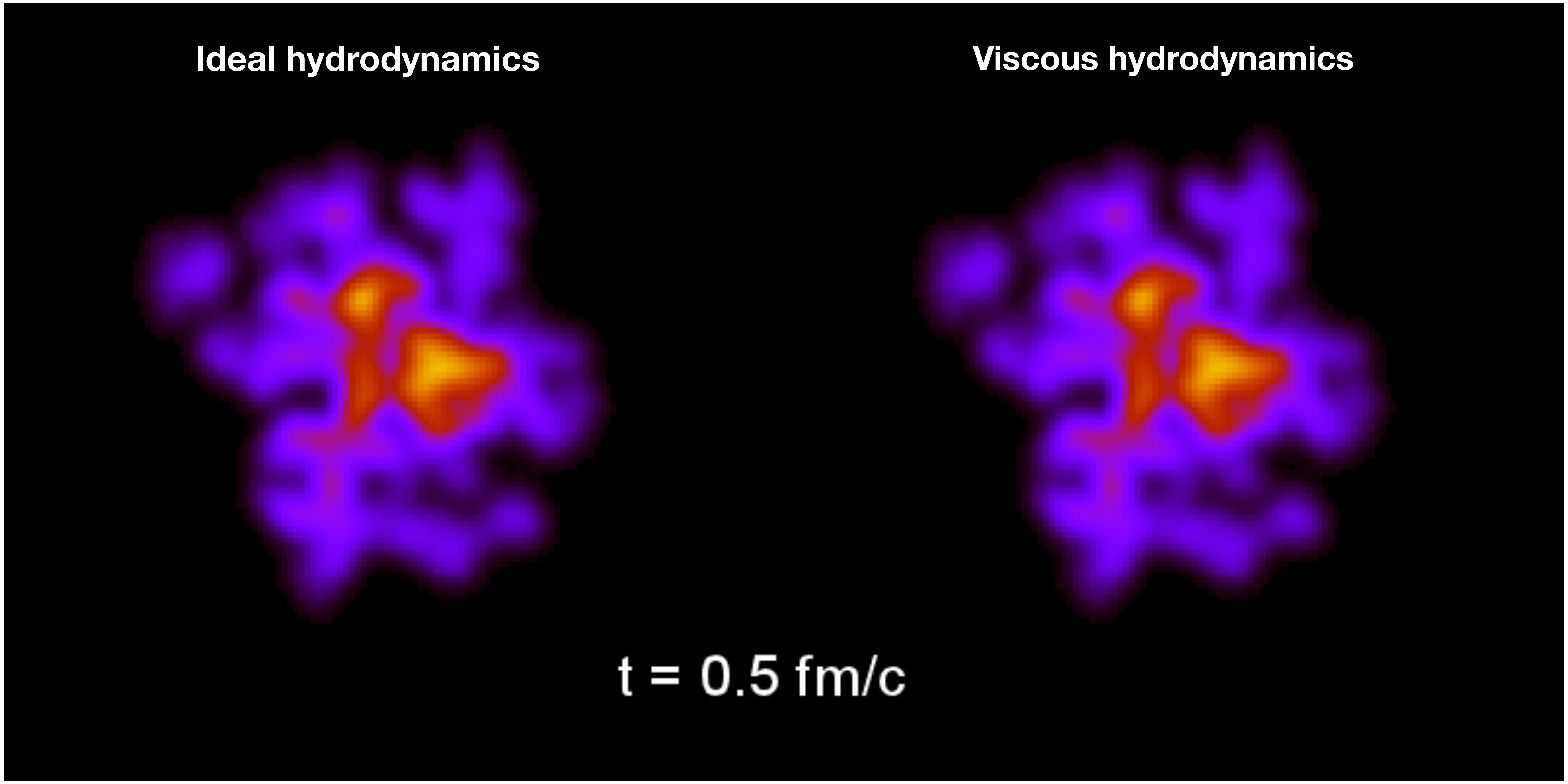
- QGP is not a hot gas of quarks and gluons… is a fluid! Measuring the imperfection factor (viscosity)….



# QGP: an almost perfect liquid

- Viscosity



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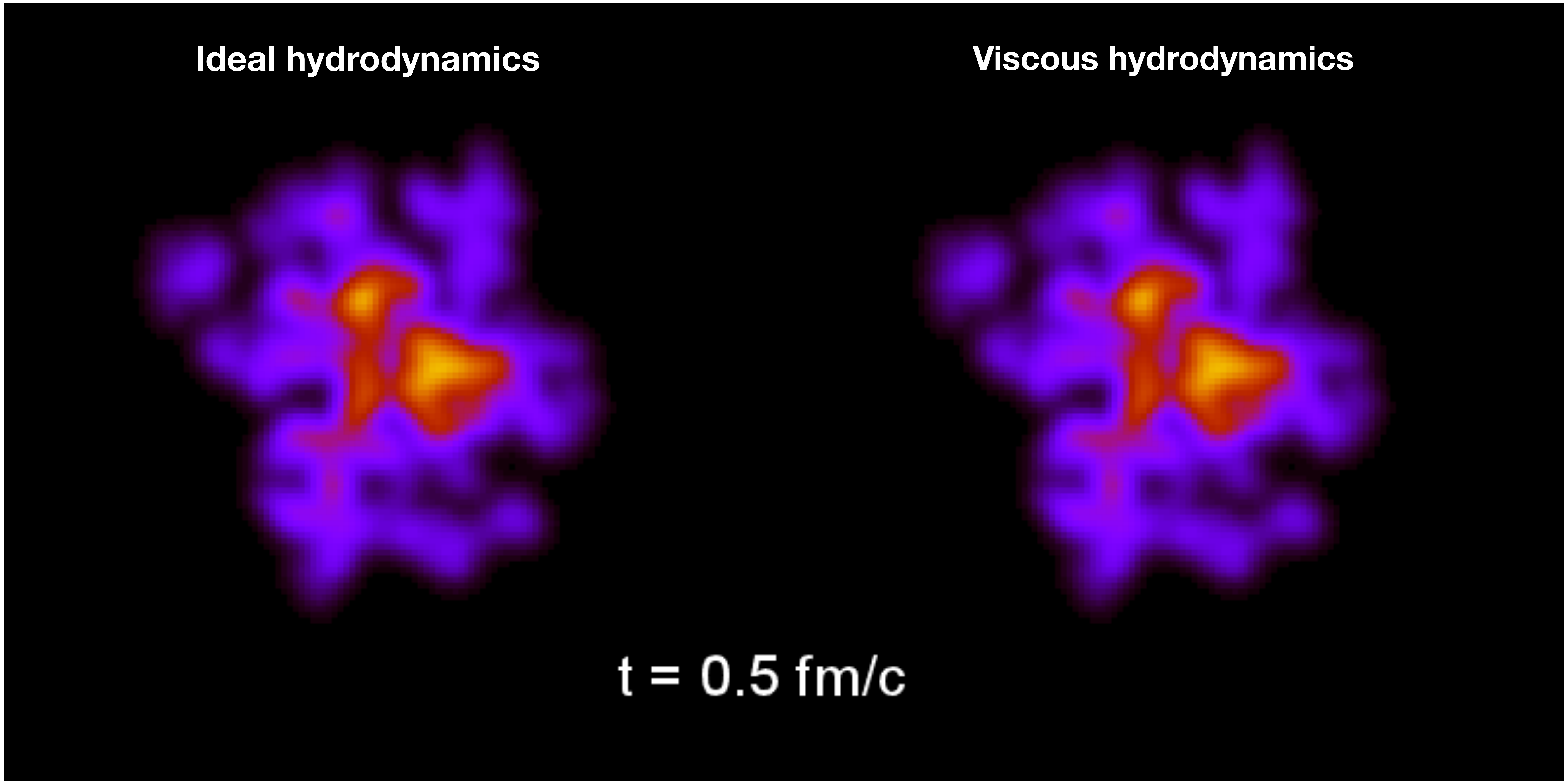
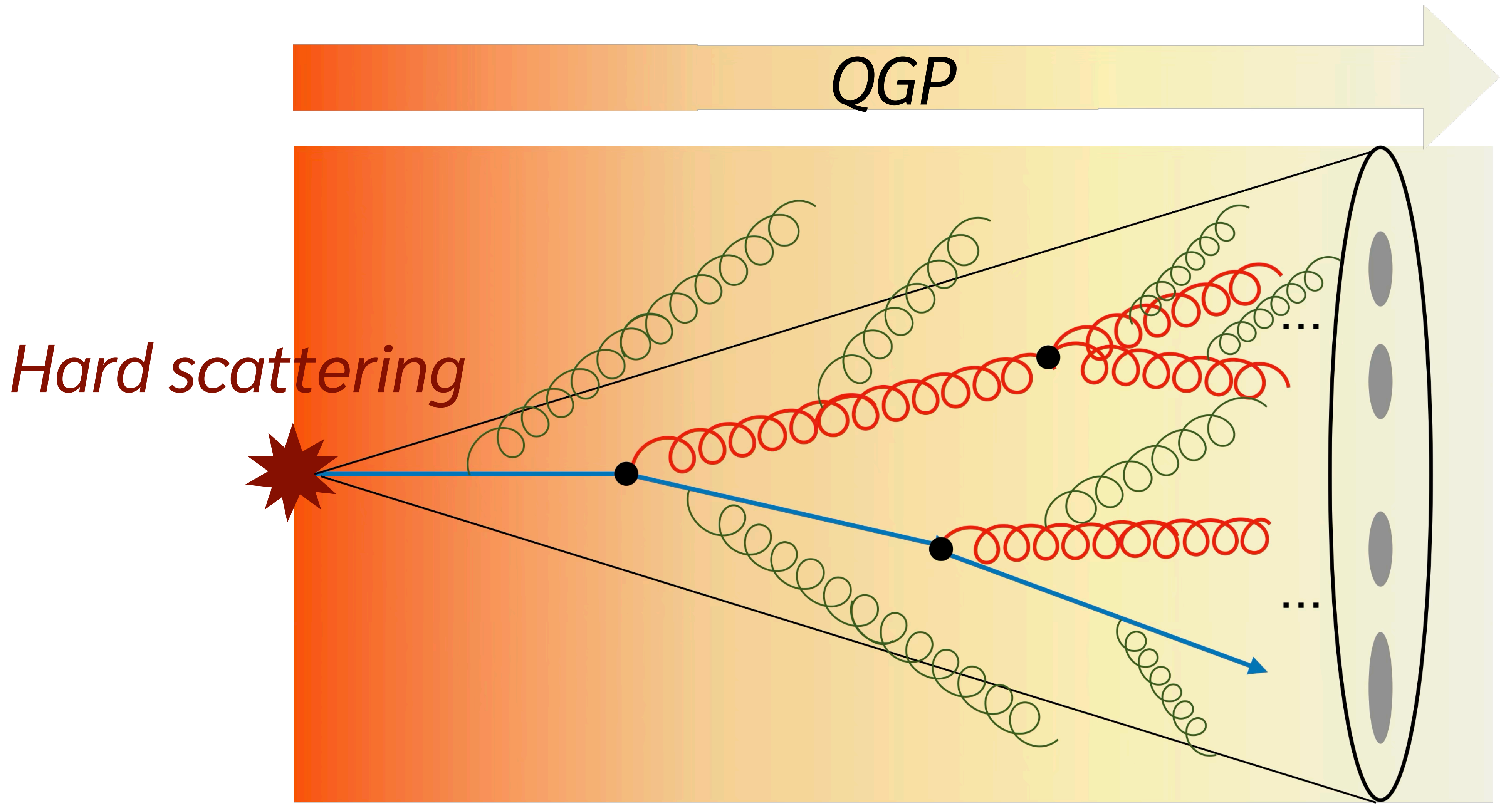


*See B. Tomé, June 11th*

# Jet Quenching Monte Carlo

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




*Hard emissions ("vacuum-like")*

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*See B. Tomé, June 11th*

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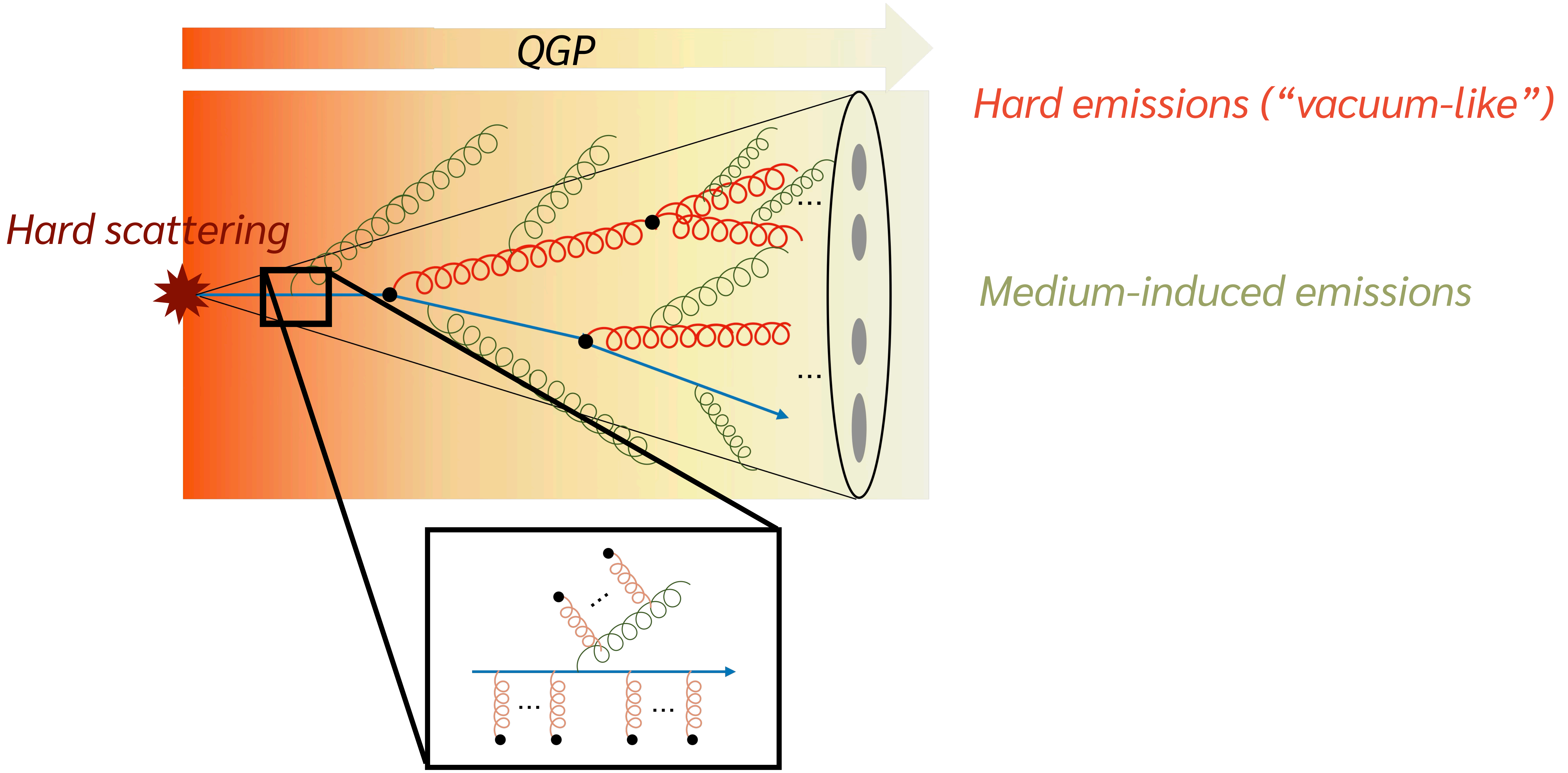

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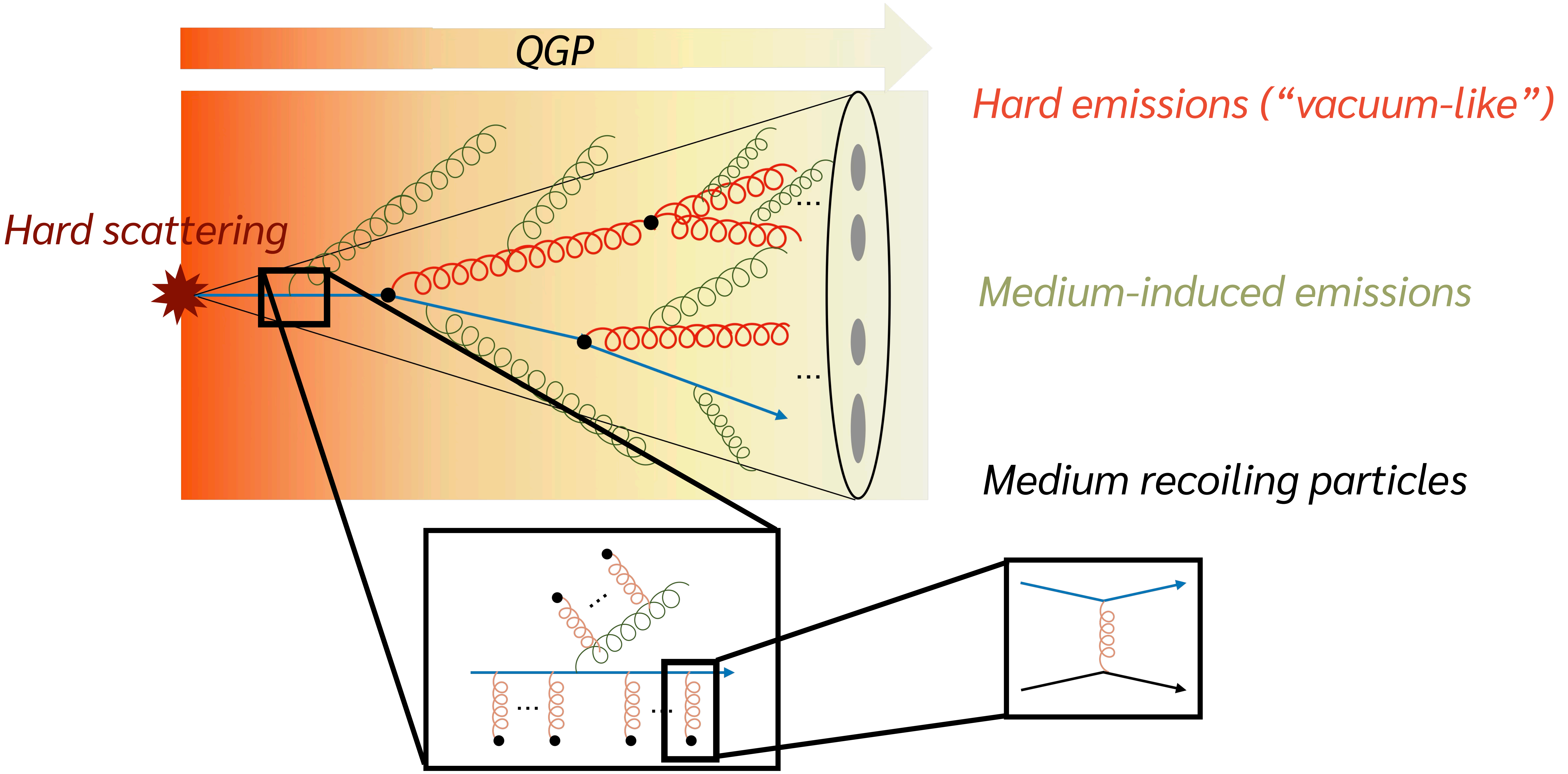

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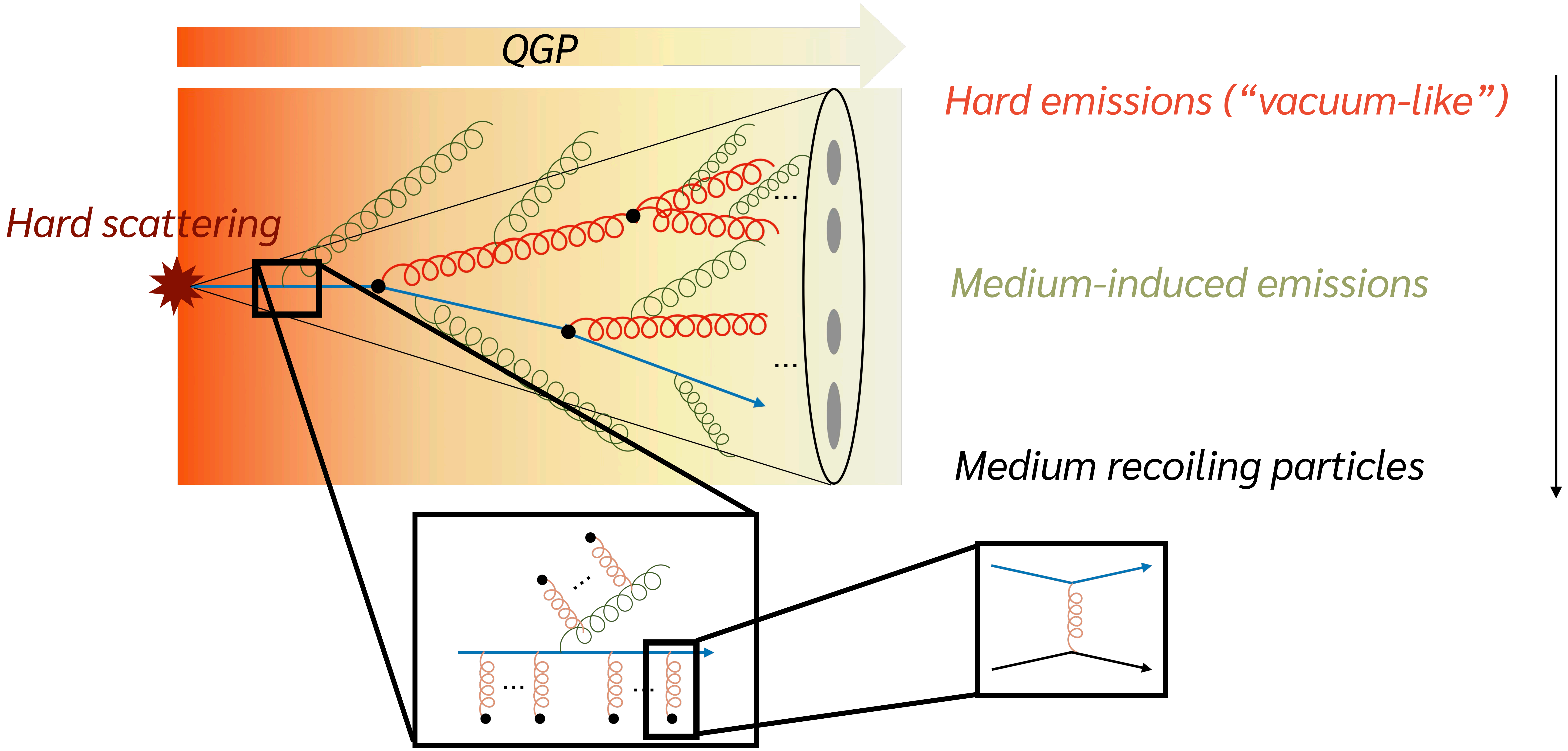
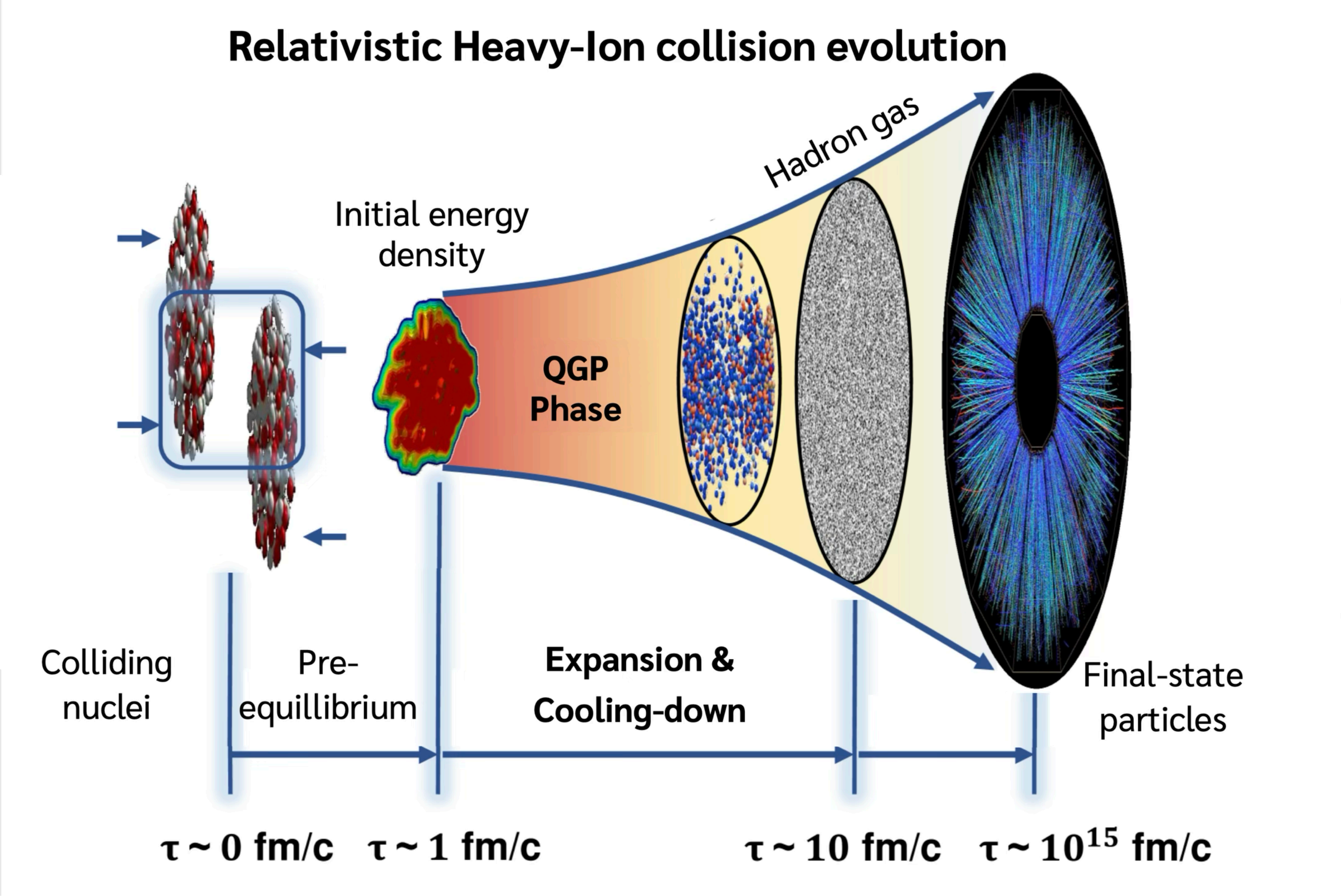



*Decreasing energy (Less calculable via perturbative methods)*

***Several approaches** with **continuous improvements Based on Monte Carlo simulation***

# The Ridge

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



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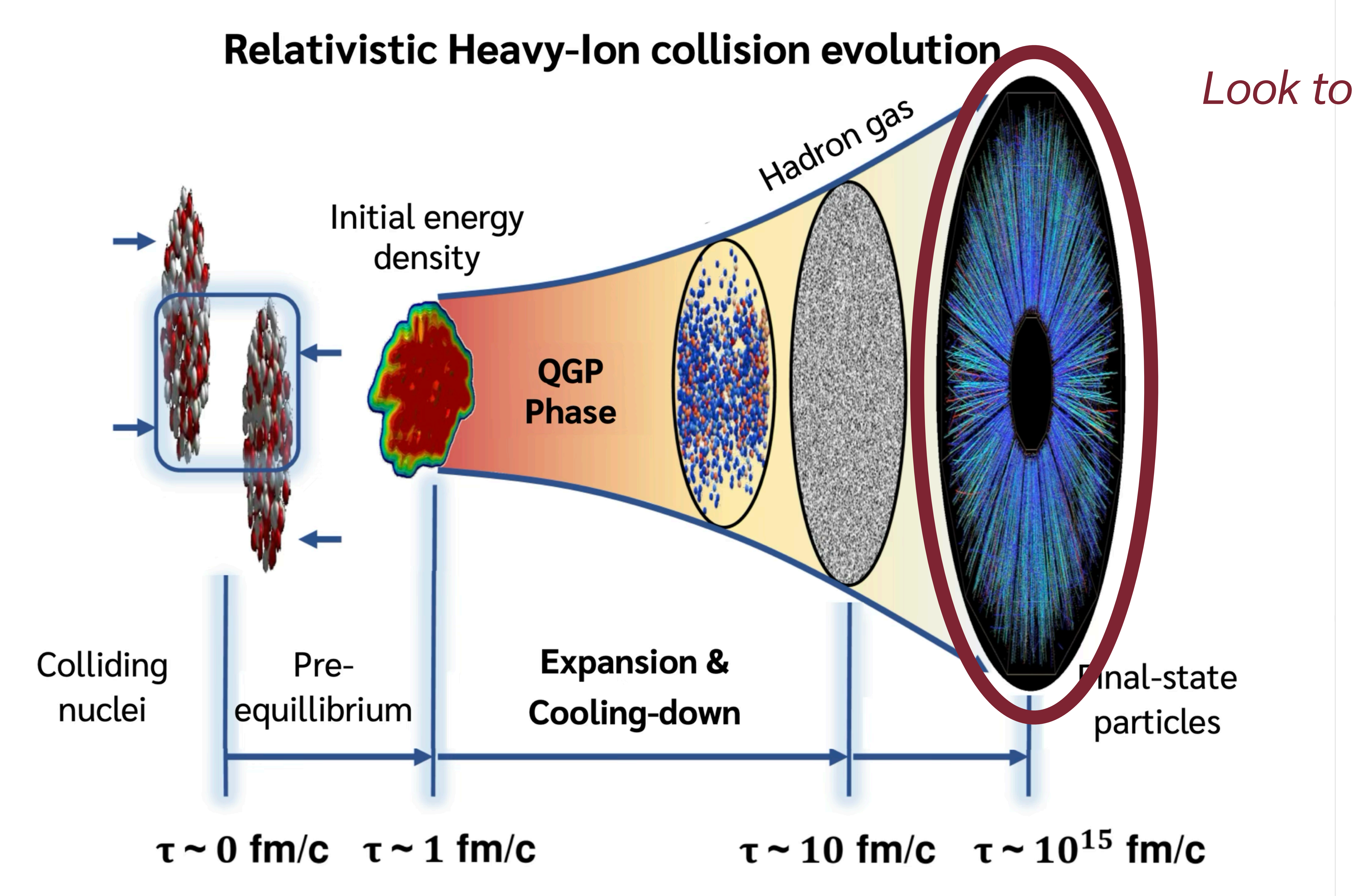
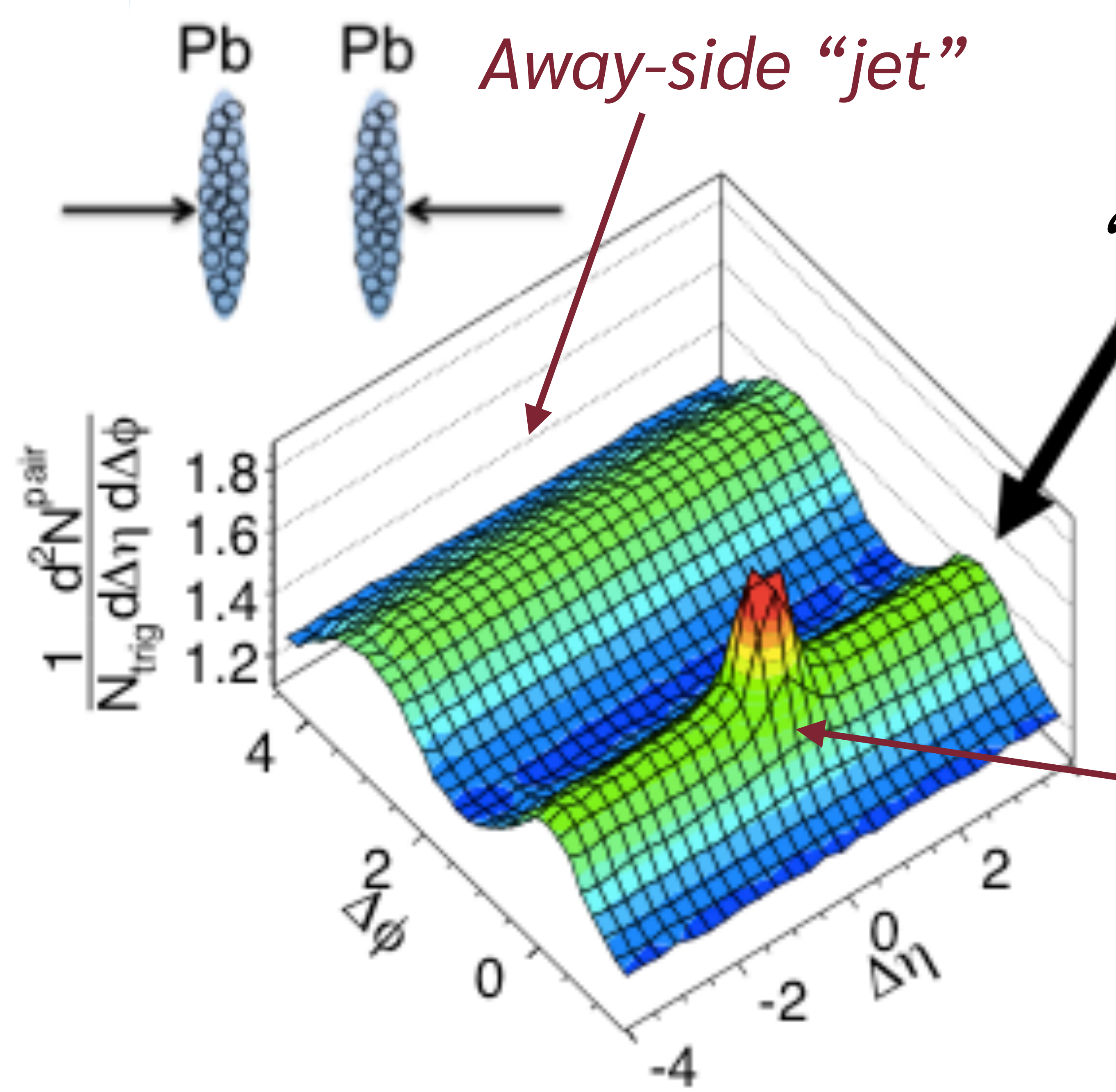



*Look to the 2-particle correlation of a heavy-ion event*

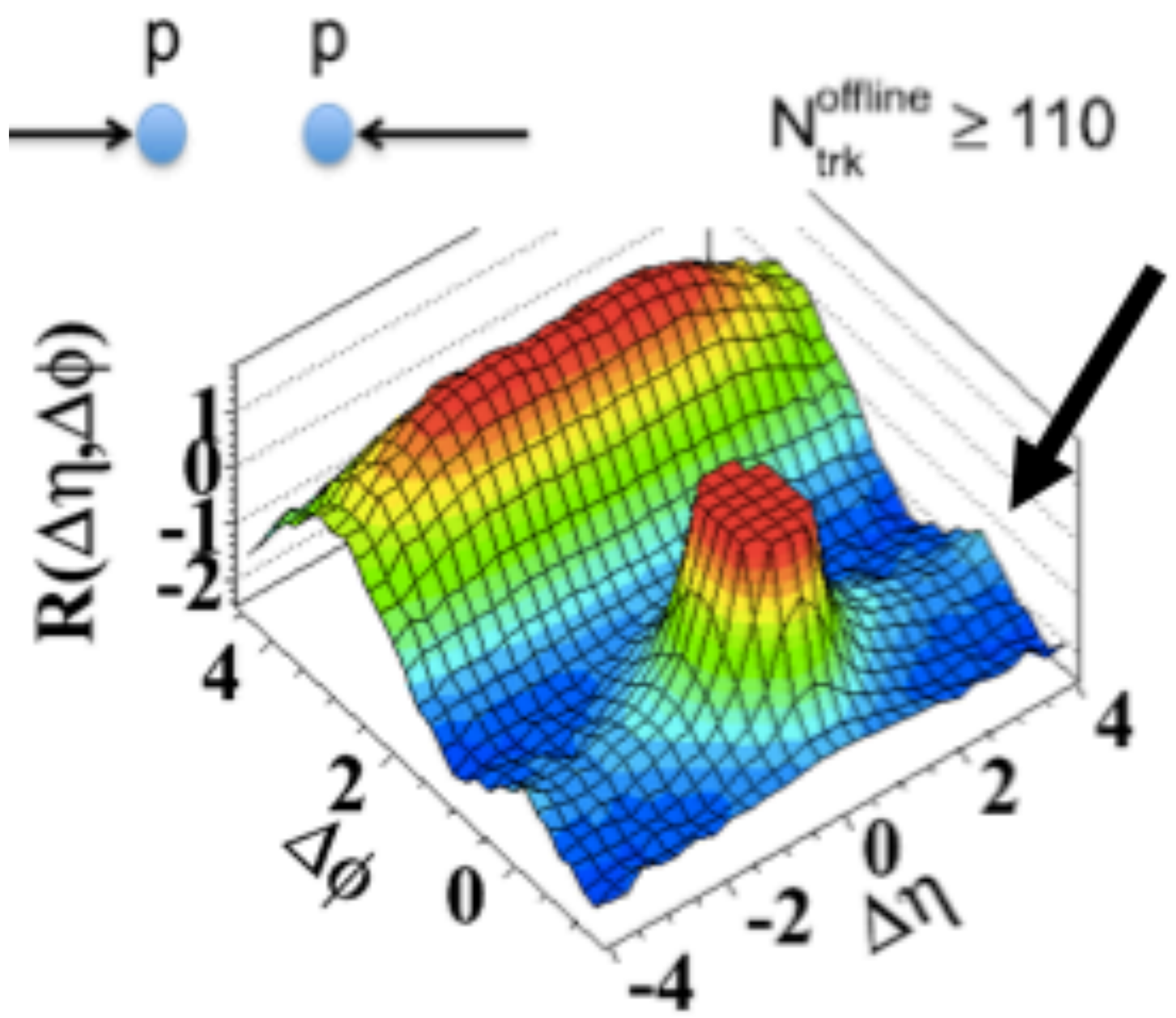


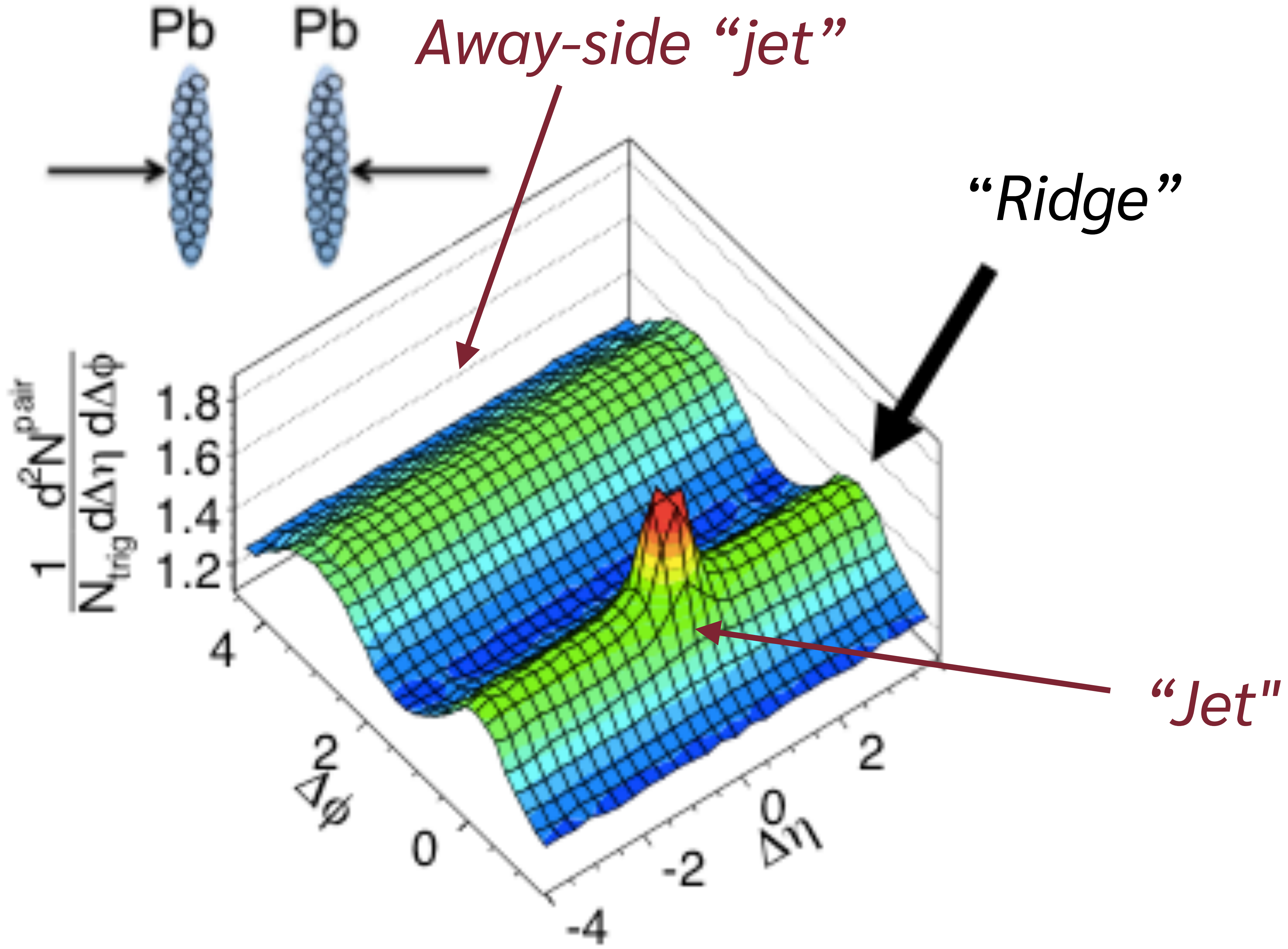

*Understood as a sign of QGP presence*

# The Ridge

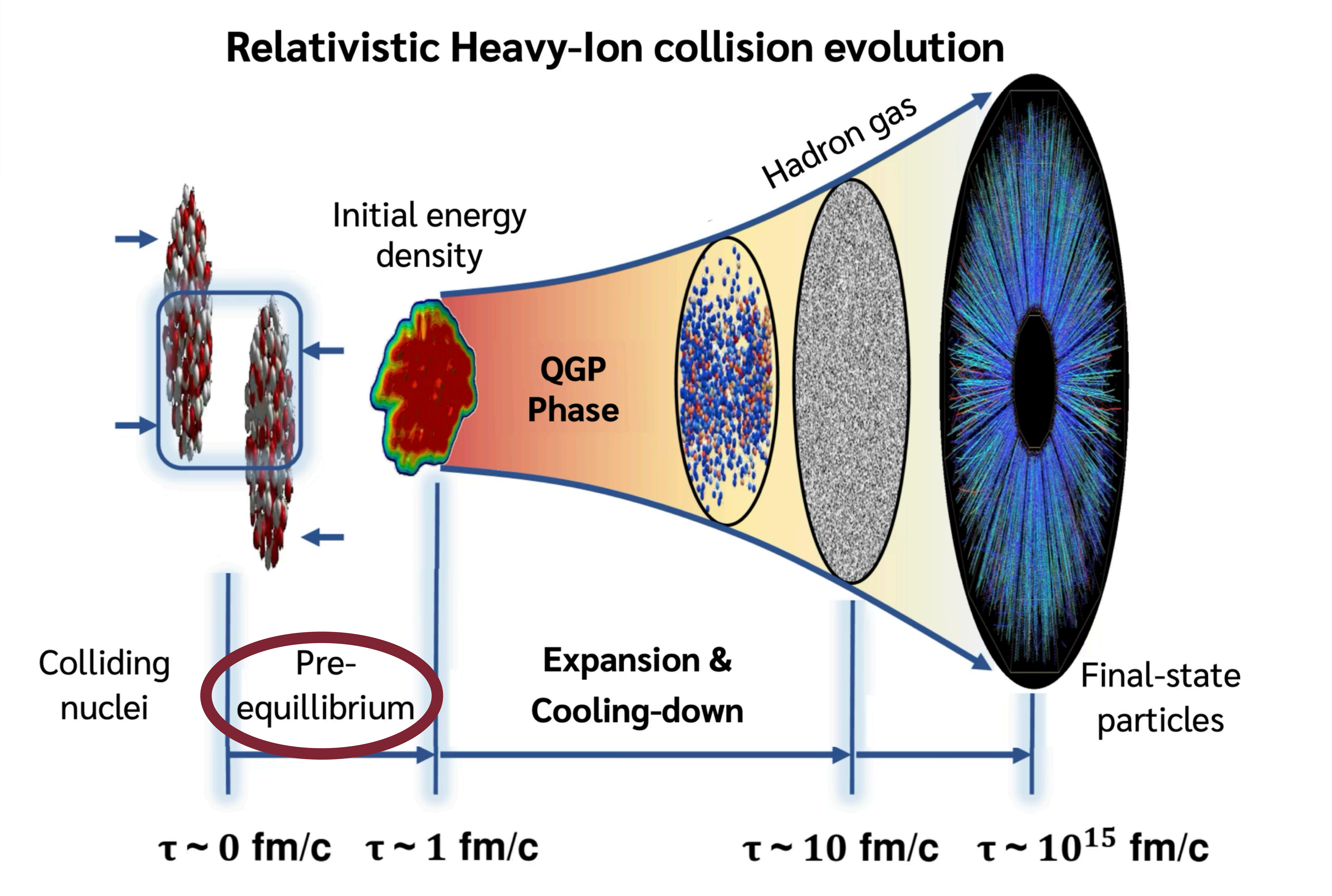
- Also visible in small systems, where QGP formation not expected

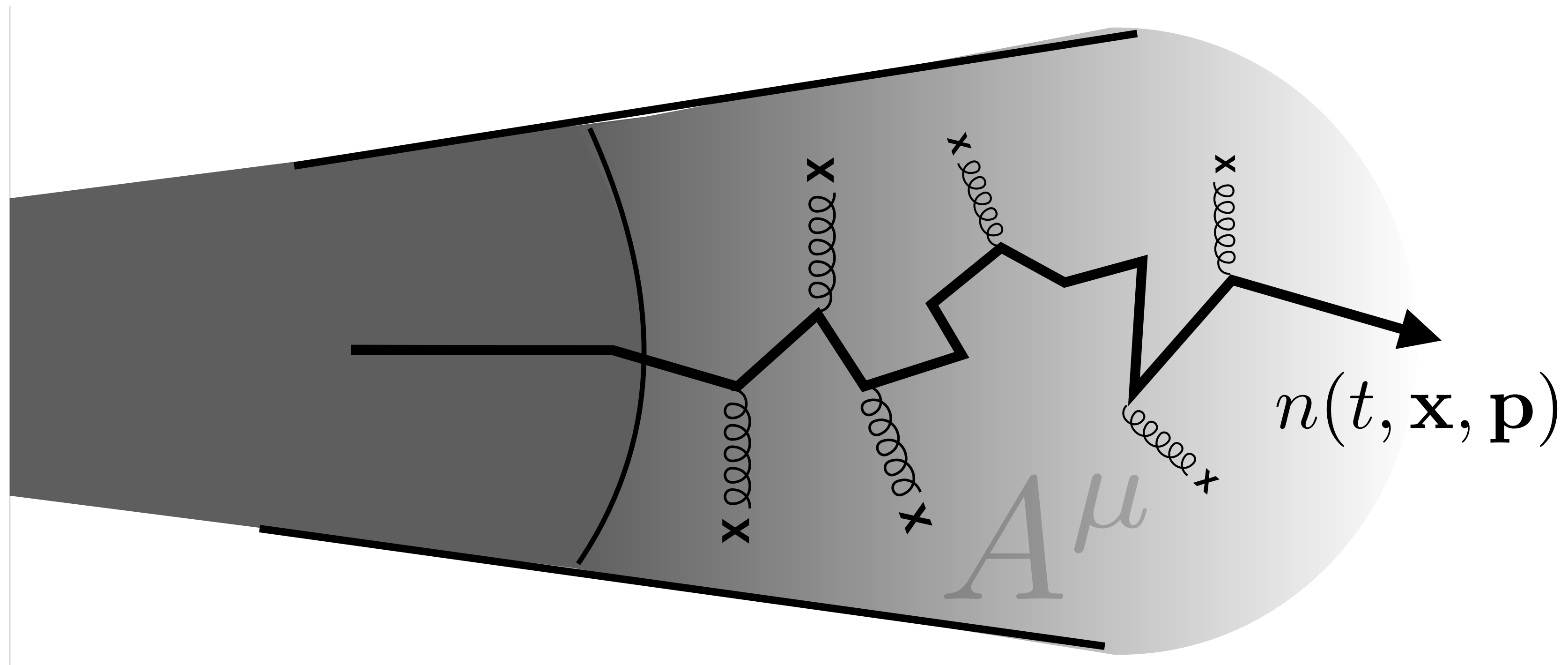
***High-multiplicity proton-proton event also display QGP-like features??***



# Pre-QGP



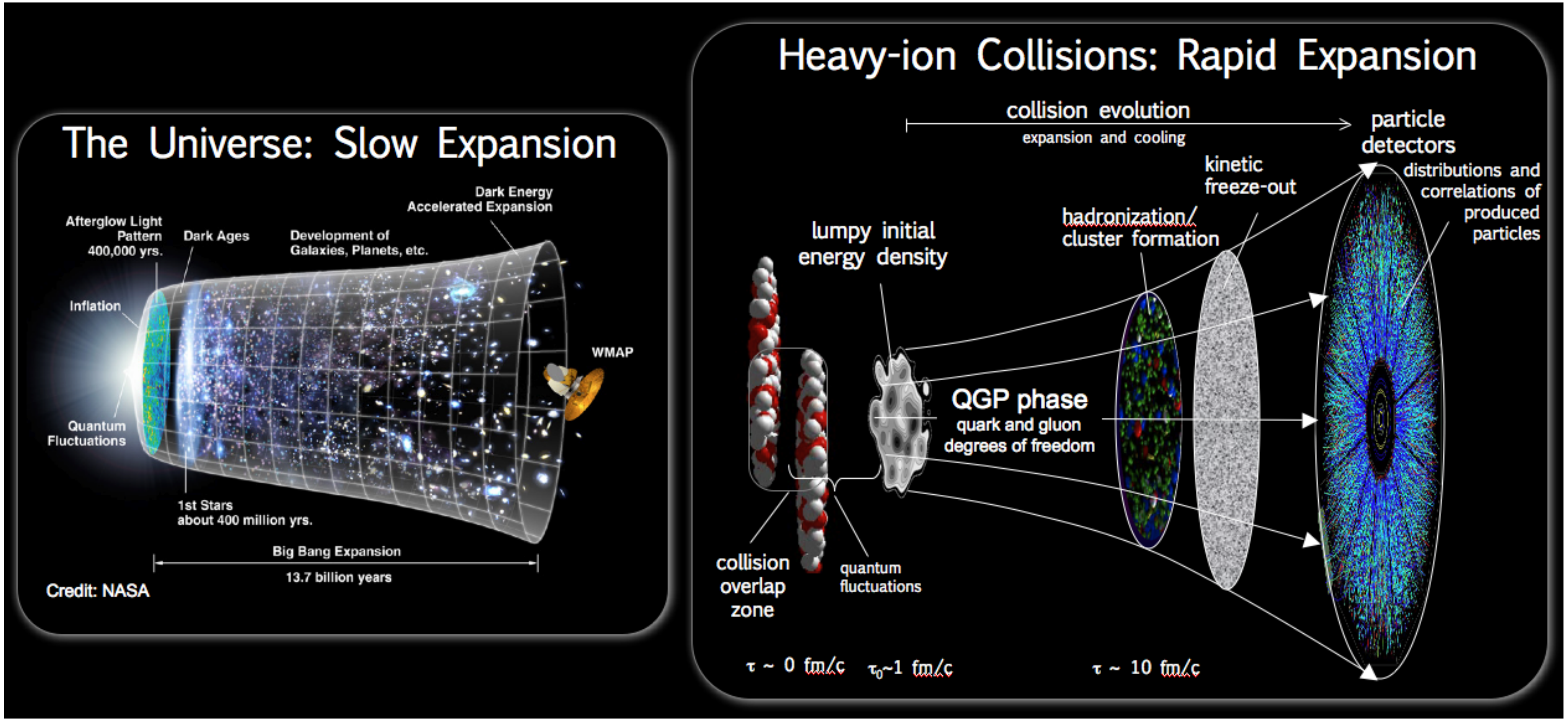




*The dynamics of the* ***pre-equilibrium*** *phase of Heavy Ion Collisions can have a* ***significant effect*** *in jet observables.*

*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



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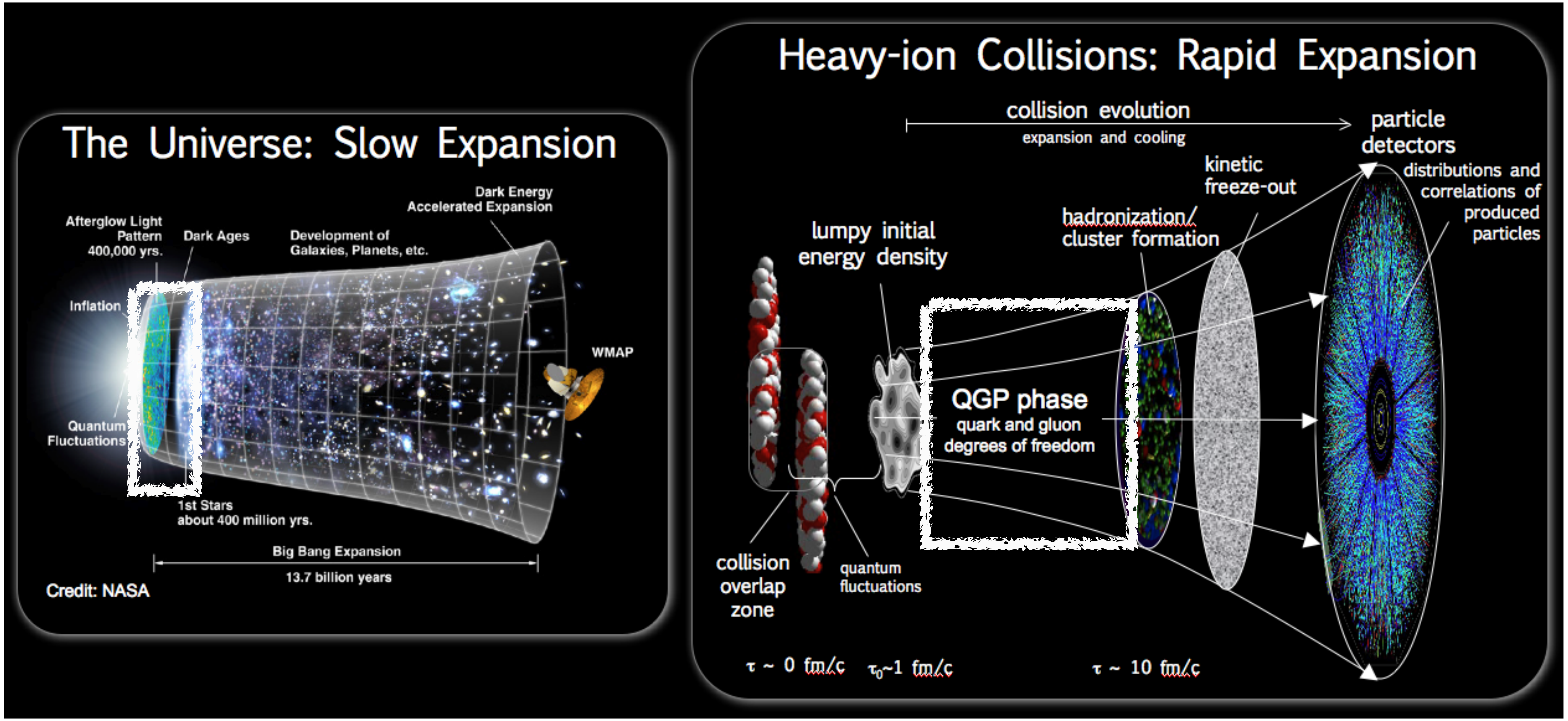
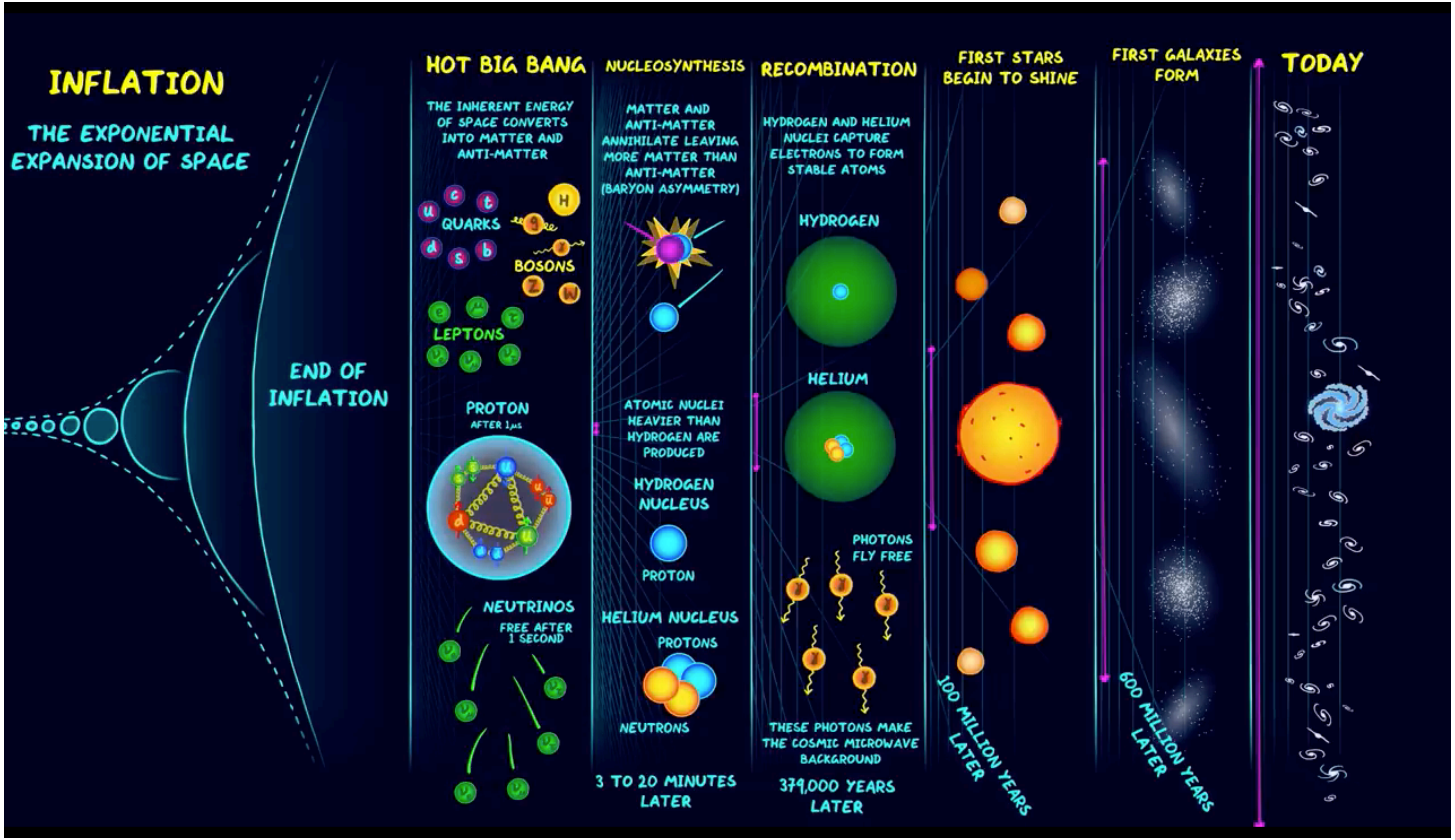


# Cosmo Evolution

?



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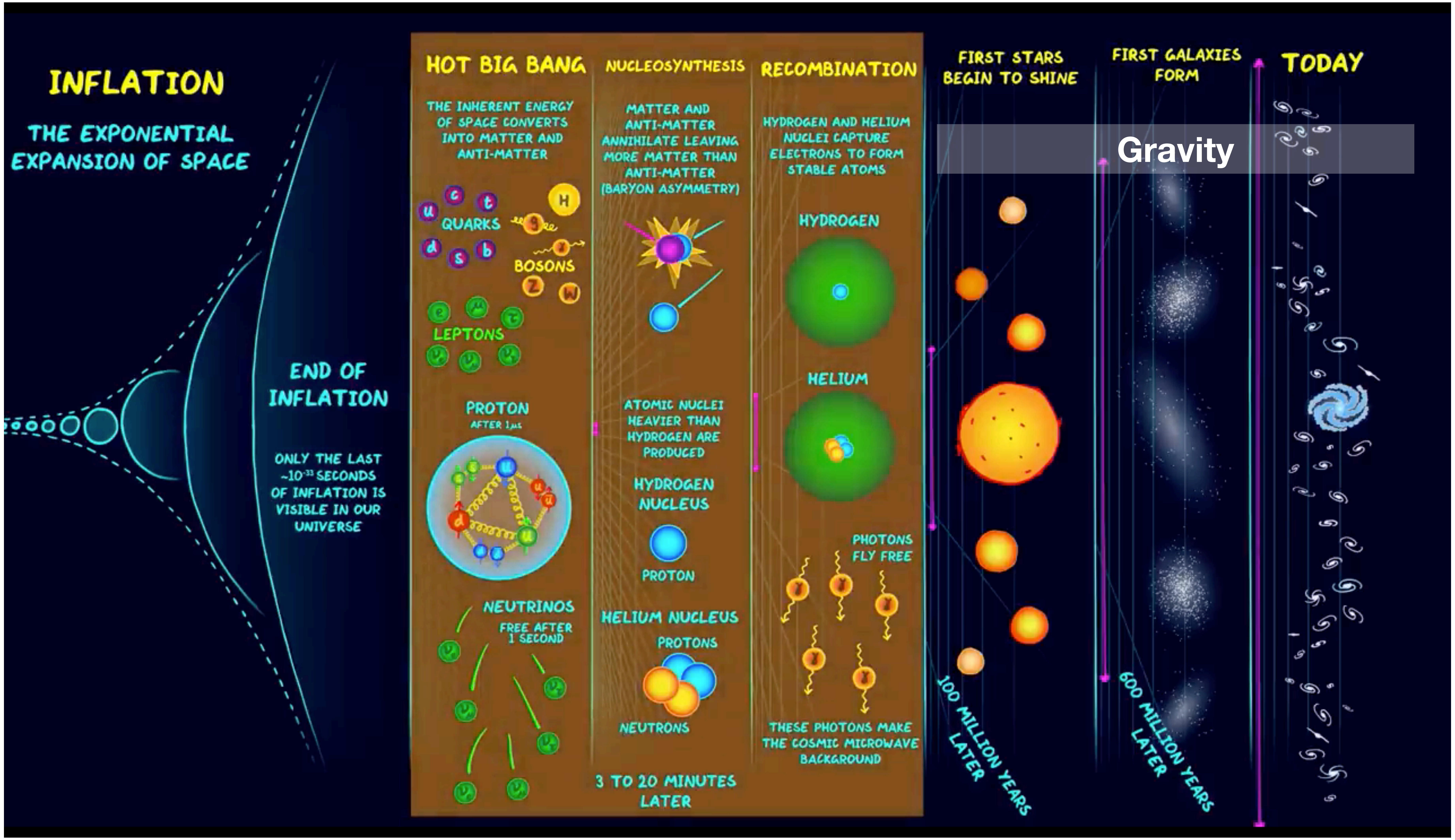

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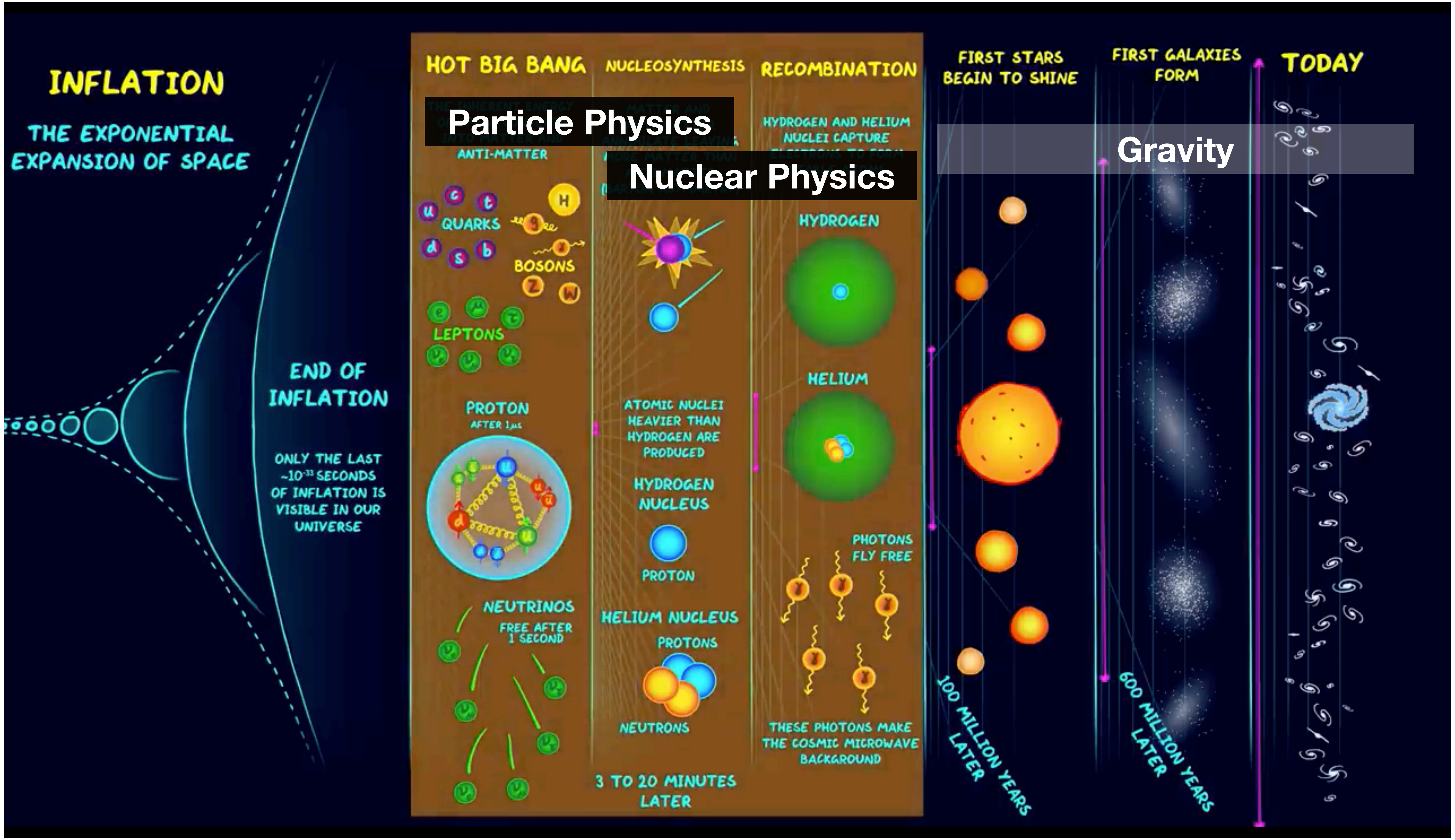

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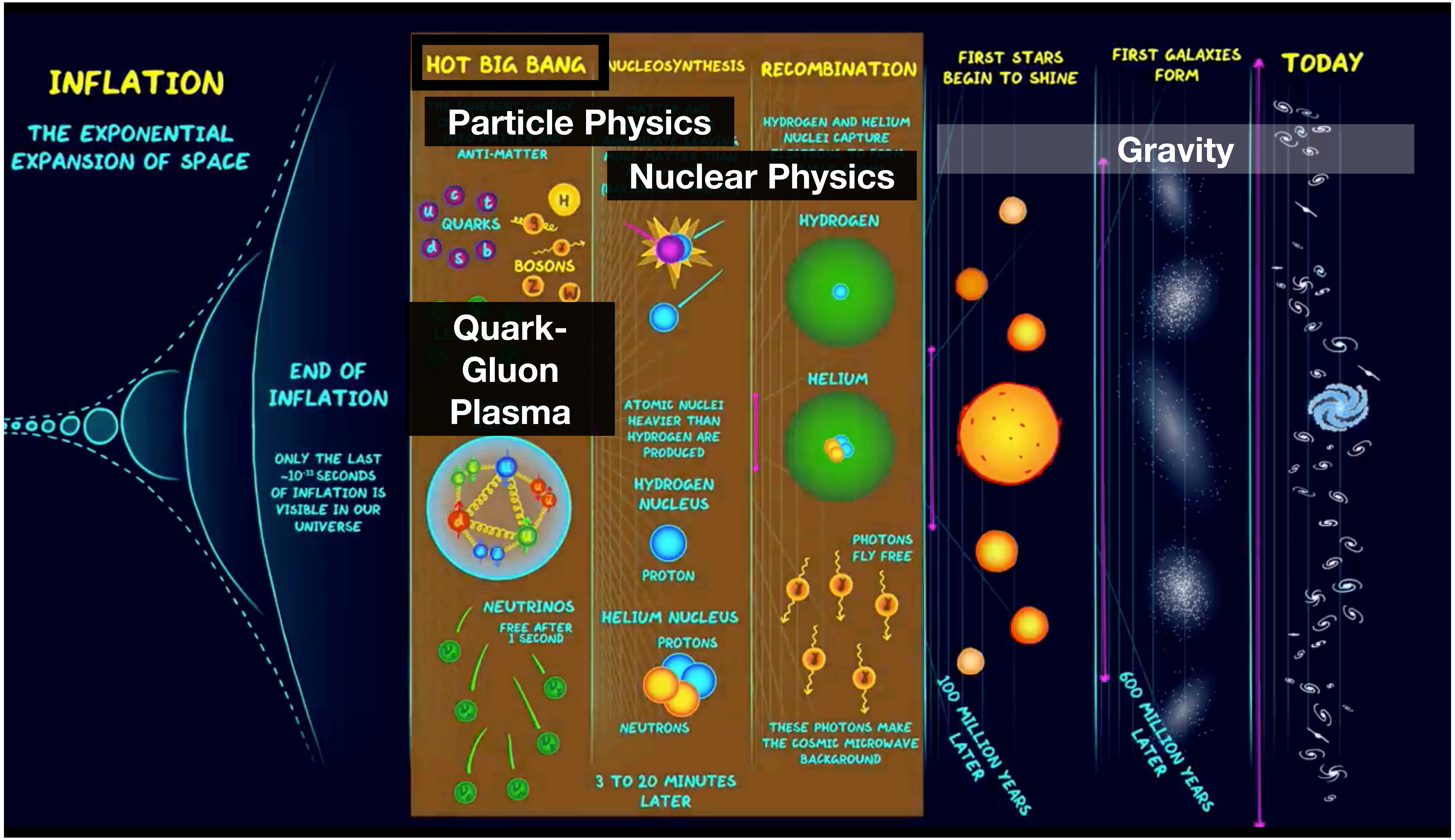


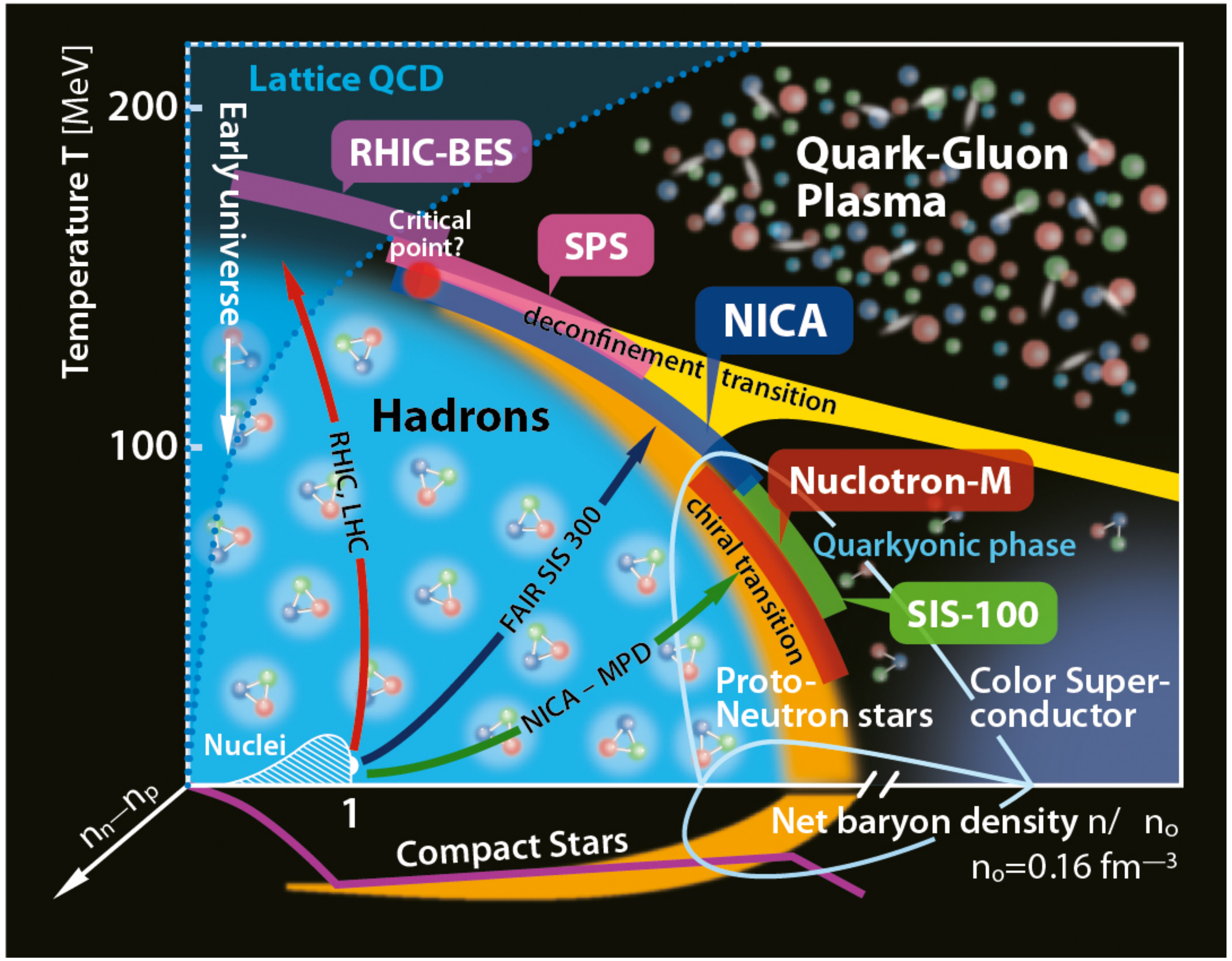
# QCD high density

- Exploring the different QCD phase diagram corner

**Early Universe** ⟷ **LHC**

**Critical point searches** ⟷ **BES (RHIC)**

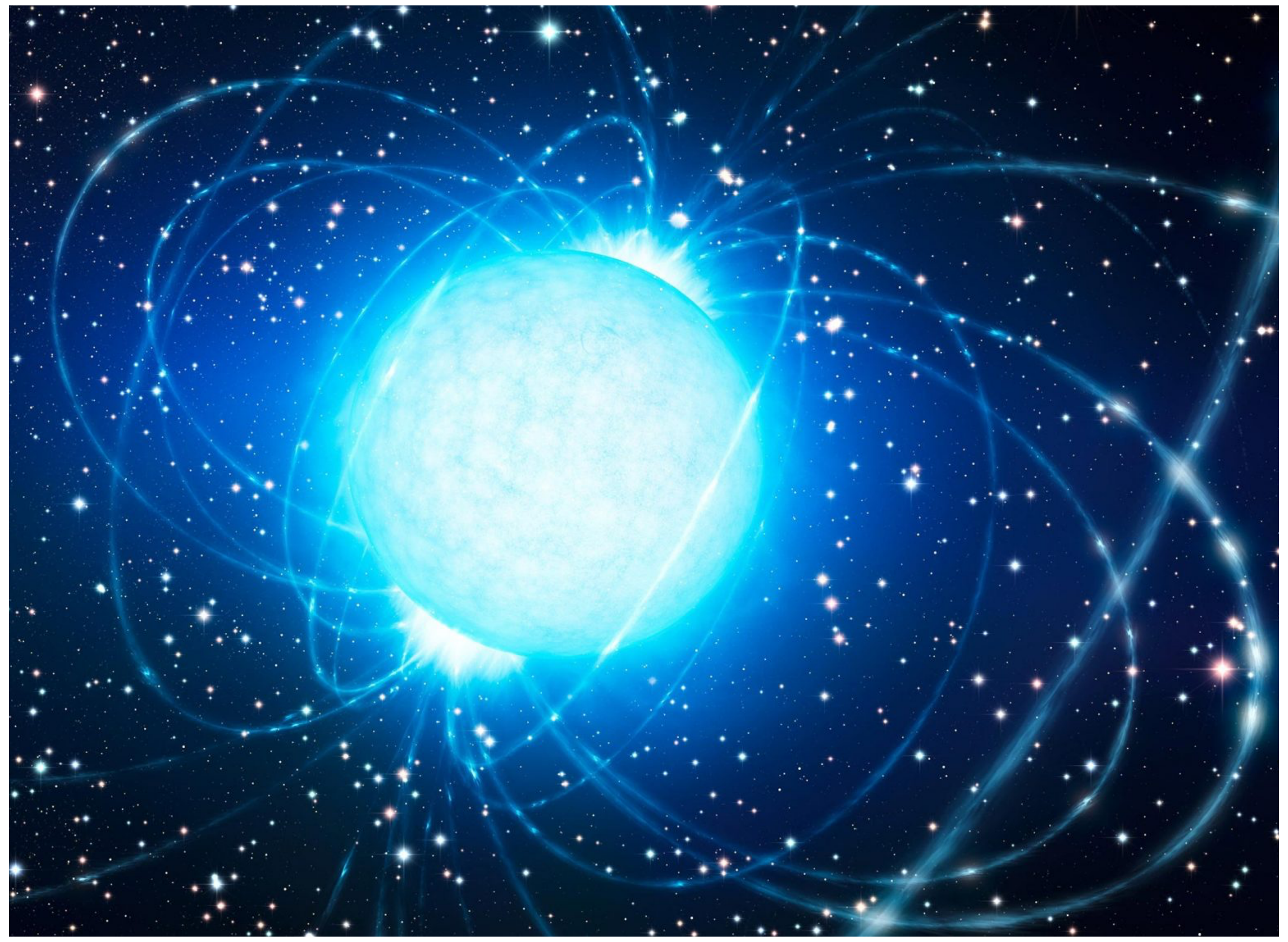
**Neutron stars** ⟷ **FAIR/NICA**



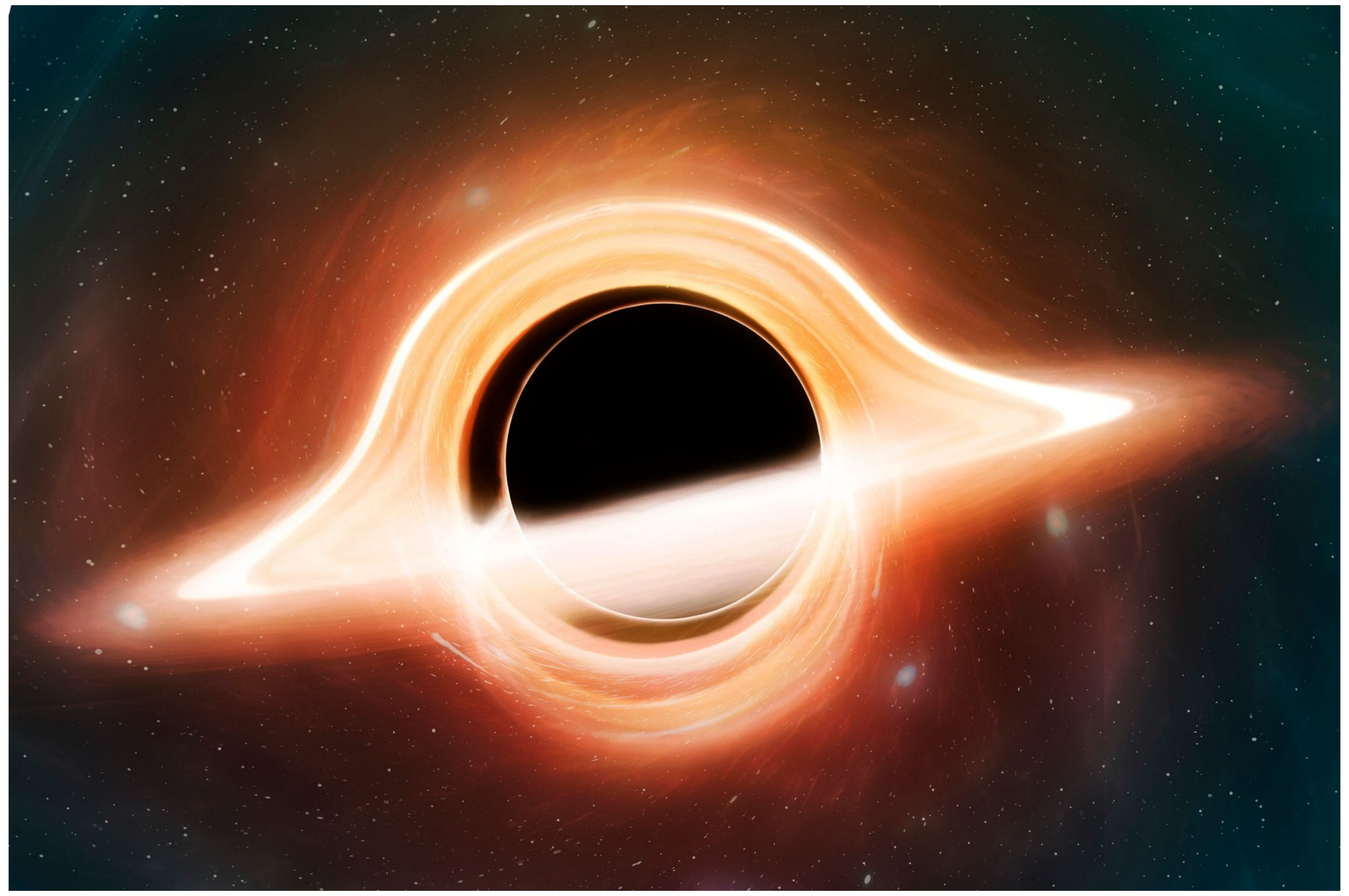
# Compact stars

- 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)**

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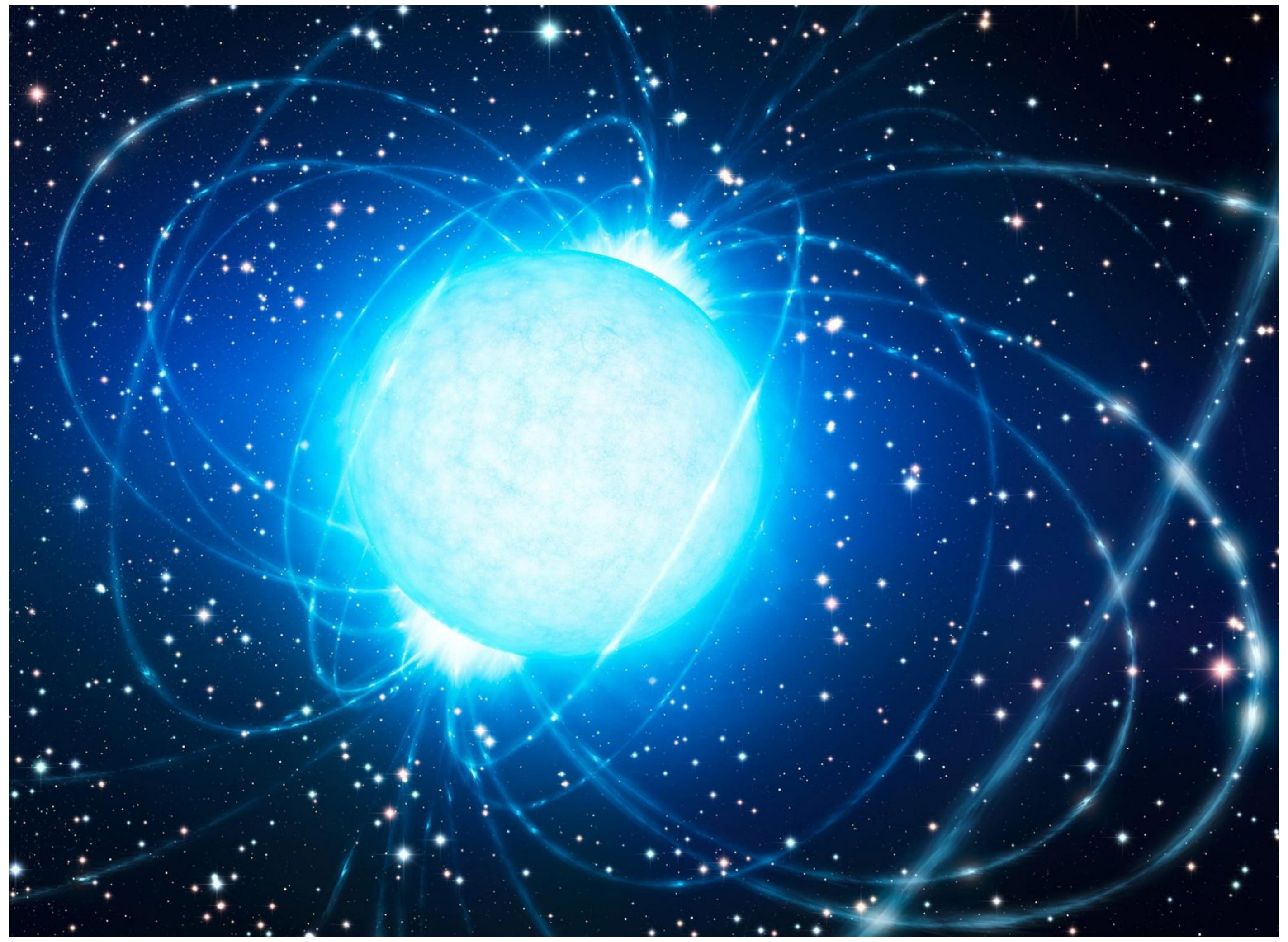
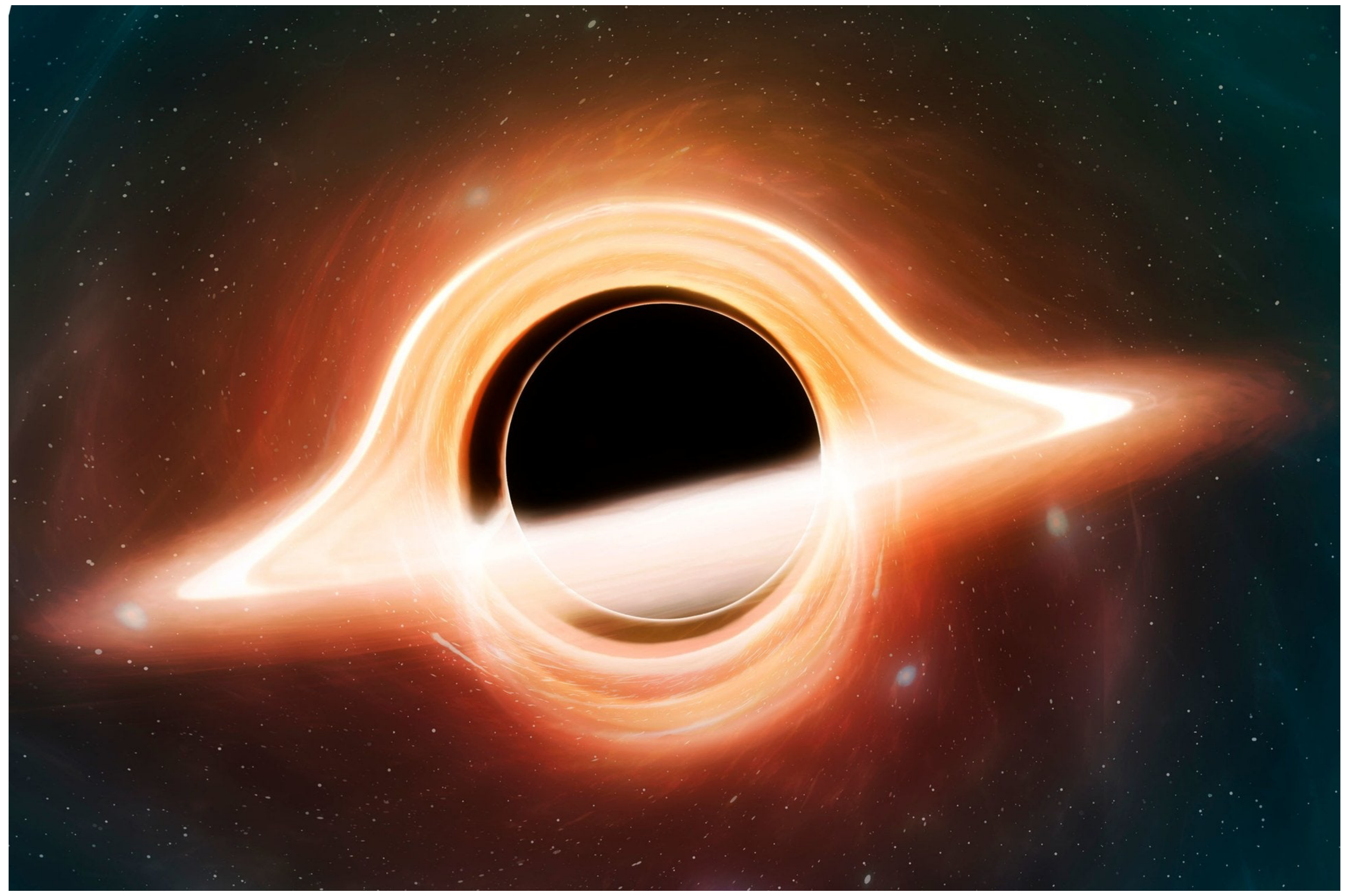


**Neutron Stars**
**(Collapse of massive stars)**

**Particularly interesting for QCD**



**Black Holes**
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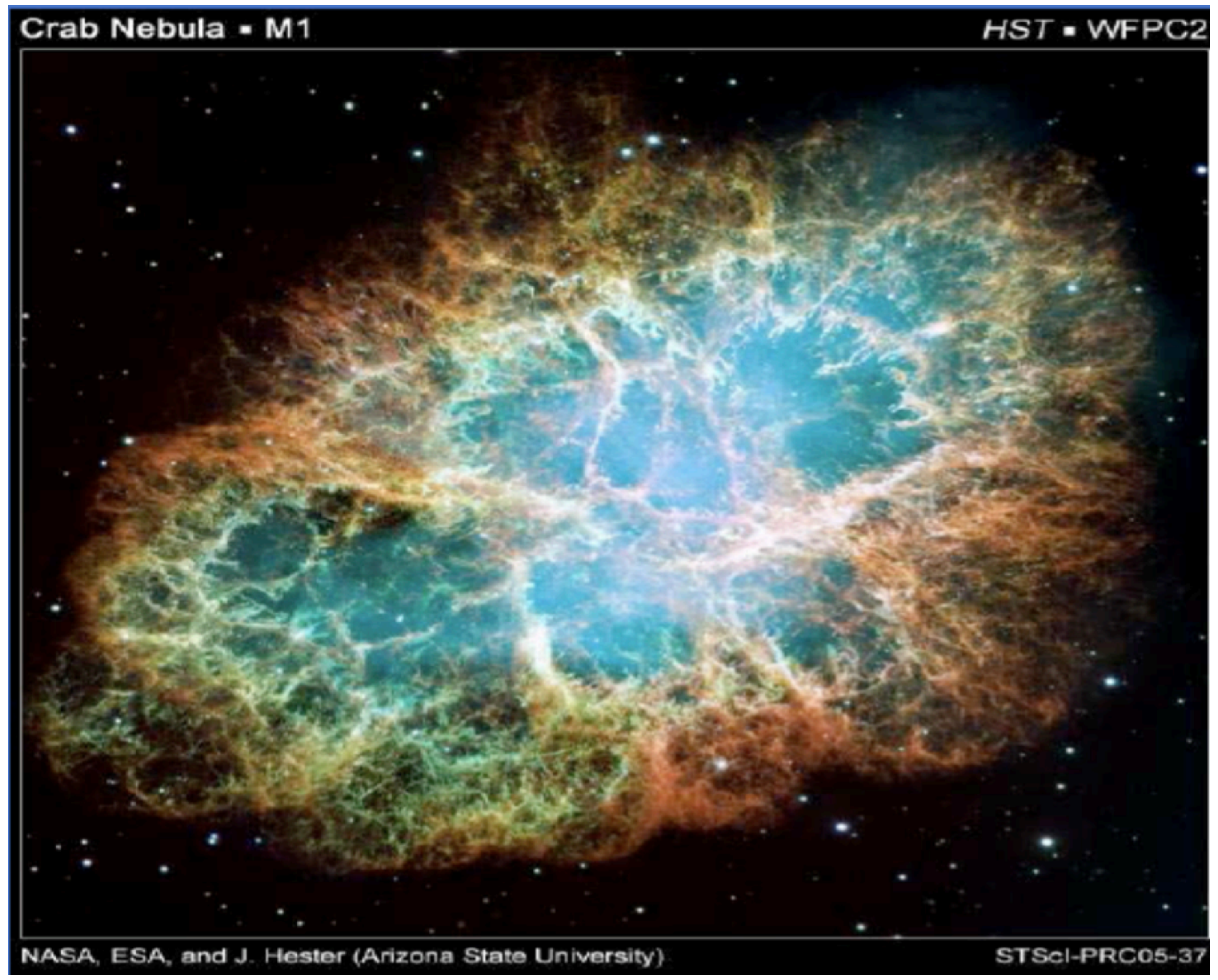
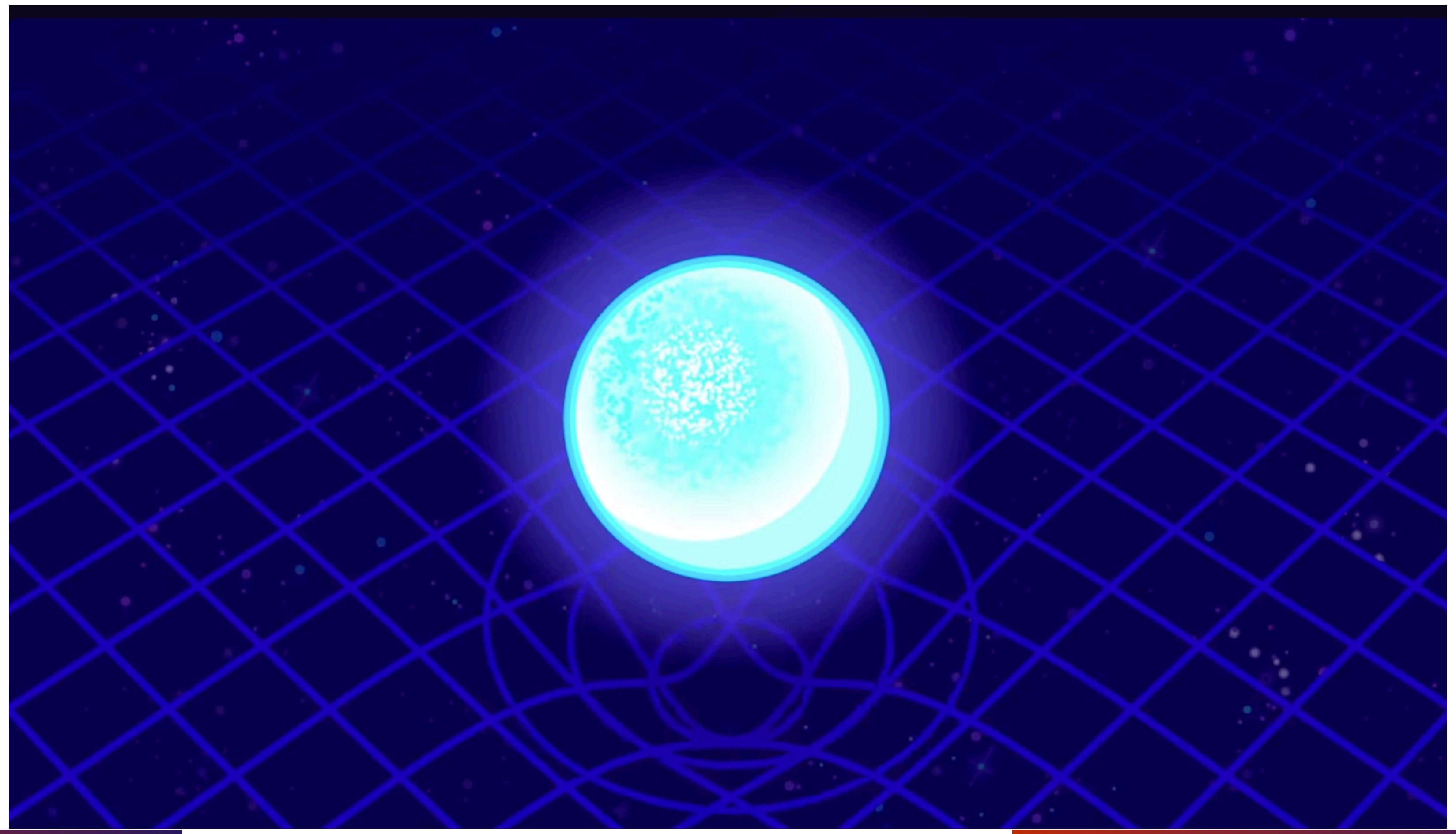
# Neutron Stars

- 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 ~1-2 $M_{sun}$, R ~ 10 Km**

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



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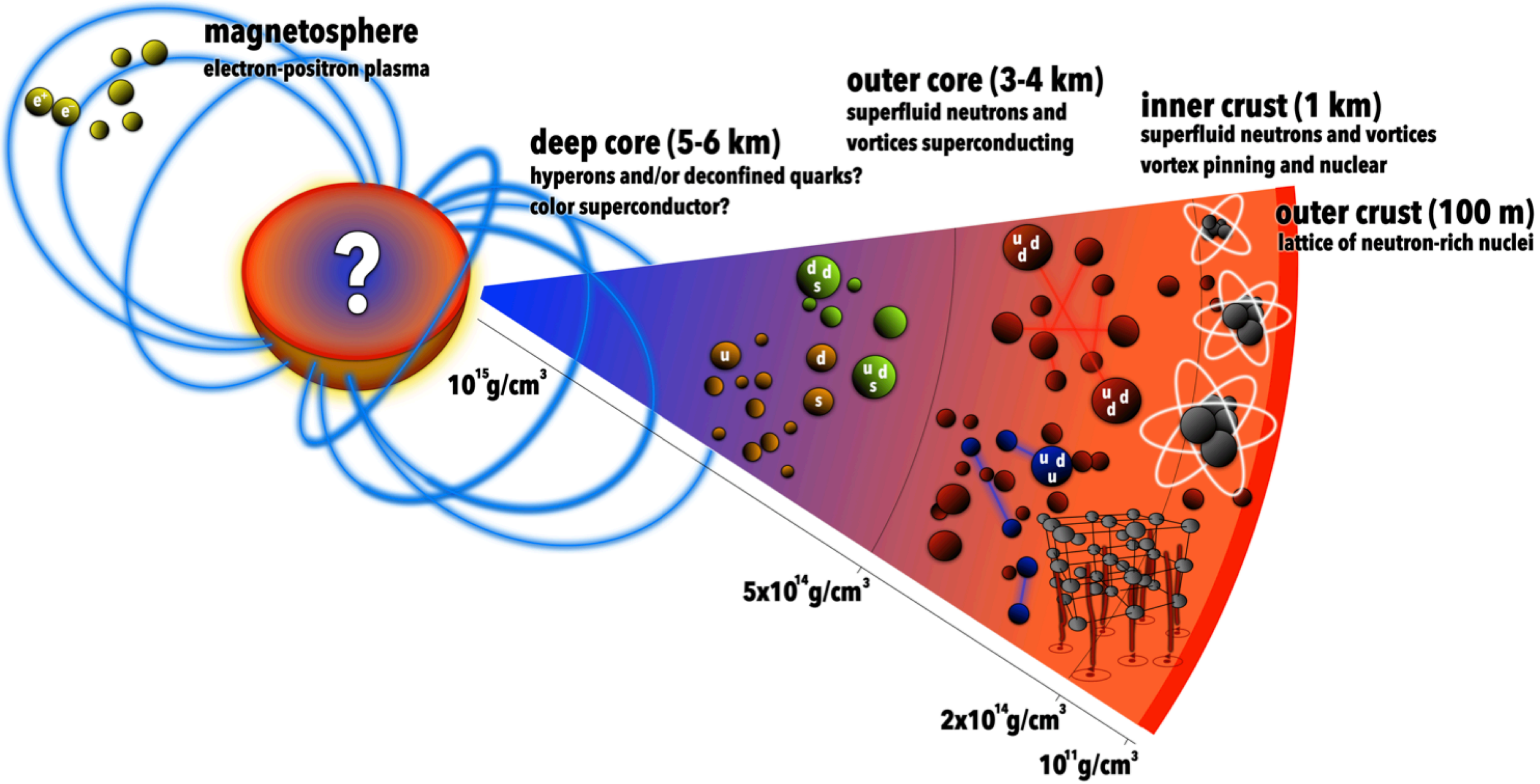

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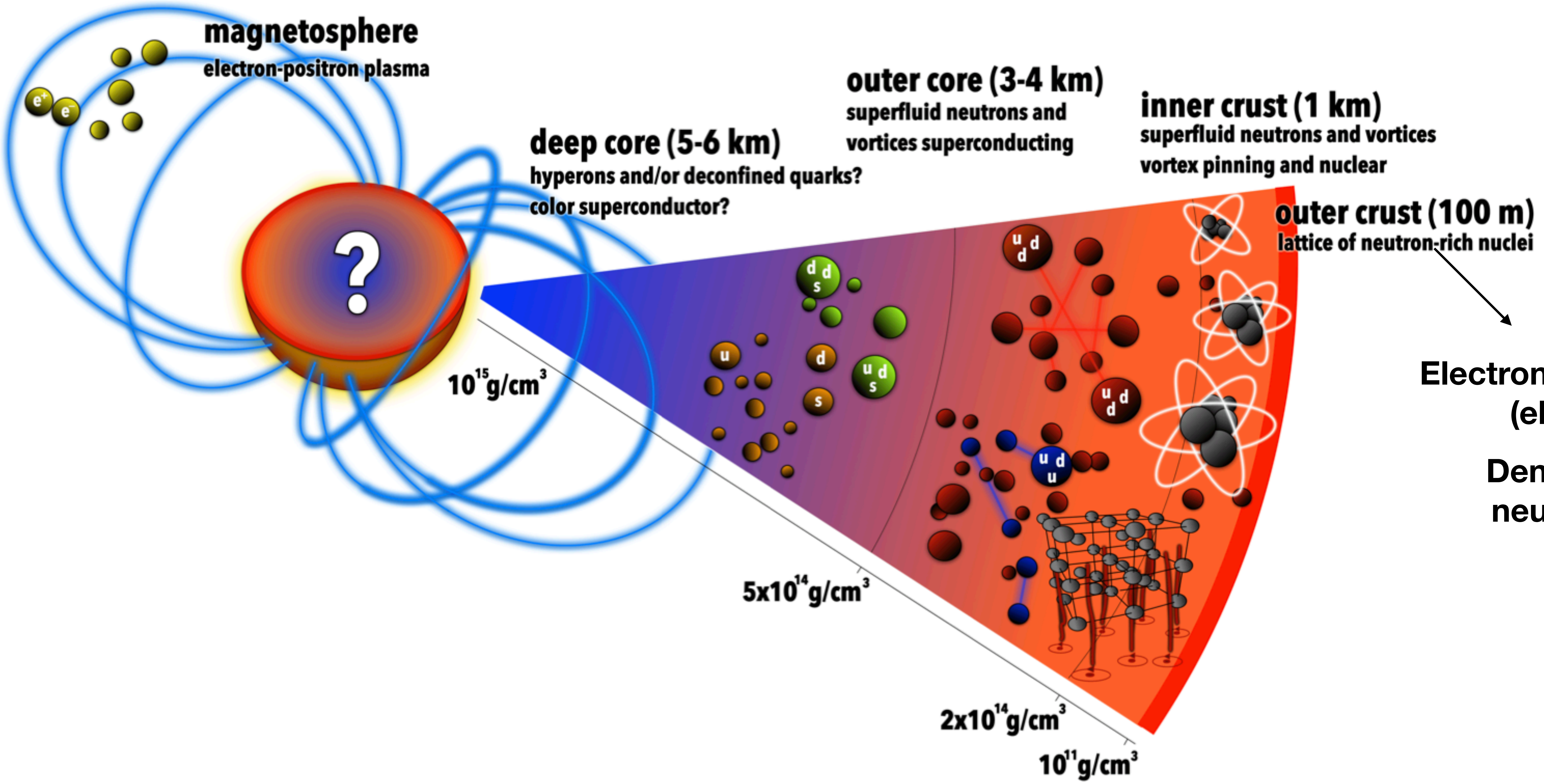
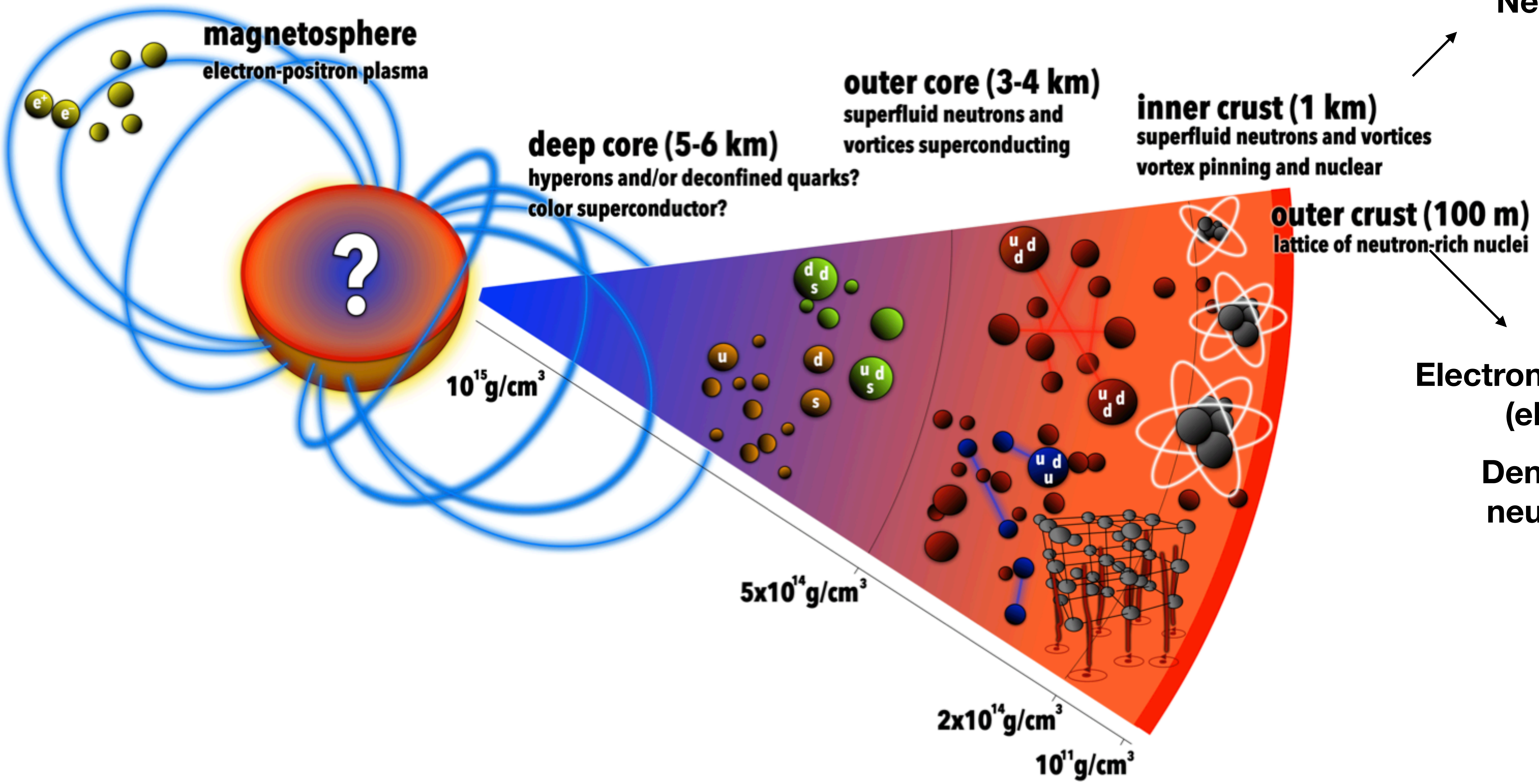



Electrons driven inside nuclei (electron capture)

Densities to produce neutron-rich (heavy) elements

# Neutron Stars




Neutron "leaking" (neutrons are free)

Electrons driven inside nuclei (electron capture)

Densities to produce neutron-rich (heavy) elements

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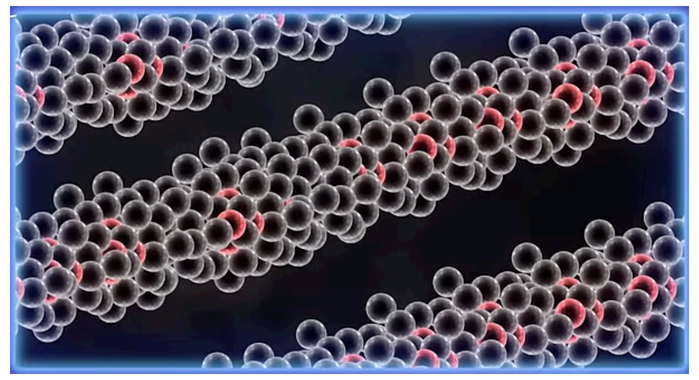
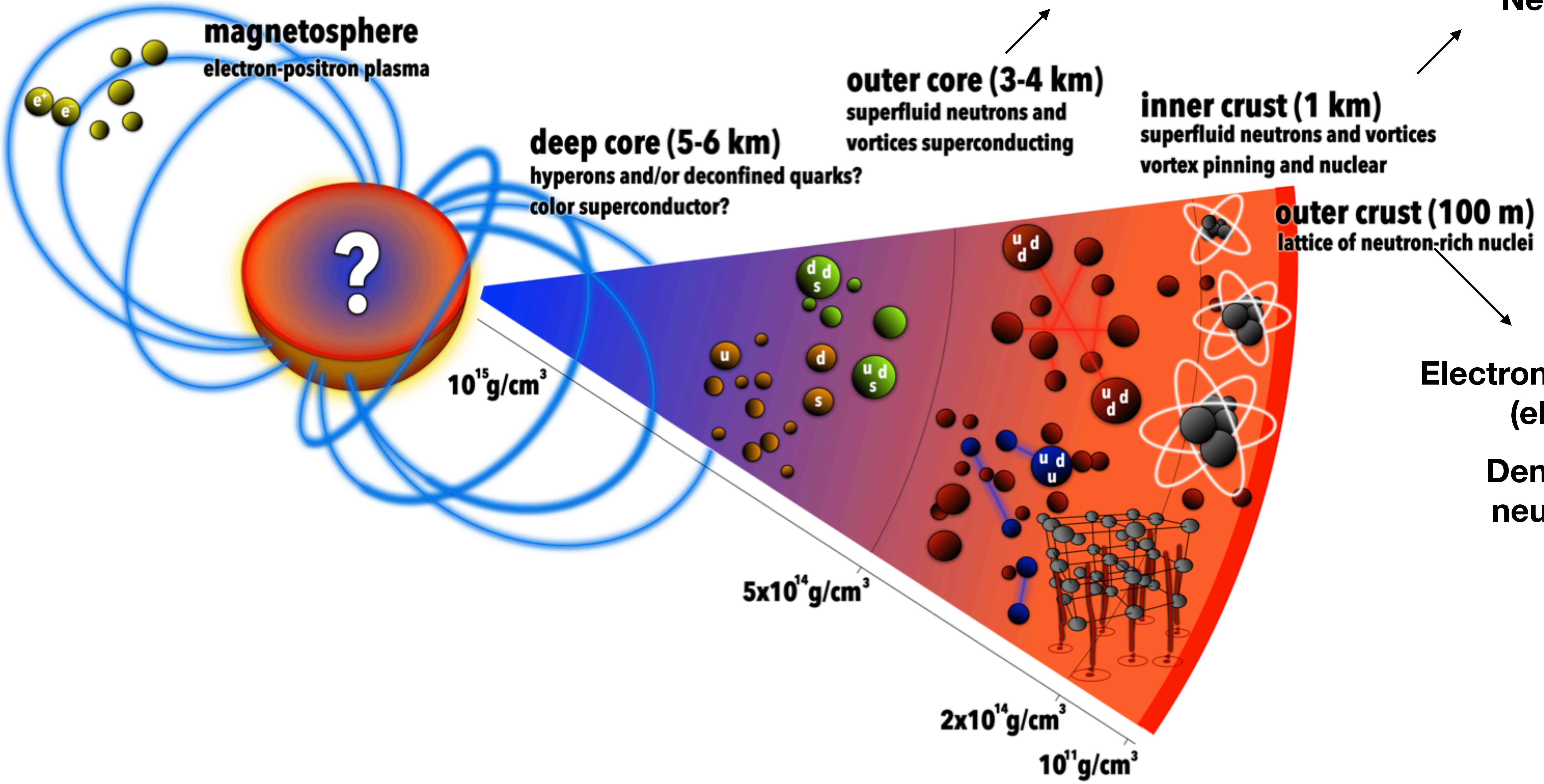


Protons outnumbered by neutrons: nuclear pasta

Neutron “leaking” (neutrons are free)

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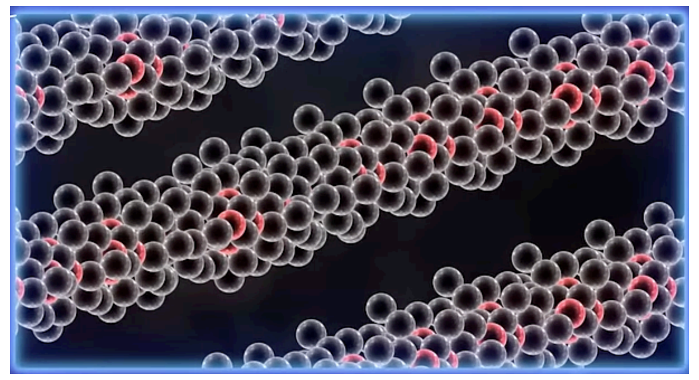

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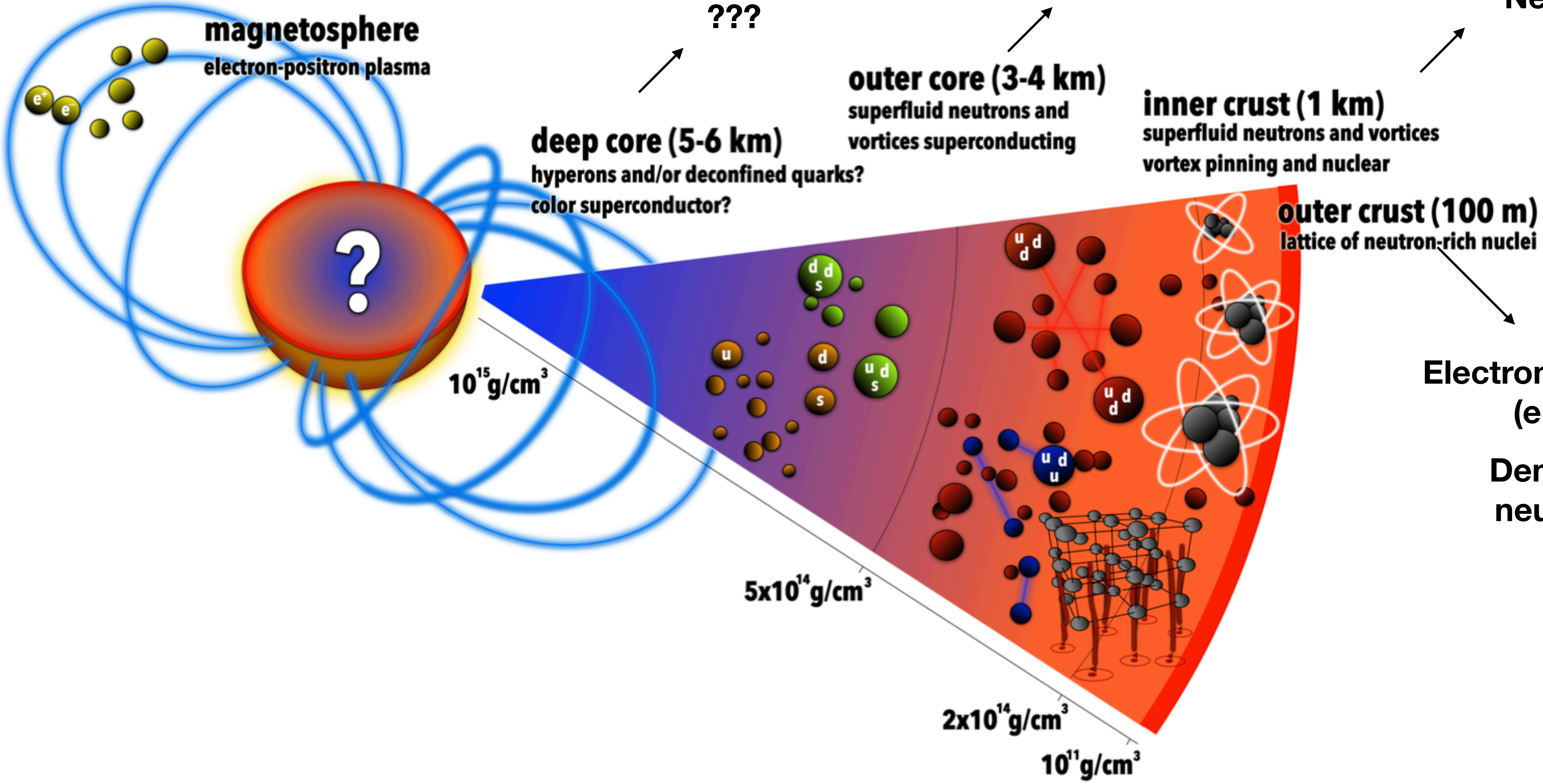
???

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Densities to produce neutron-rich (heavy) elements

# Neutron Stars

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