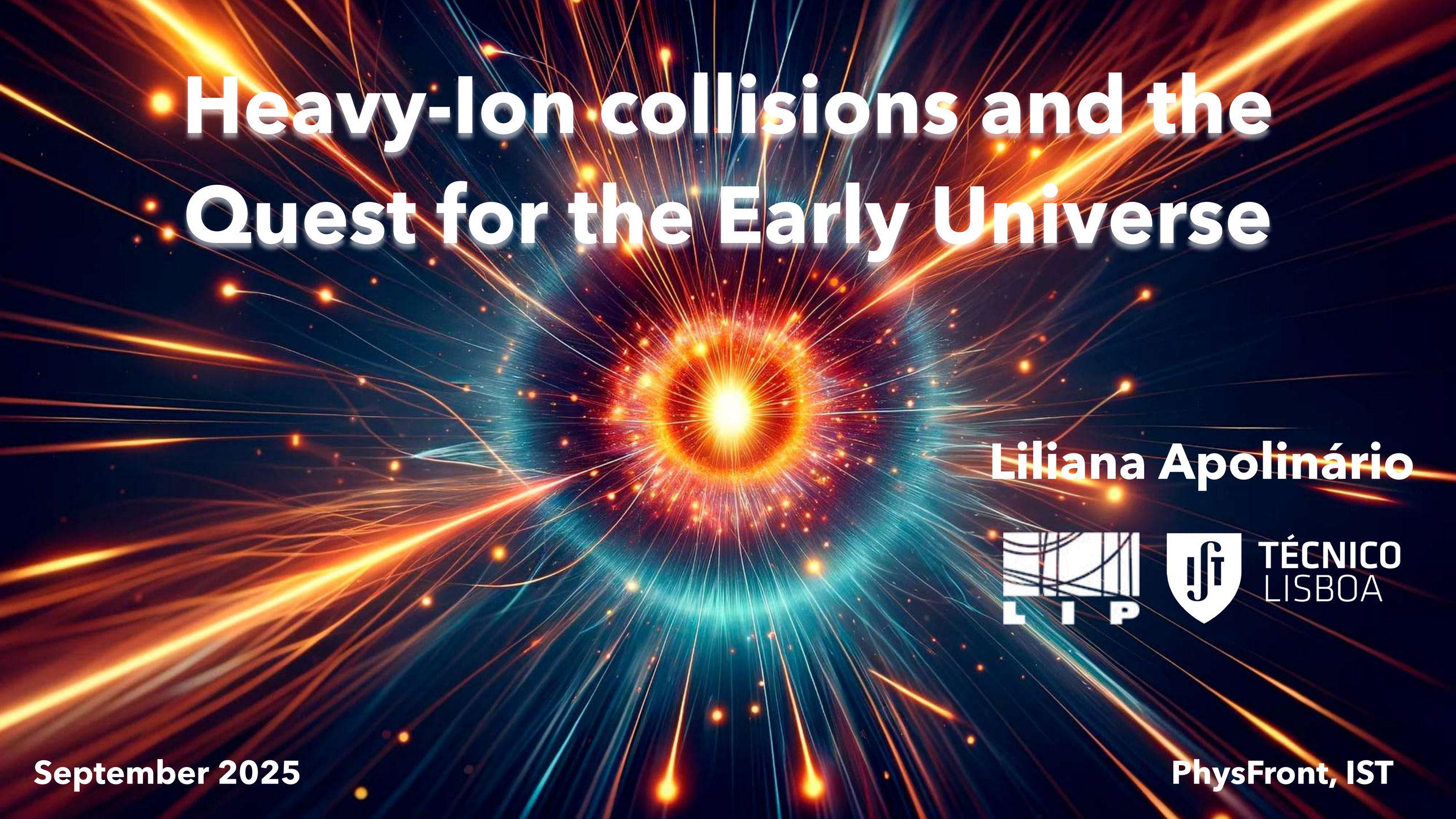
Heavy-Ion collisions and the Quest for the Early Universe



Liliana Apolinário

LIP

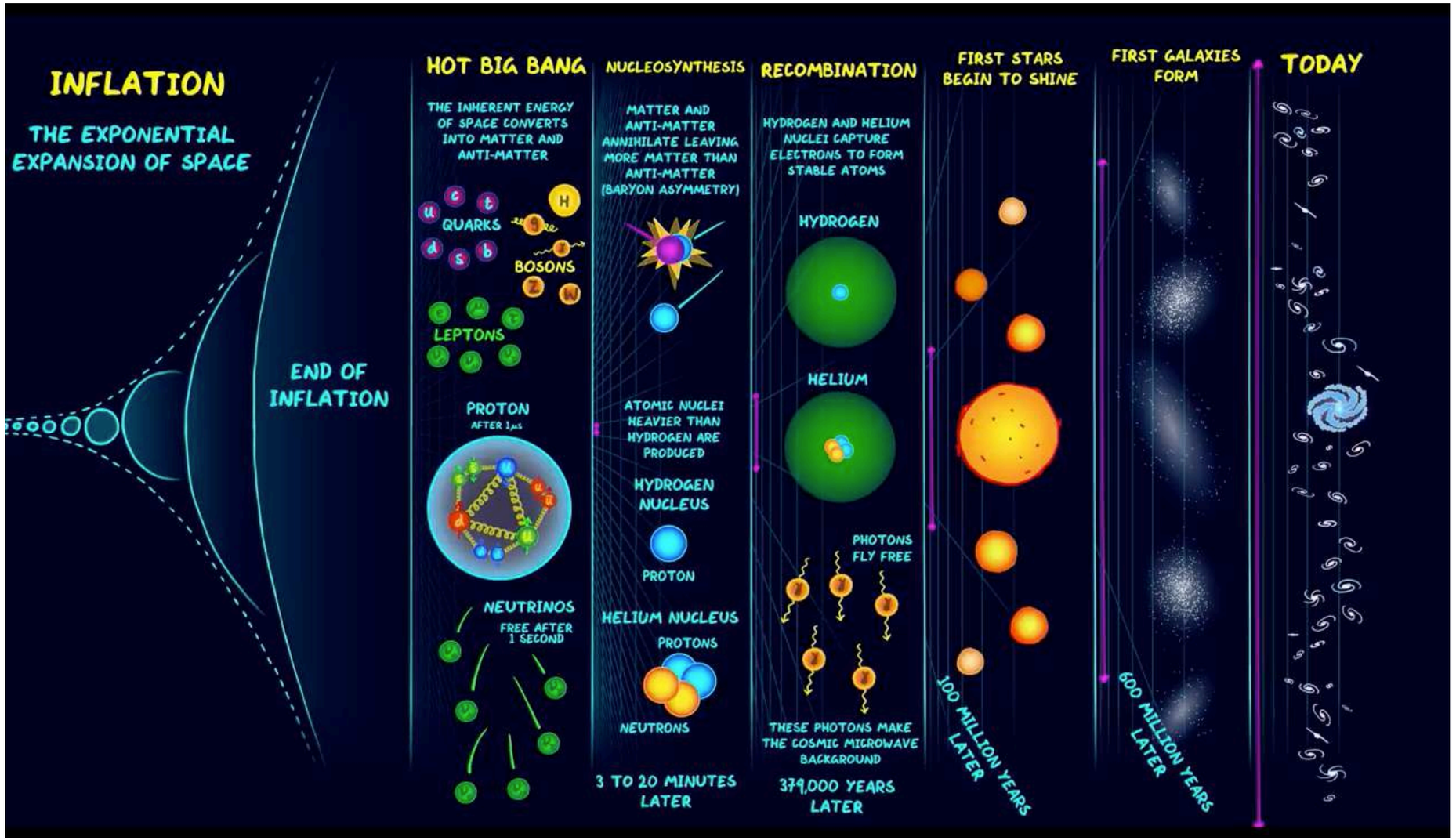
TÉCNICO LISBOA

September 2025

PhysFront, IST

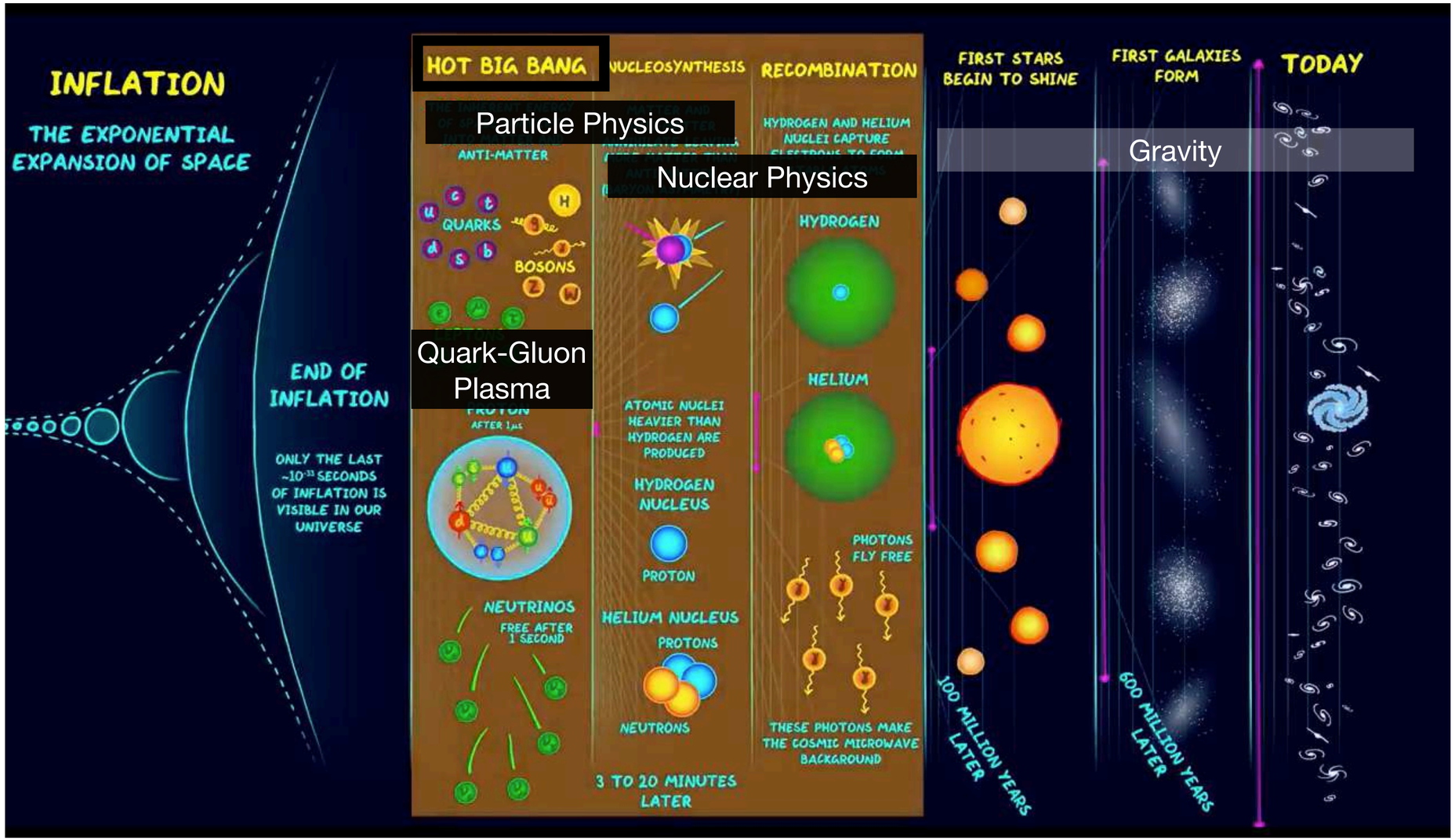
Cosmos Evolution

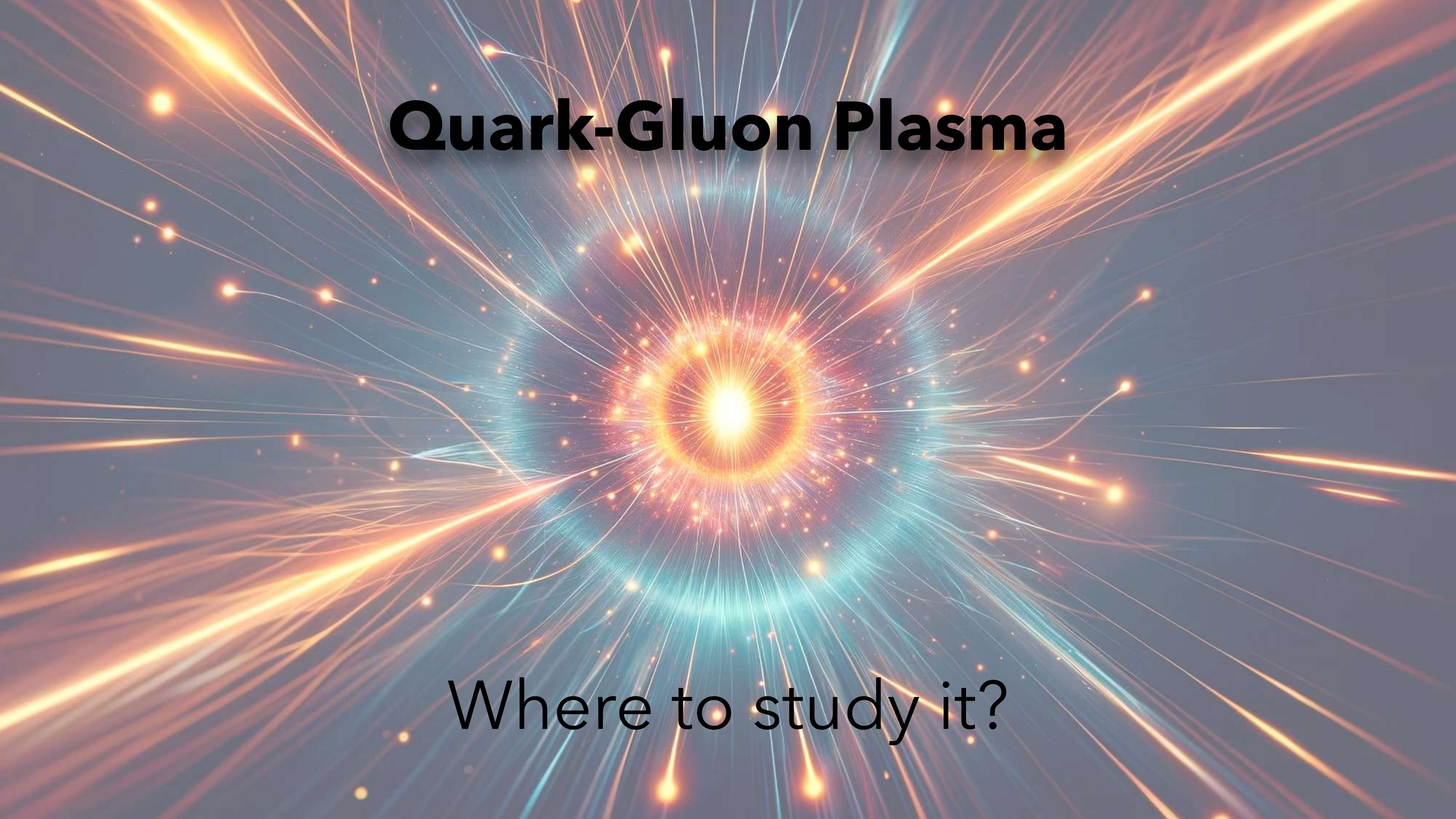
?



Cosmos Evolution

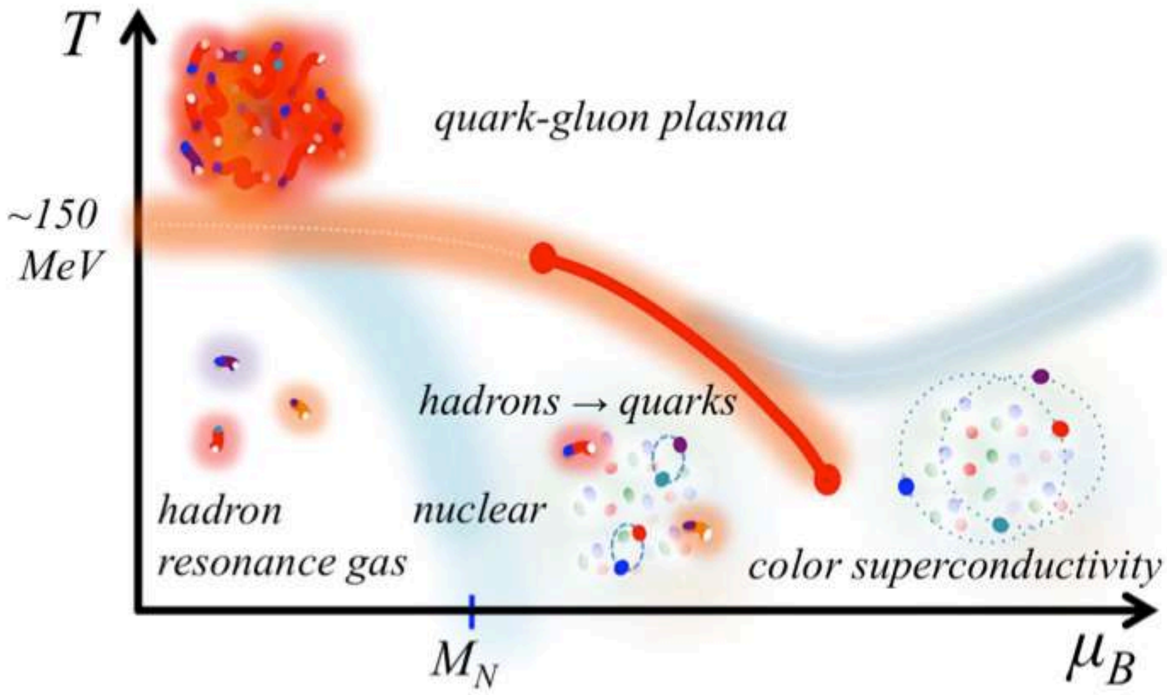
?

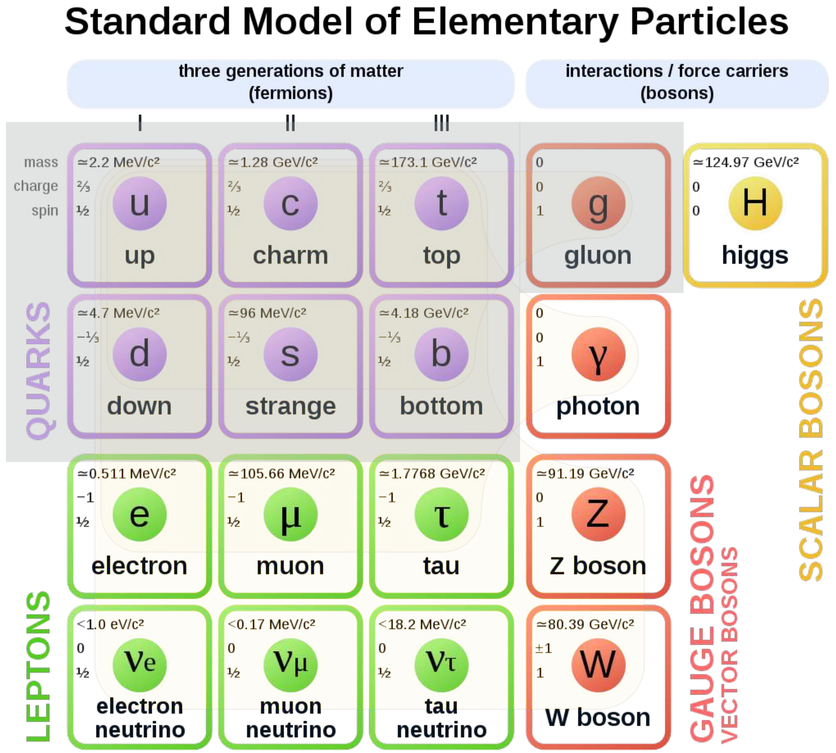



Quark-Gluon Plasma
Where to study it?

QCD Phase Space

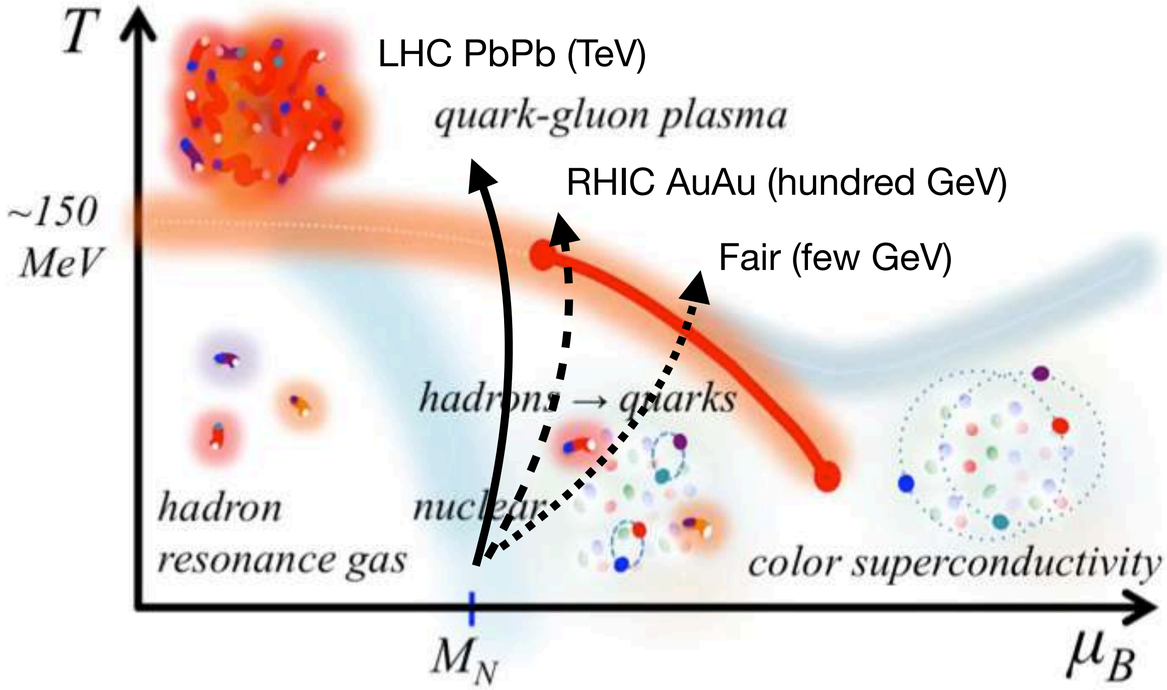
- Our matter is just one of all possible states of matter:

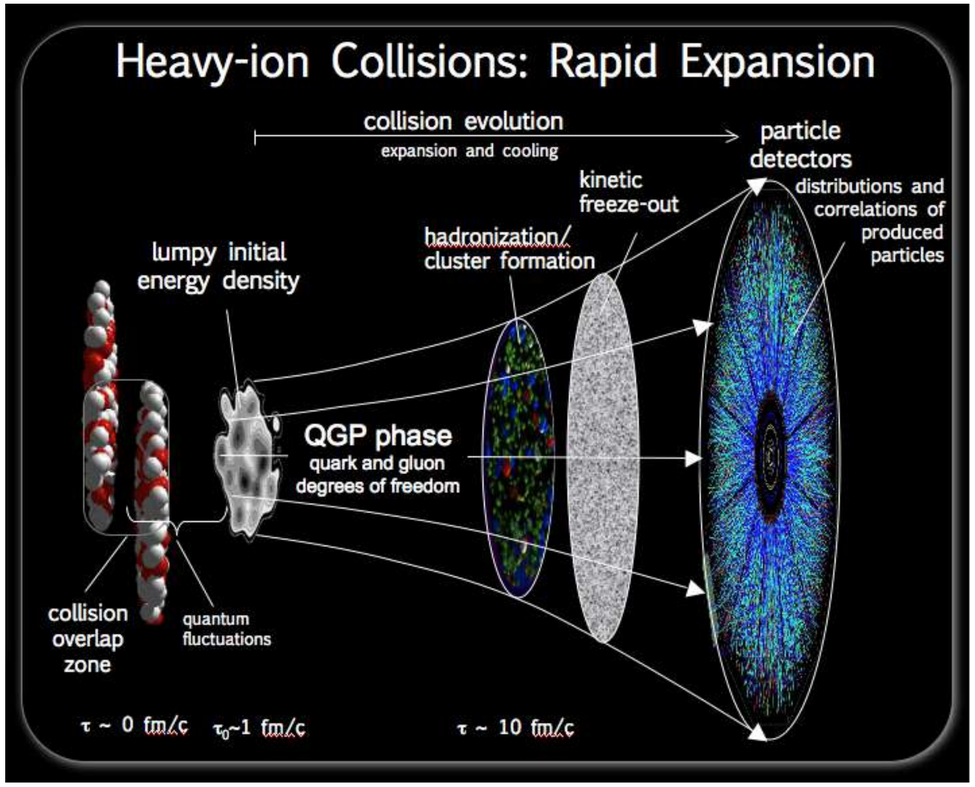




Heavy-Ion Collisions

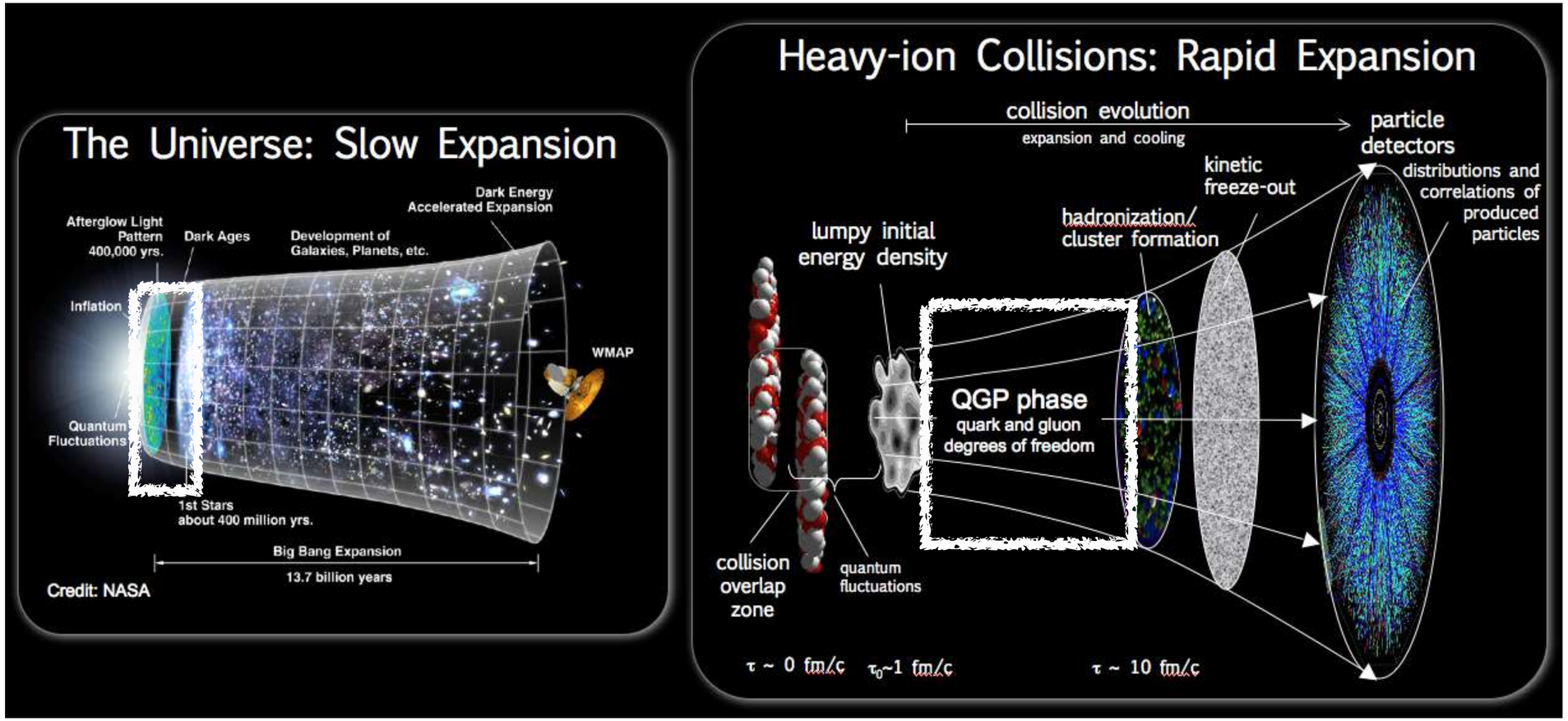
- Heavy-Ion Collisions allow to probe the QCD phase space in a controlled laboratory

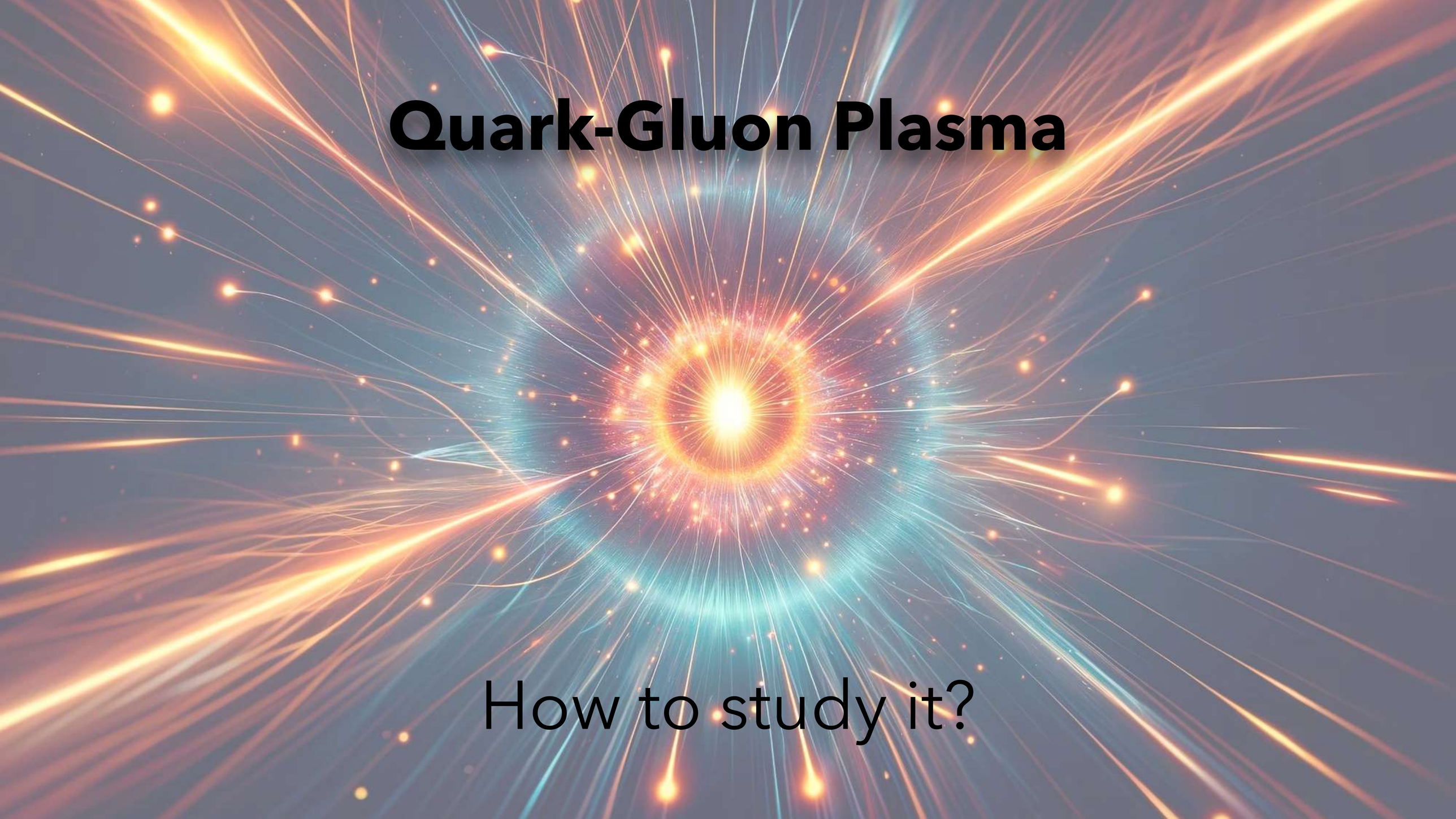




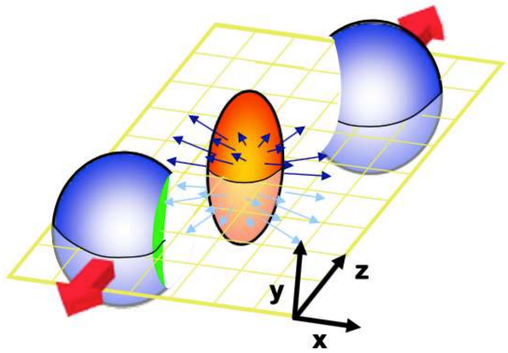
QGP: Universe vs Laboratory

- Quark-Gluon Plasma: Slow vs Rapid expansion



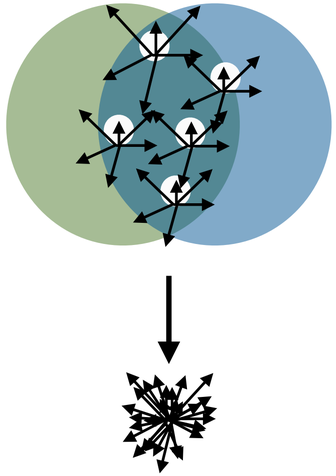

Quark-Gluon Plasma
How to study it?

Fluidity

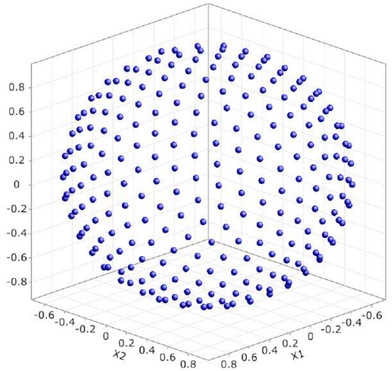


- Try different centralities and check response of the system to initial spatial anisotropy:

Superposition of multiple pp collisions



Uniform distribution of particles?



Fluidity

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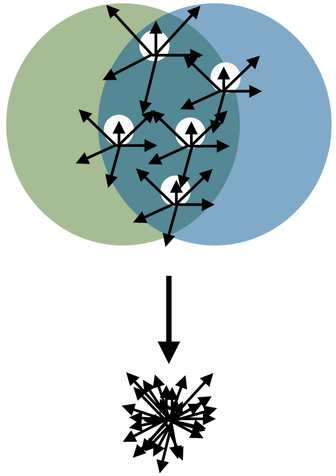

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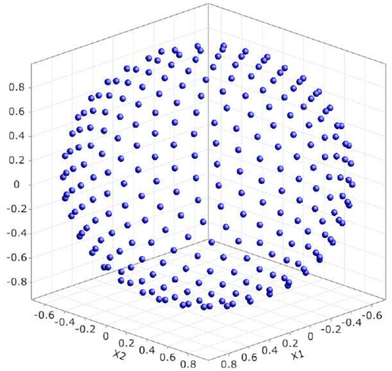
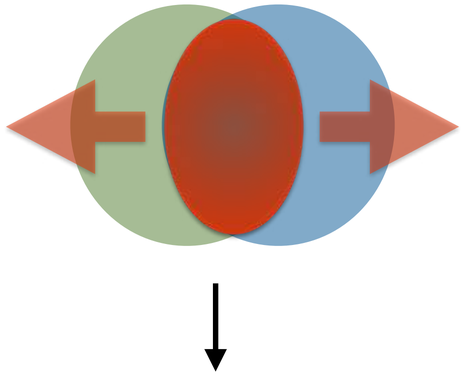
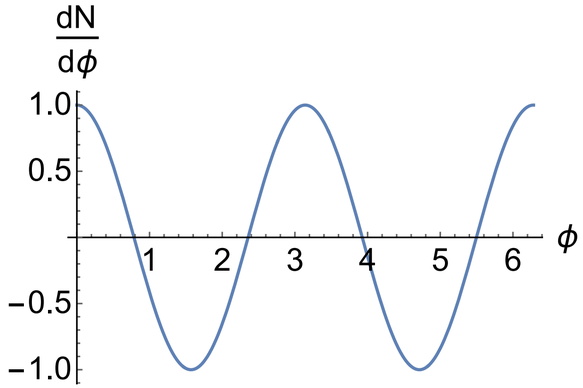
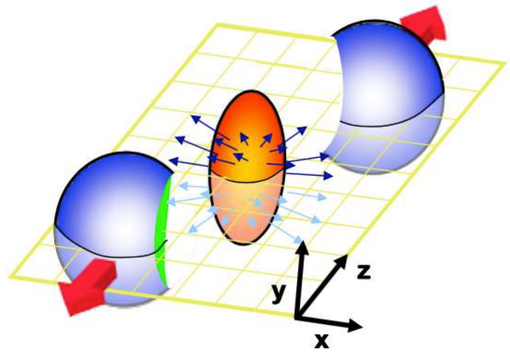


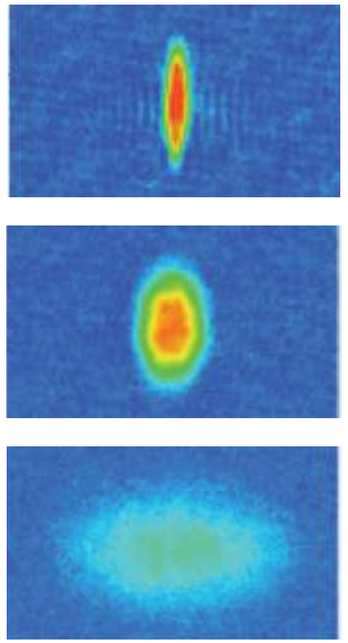
Collective bulk behaviour



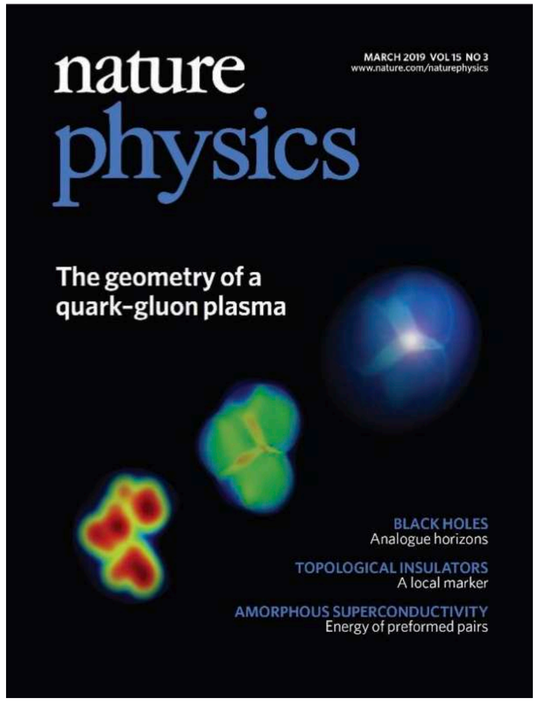
Initial anisotropies propagate to the final state



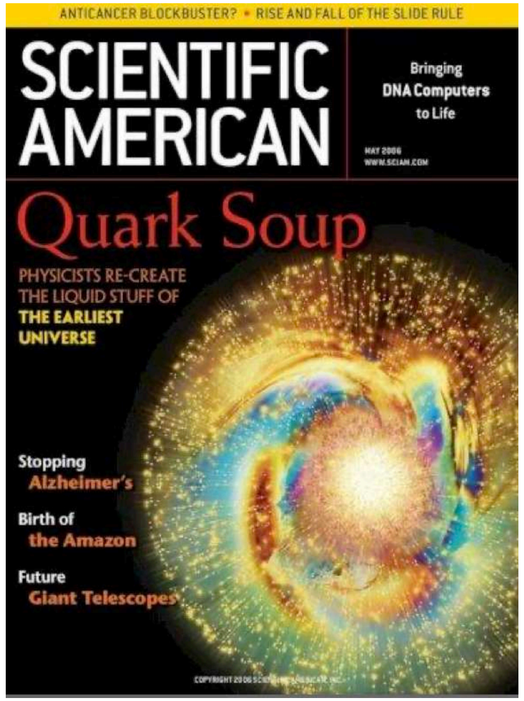




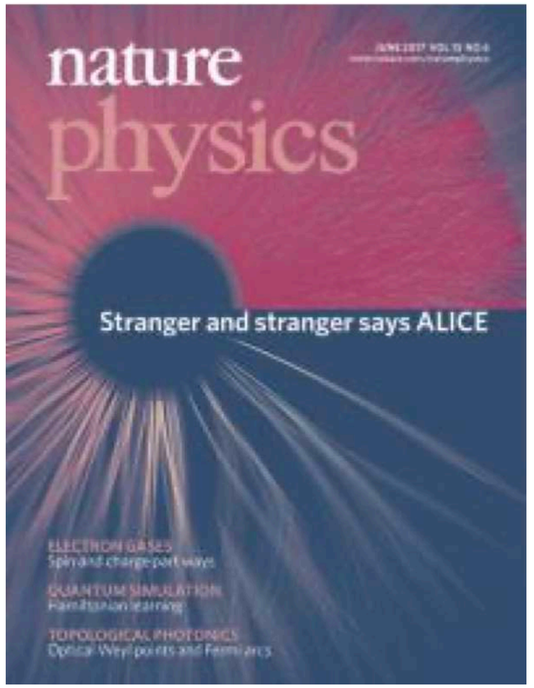
Plasma?... or Fluid?



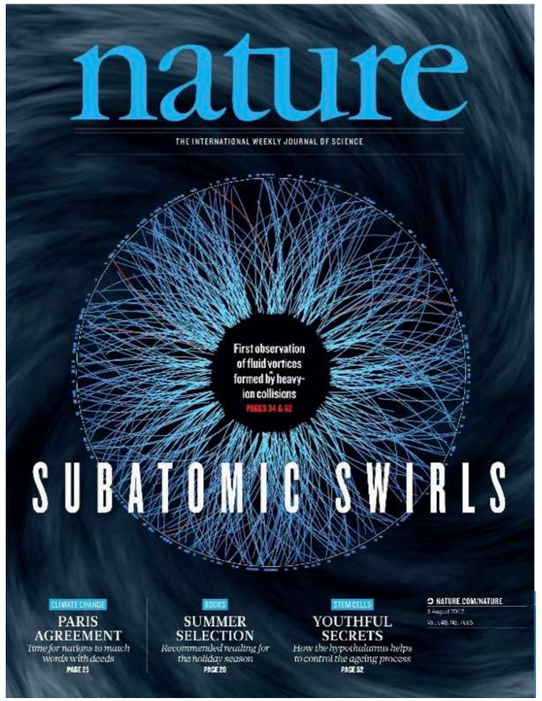
(Almost) perfect fluid!



Temperatures larger than sun



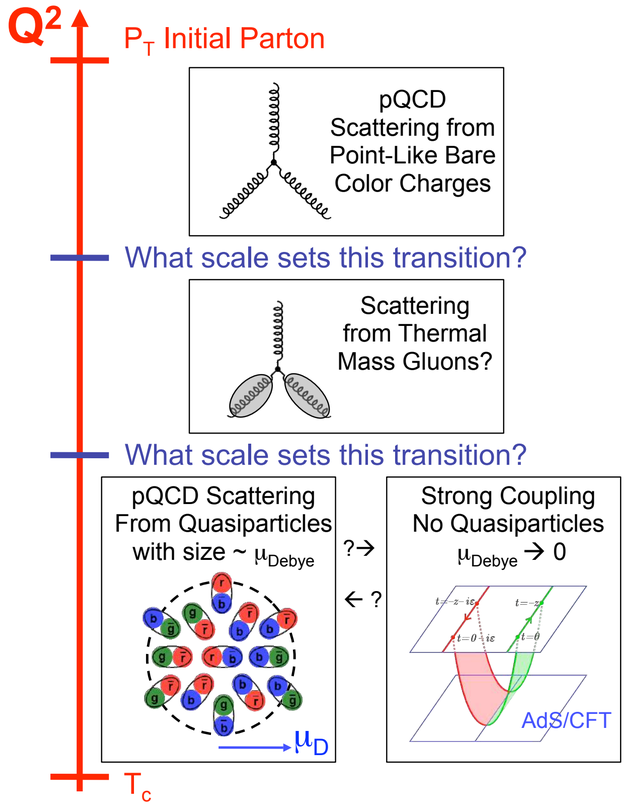
Fluid with strange particles

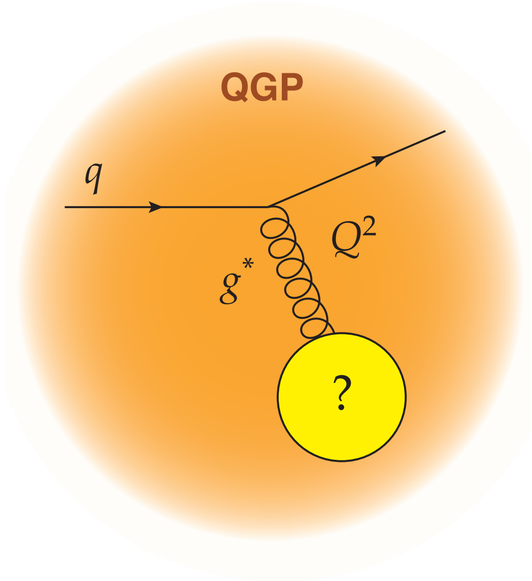


Vorticity above Jupyter Great Red Spot?

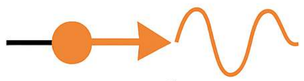
What “is” the QGP?

- QGP elementary constitution? How to build collectivity from collection of elementary particles?

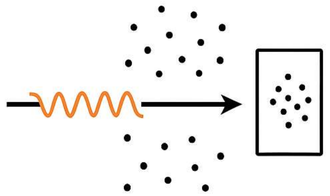




Wave-particle duality



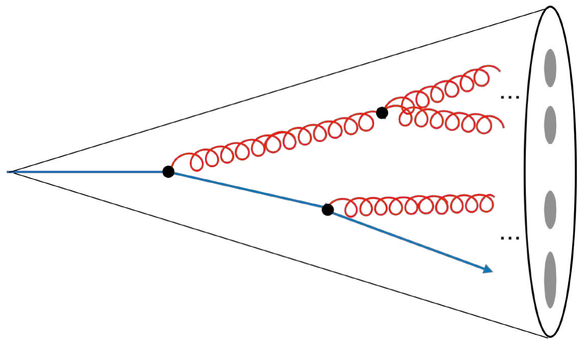
High-energy ⇒ High-resolution

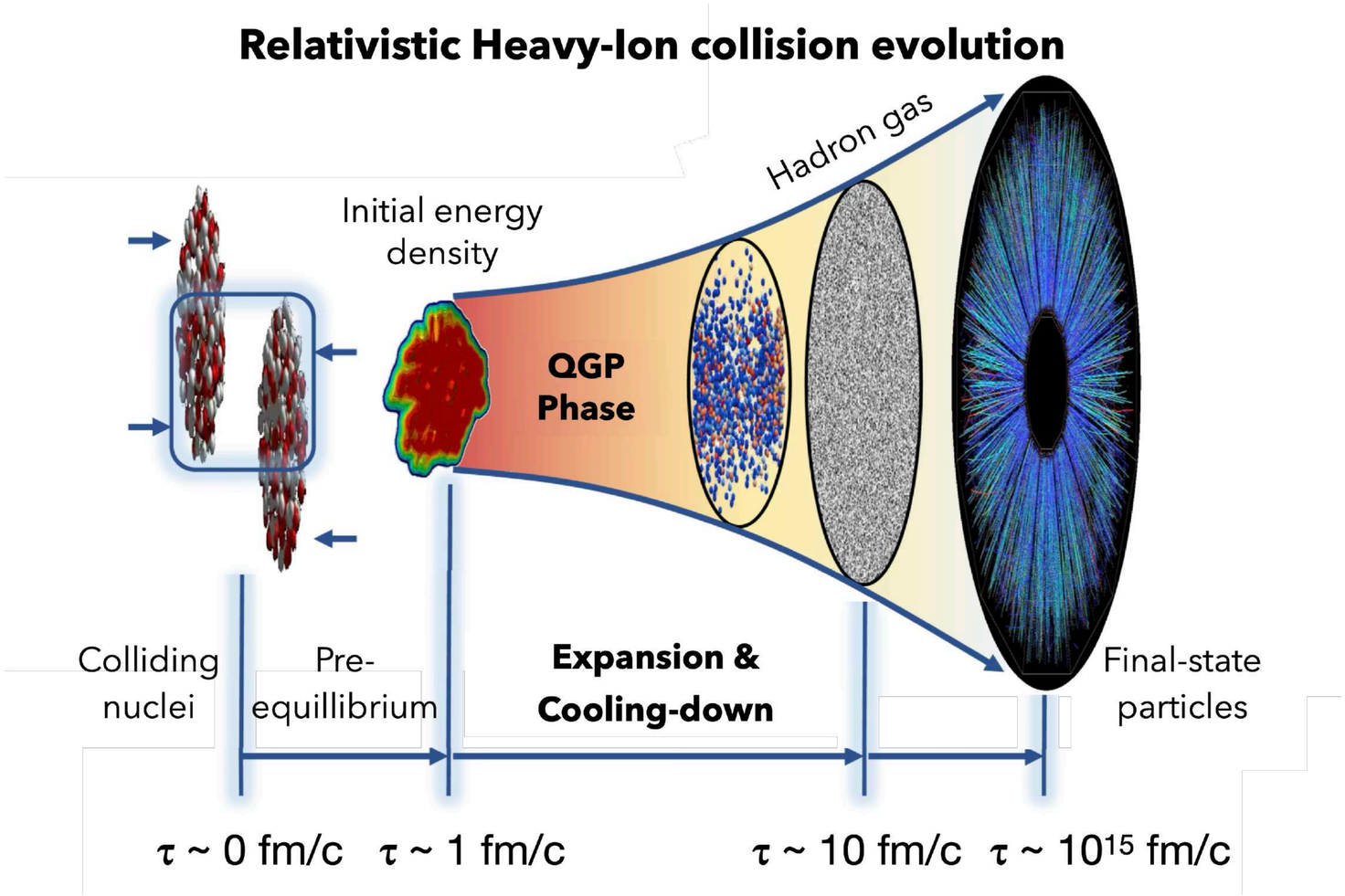


Need a high-energy quark/gluon!

QCD Jets in the QGP

- How QGP phase affects propagation of high-energy quarks and gluons?

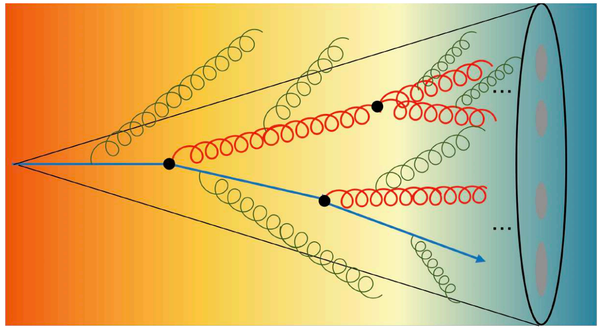


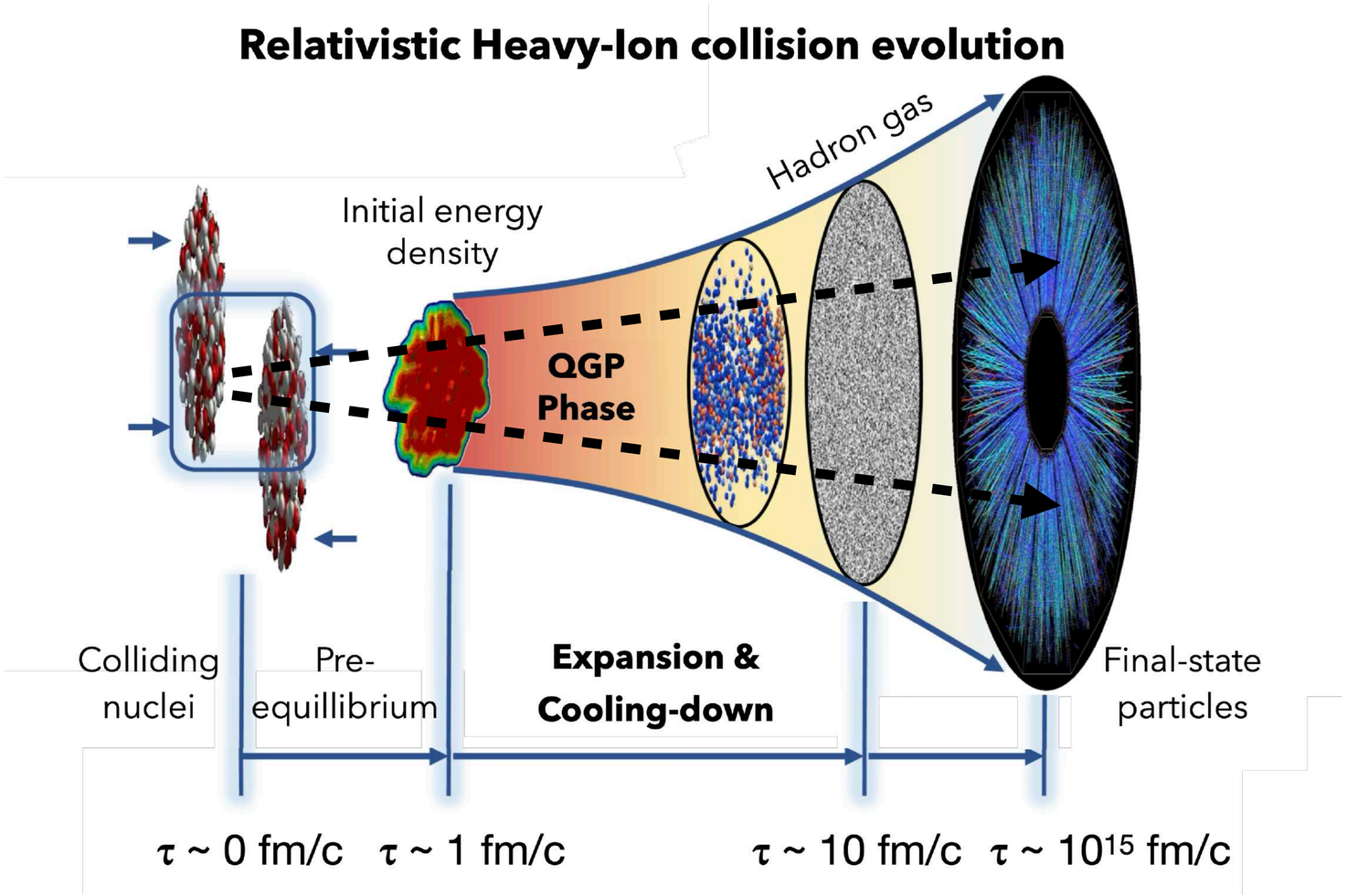


QCD Jets in the QGP

- How QGP phase affects propagation of high-energy quarks and gluons?

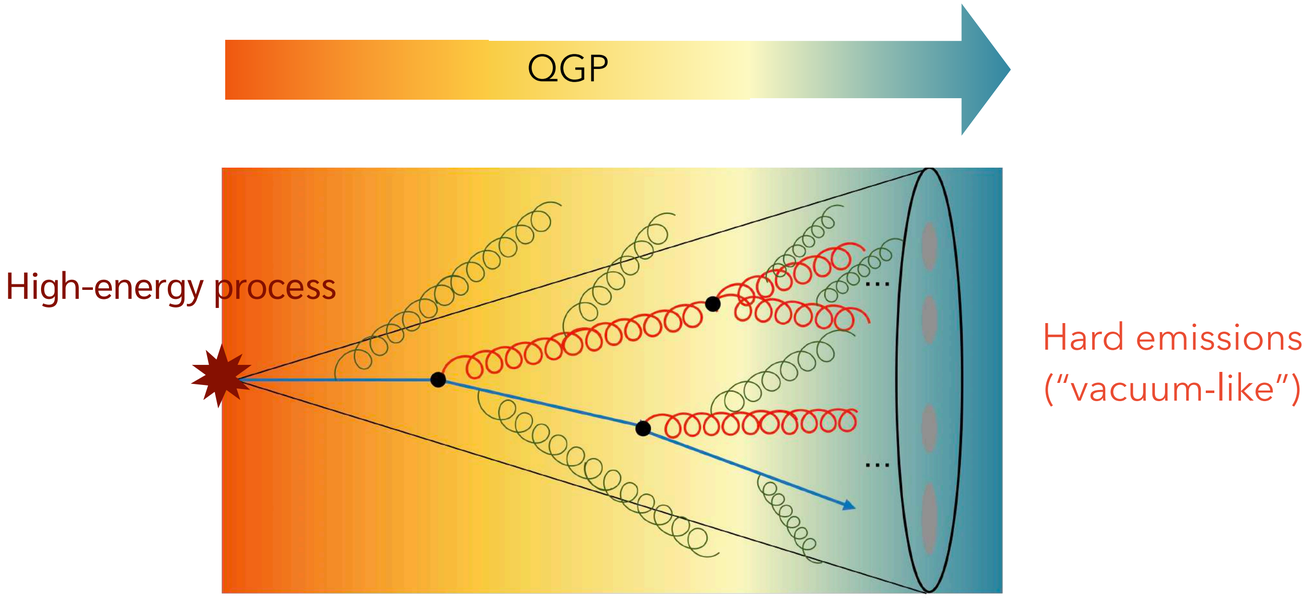
Jets will propagate and interact with the produced QGP resulting into **jet energy loss** and **changes** on **jet substructure**





Jet Quenching

- Aiming for a higher sensitivity of QGP elementary processes to uncover QGP nature:



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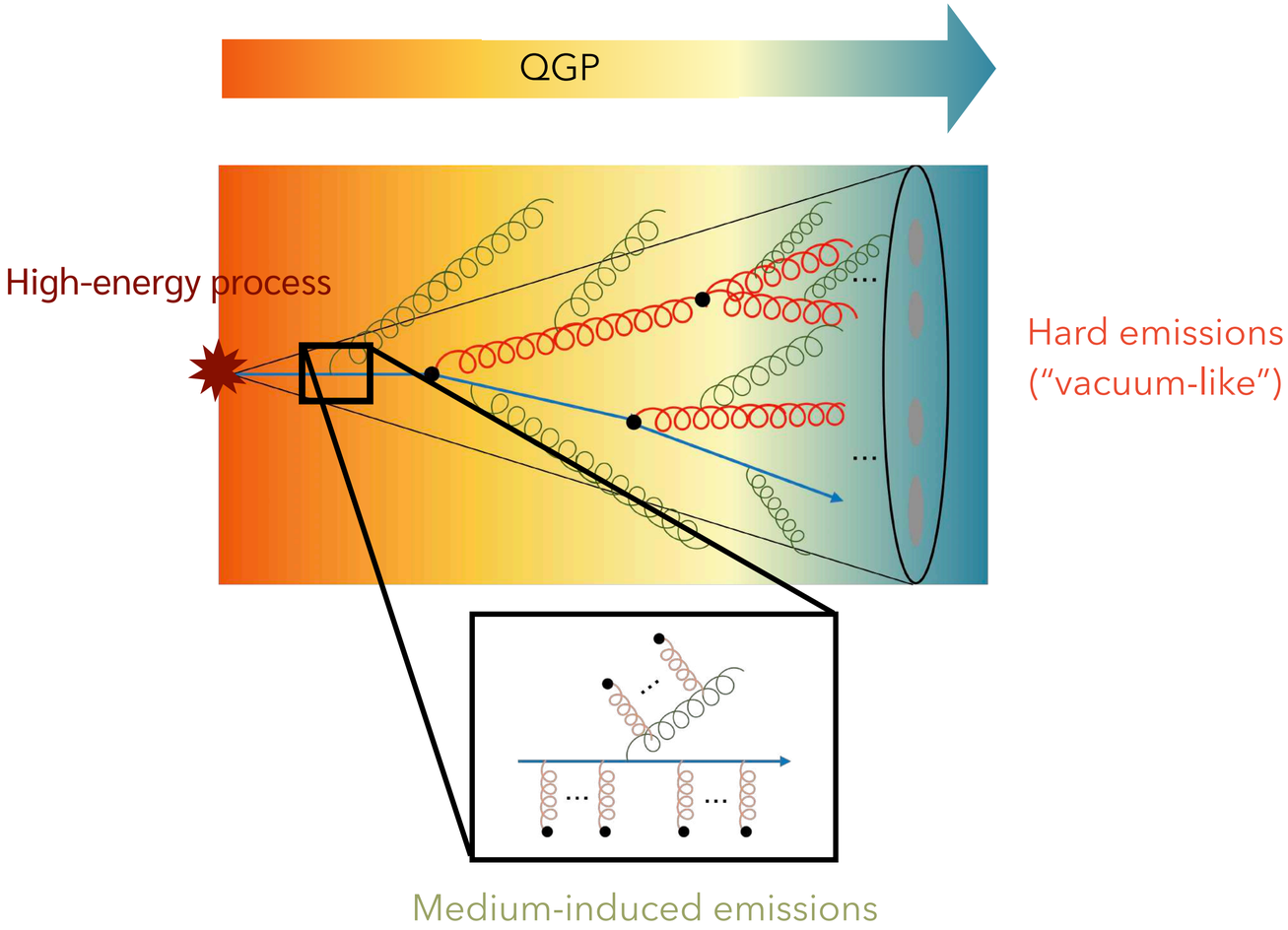

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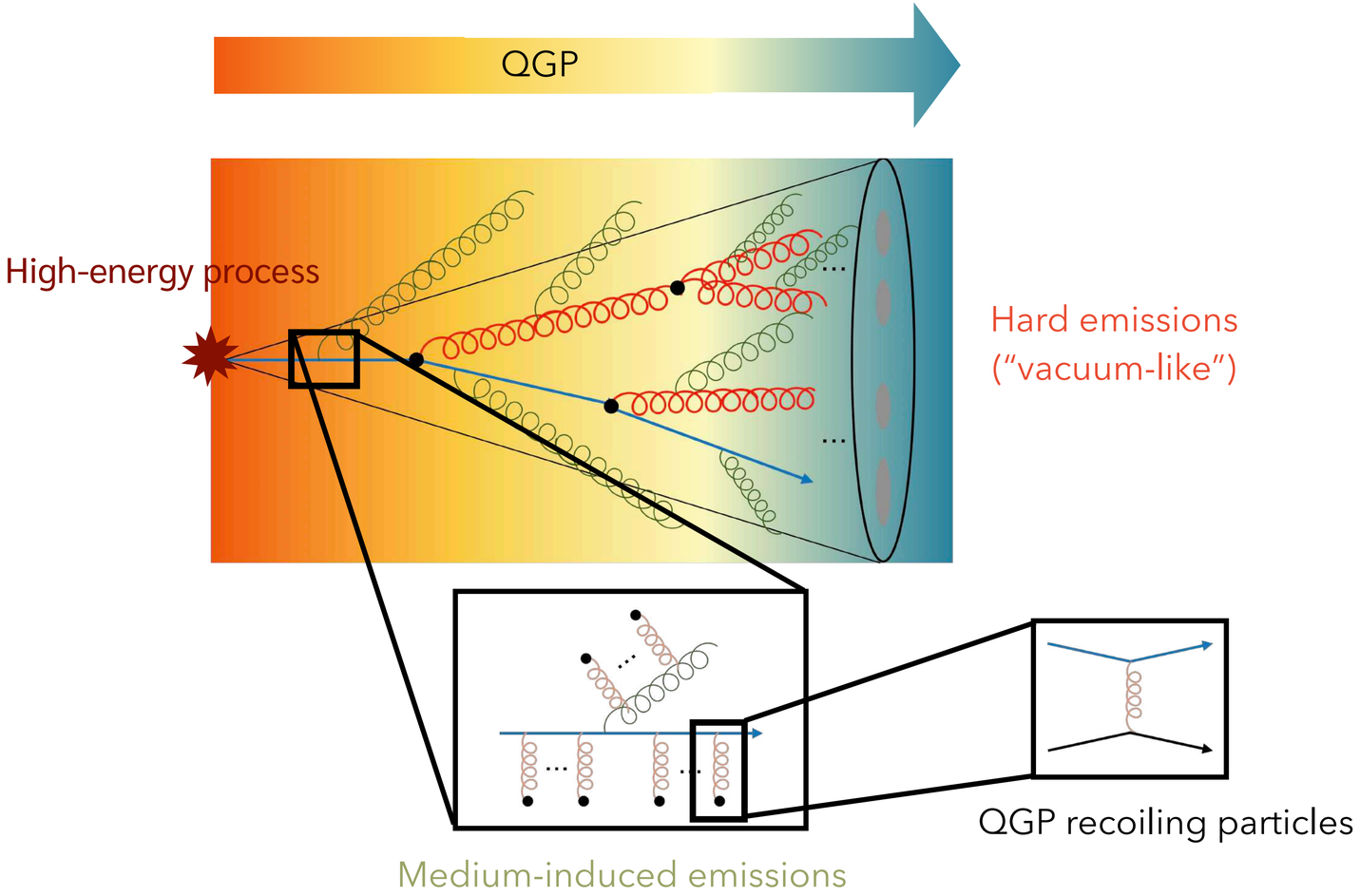
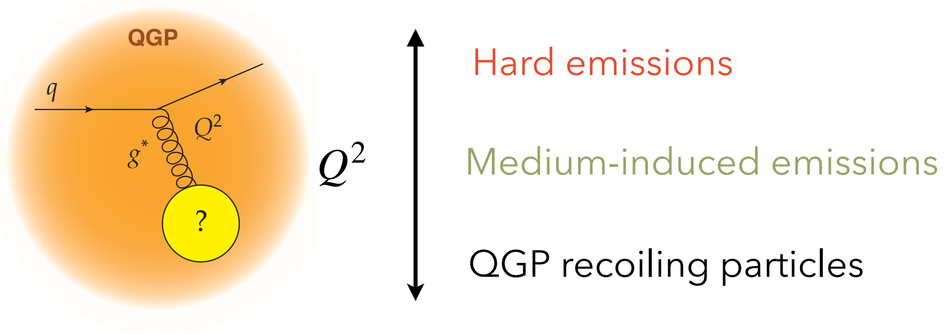




Current challenges:

- *Theoretical description*: Where does perturbative QCD break down?
- *Phenomenological limitations*: How do recoiling medium particles affect jet observables?
- *Experimental observations*: What are the conditions to form a QGP?

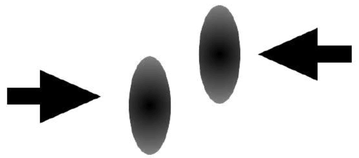
CHRONOQCD

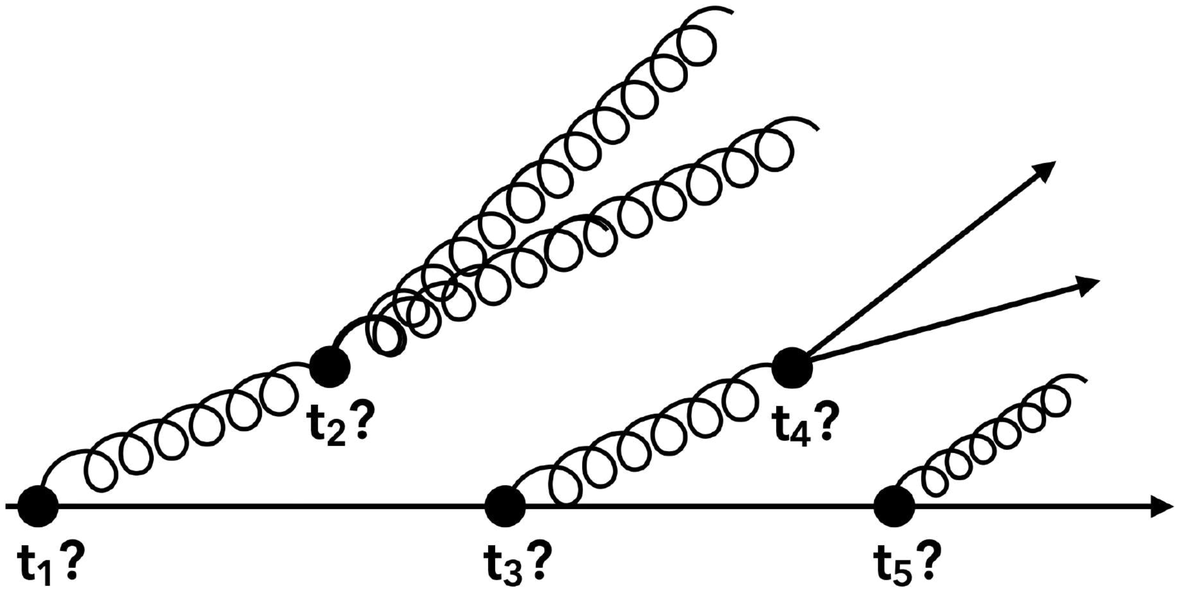
Unveiling the Time Dynamics of Quantum Chromodynamics in the Quark-Gluon Plasma

A new question

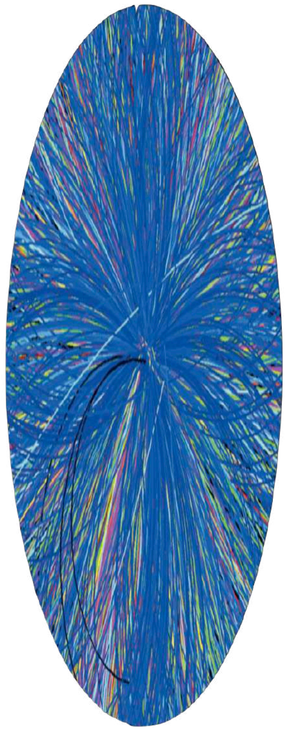
How to probe the time structure of QCD radiation?

Proton-proton Collision





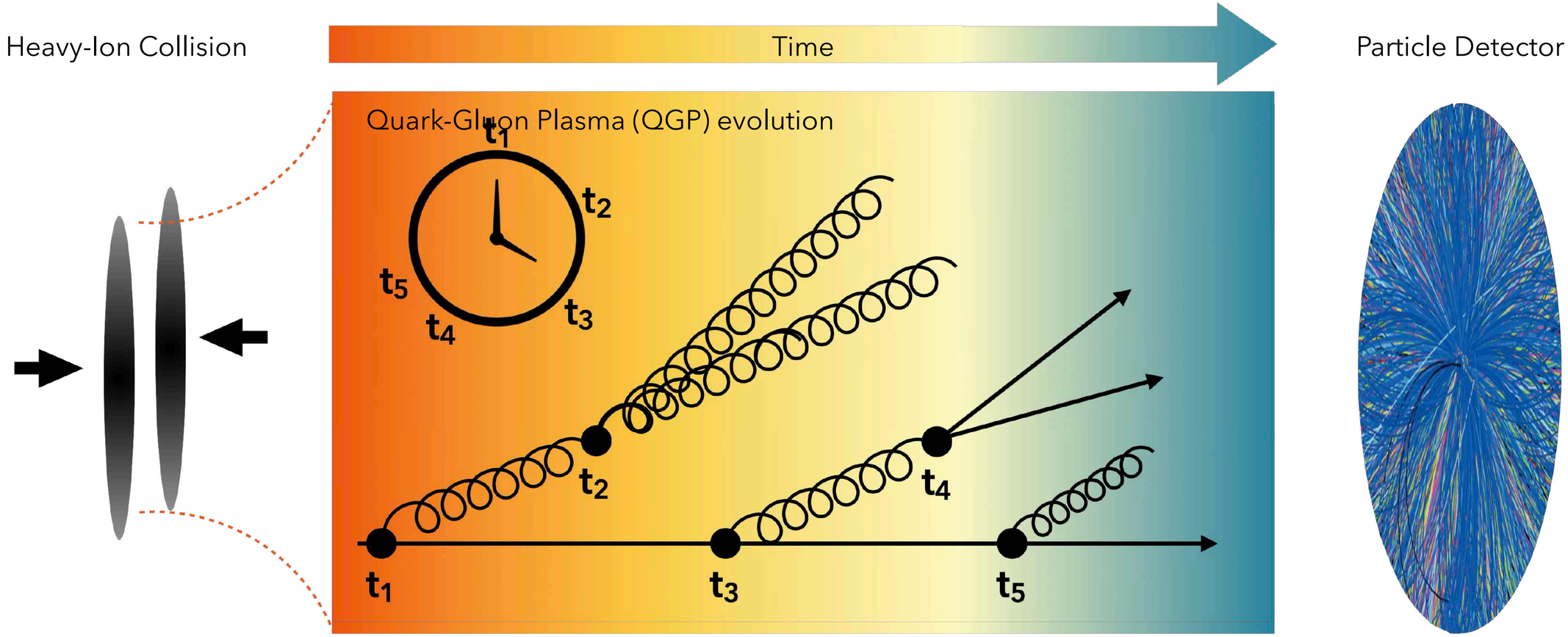
Particle Detector



A new question

How to probe the time structure of QCD radiation?

Use the Quark-Gluon Plasma as a reference frame!

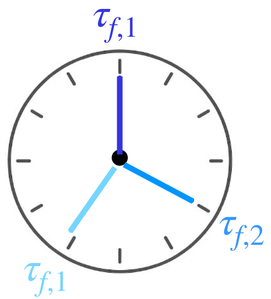


Break from conventional approaches and develop a space-time based formulation for QCD jets

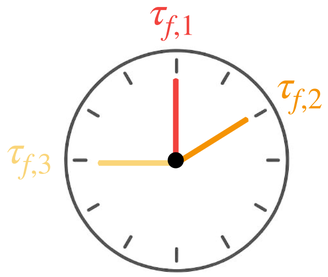
Space-time picture of jets

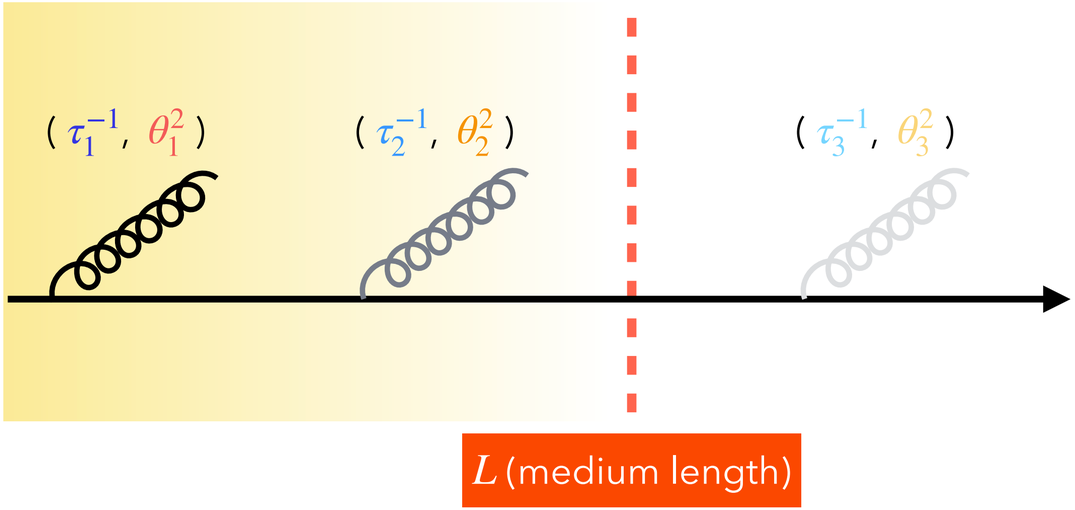
- **First proof** that **parton showers cannot be** regarded as **virtual objects** in a heavy-ion environment:
  - Number of jets that survive the medium lifetime depends on its space-time evolution

τ^{-1} space-time picture



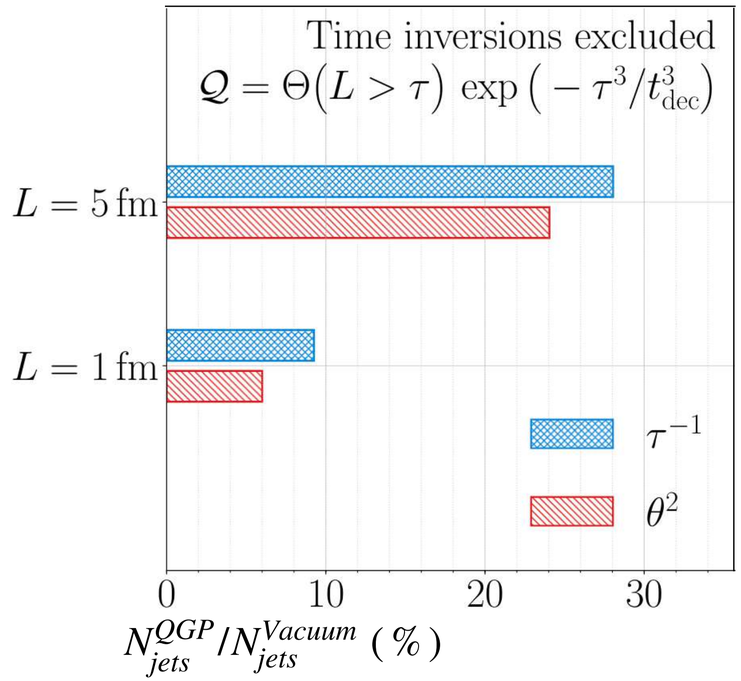
θ^2 space-time picture





(very conservative test under theoretically controlled conditions)

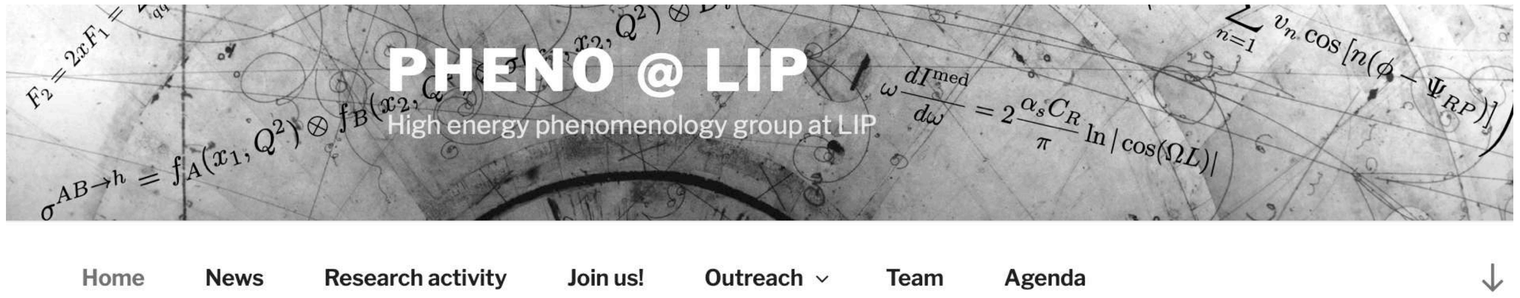
Apolinário et al., JHEP (2025)



Research Opportunities

Heavy-ion collisions offer a unique laboratory to test the fundamental laws of nature!

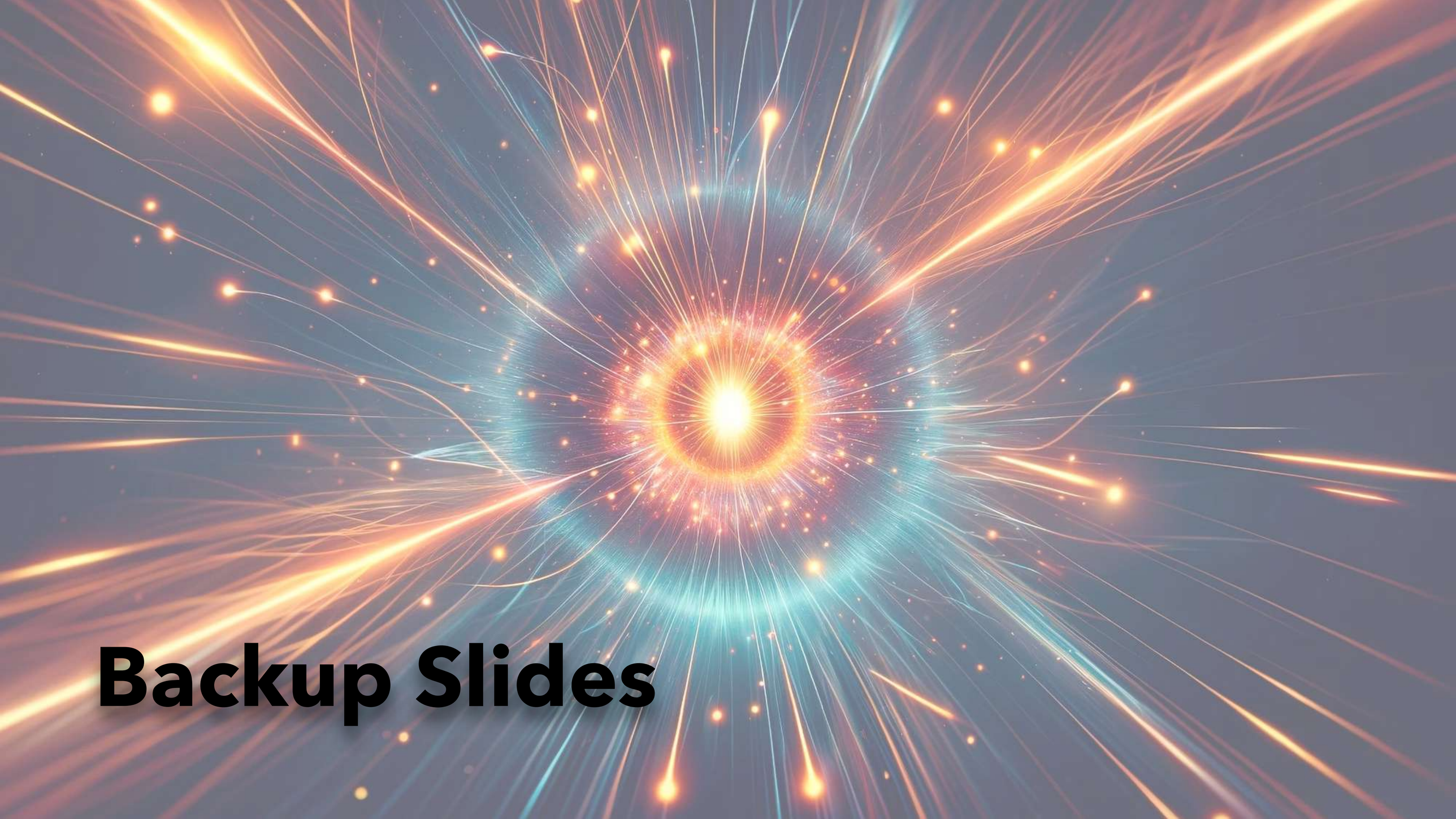
If you're interested or want more details contact me through: liliana@lip.pt



Acknowledgements

REPÚBLICA
PORTUGUESA

Fundação
para a Ciência
e a Tecnologia



Backup Slides

Laboratories

Brookhaven National Lab (USA)

CERN

Colliders

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

Perimeter: 3.8 km

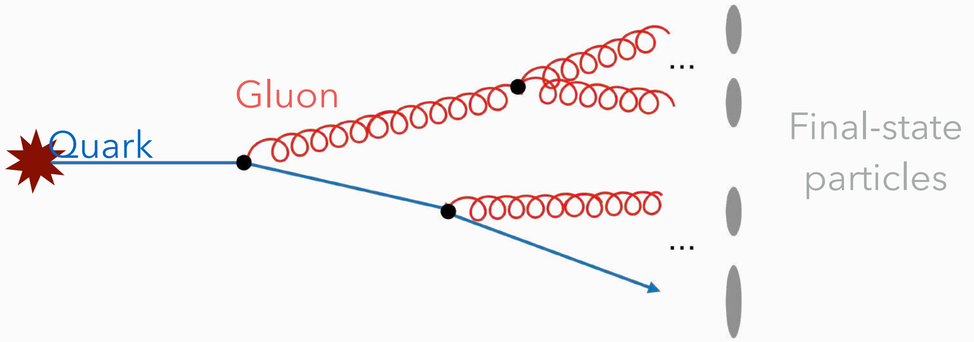
CERN
Large Hadron Collider (LHC)

Perimeter: 27 km

QCD Jets

- What happens to a high-energy quark/gluon?
  - It forms a shower of additional quarks and gluons

"Theory" perspective



"Experiment" perspective

QCD Jets

- What happens to a high-energy quark/gluon?
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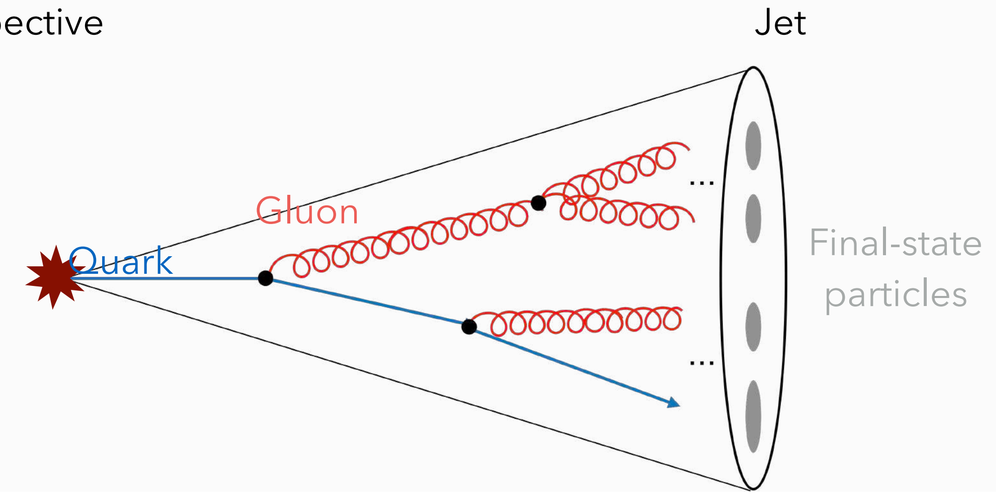
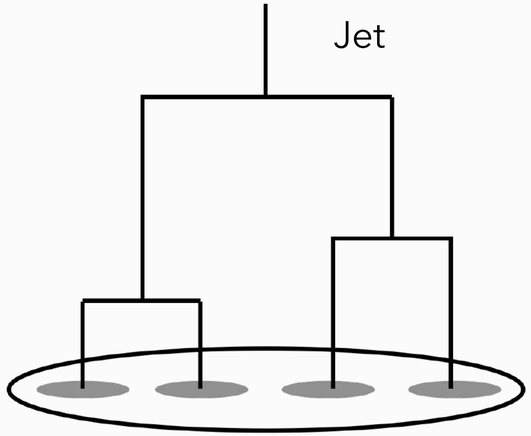
- **QCD Jets**: cluster of final-state particles that originated from a quark/gluon fragmentation
  - **Proxies** for the **quarks and gluons (partons)**

"Theory" perspective



"Experiment" perspective



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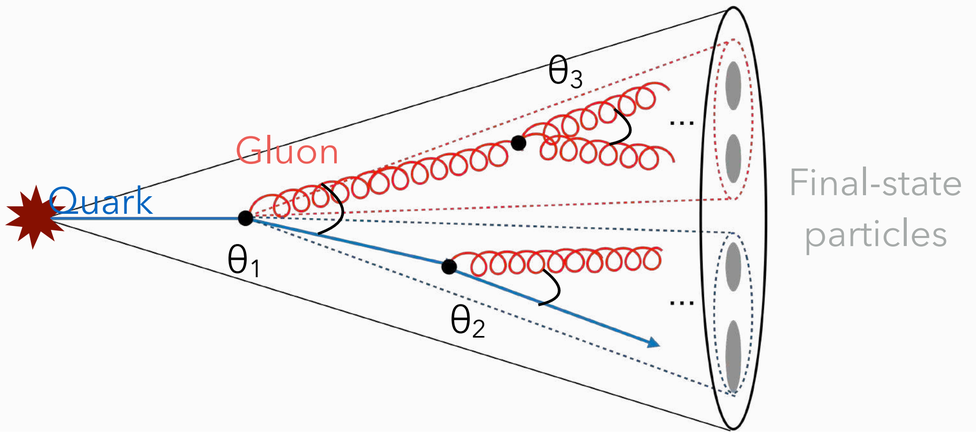
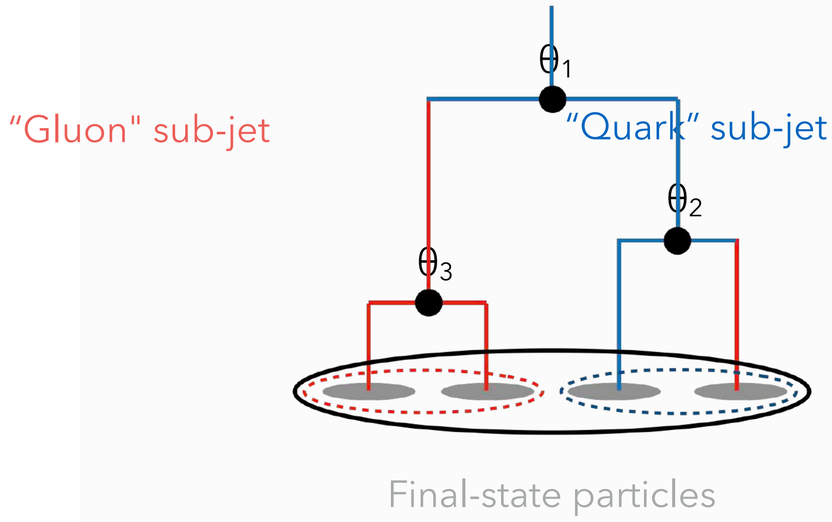


"Experiment" perspective

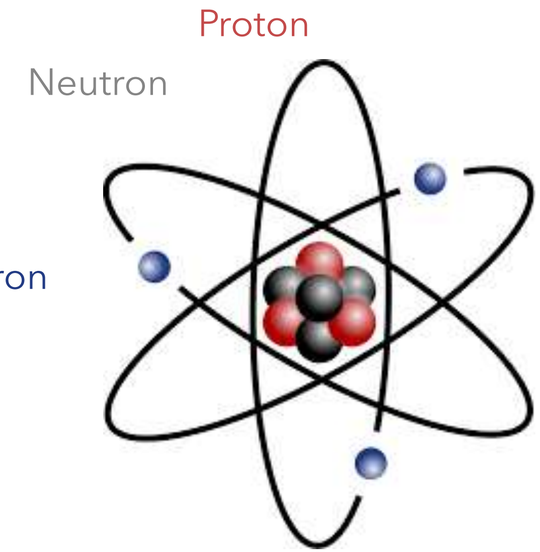
Quark/gluon fragmentation:
Well described in vacuum and accessible experimentally via jet substructure

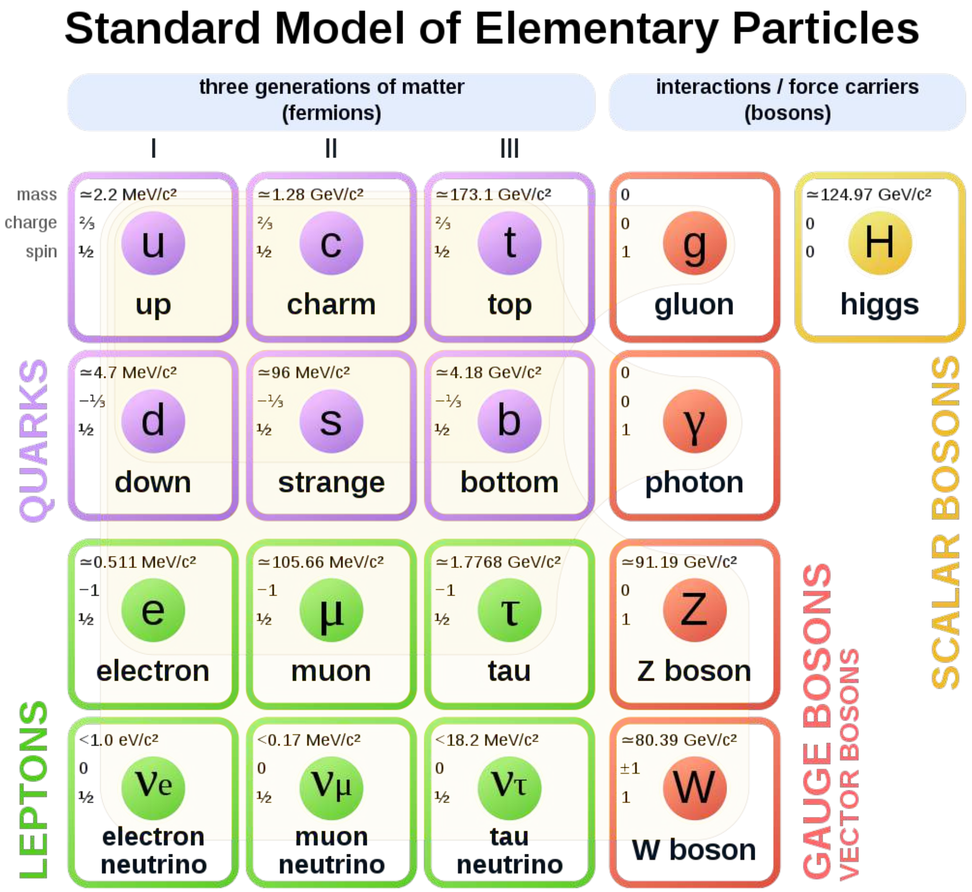
$\theta_1 > \theta_2 > \theta_3$



Standard Model

- Particle Physics: Visible matter can be explained by
  - 6 Quarks + 6 Leptons
  - Interaction through 4(+1) bosons

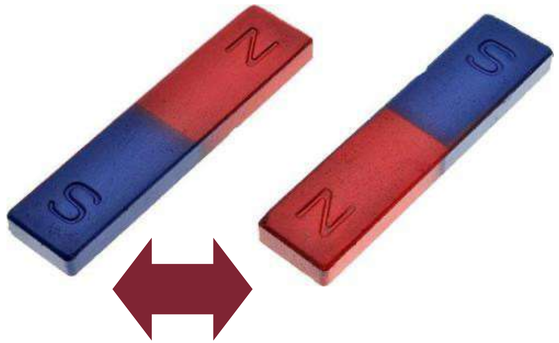




Sectors of the SM

- Quantum Electrodynamics

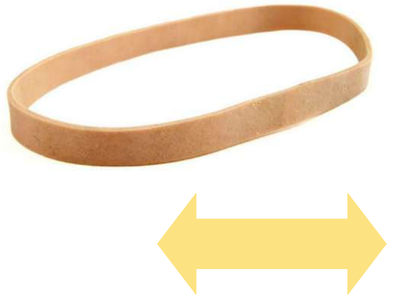
Increasing force



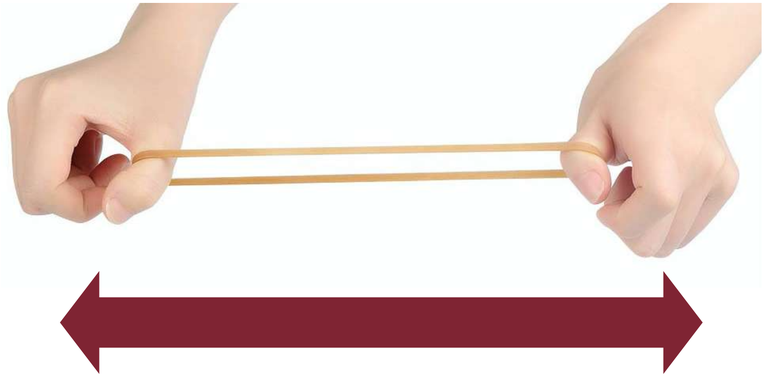
Decreasing force

- **Quantum Chromodynamics**

Decreasing force

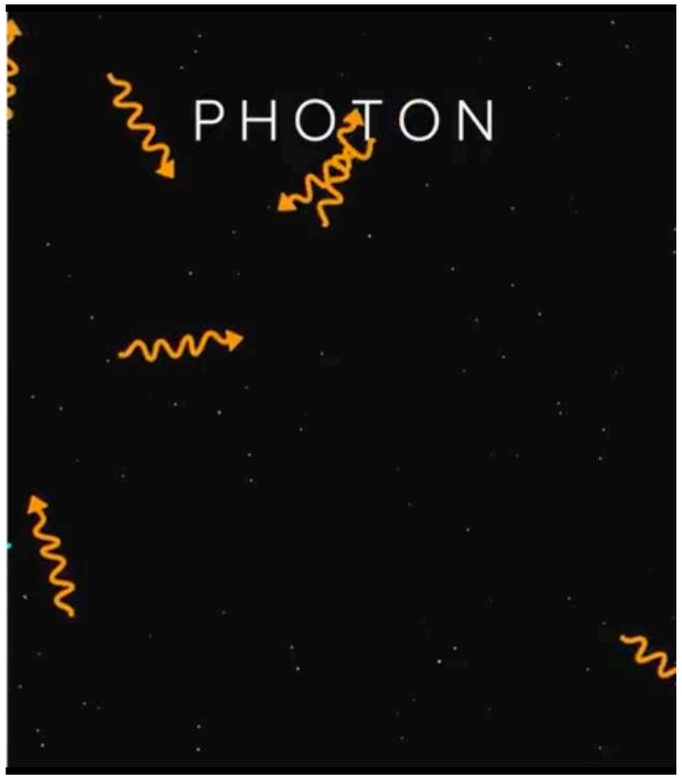


Increasing force

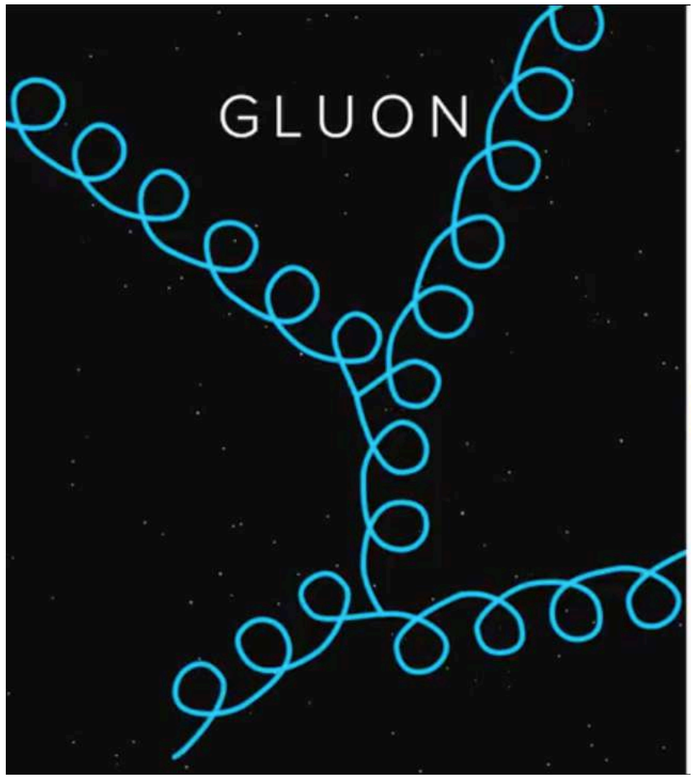


Sectors of the SM

- Quantum Electrodynamics



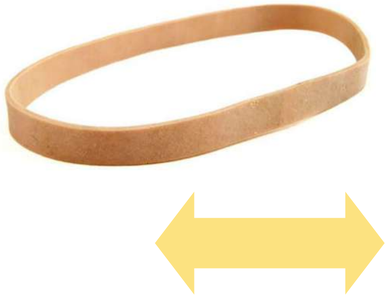
- **Quantum Chromodynamics**



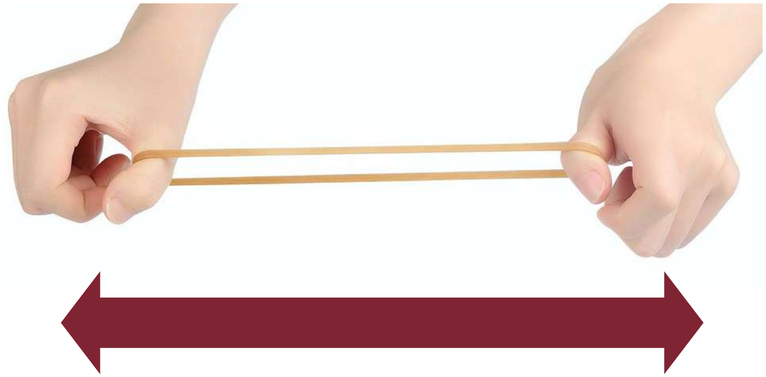
Confinement

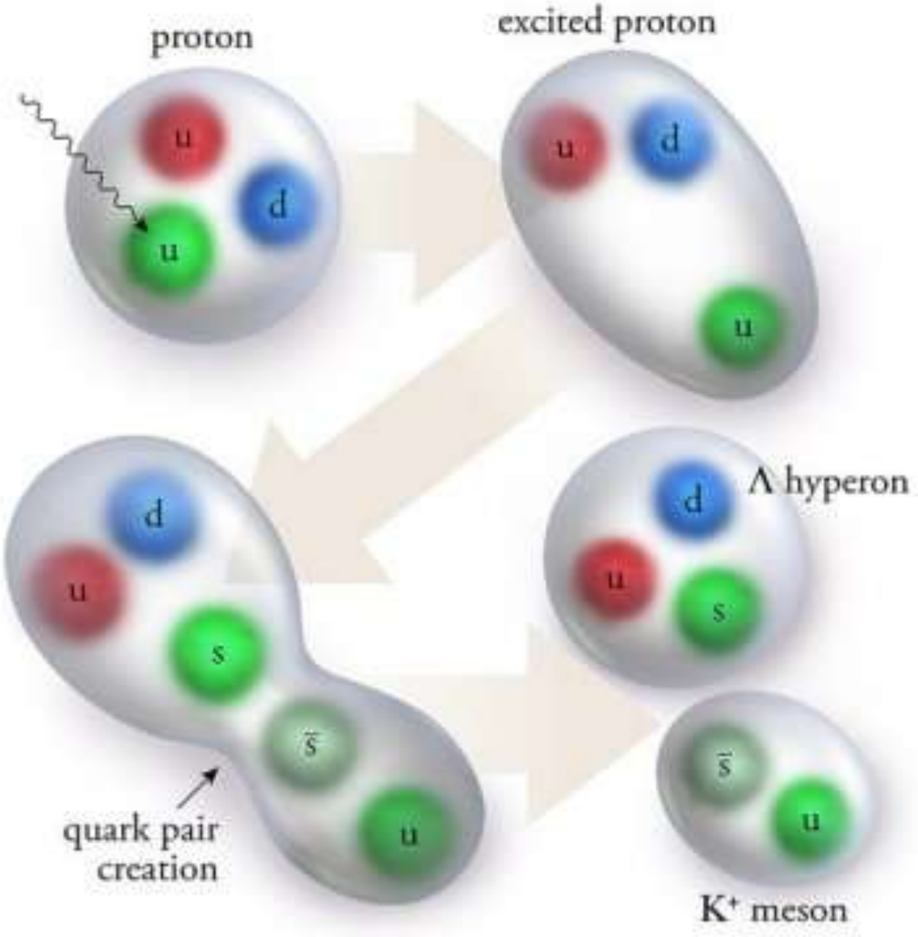
- What happens when I try to pull a quark from inside of a proton?

Decreasing force

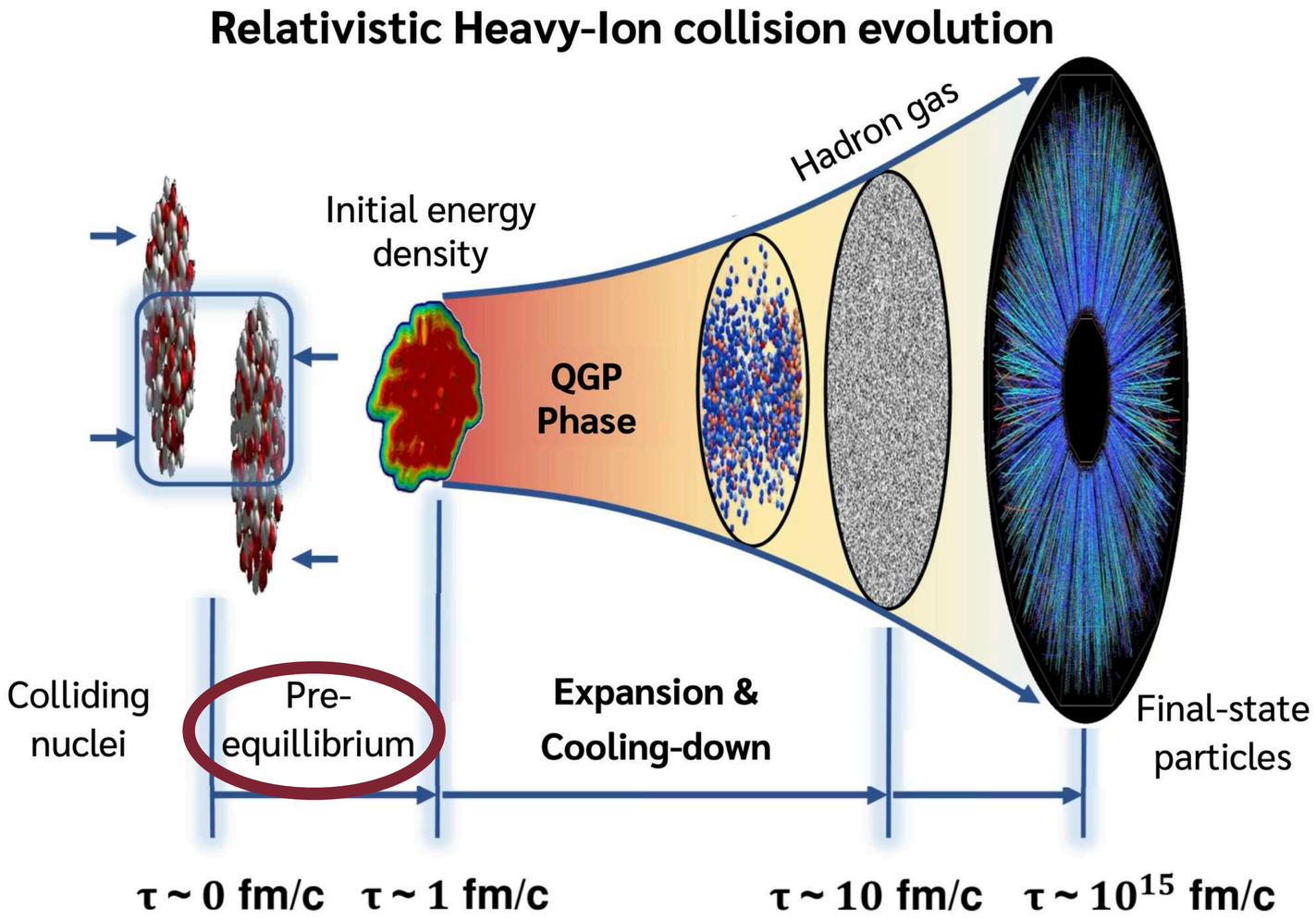


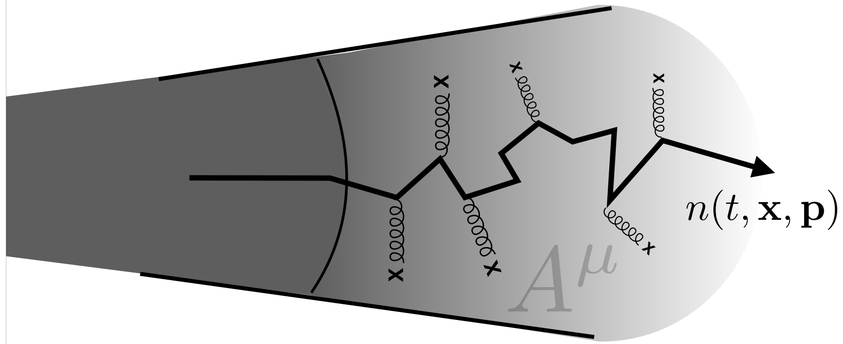
Increasing force





Heavy-Ion Collisions





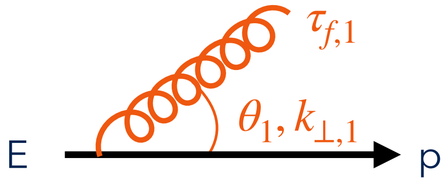
The dynamics of the **pre-equilibrium** phase of Heavy Ion Collisions can have a **significant effect** in jet observables.

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

C. Andrés, L. Apolinário, F. Dominguez, M. Gonzalez, C. Salgado, JHEP (2023), J. Soares MsC thesis

Proof of principle

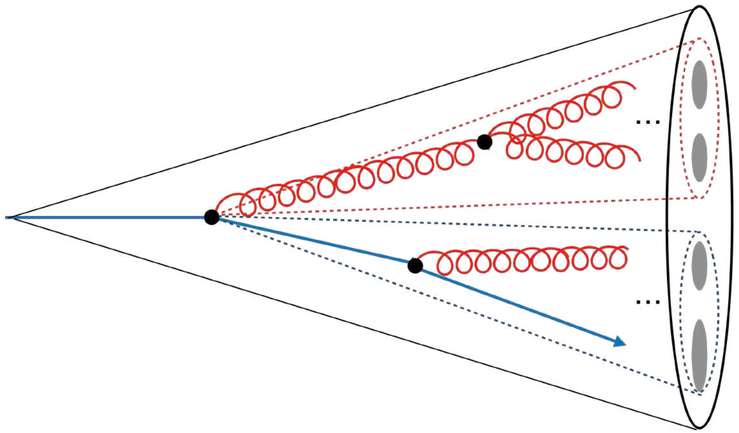
- **New τ-jet** clustering algorithm based on **QCD Parton Formation time** *Apolinário et al., EPJC (2021), Apolinário et al., EPJC (2024)*

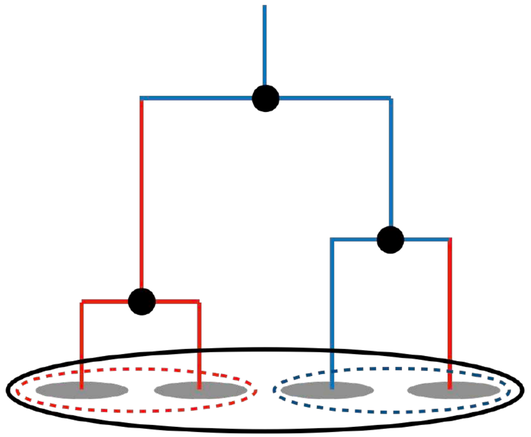


$$\tau_{form} \sim \frac{E}{M_{virt}} \frac{1}{M_{virt}}$$

Time it takes for a quark/gluon to radiate
(Estimated from Heisenberg uncertainty principle)

- **Order** jet sub-structure in **formation time**:





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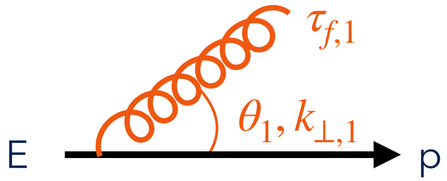

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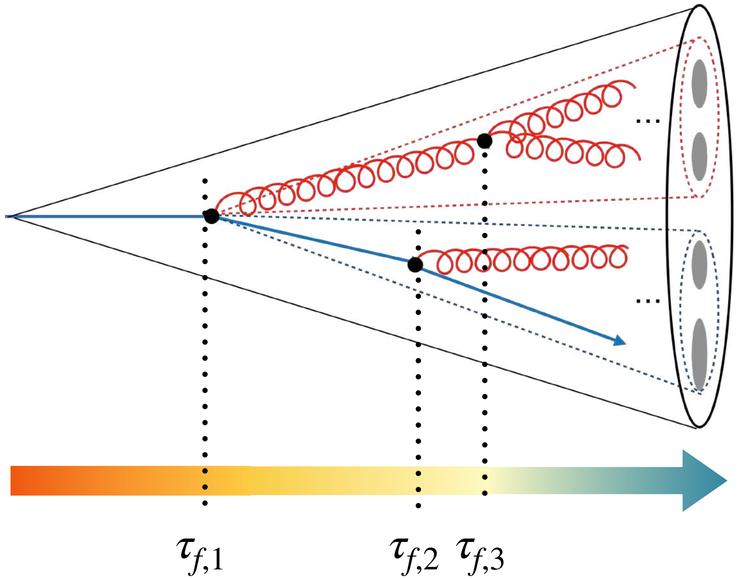
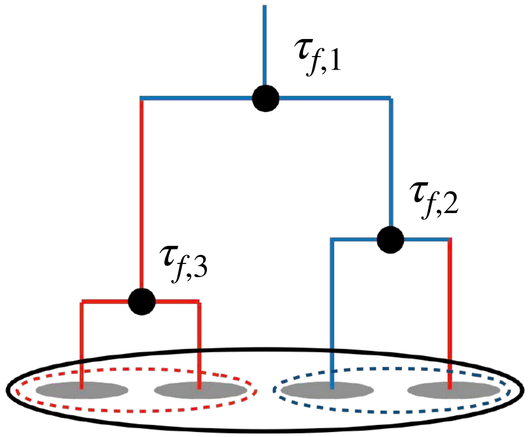
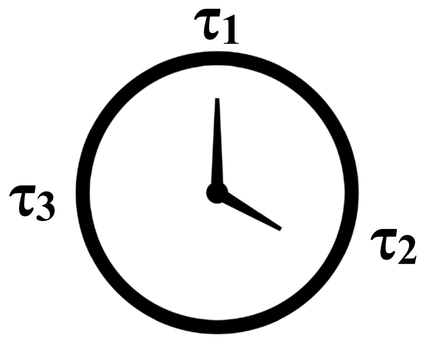
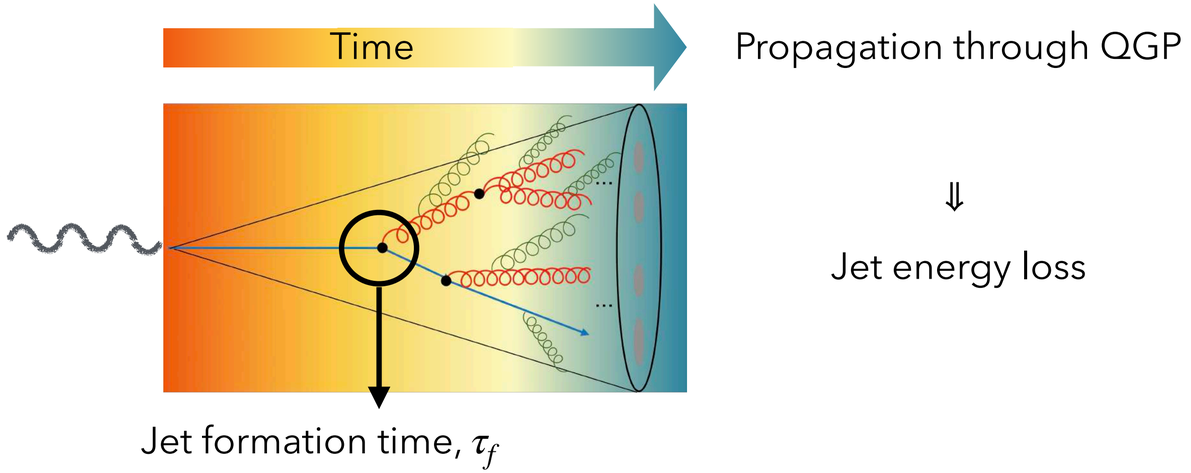




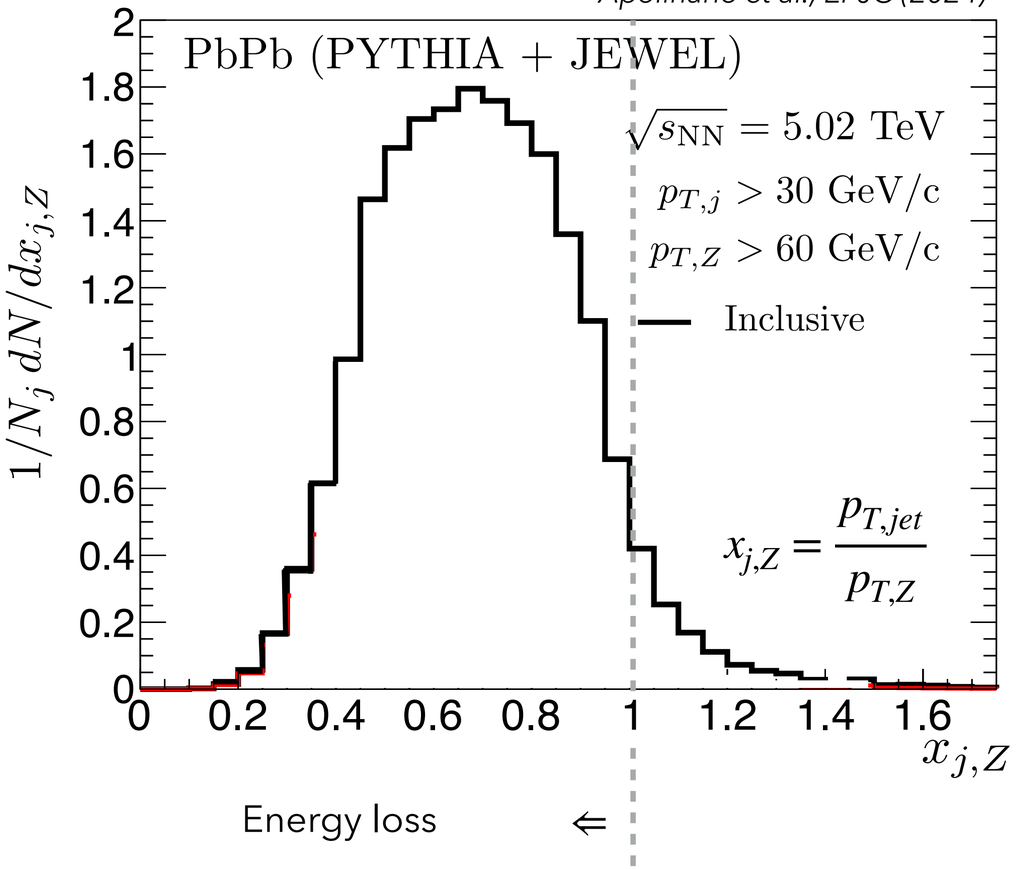


Proof of principle

- **Pioneer application** of QCD parton formation time to jets in heavy-ions:
  - Proven to have a **strong correlation** with **QGP-induced processes**



Apolinário et al., EPJC (2024)



Proof of principle

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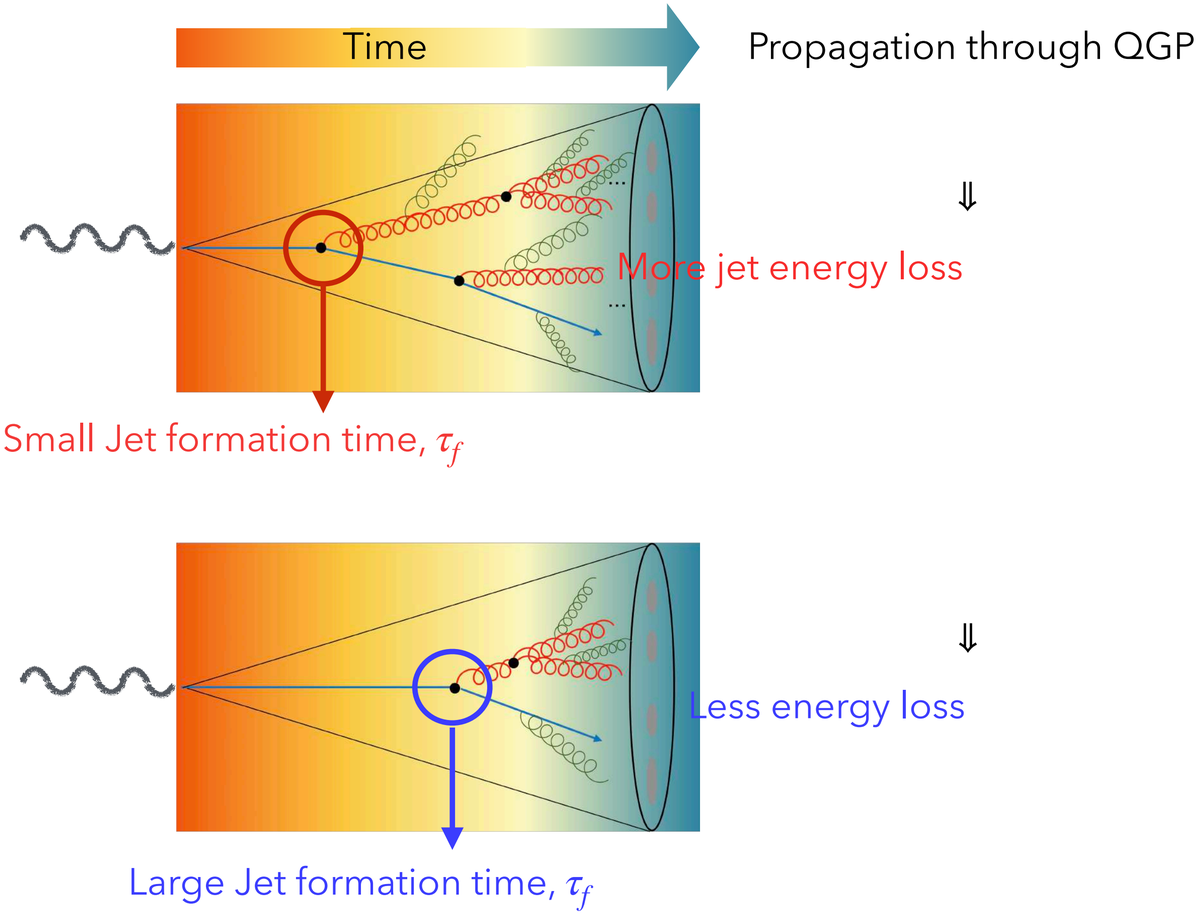
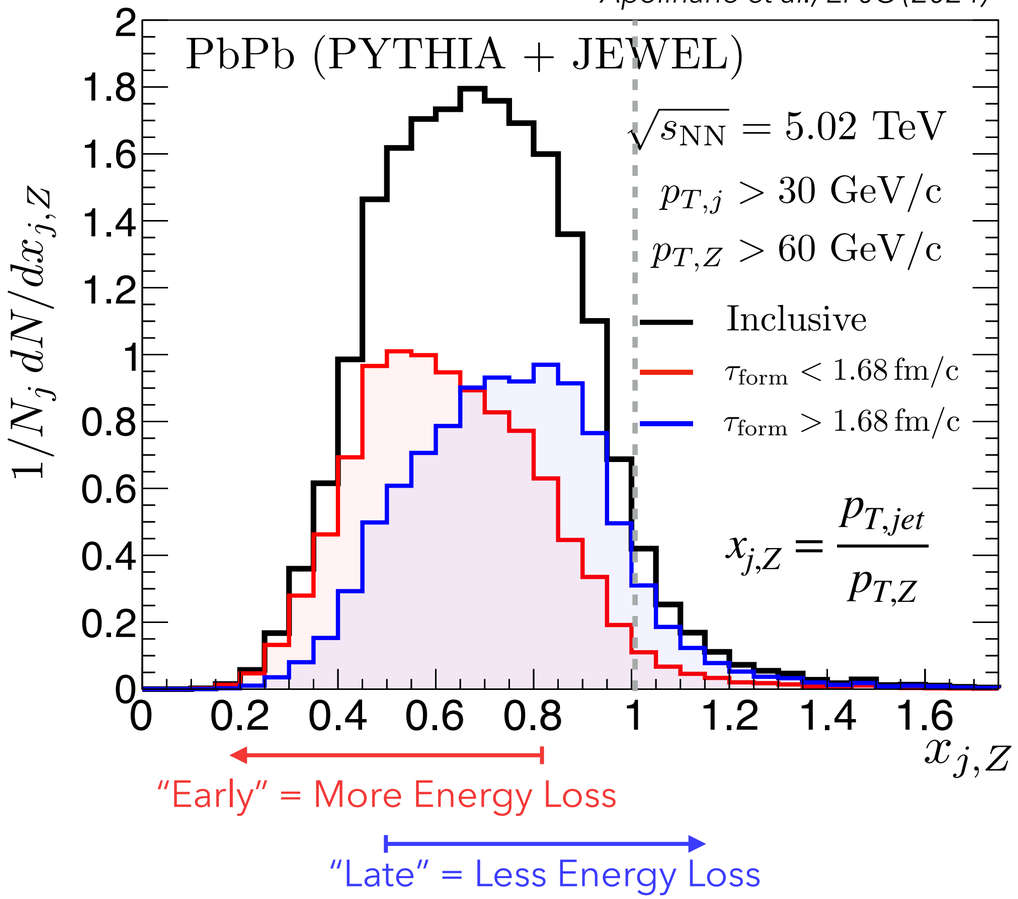
  - Proven to have a **strong correlation** with **QGP-induced processes**

To be measured @LHC by ATLAS, CMS and ALICE



Apolinário et al., EPJC (2024)



Pheno Group @ LIP

- Theorists and Experimentalists that work together in particle Physics









Pheno Core activities	
QCD	Forward Physics
QGP Studies	BSM Searches