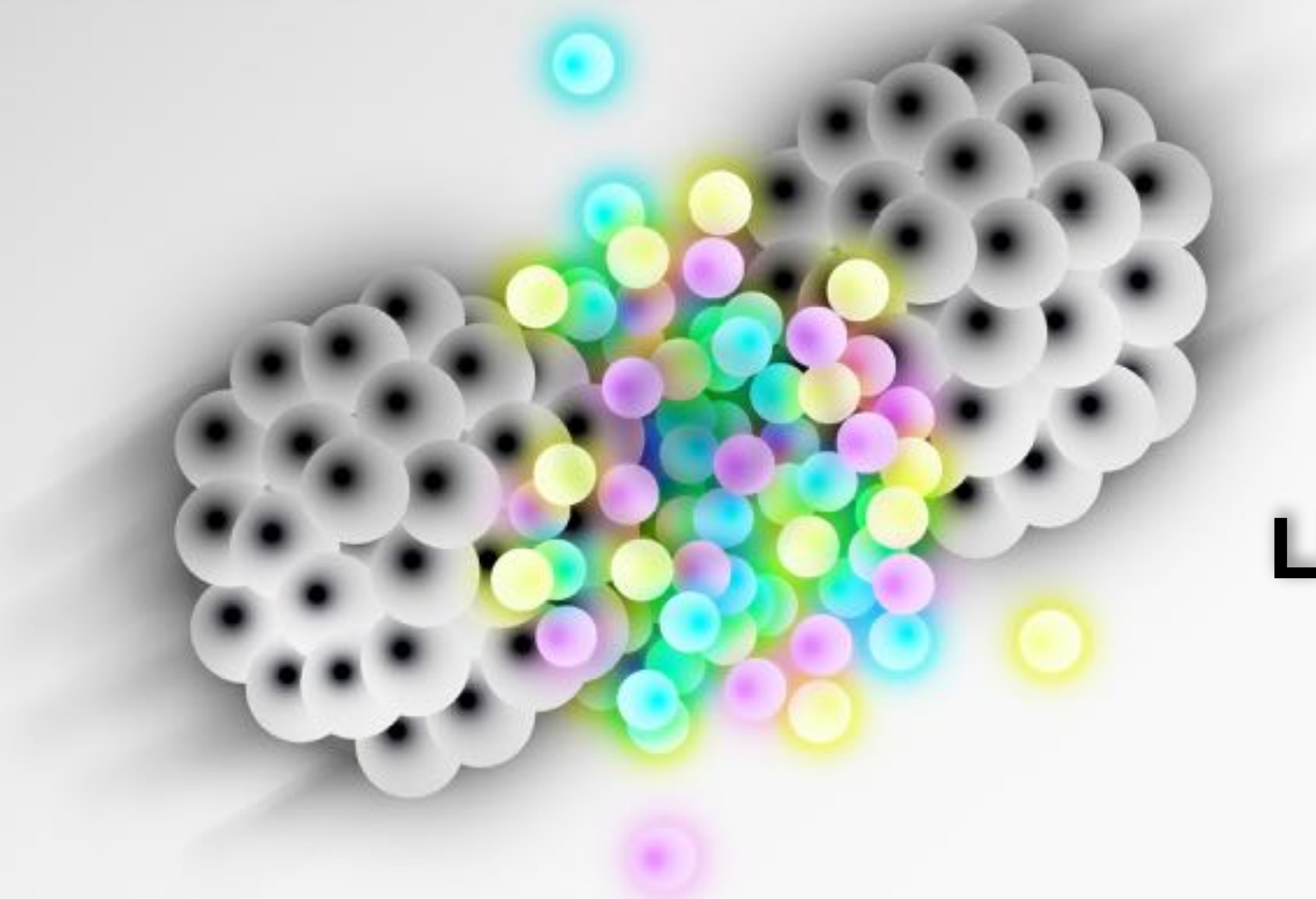
Dynamics of quarks and gluons in a hot and dense medium



Liliana Apolinário

LIP

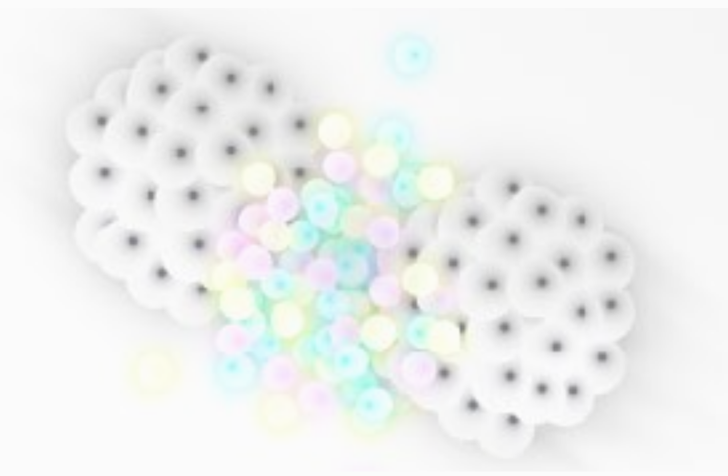
3rd Lisbon mini-school on Particle and Astroparticle Physics

Feb 2018

SM & QCD

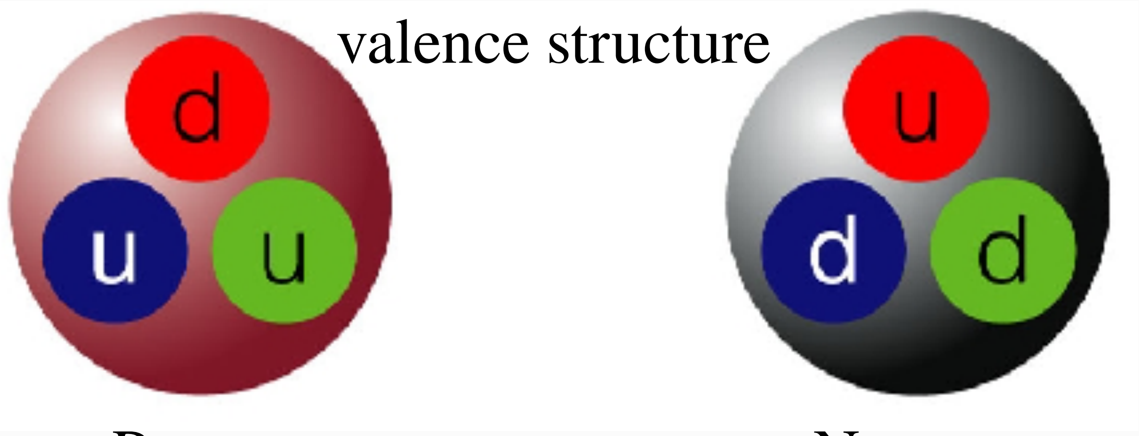
- Standard model

SM & QCD



- Standard model ➜ Quantum Chromodynamics (QCD)

Most of ordinary matter at room temperature



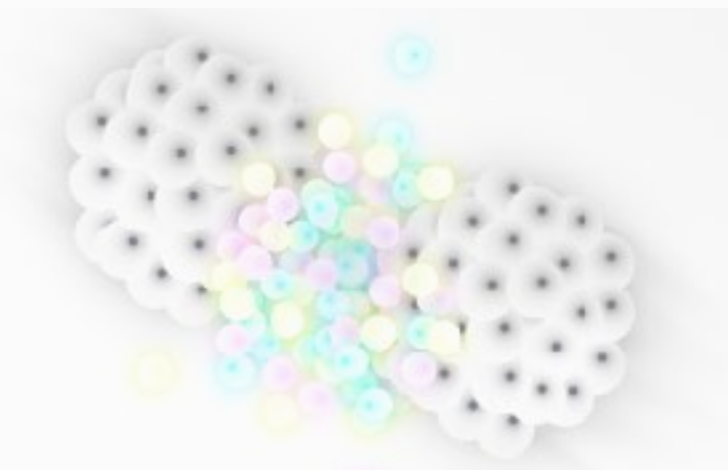
Proton Neutron

$\ni \{u, d, \ldots, g\}$

$\neq \{u, d, \ldots, g\}$

QCD is the strongest and least understood force in nature

SM & QCD



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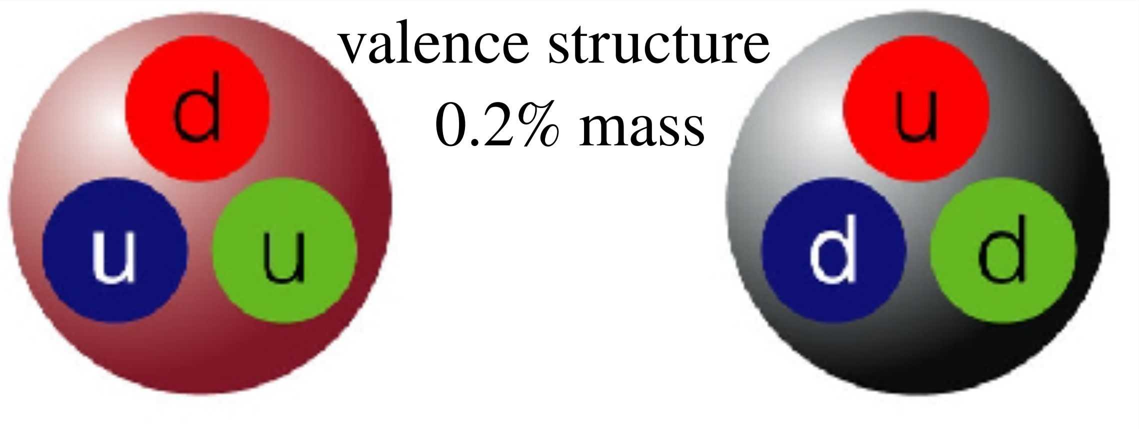


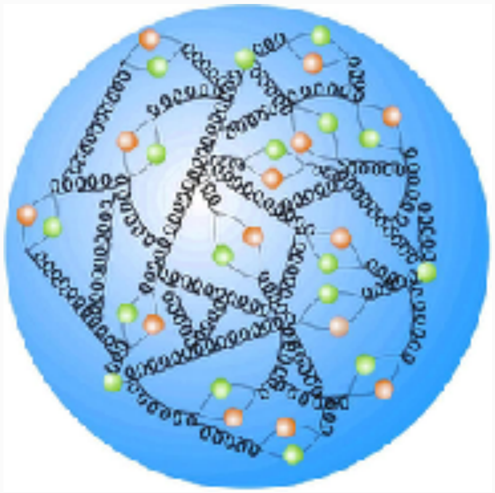
Proton

Neutron

$\ni \{u, d, \ldots, g\}$

$\neq \{u, d, \ldots, g\}$

(more realistic) proton structure



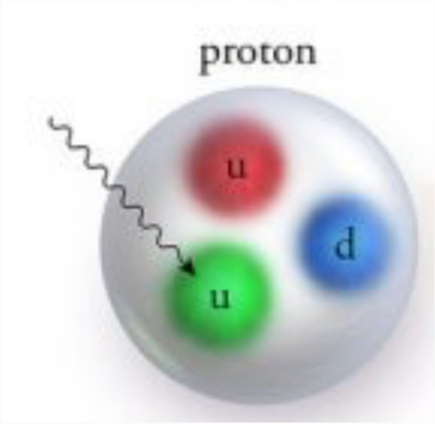
valence + sea

(quarks and gluons)

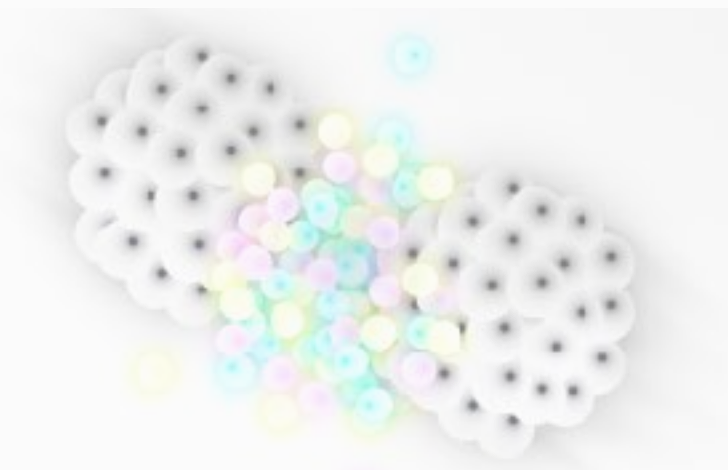
100% mass

SM & QCD

- QCD: Asymptotic freedom and confinement



SM & QCD



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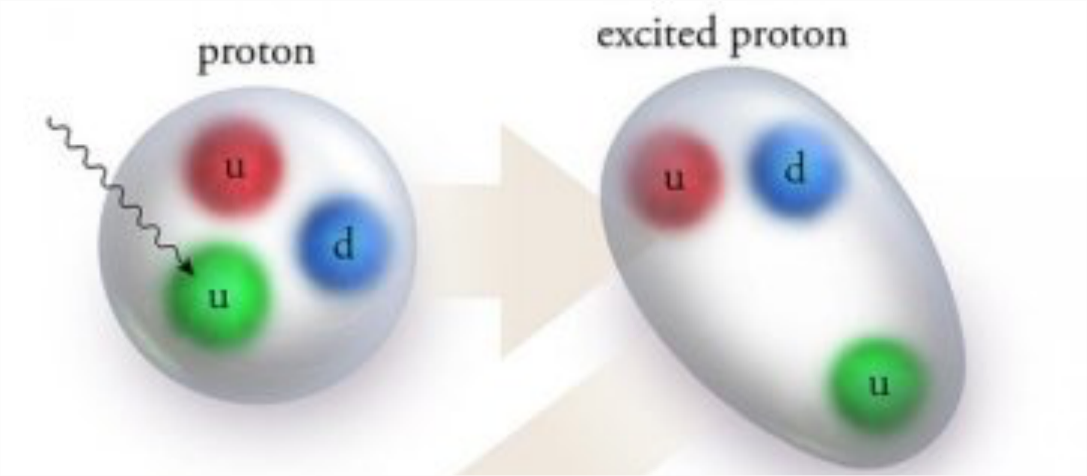

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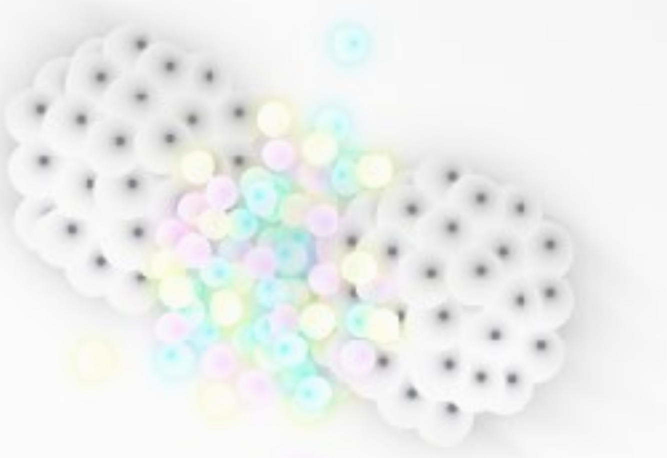

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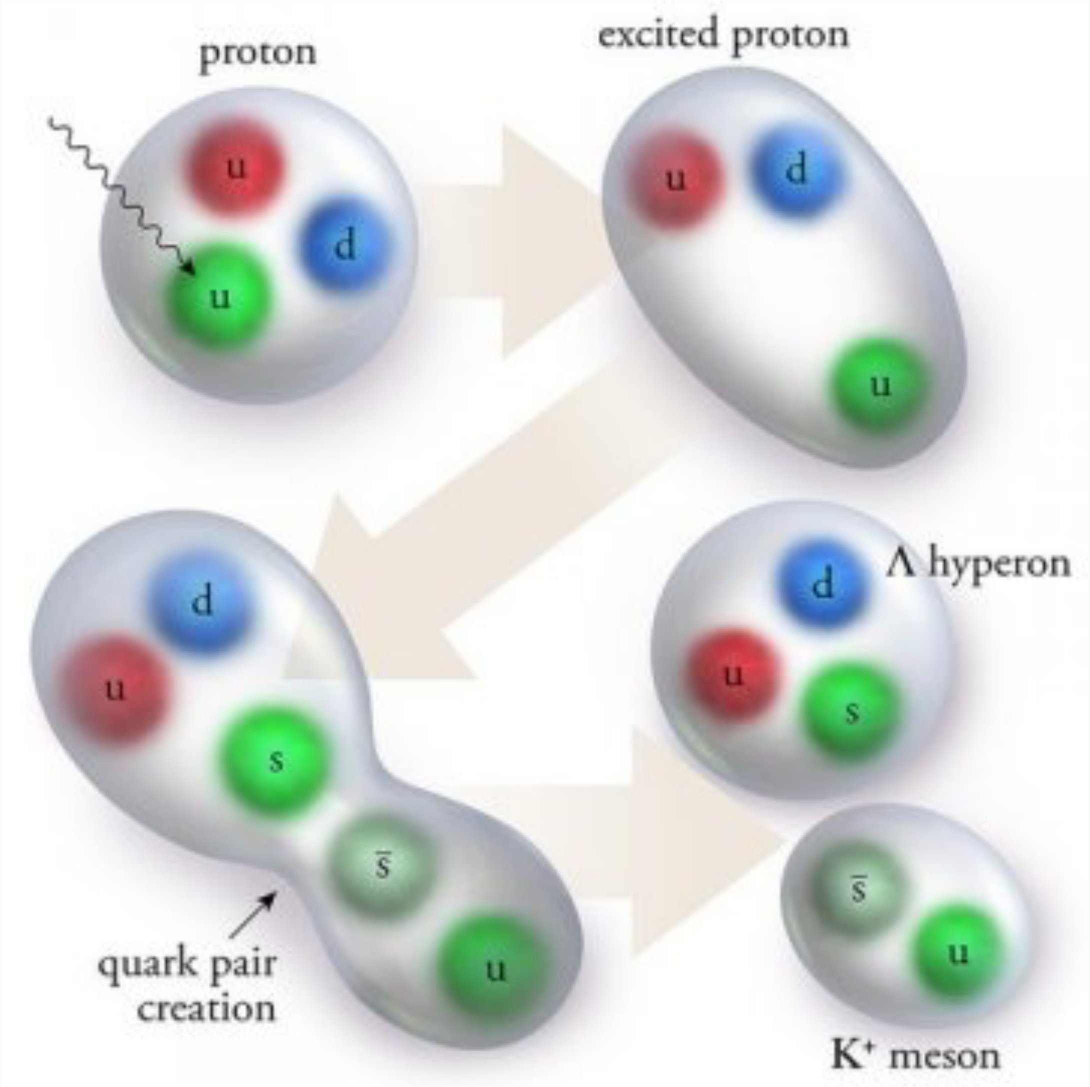
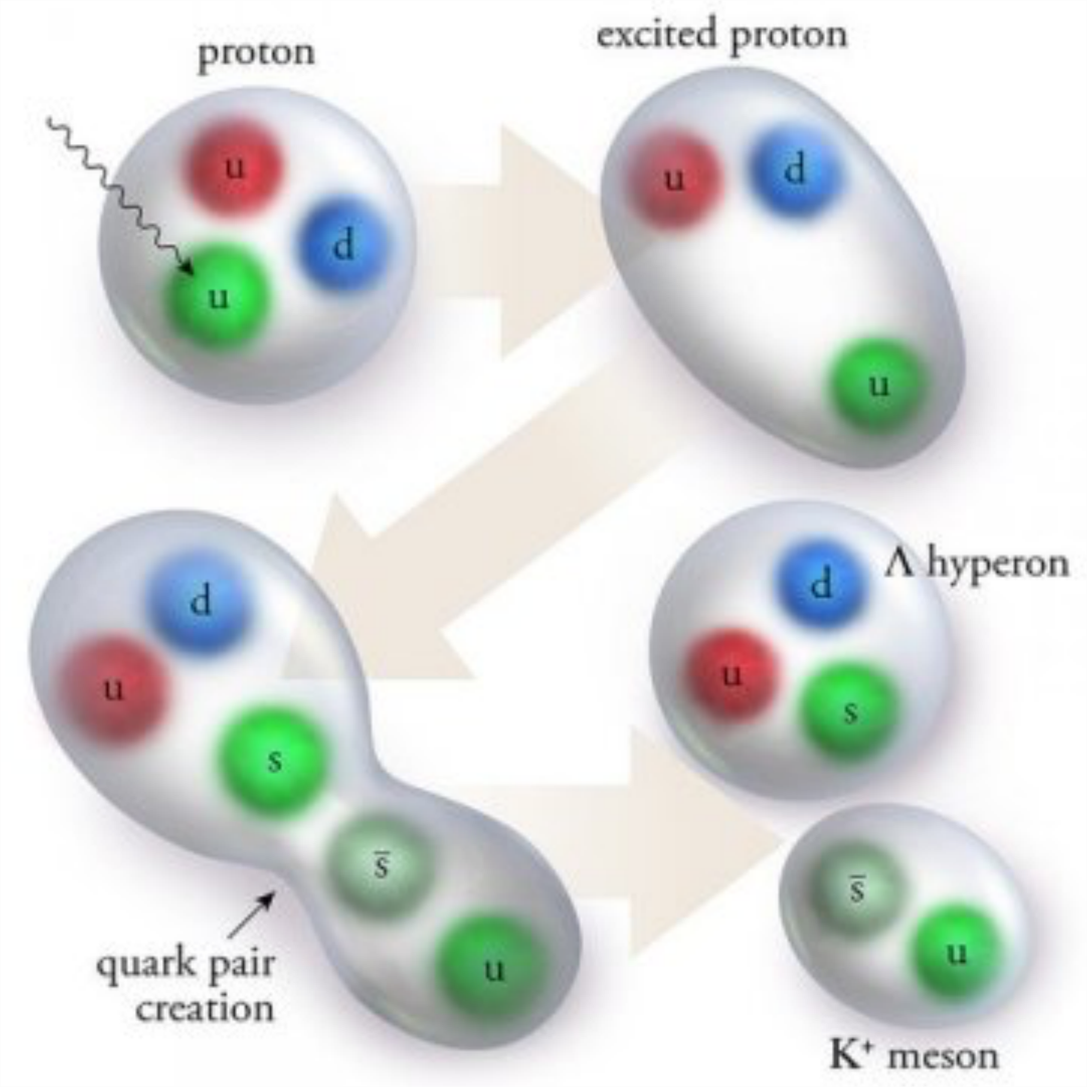


Quark Confinement

How do we study them?

SM & QCD

- QCD: Asymptotic freedom and confinement



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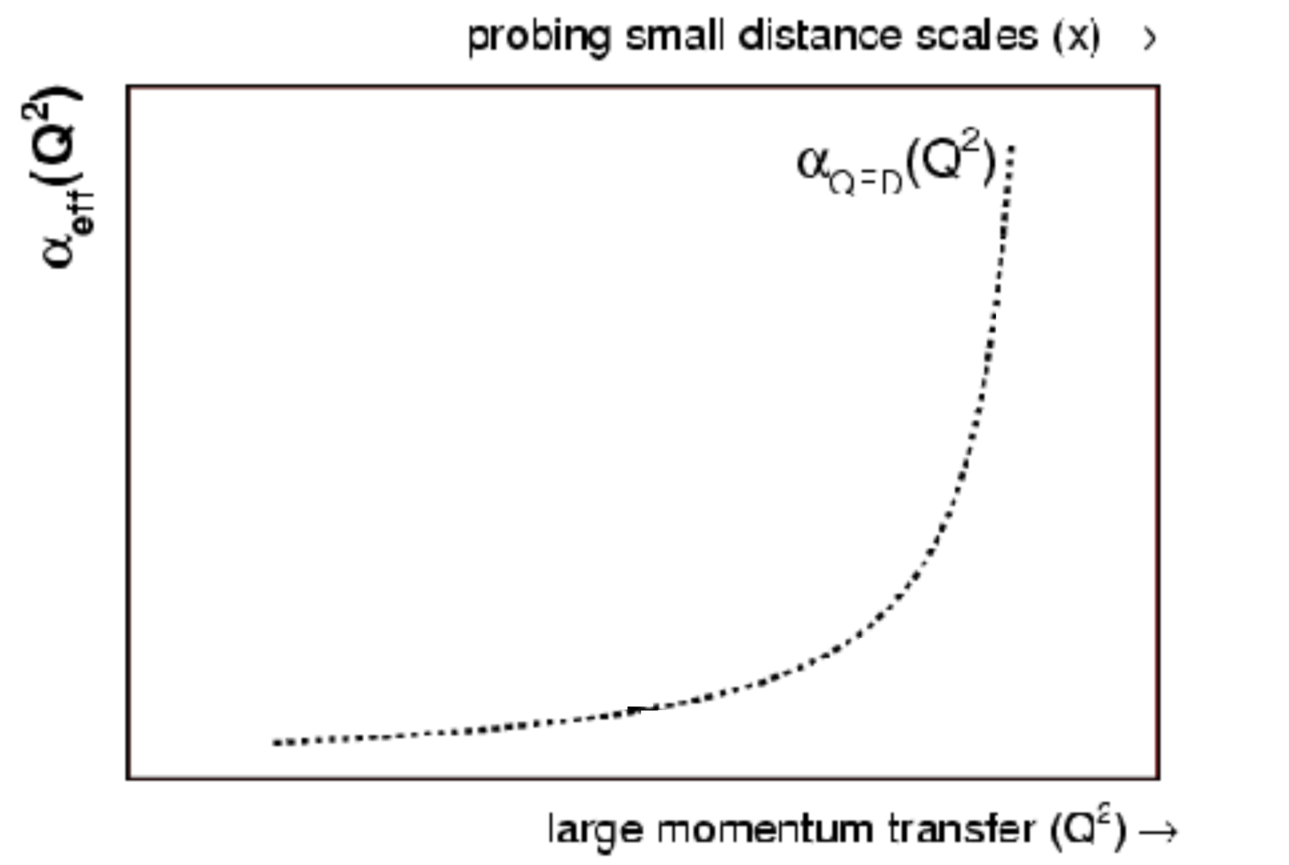

SM & QCD

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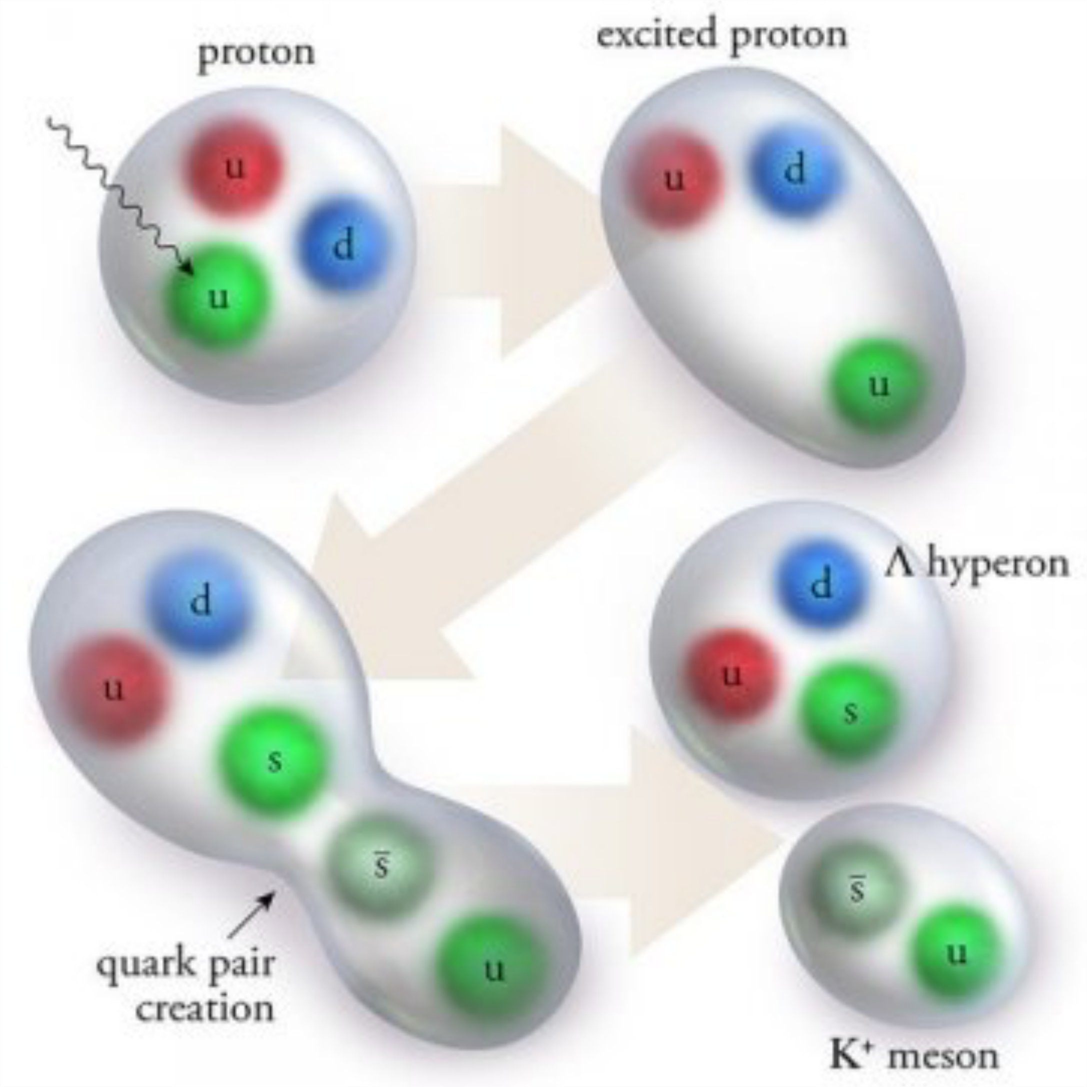

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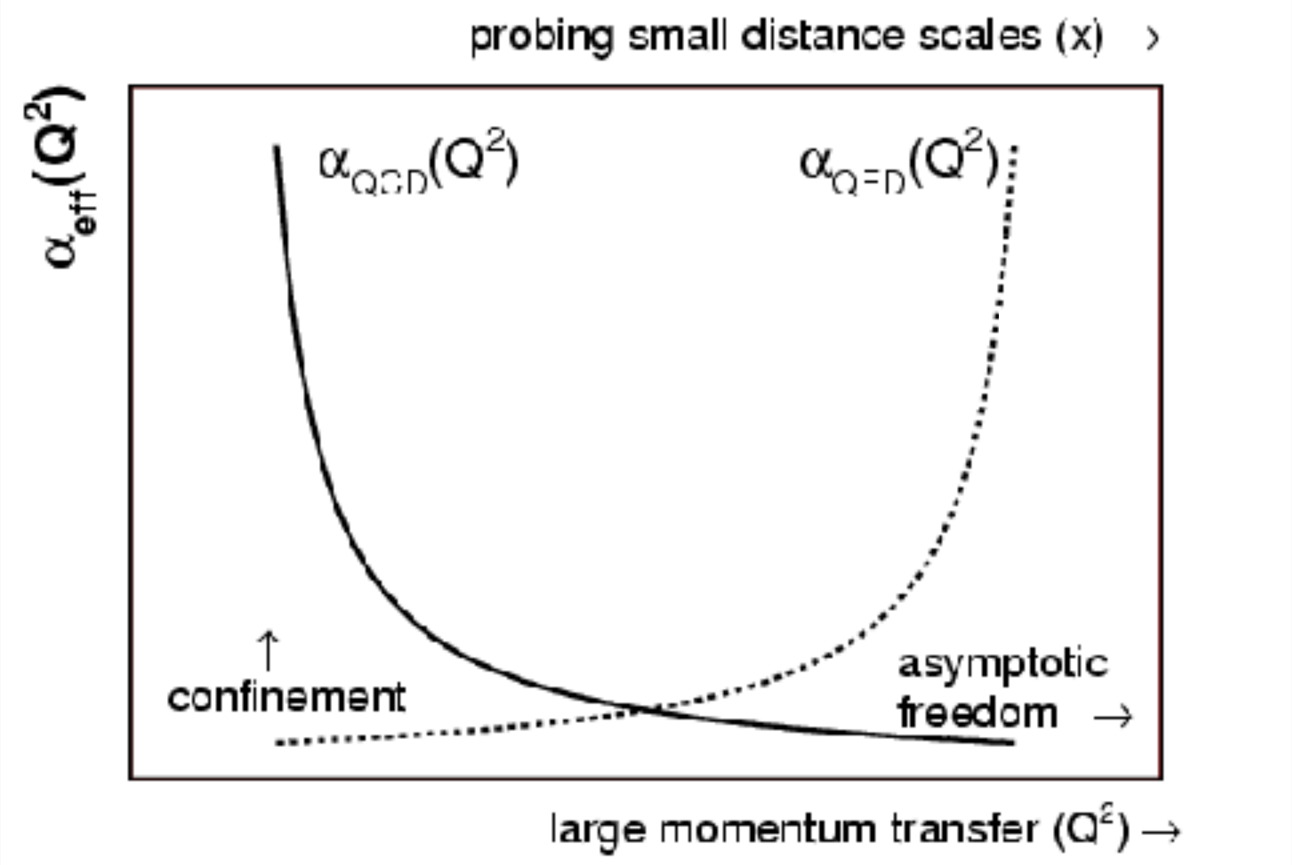

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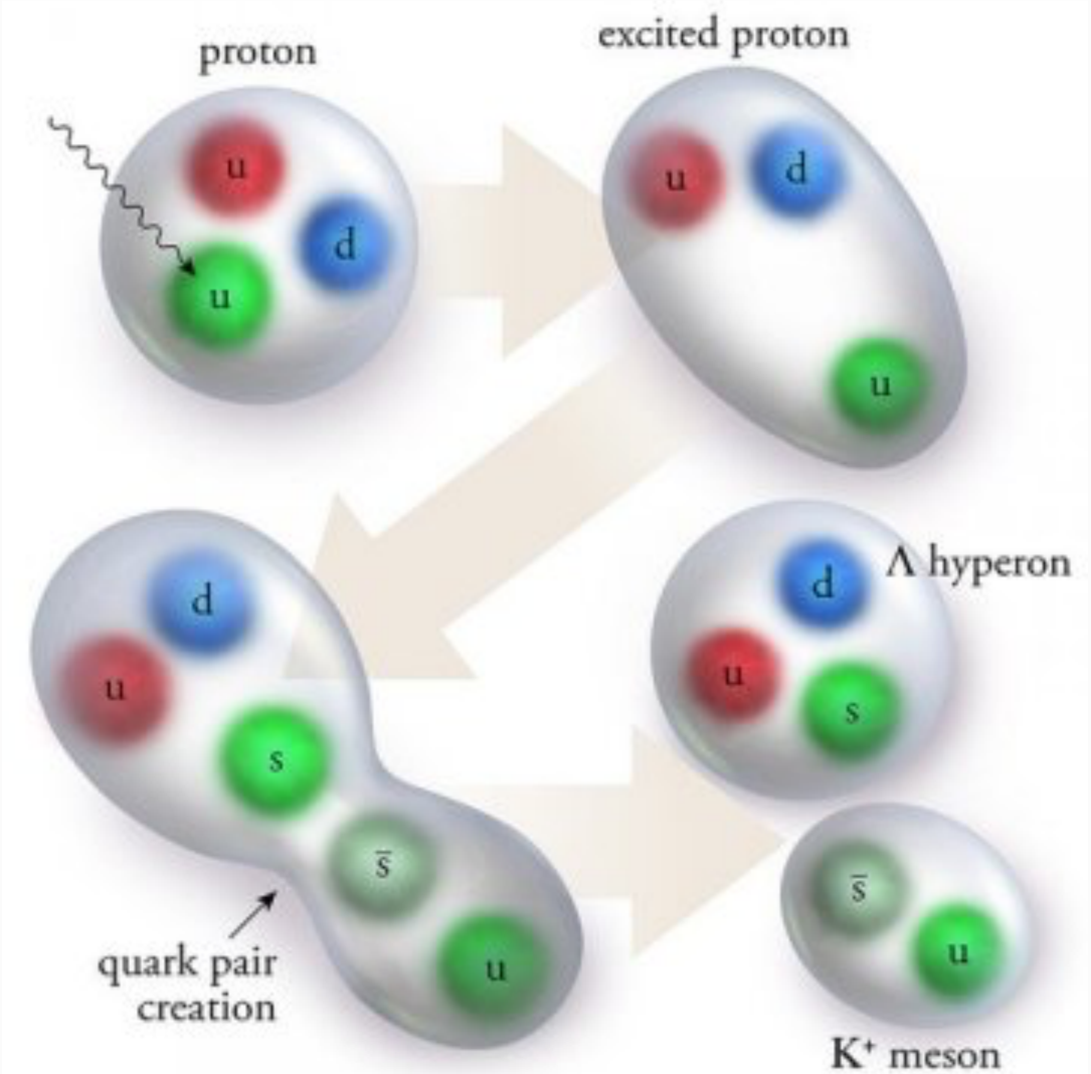

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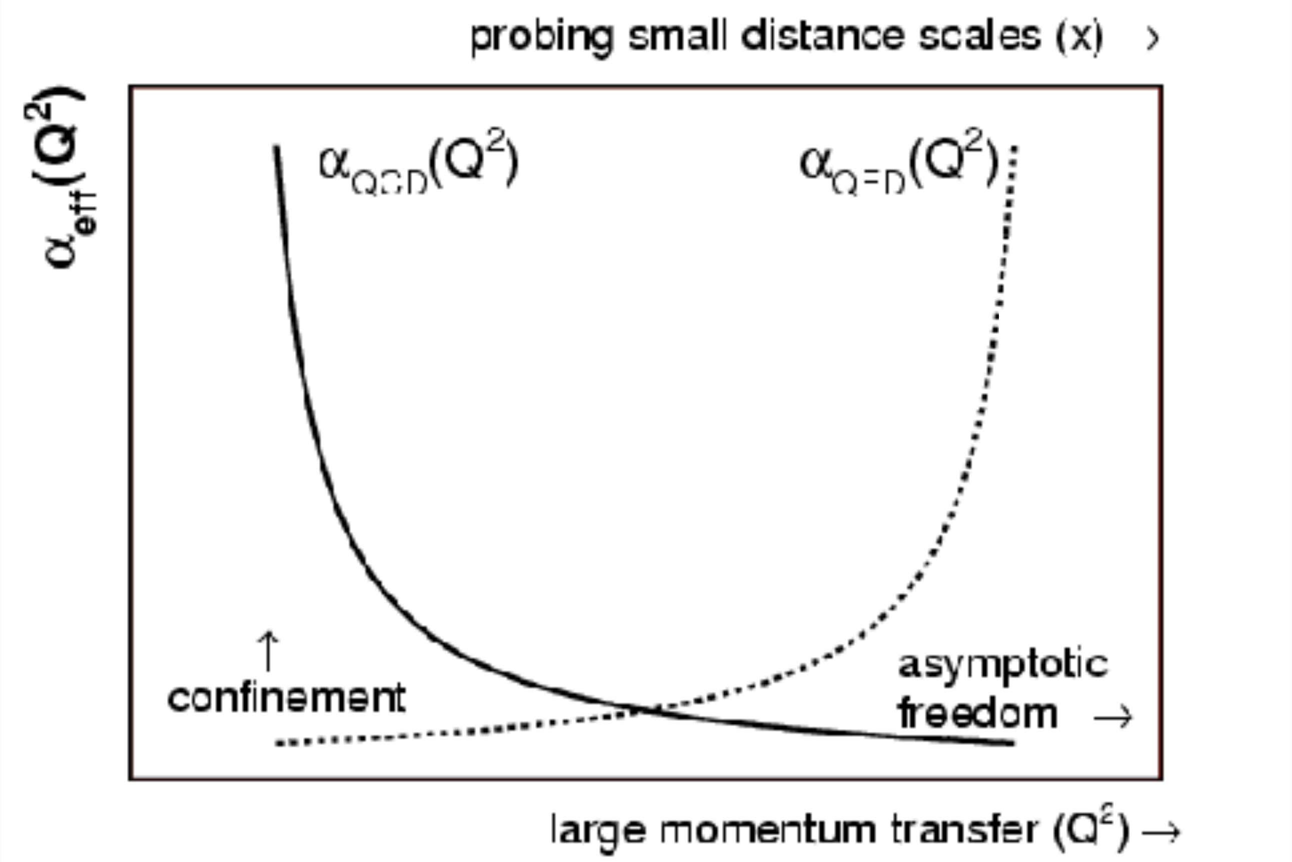
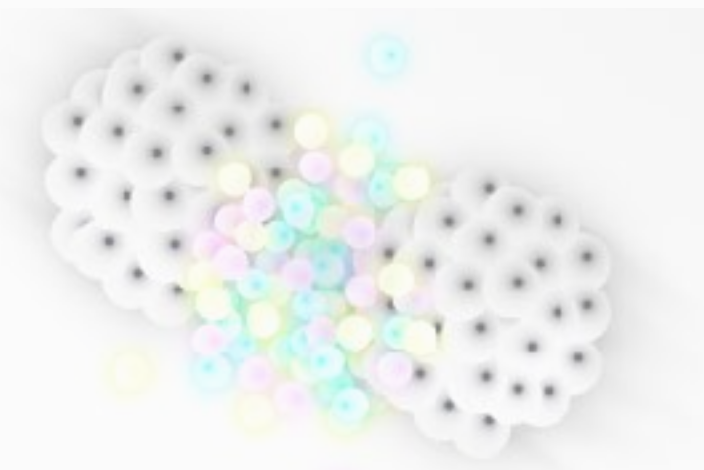


Large distances ⟷ Small distances

SM & QCD



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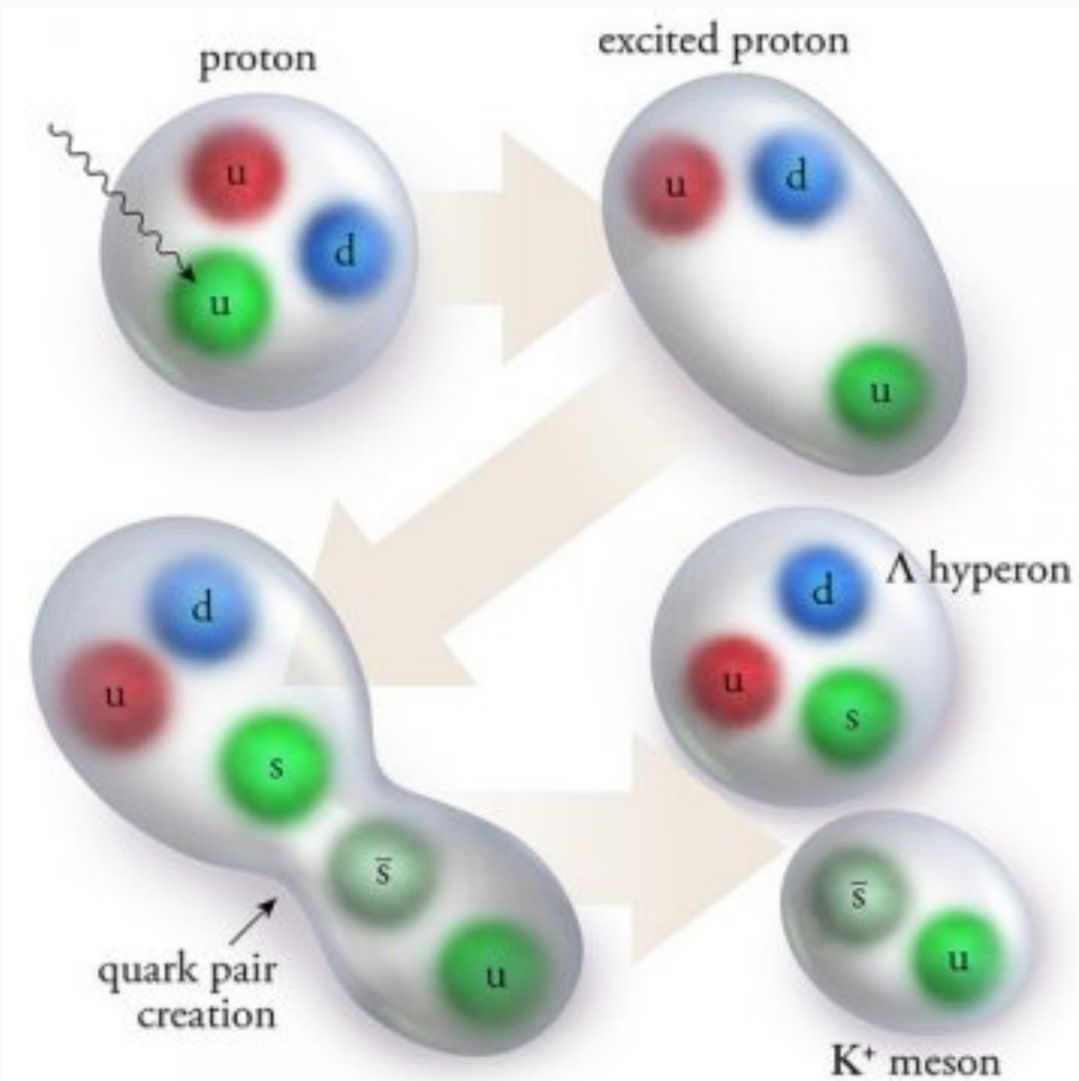

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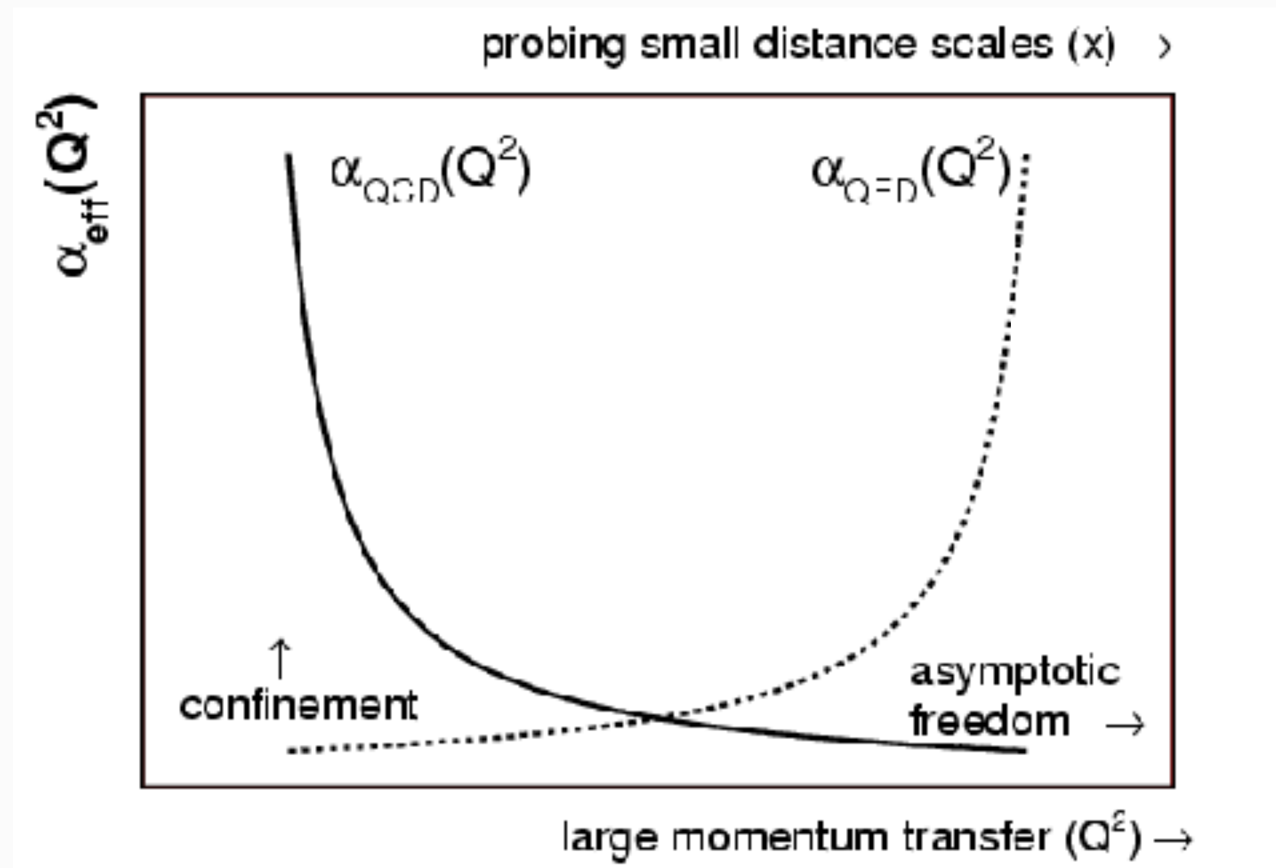
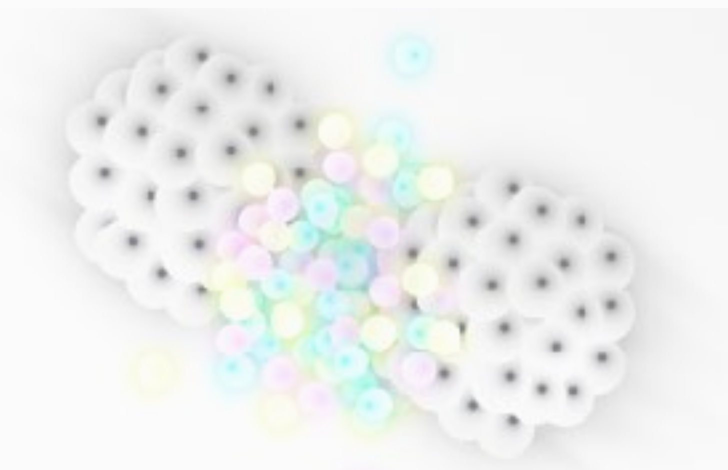


Large distances ⟷ $\boxed{\text{Small distances}}$

QCD Lagrangian within perturbation theory!

➜ perturbative QCD

Perturbative QCD



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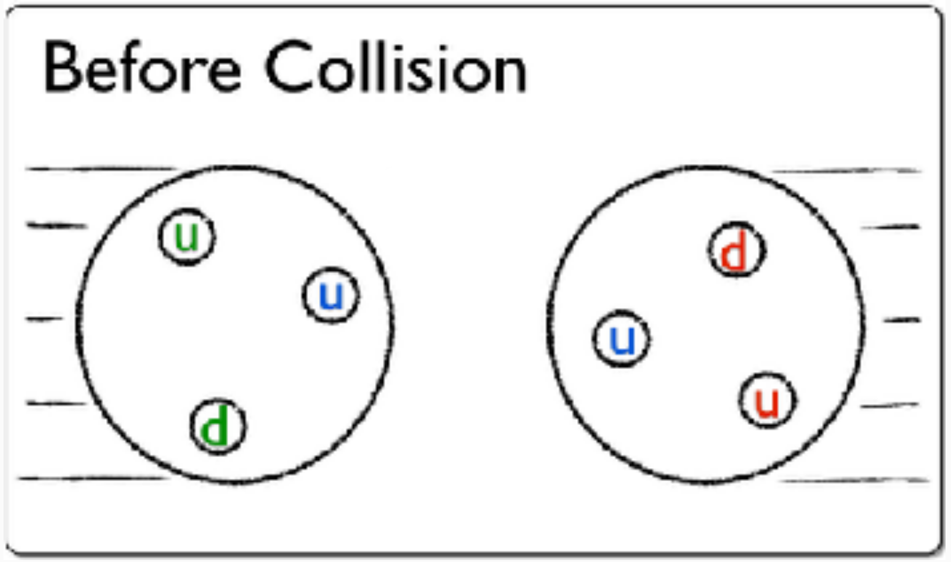

Perturbative QCD

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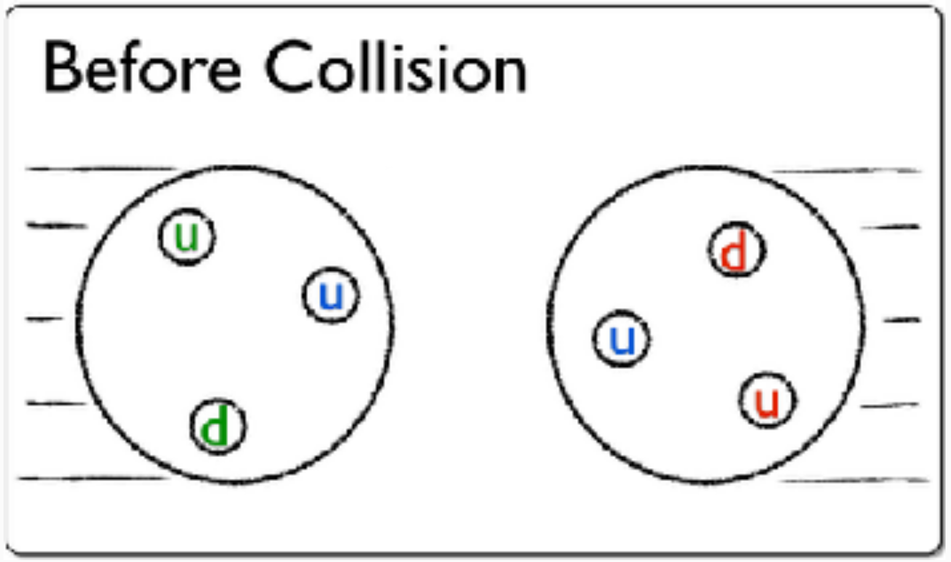
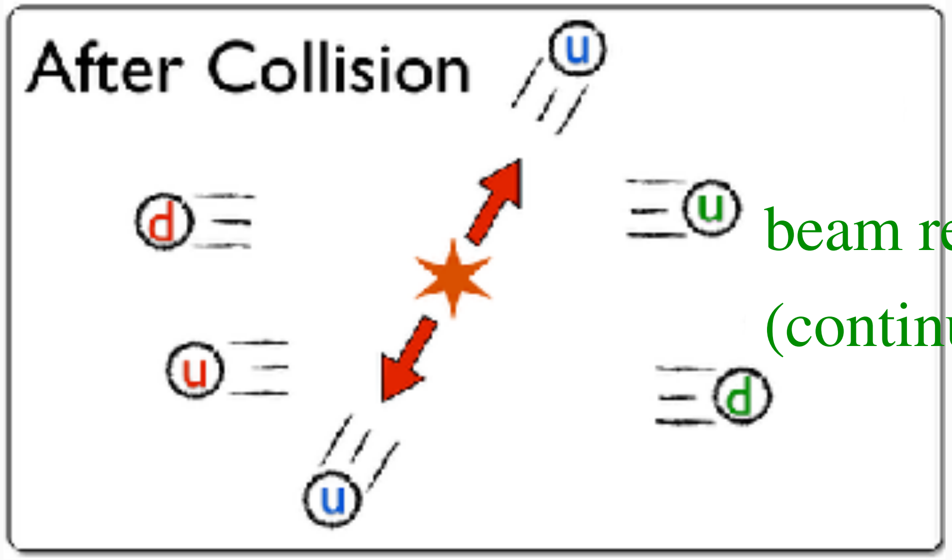
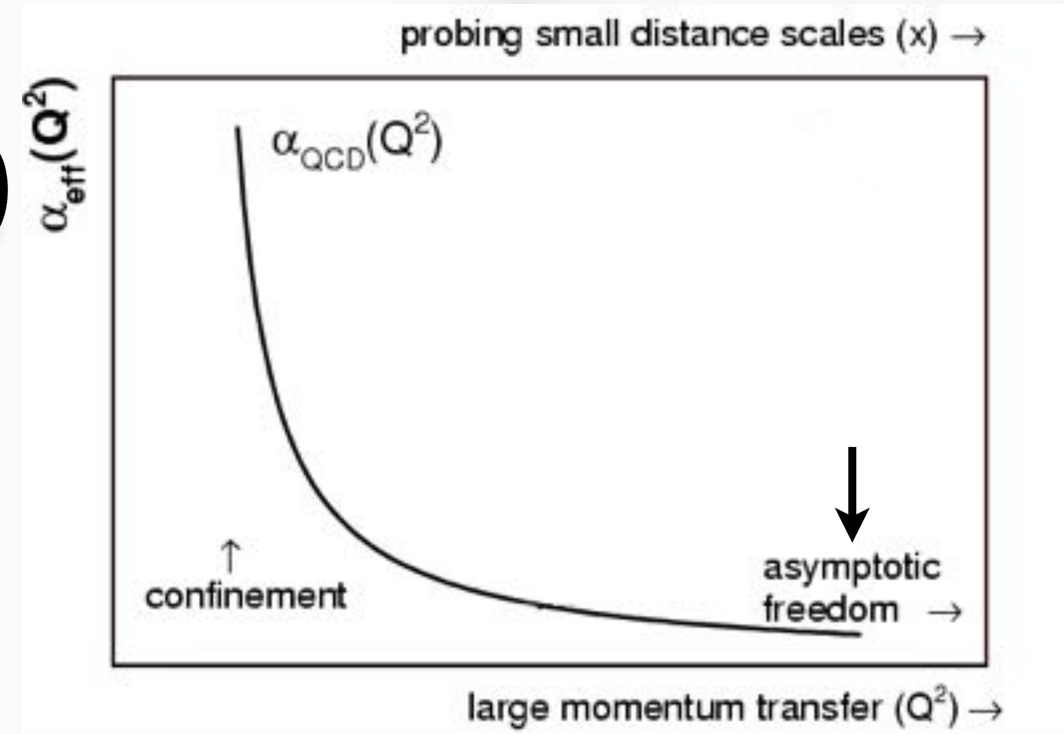


High momentum quarks
(in the transverse direction)



beam remnant
(continue in the beam direction)

Perturbative QCD



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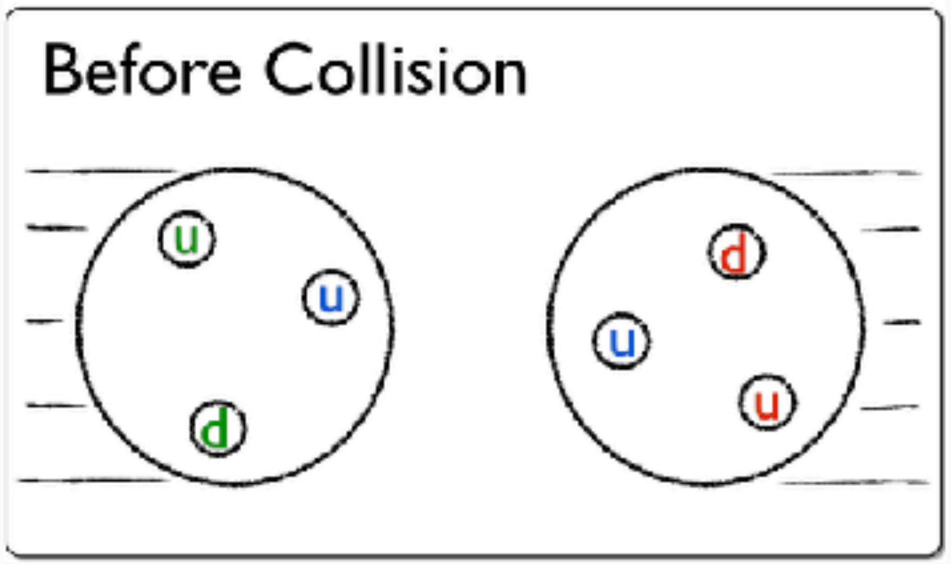

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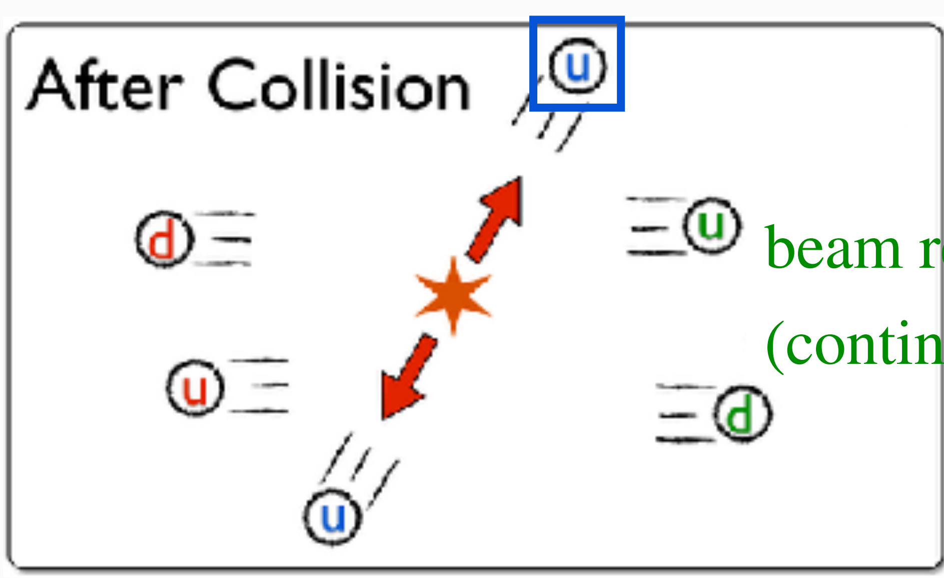

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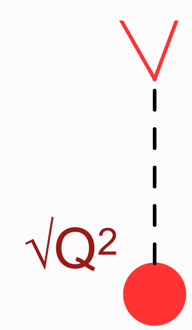

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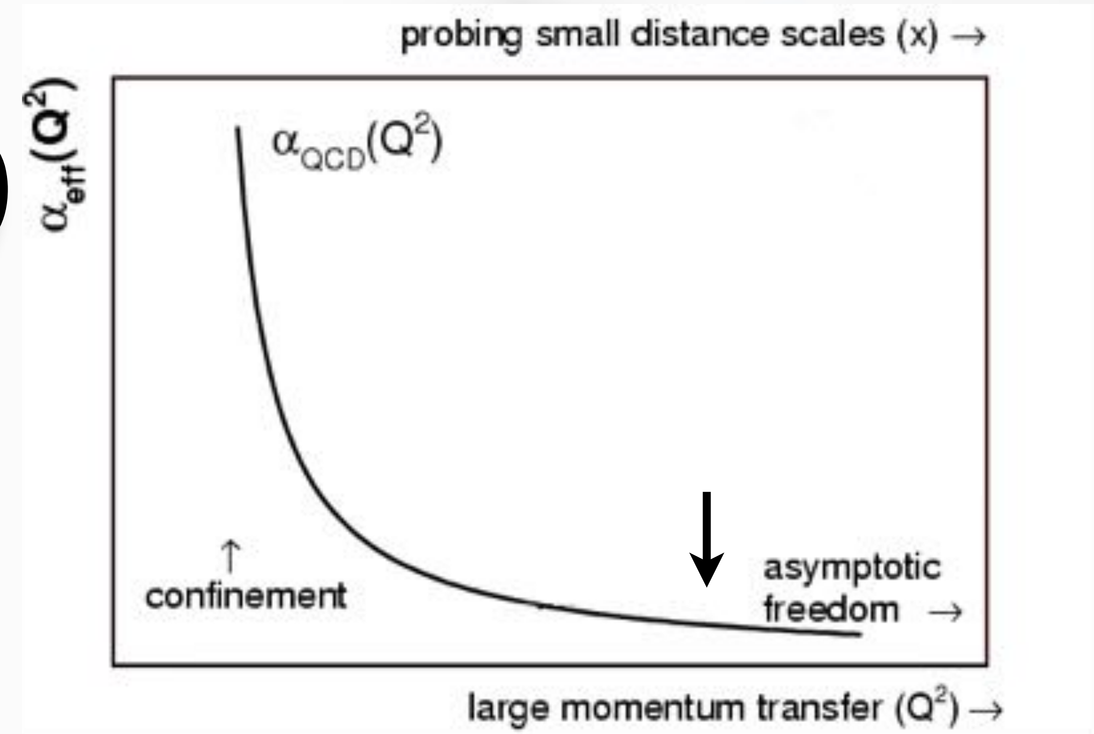

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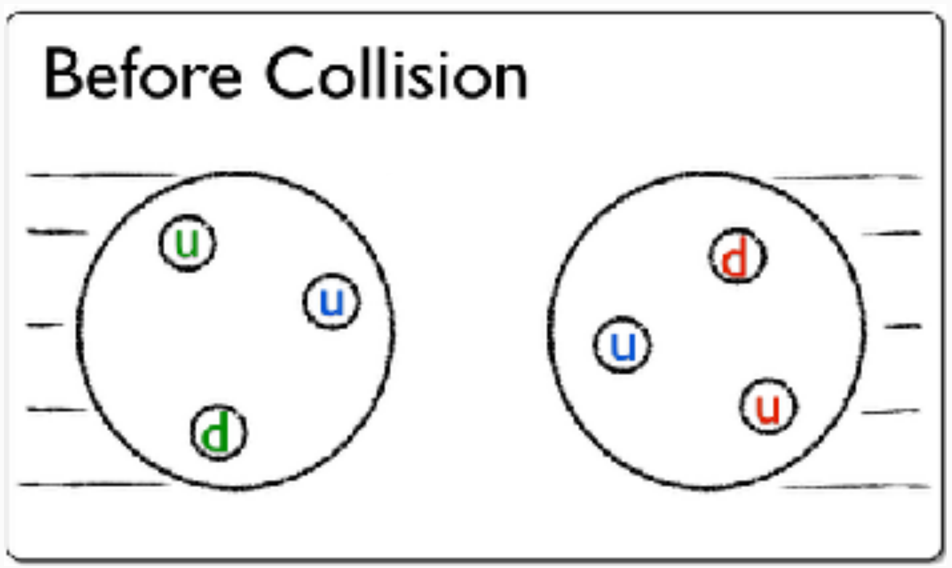

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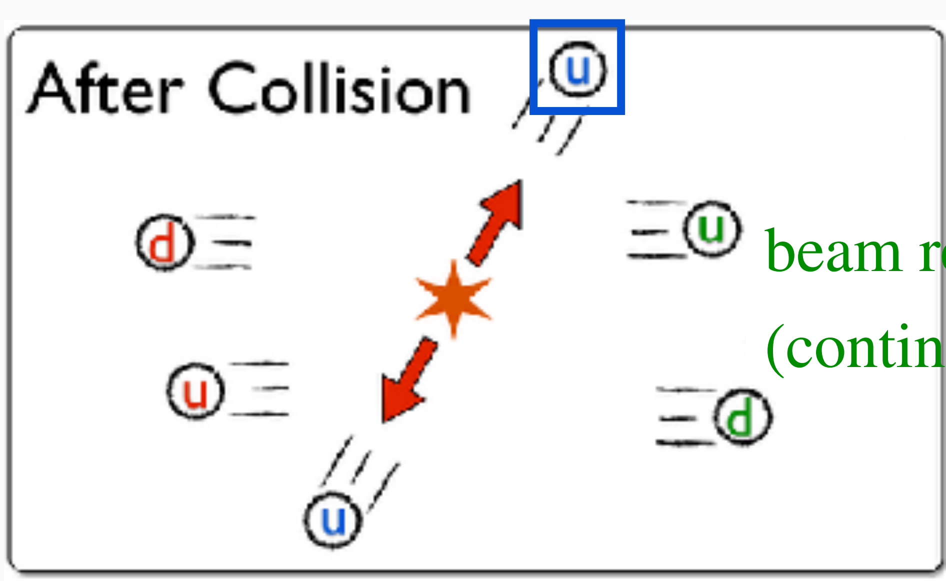

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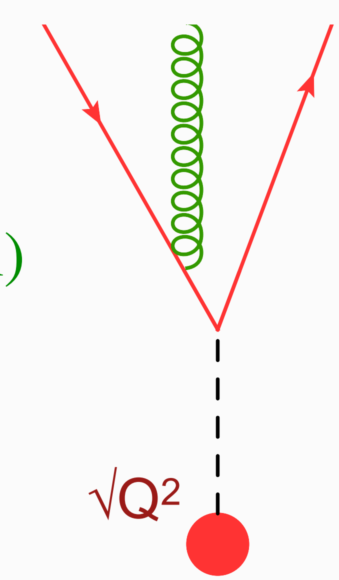

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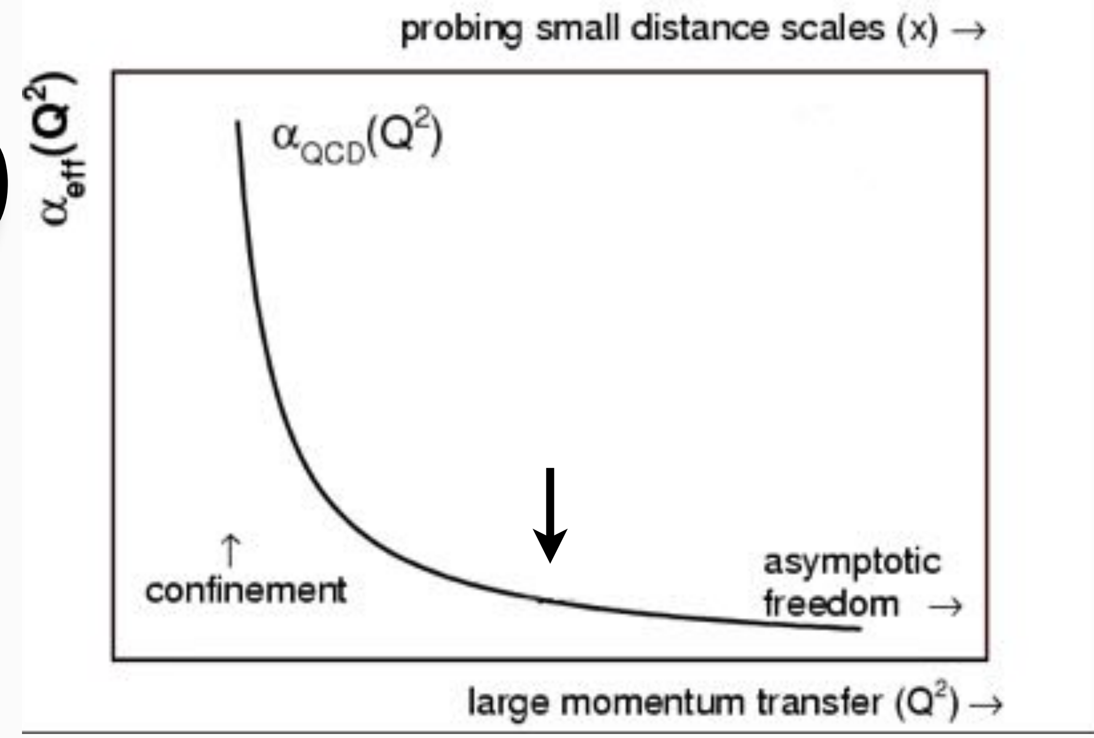

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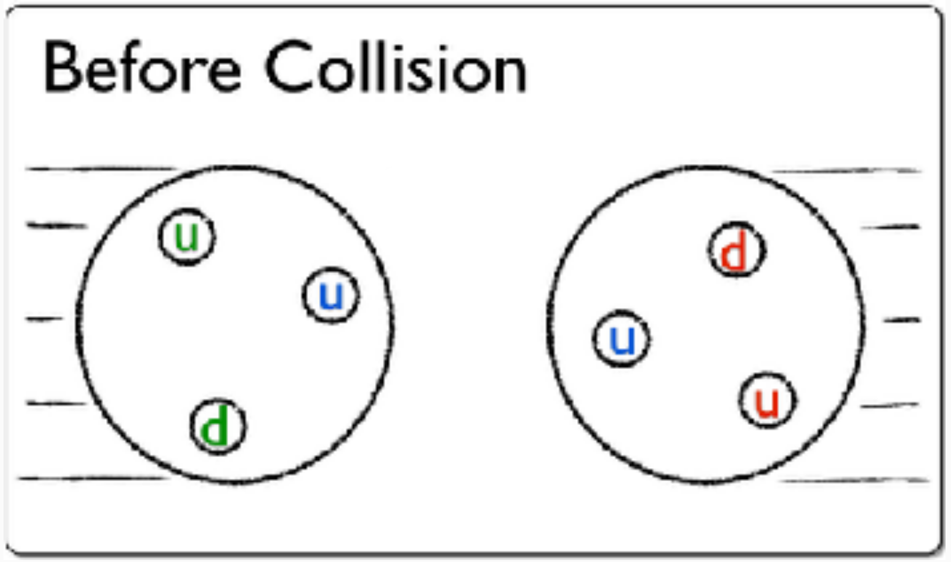

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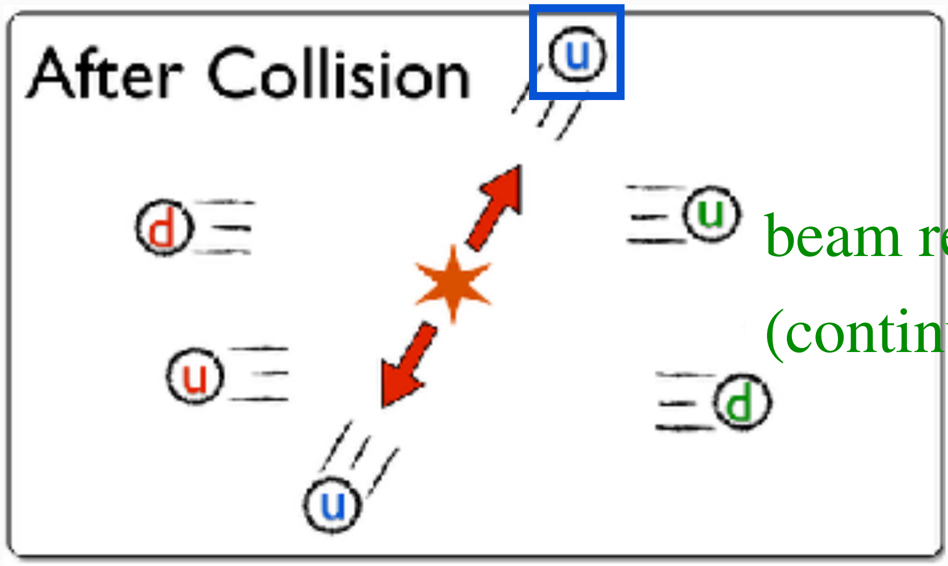

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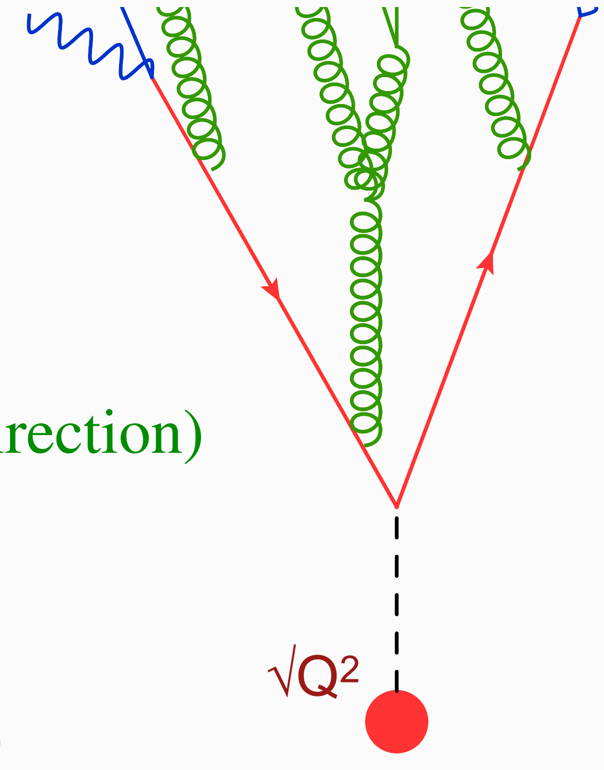

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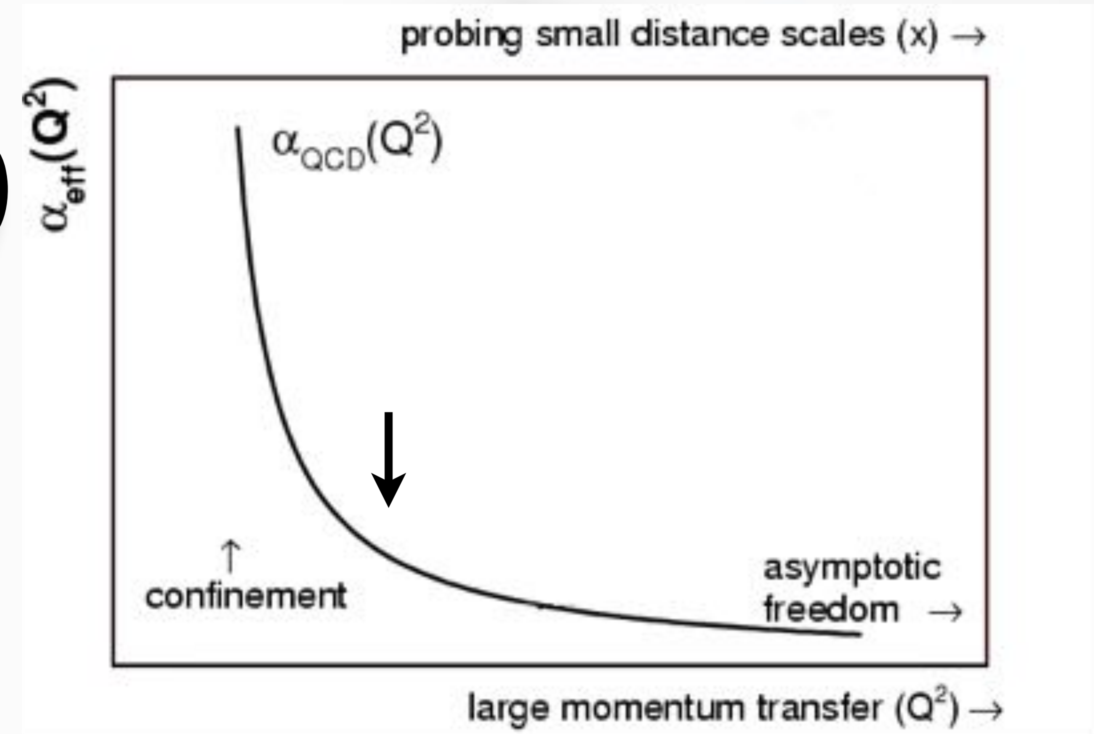

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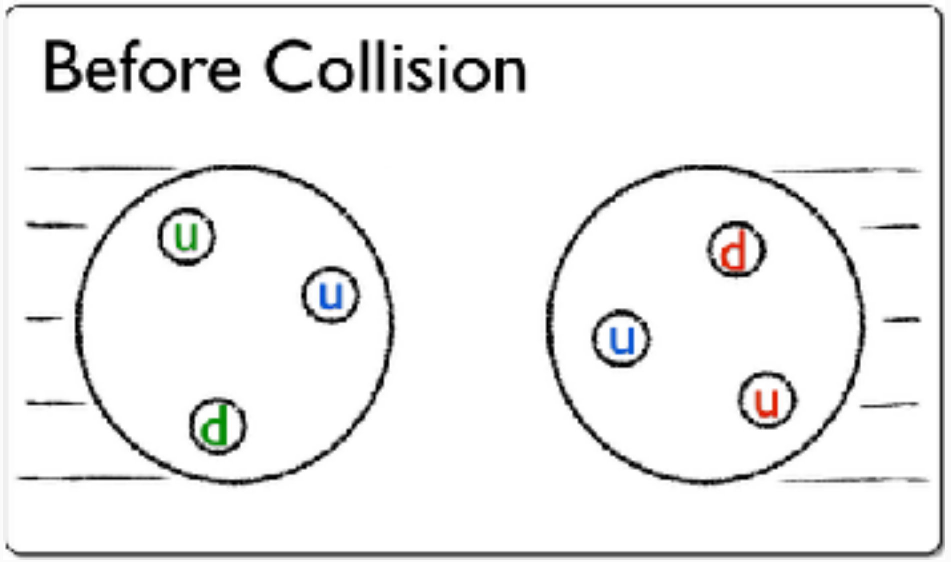

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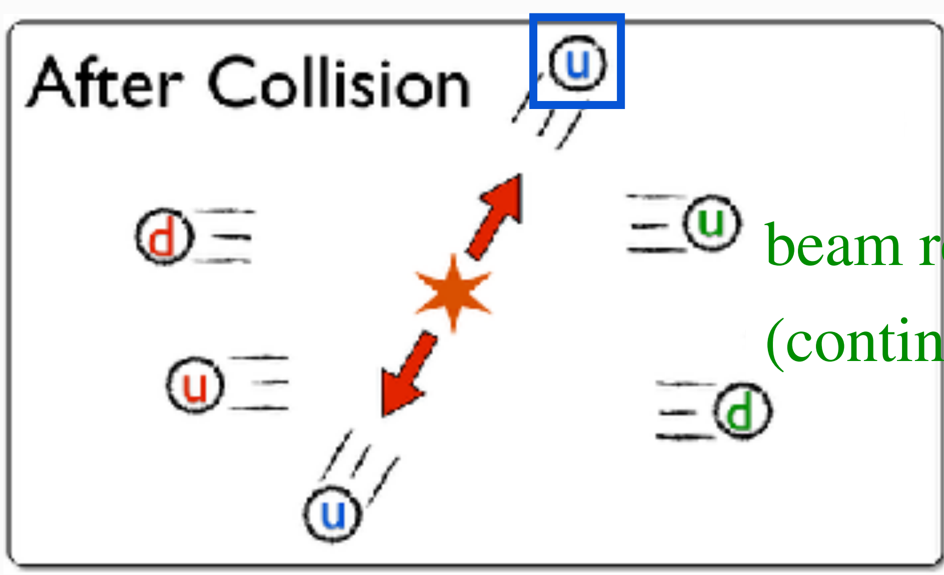

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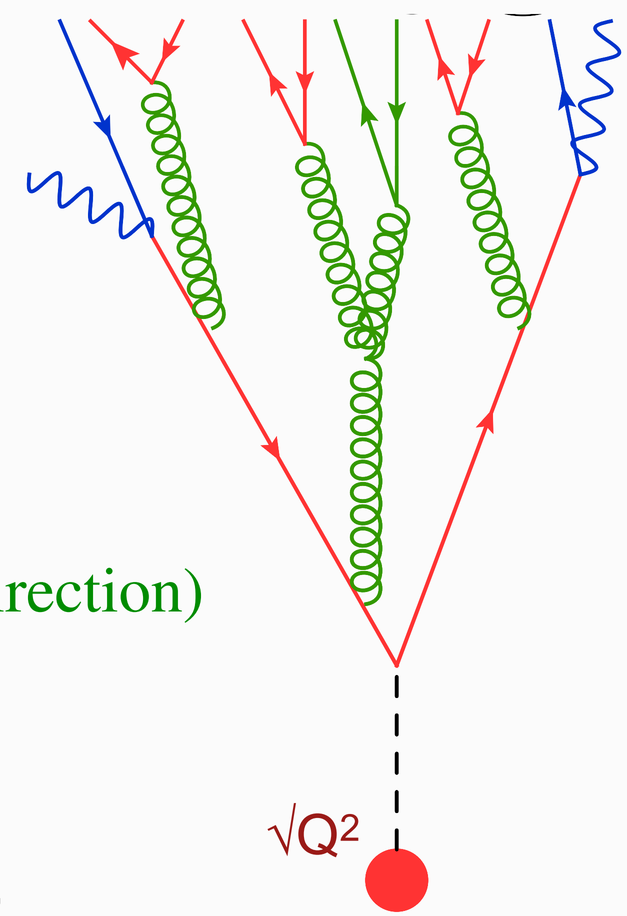

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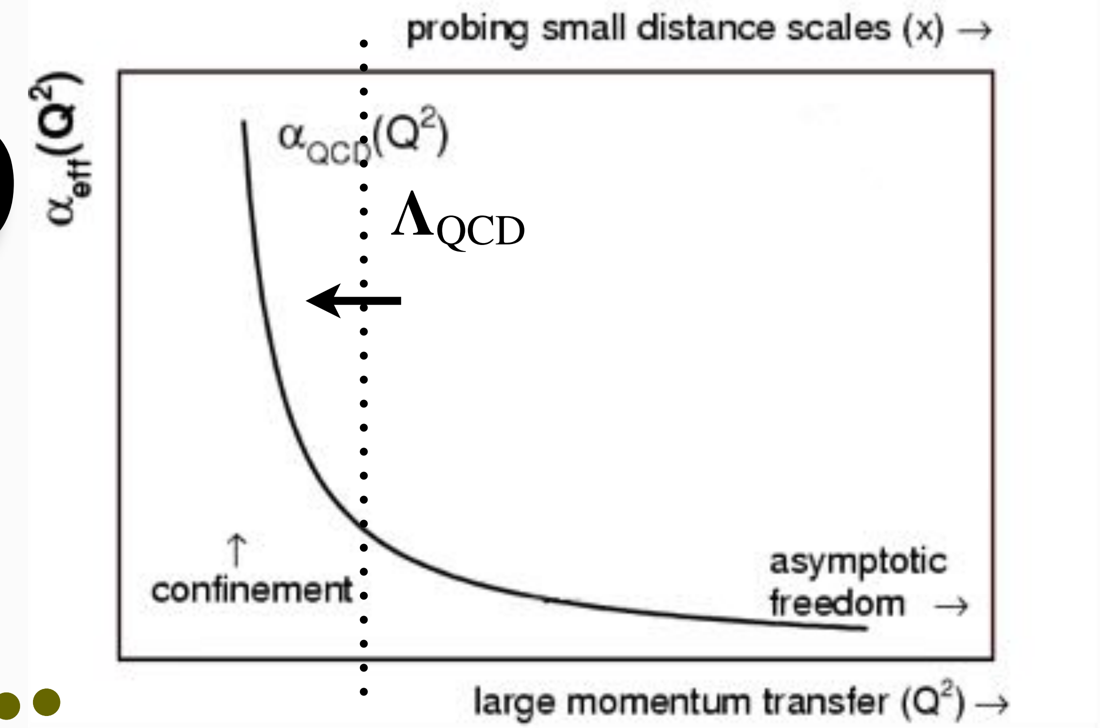

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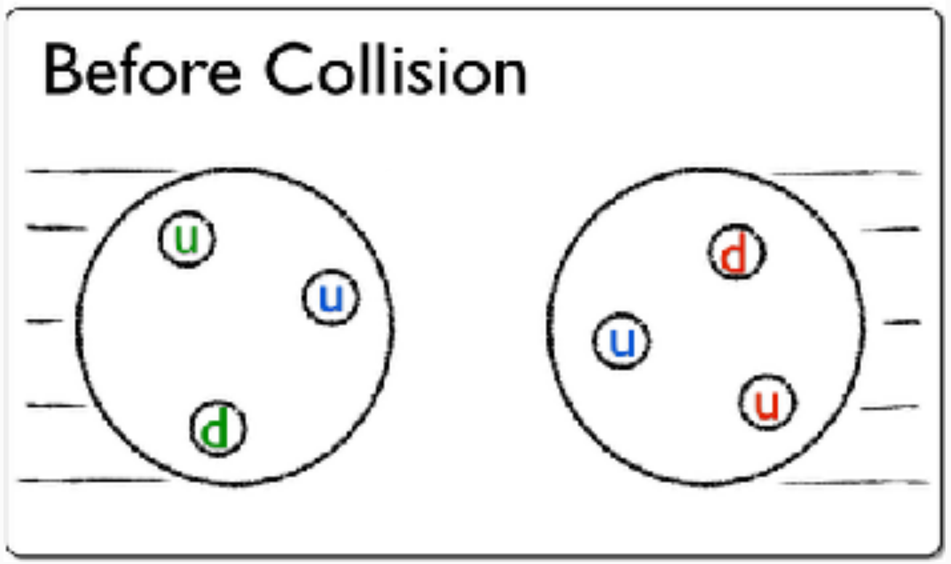
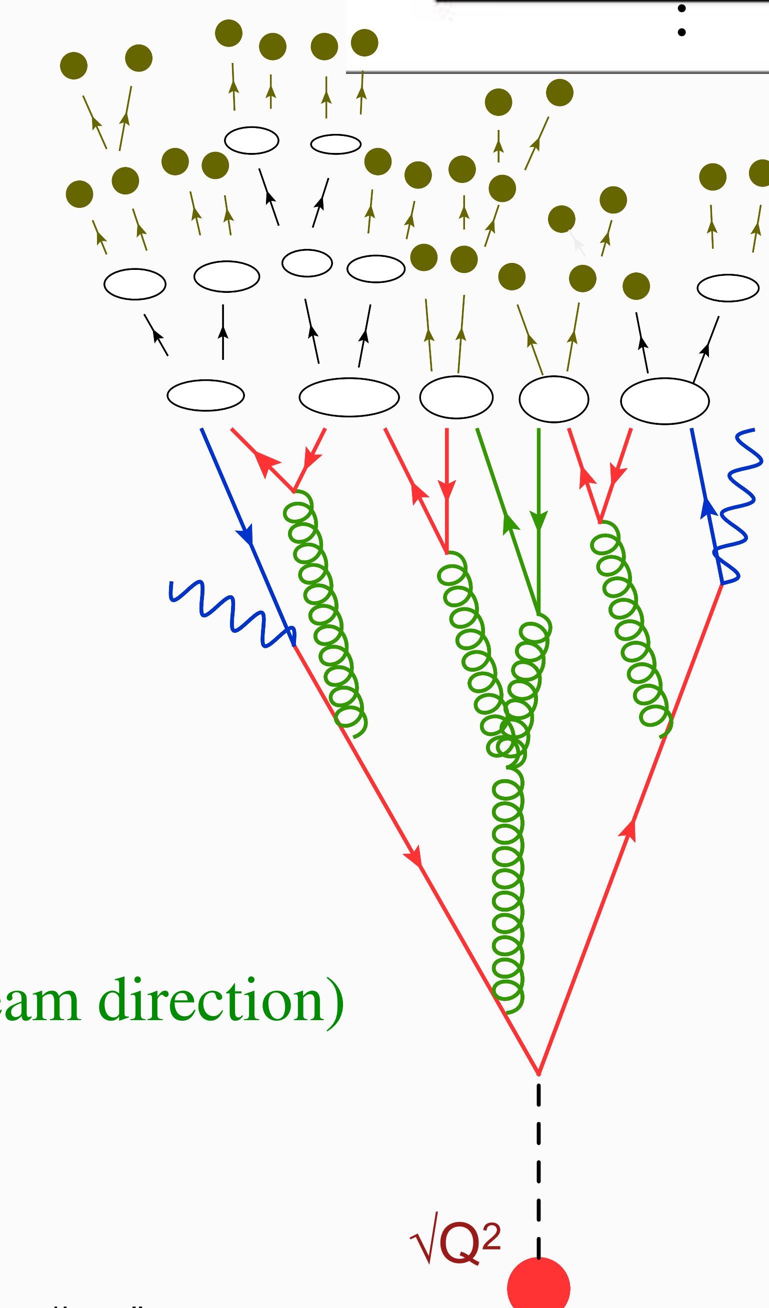


Particles @ detector

Λ_{QCD}



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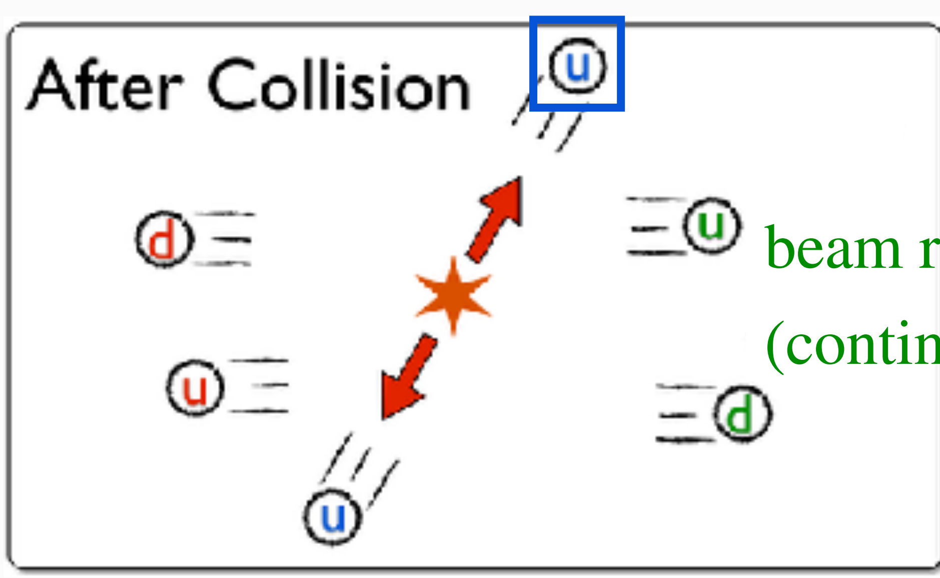

beam remnant

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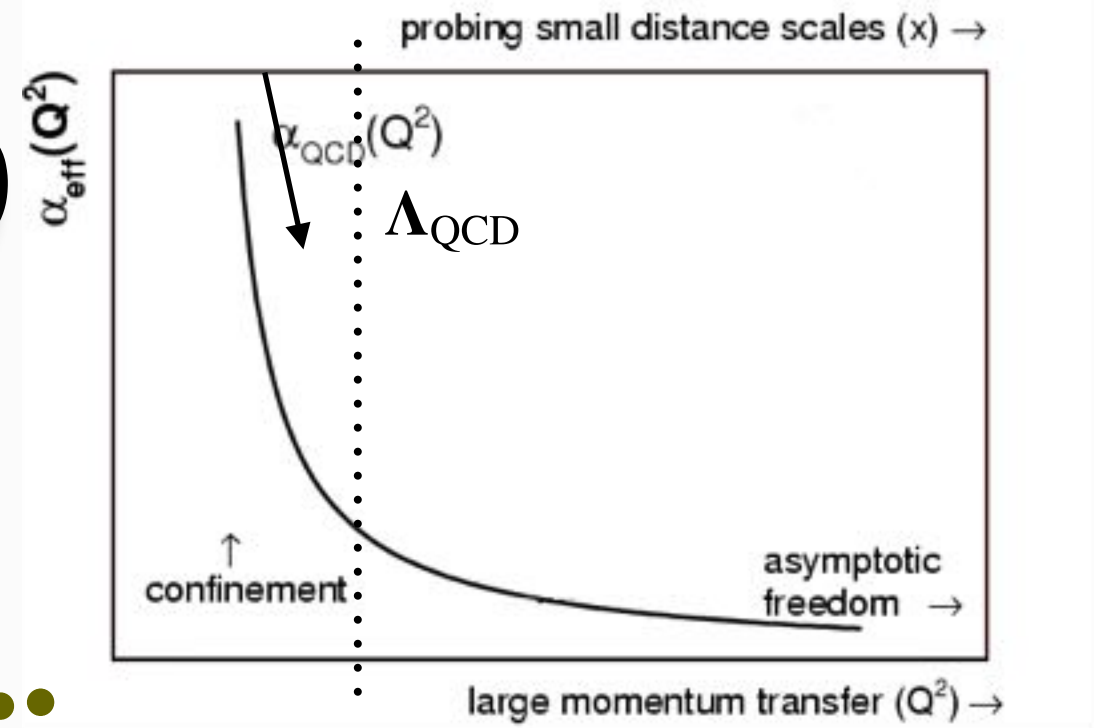

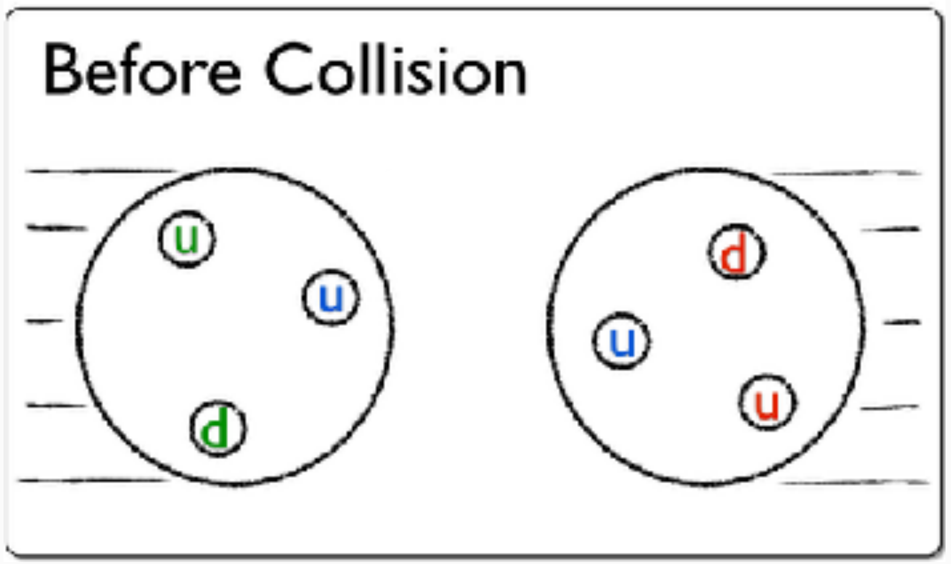

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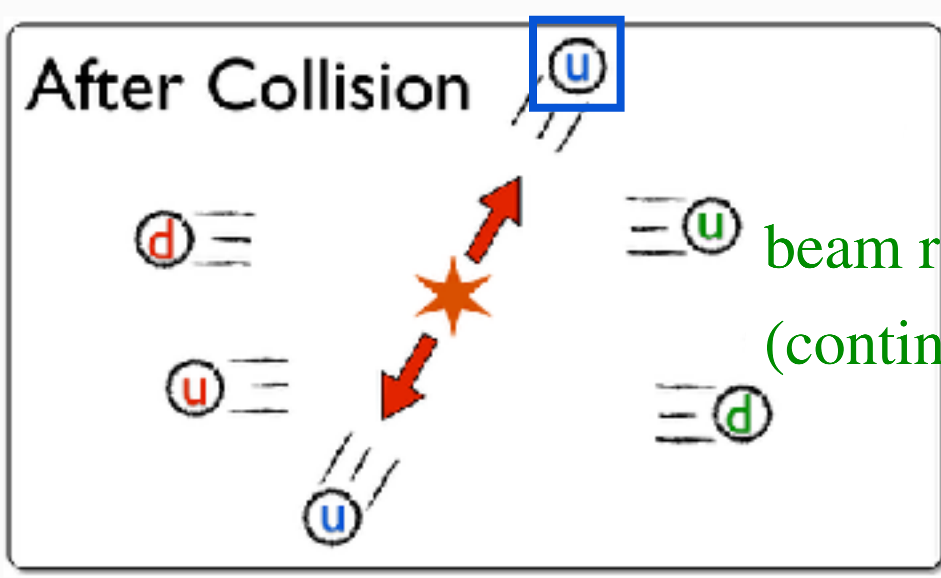

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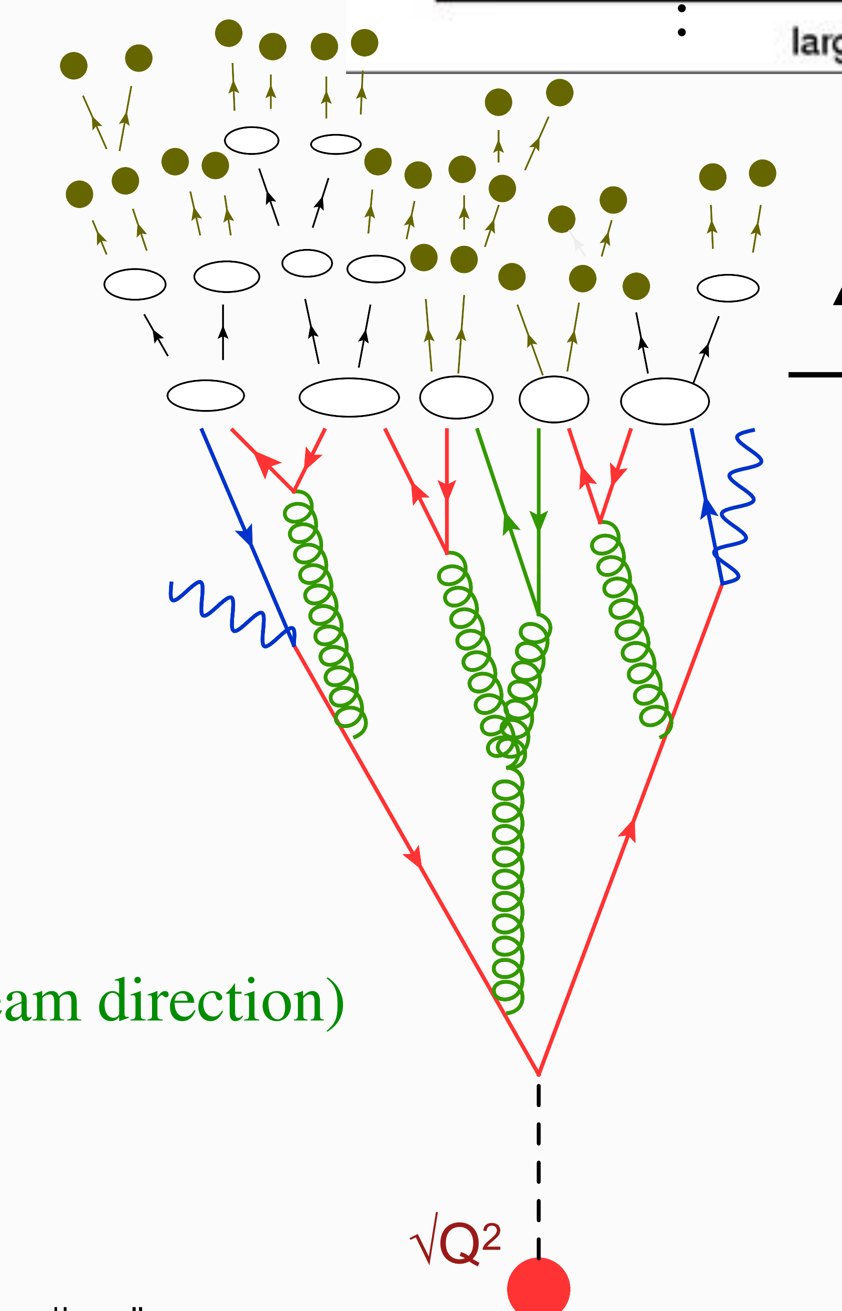

Hadronization
(non pQCD)

$\sqrt{Q^2}$

Perturbative QCD

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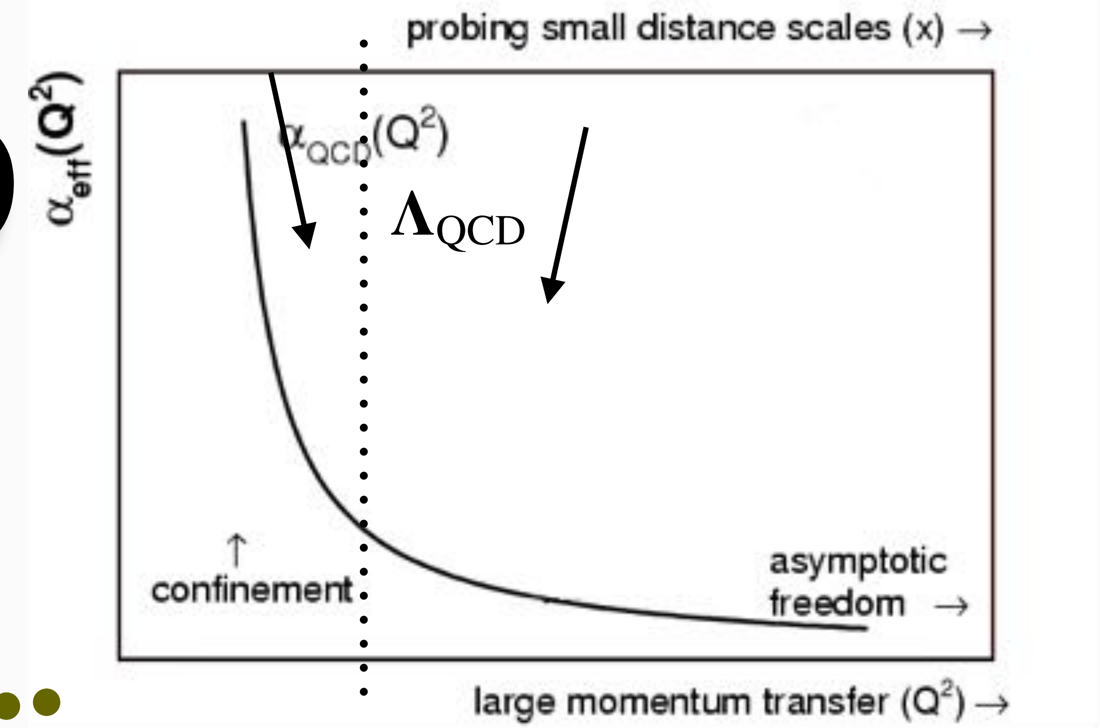

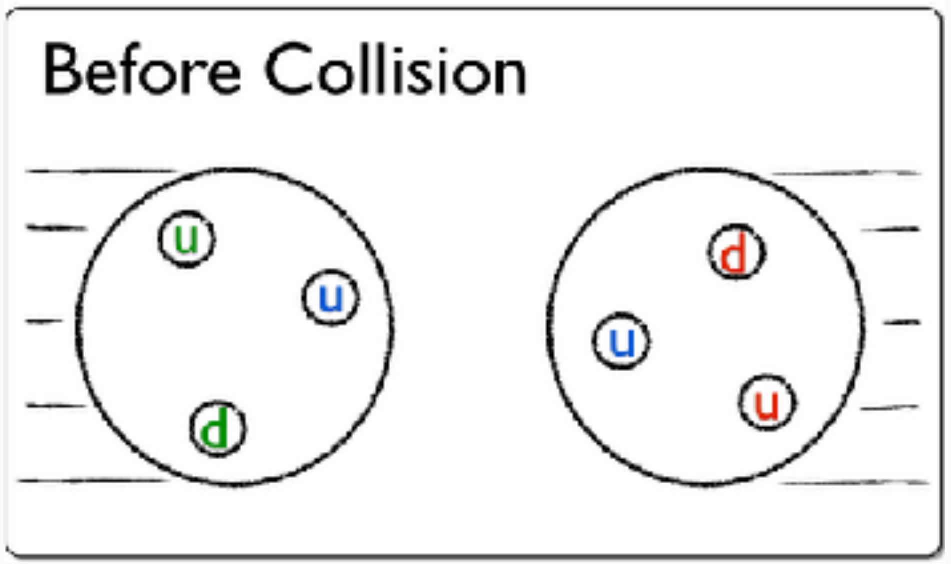

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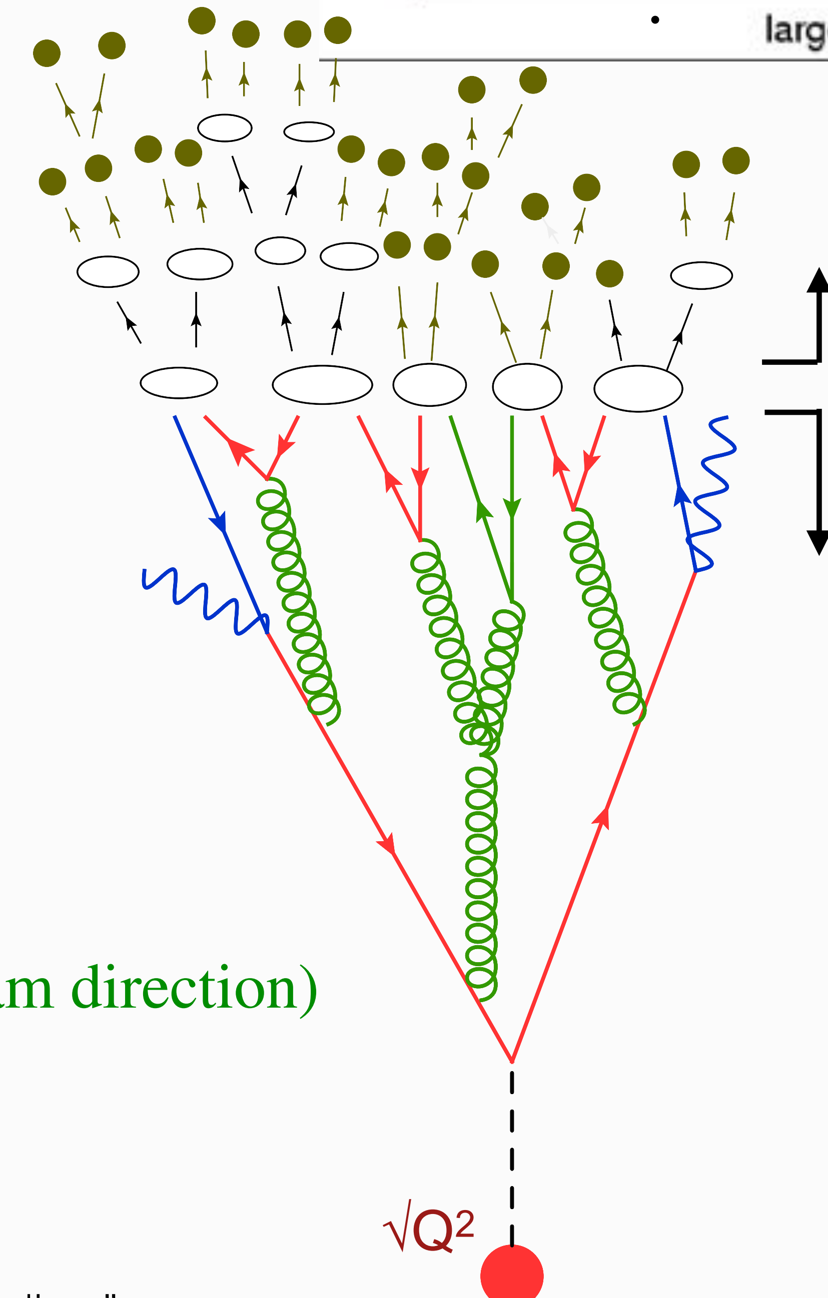
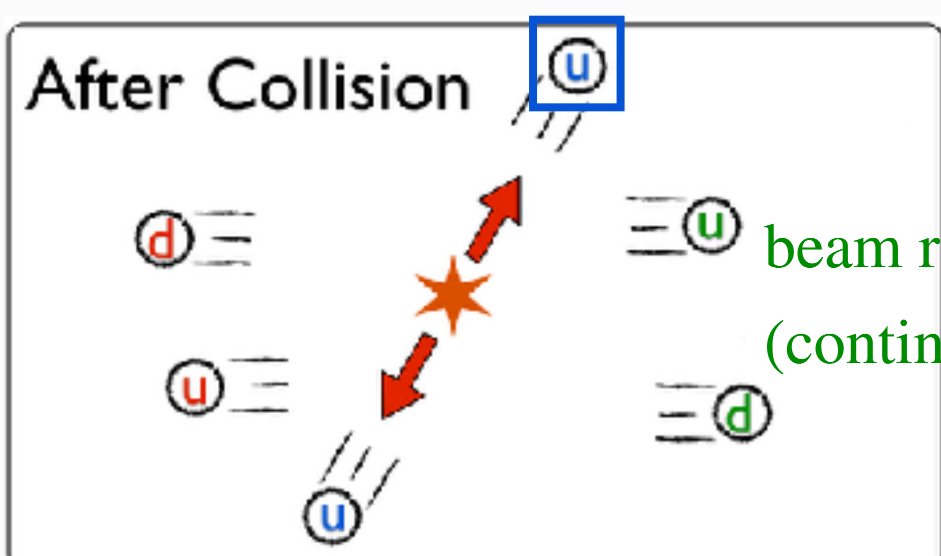


Hadronization
(non pQCD)

parton shower/
branching (pQCD)

High momentum quarks
(in the transverse direction)



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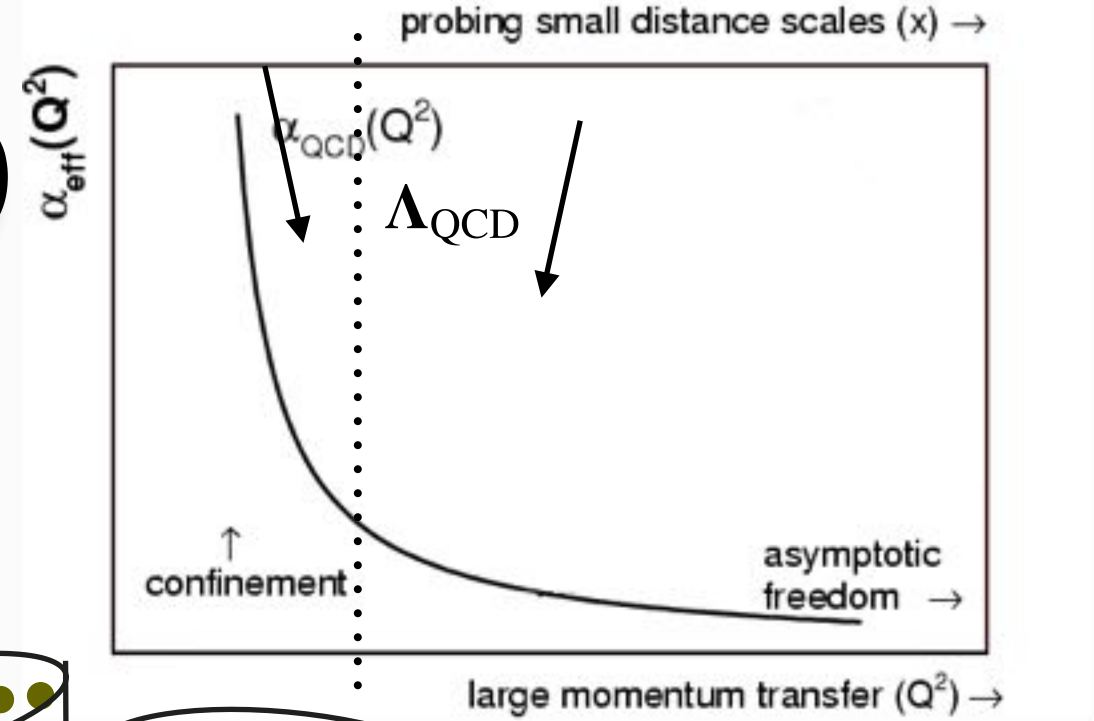
Perturbative QCD



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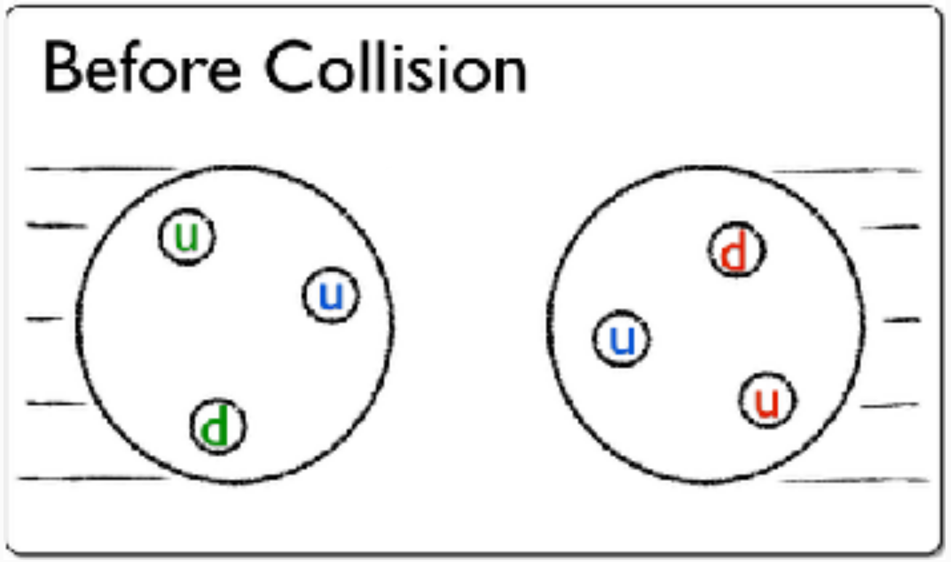

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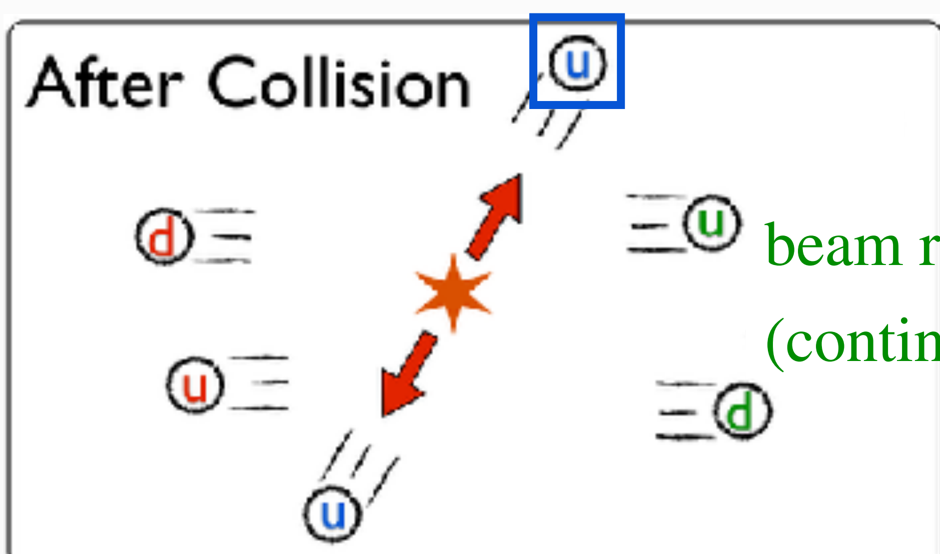

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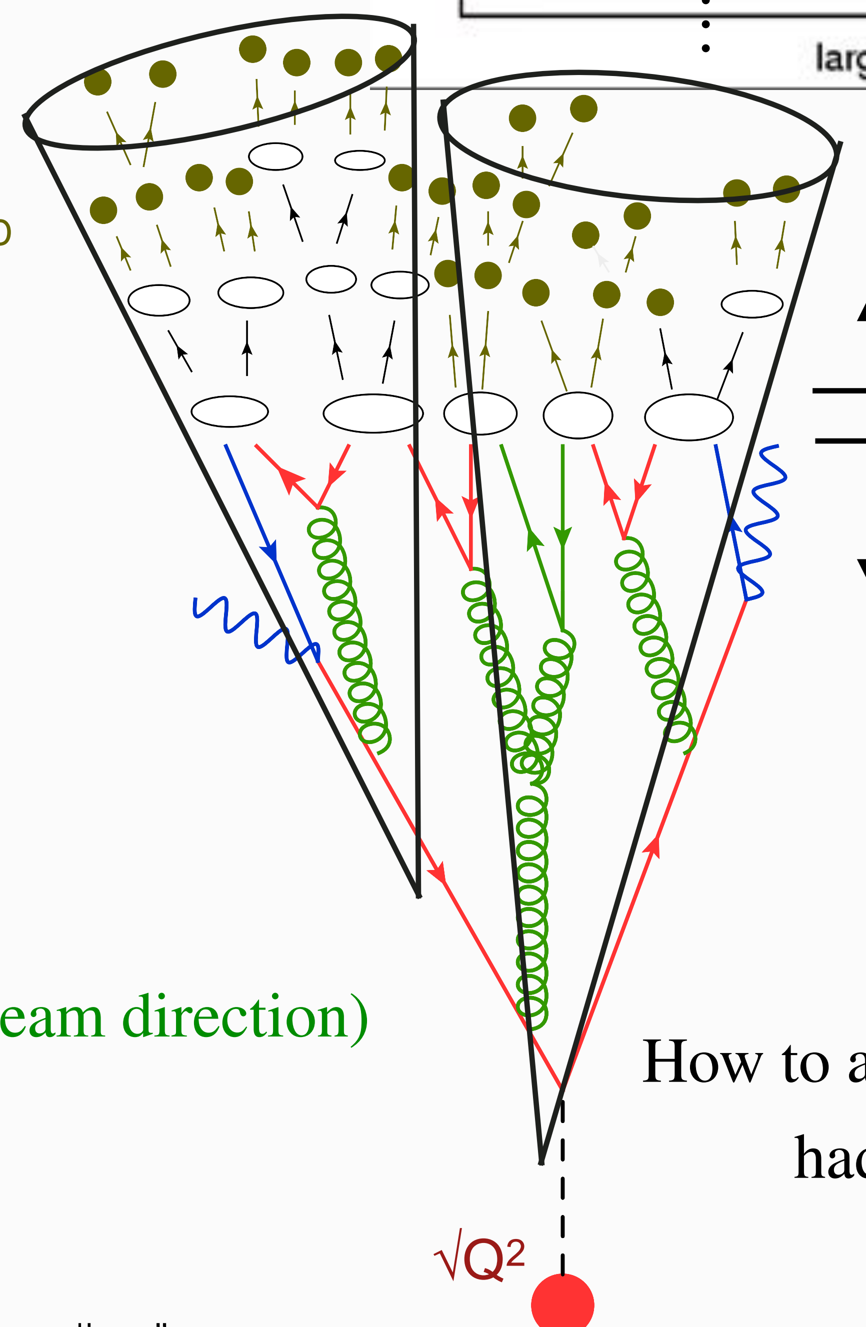


Hadronization

(non pQCD)

parton shower/

branching (pQCD)

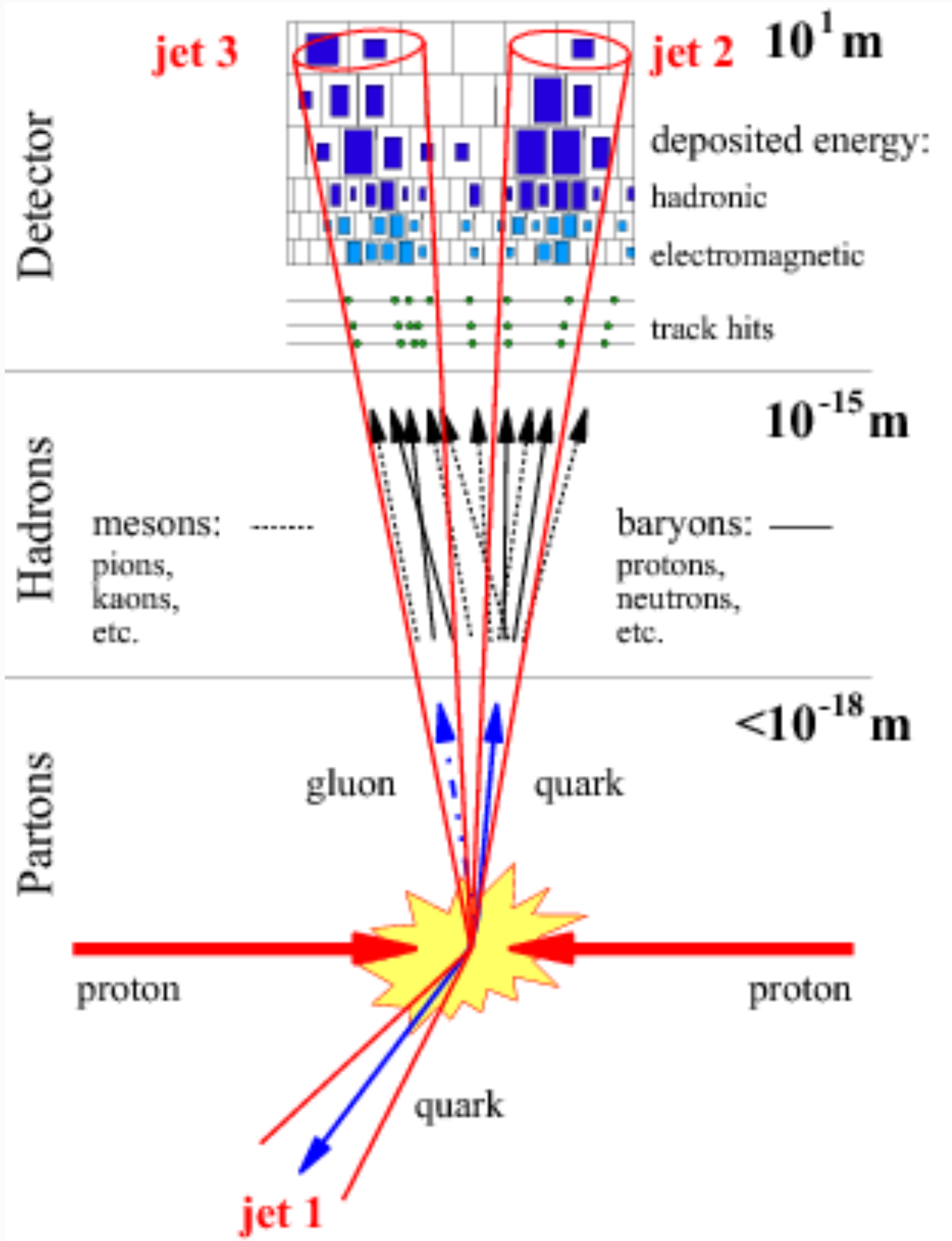
How to avoid sensitivity to

hadronization?

➜ jets

Jets in pp collisions

- Jet: Cluster of particles produced from a hard process



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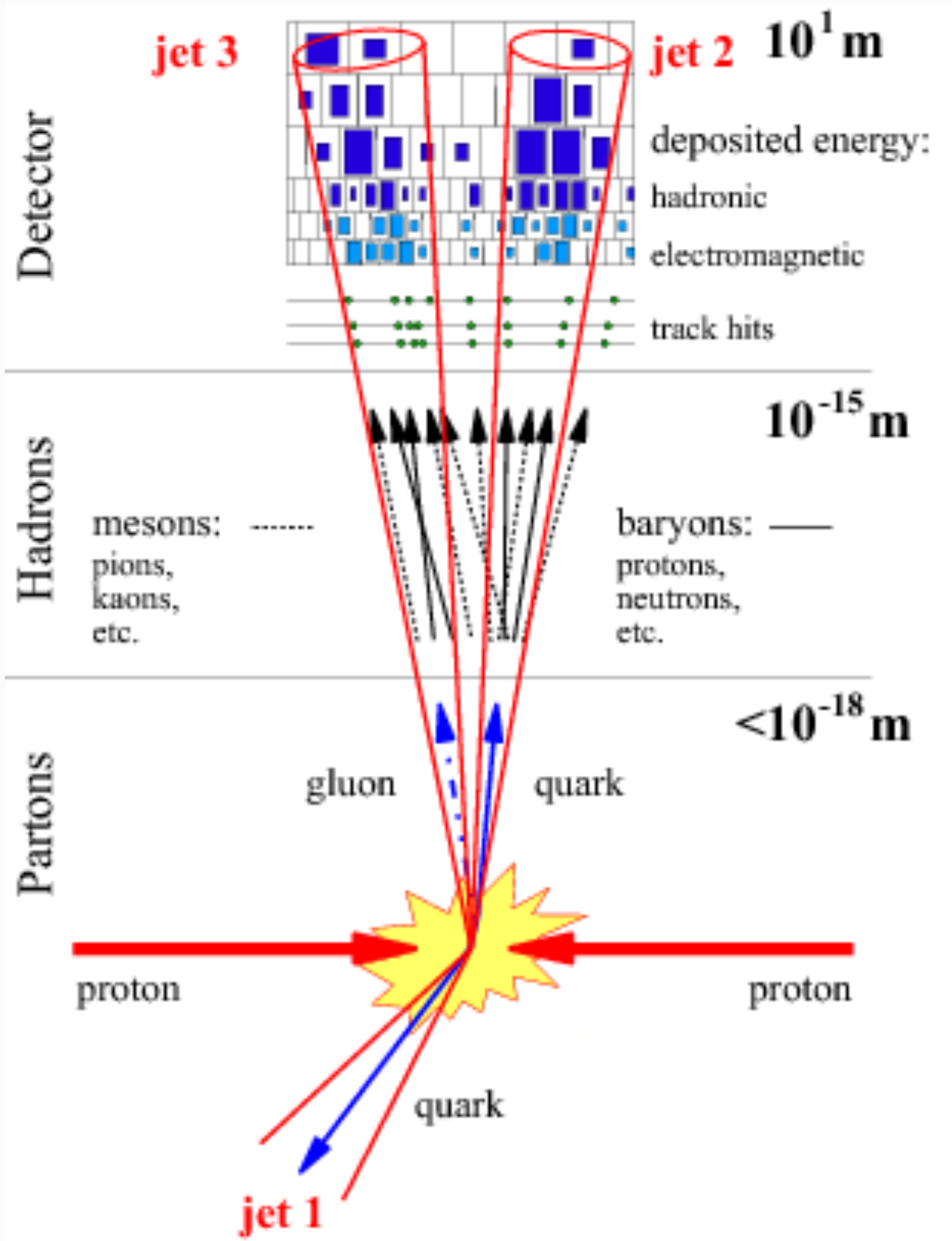
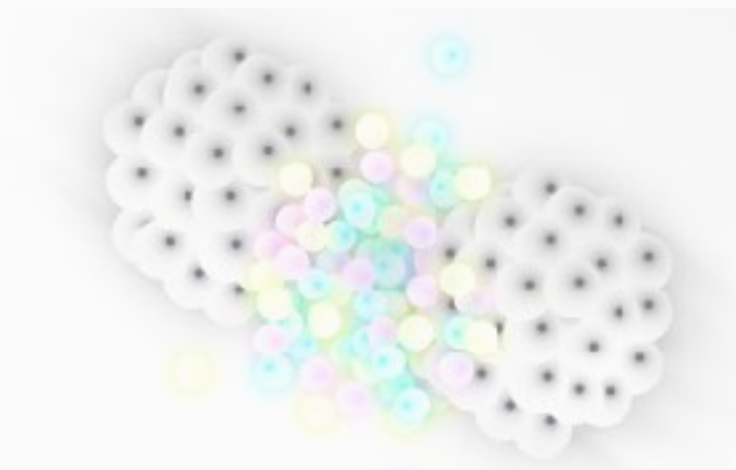


Same object independently of the “language” one uses (Th/Ph/Ex)

Jets in pp collisions



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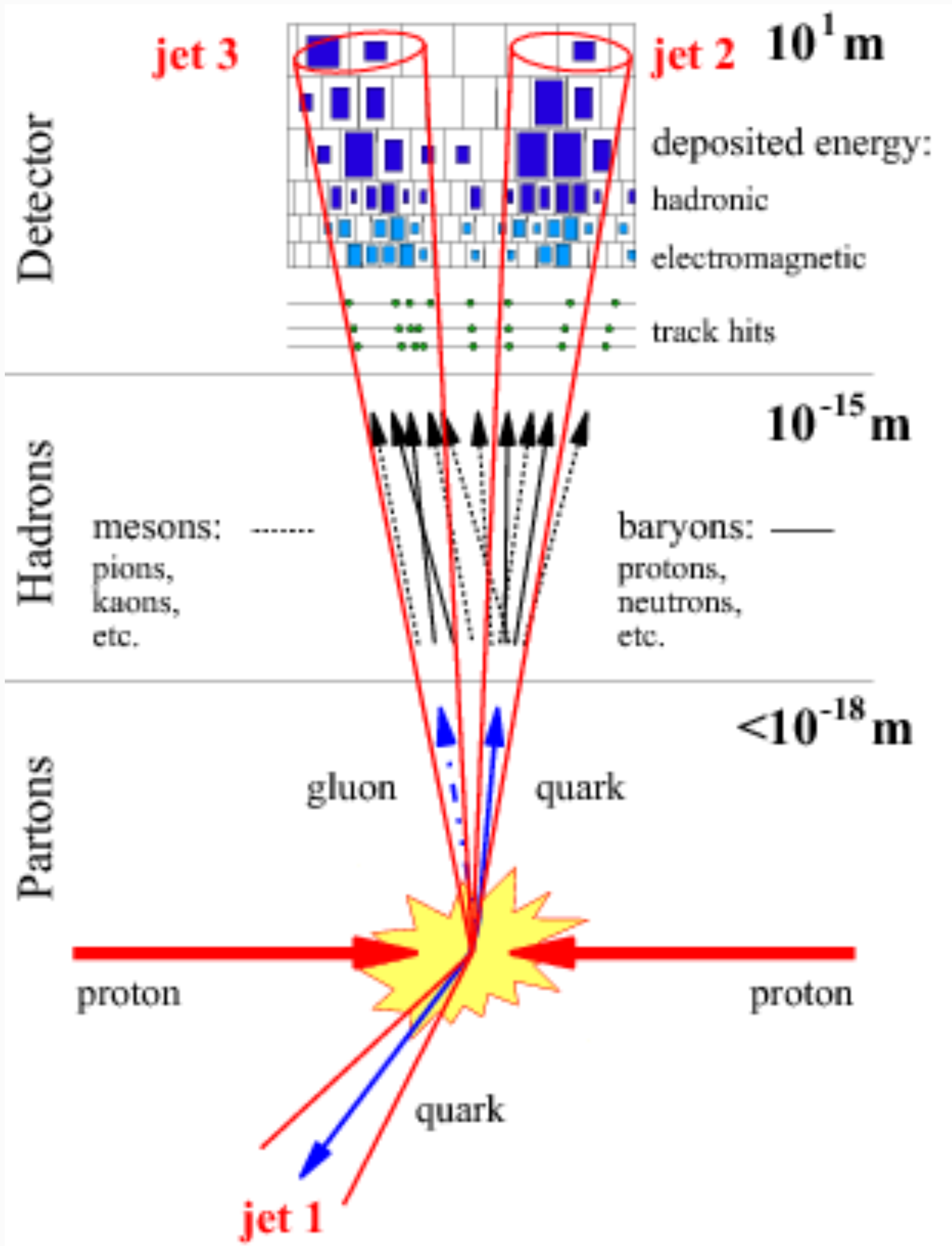

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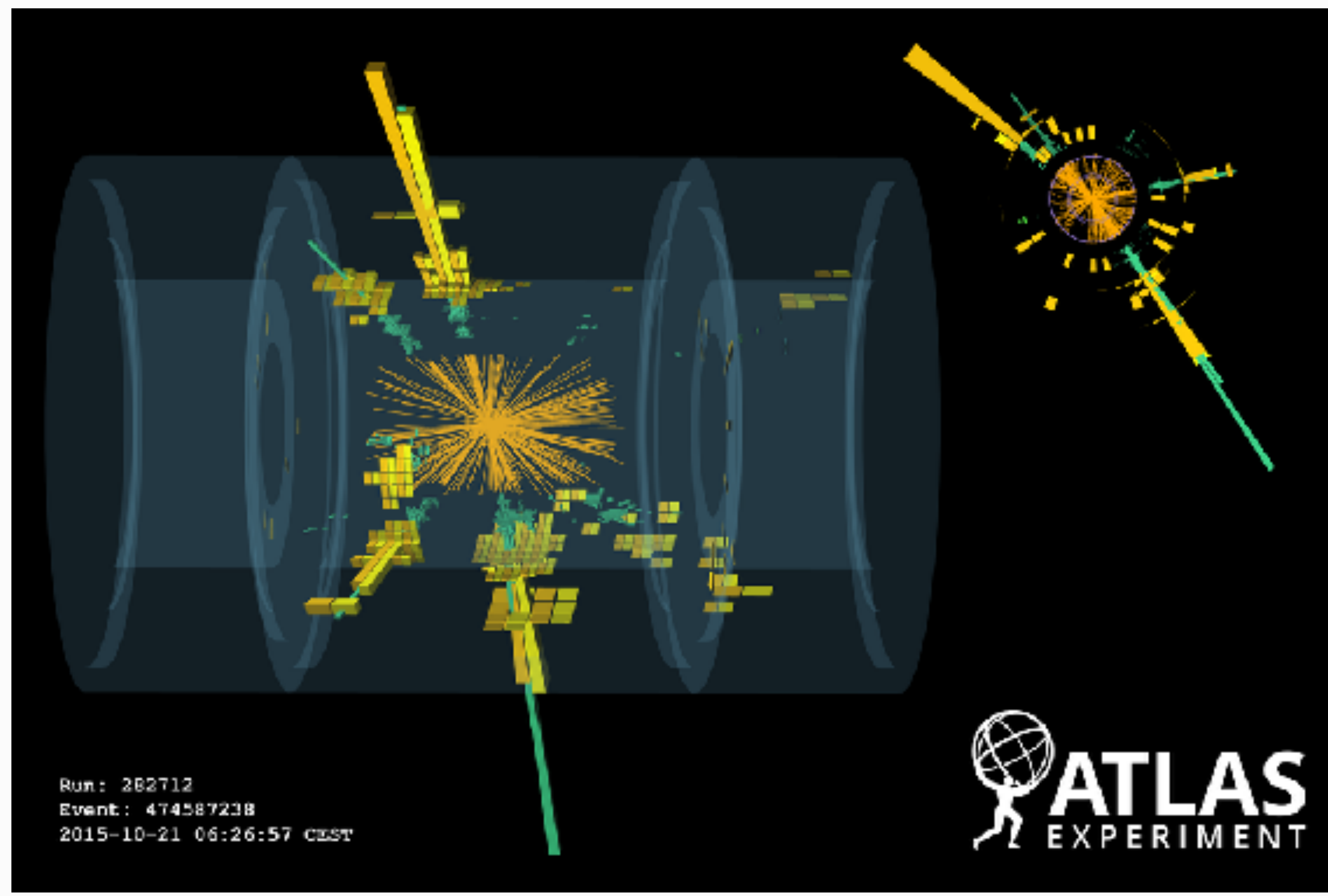

Jets in pp collisions

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Jets in pp collisions

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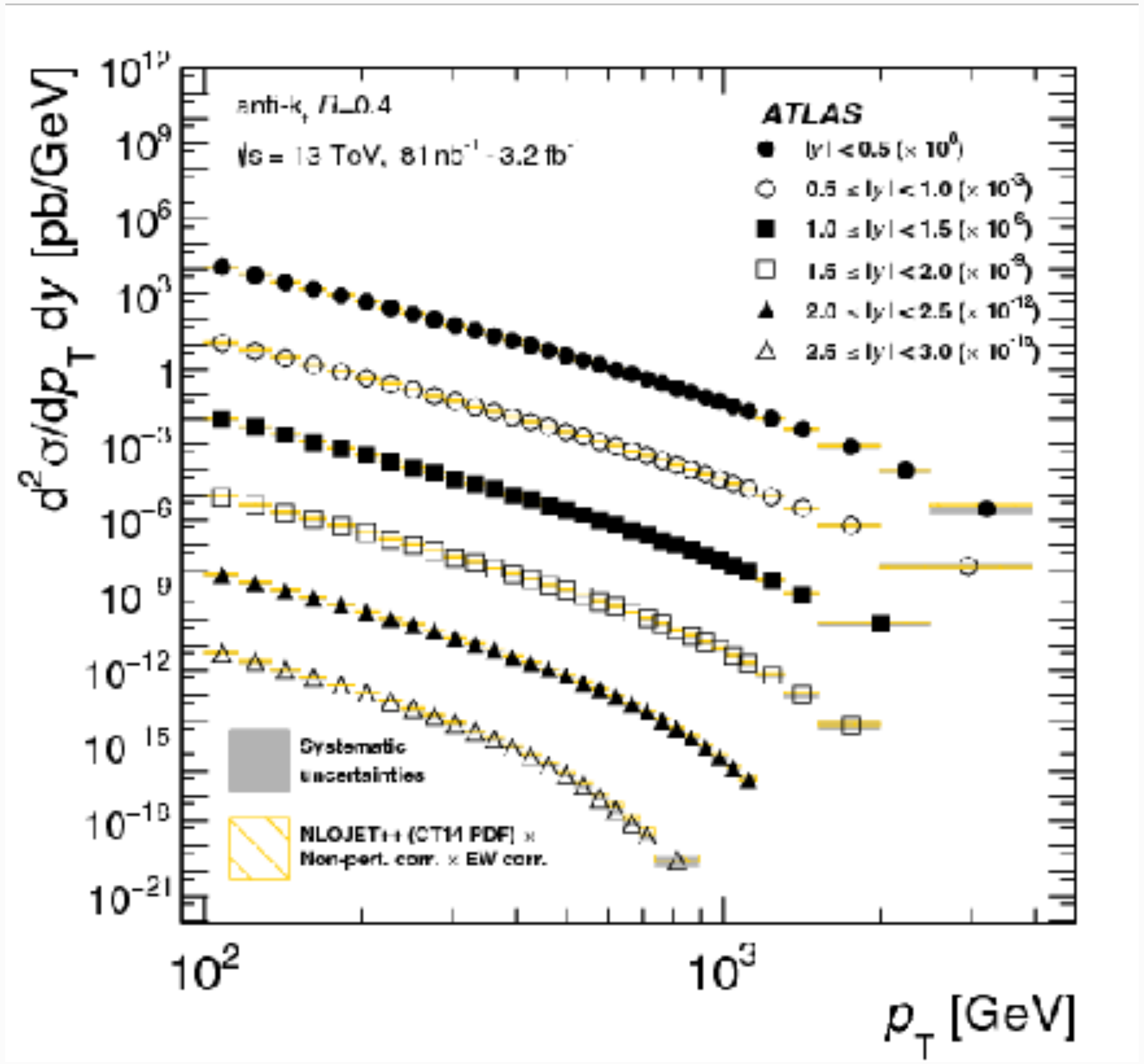
  - Theoretical understanding from first principles
    - QCD able to describe accurately jet production 10 orders of magnitude in cross-section!



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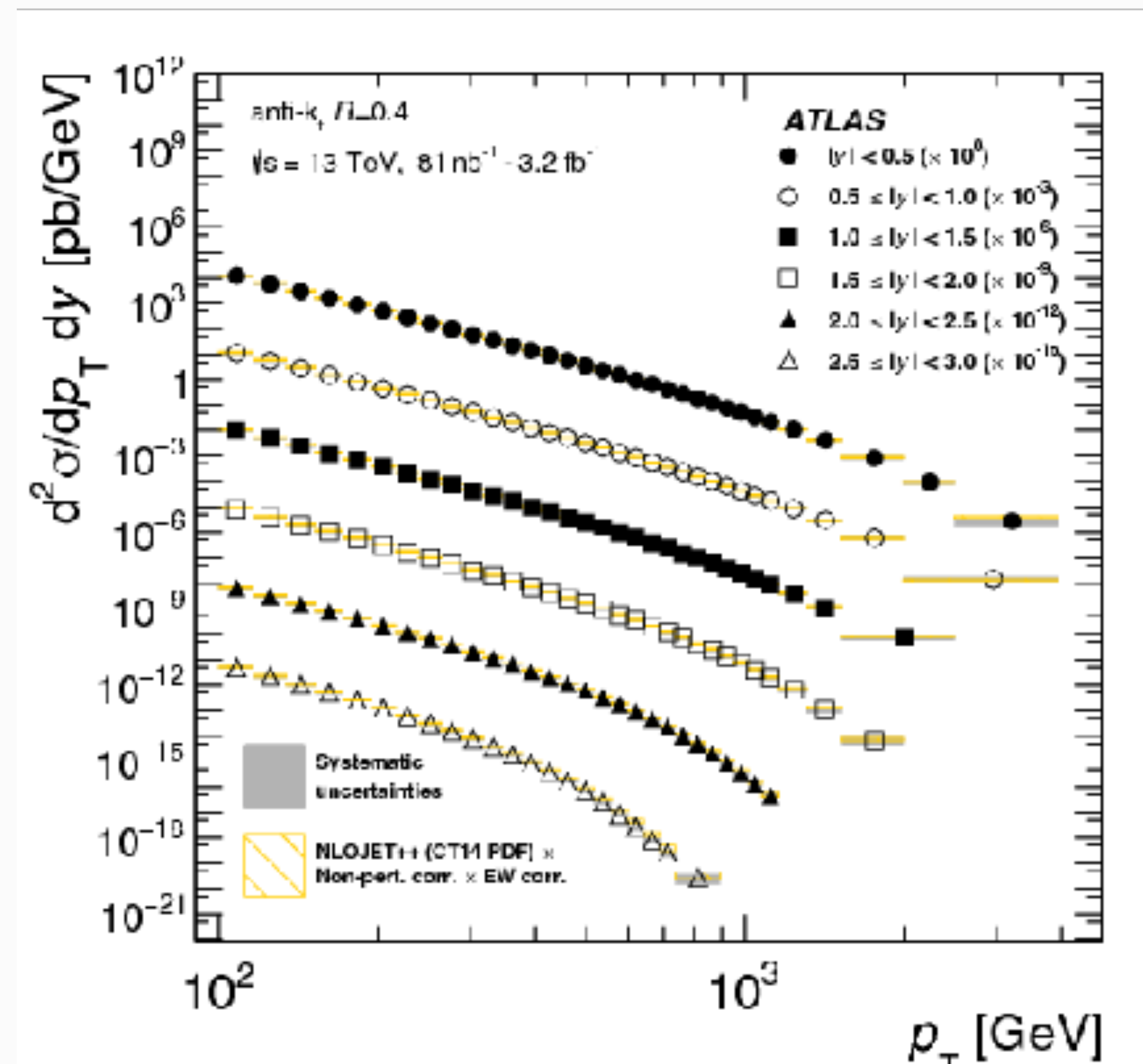

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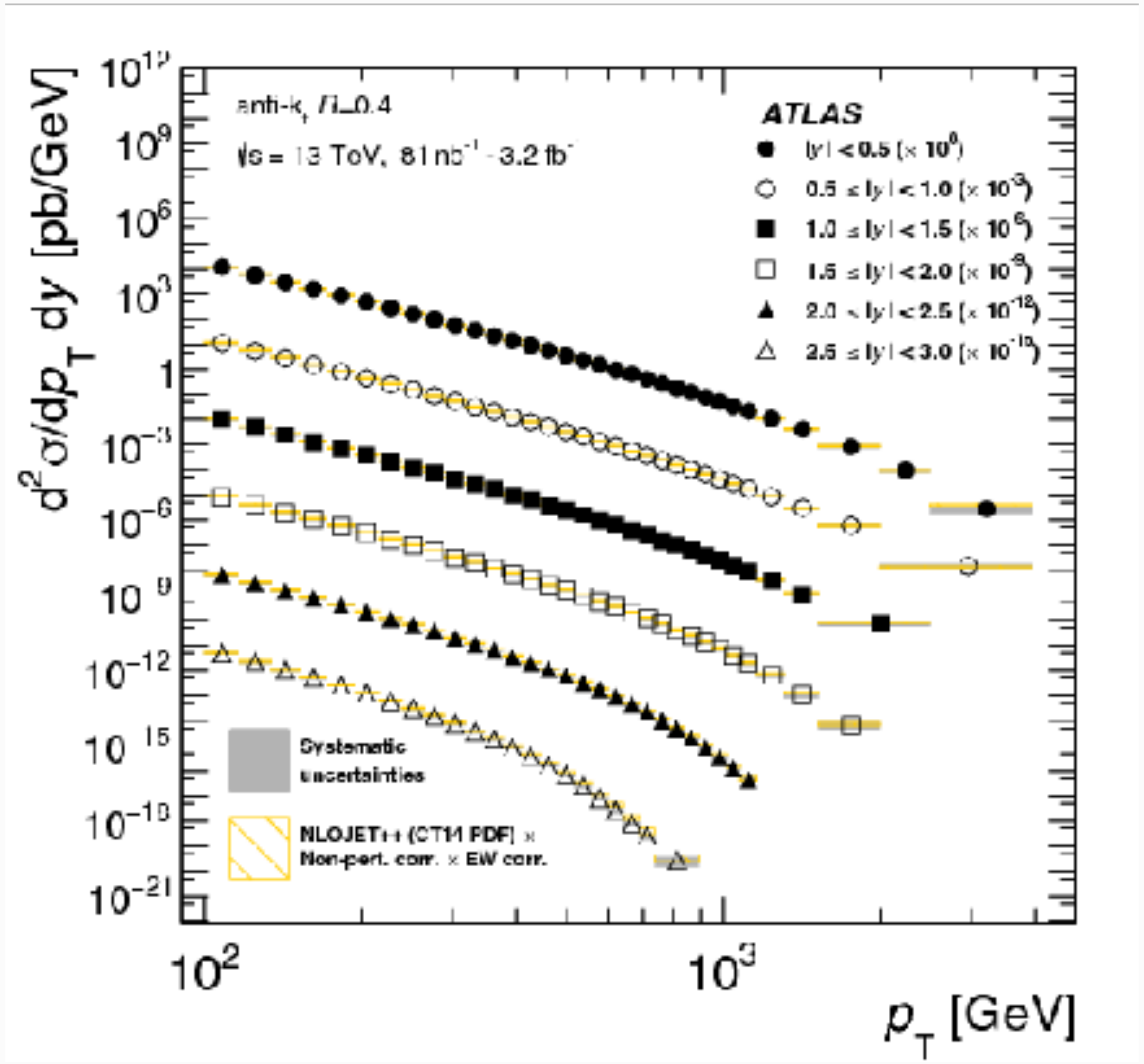

Jets reflect the behaviour of few coloured particles at a very high energy scale

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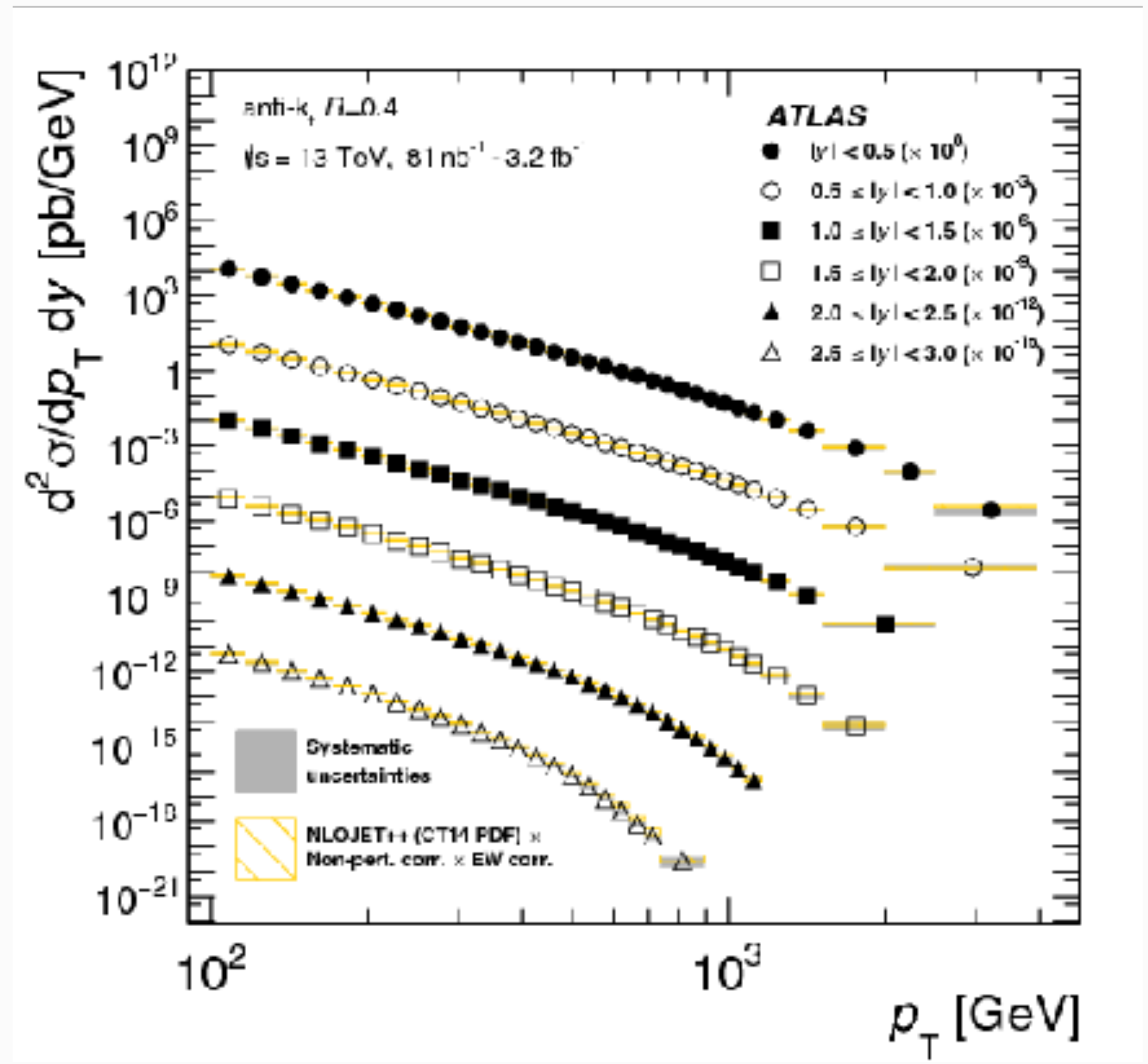
  - Well controlled experimentally
    - Used in a multitude of phenomenological studies (top quark physics, Higgs, Electroweak, BSM searches, …)

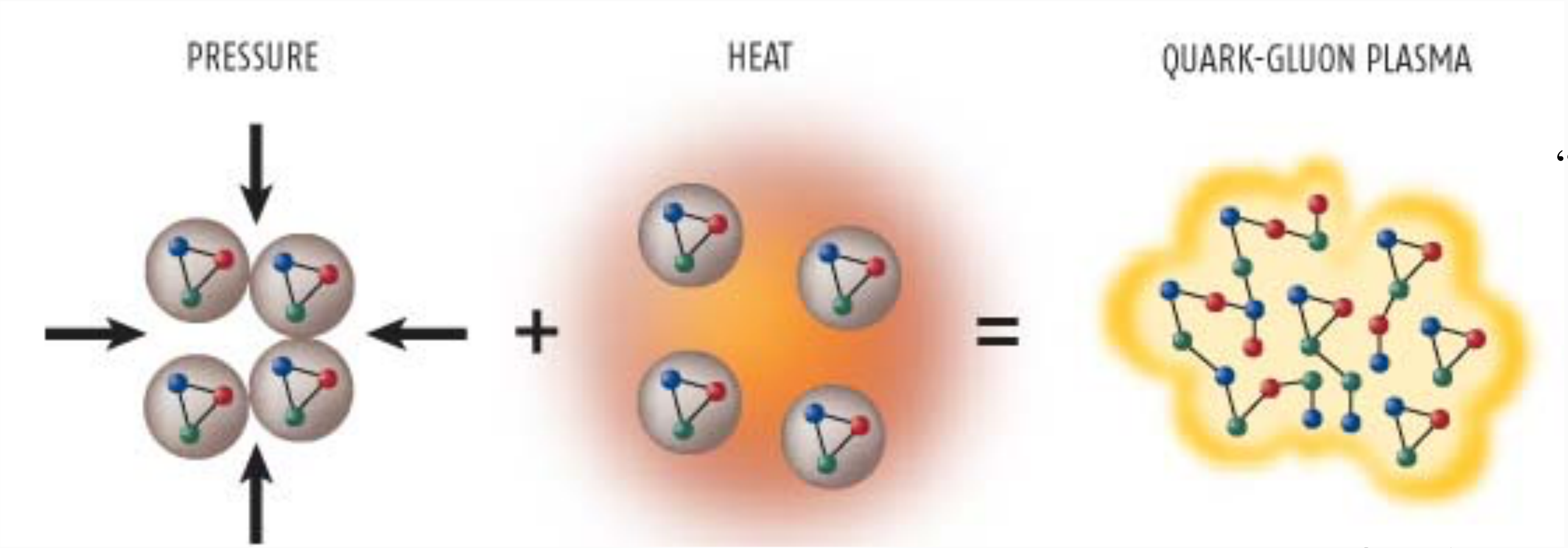


Jets reflect the behaviour of few coloured particles at a very high energy scale

Isn't a little too limited?

Quark-Gluon Plasma

- Quark-Gluon plasma (QGP)



Confined

Deconfined

QCD theory (*1973*)
SU(3) Color symmetry; confinement; asymptotic freedom, …

QGP initial idea (*1975*)
"Weakly coupling quark soup"

State of matter where quarks and gluons are asymptotically free

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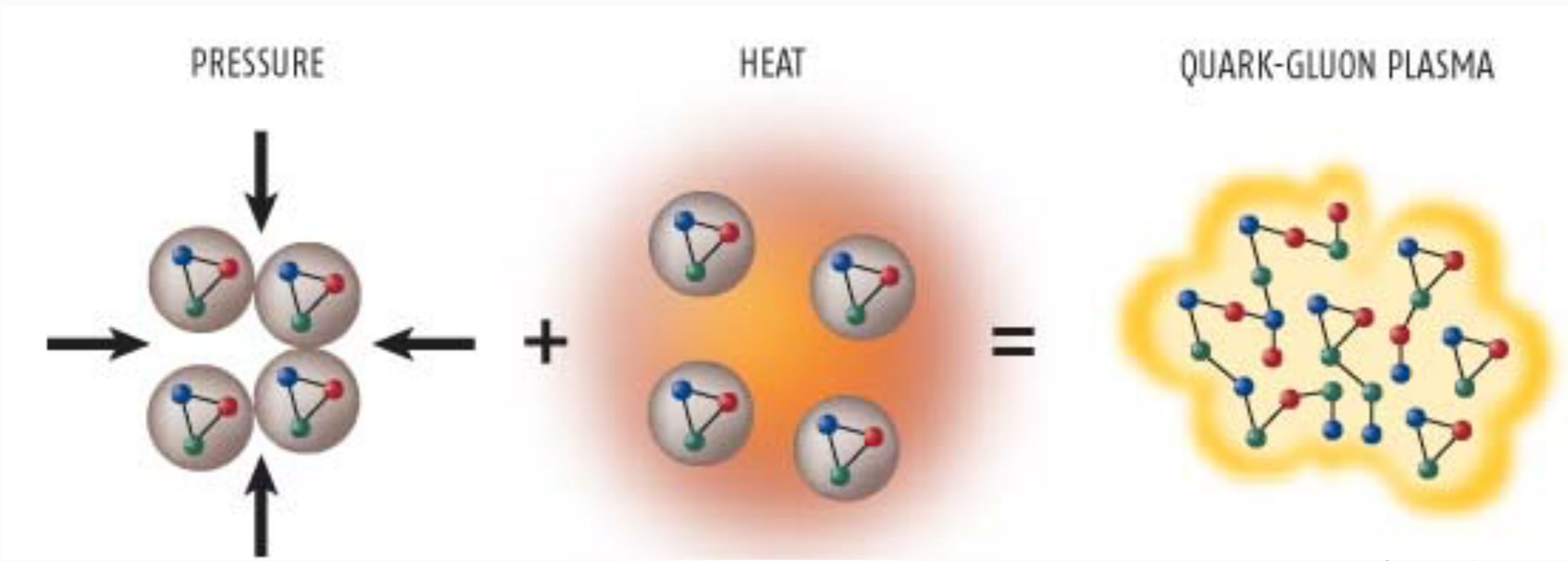

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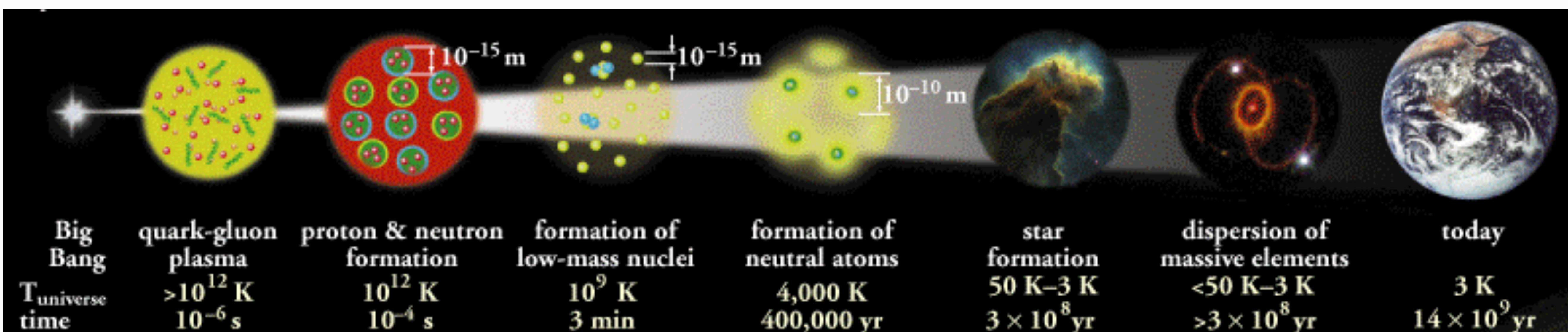

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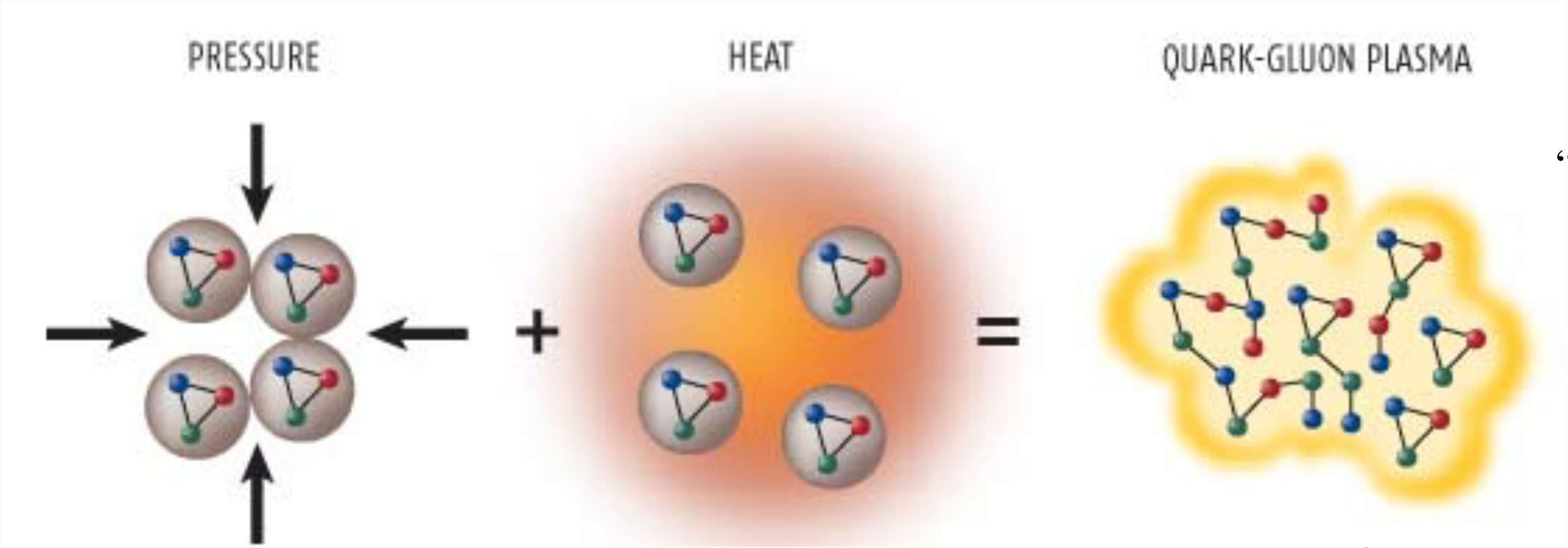

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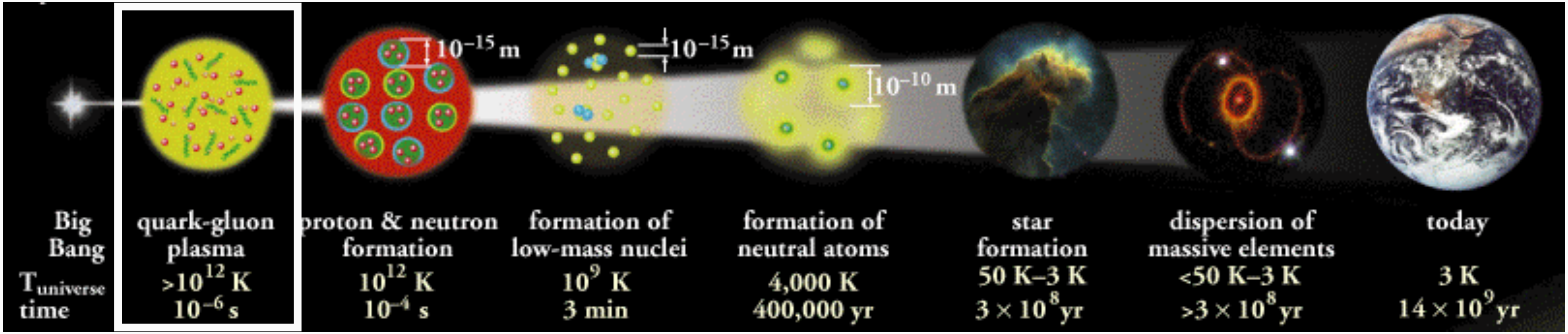
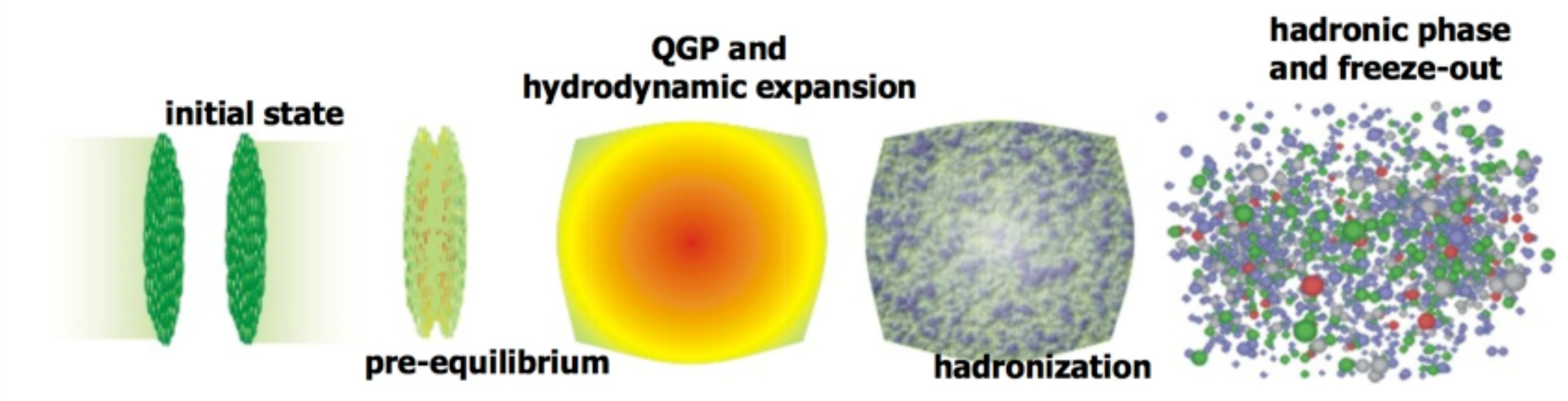


Heavy-Ion Collisions

- How to study the QGP?
  - Not by building a telescope, but by building an accelerator!

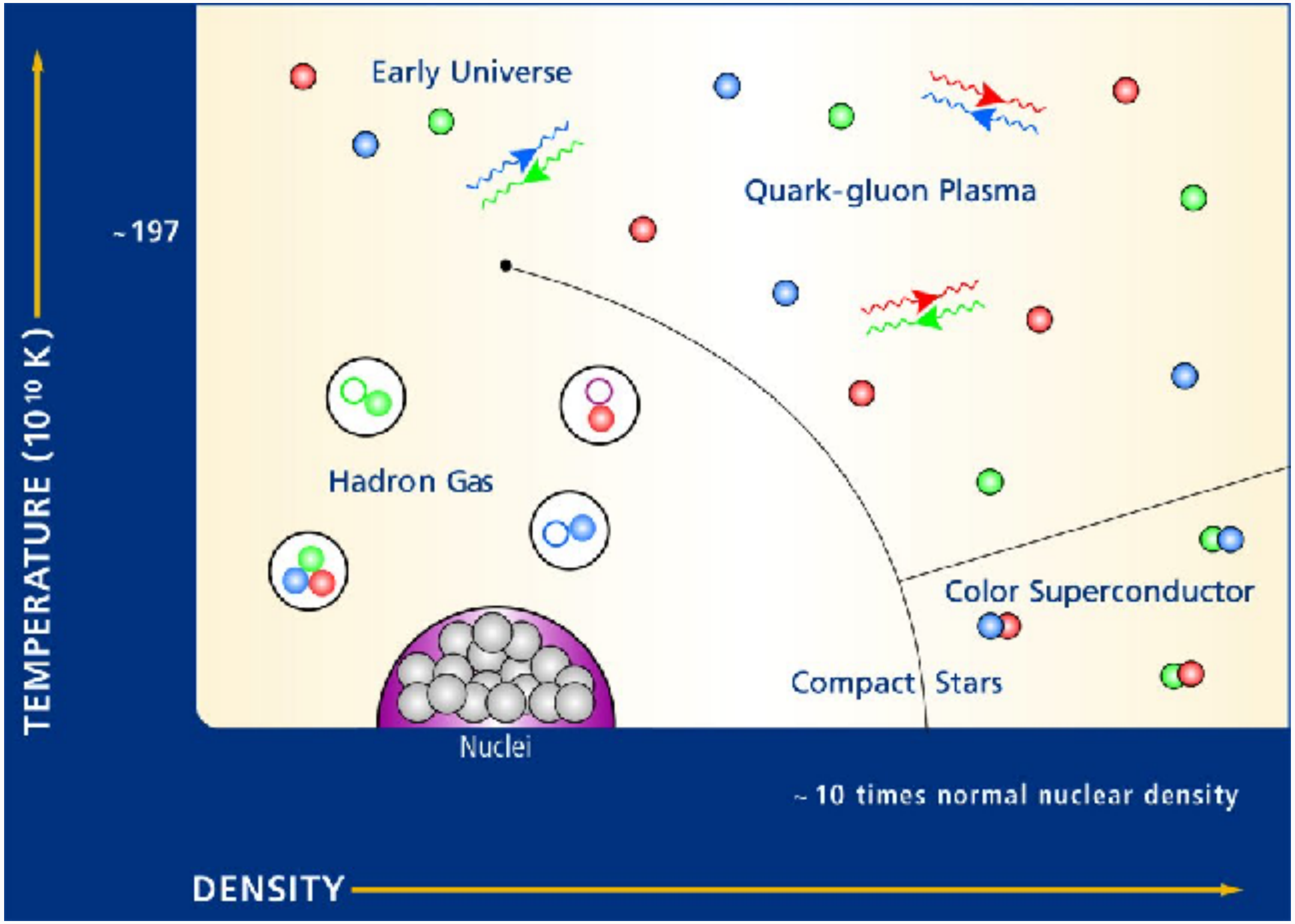


Current ultra-relativistic heavy-ion colliders:

	RHIC	LHC
$\sqrt{s_{cm}}$ (TeV)	0.2	2.75/5.5
Nuclei	AuAu	PbPb

QCD Phase Diagram

- Exploring the QCD Phase diagram:



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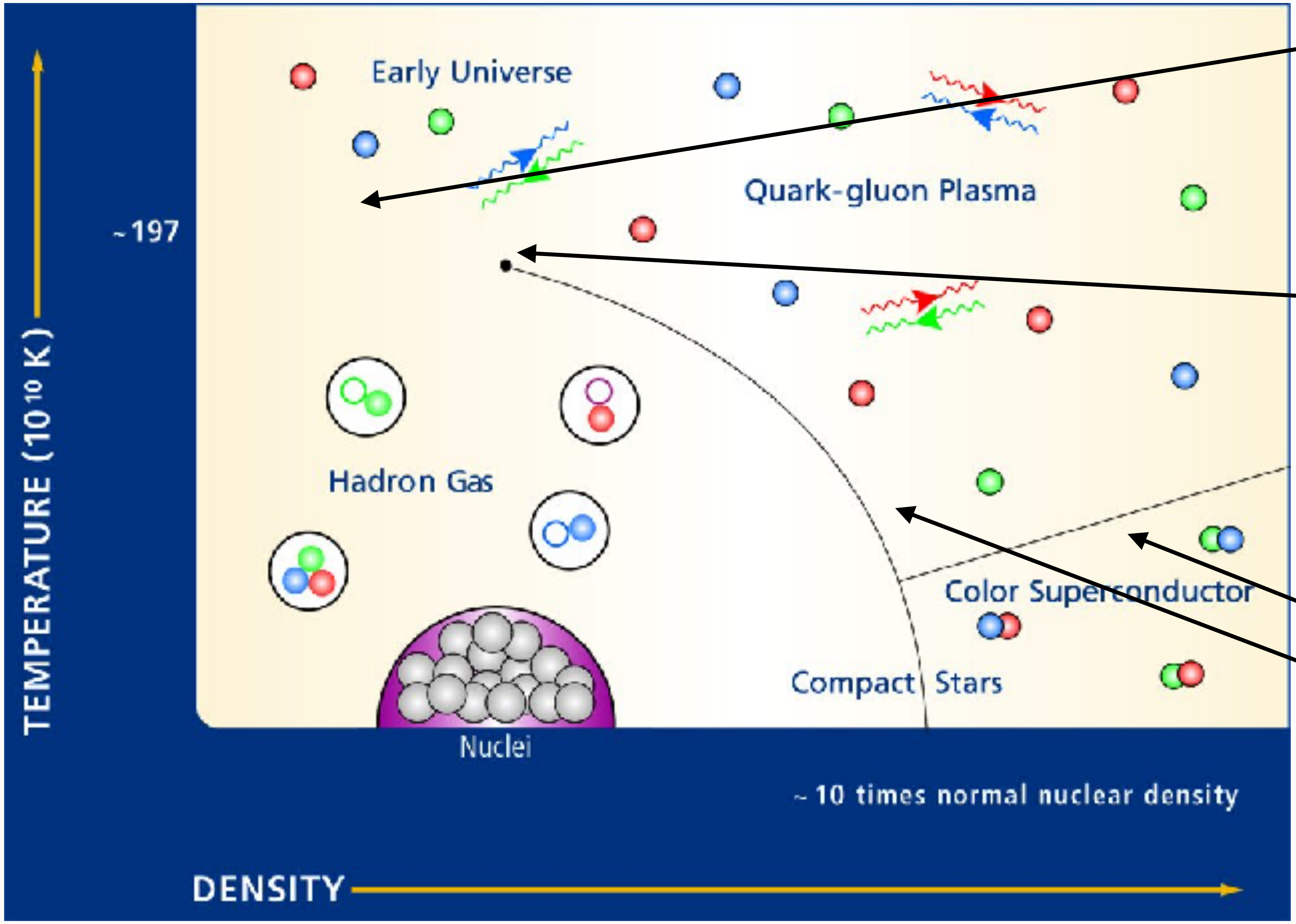

Cross-Over
(second order phase transition)

Critical point (?)

First order phase transition
(thermodynamic singularities
of the system)

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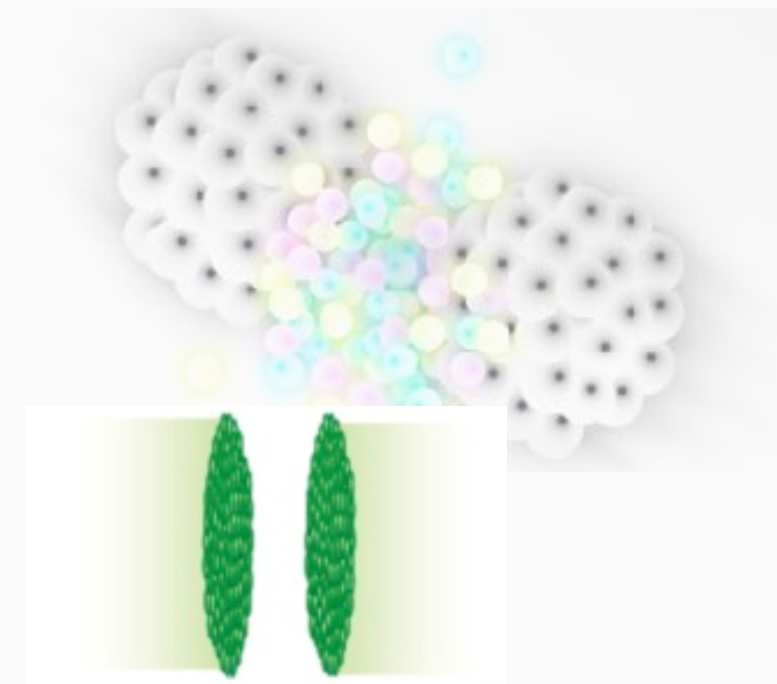

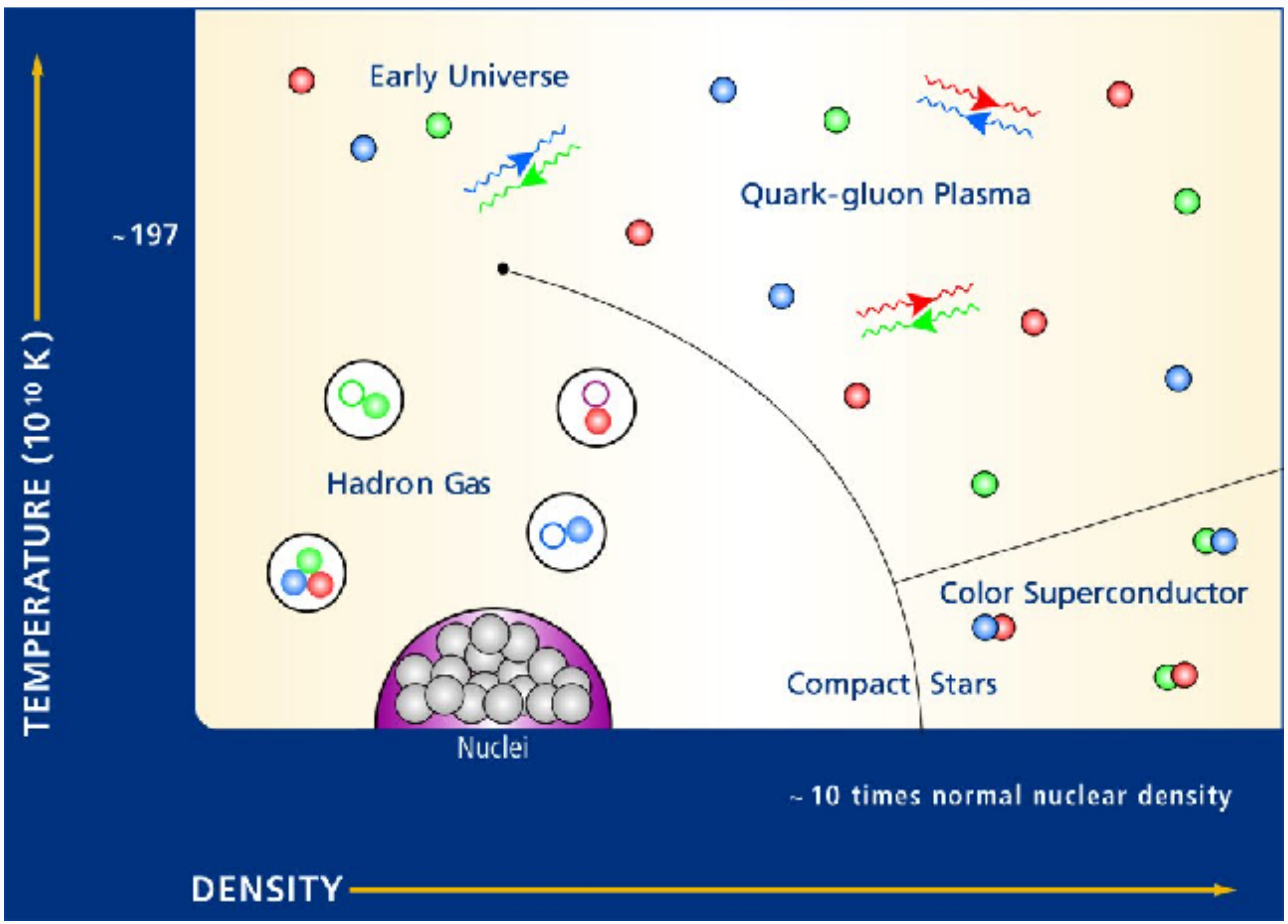

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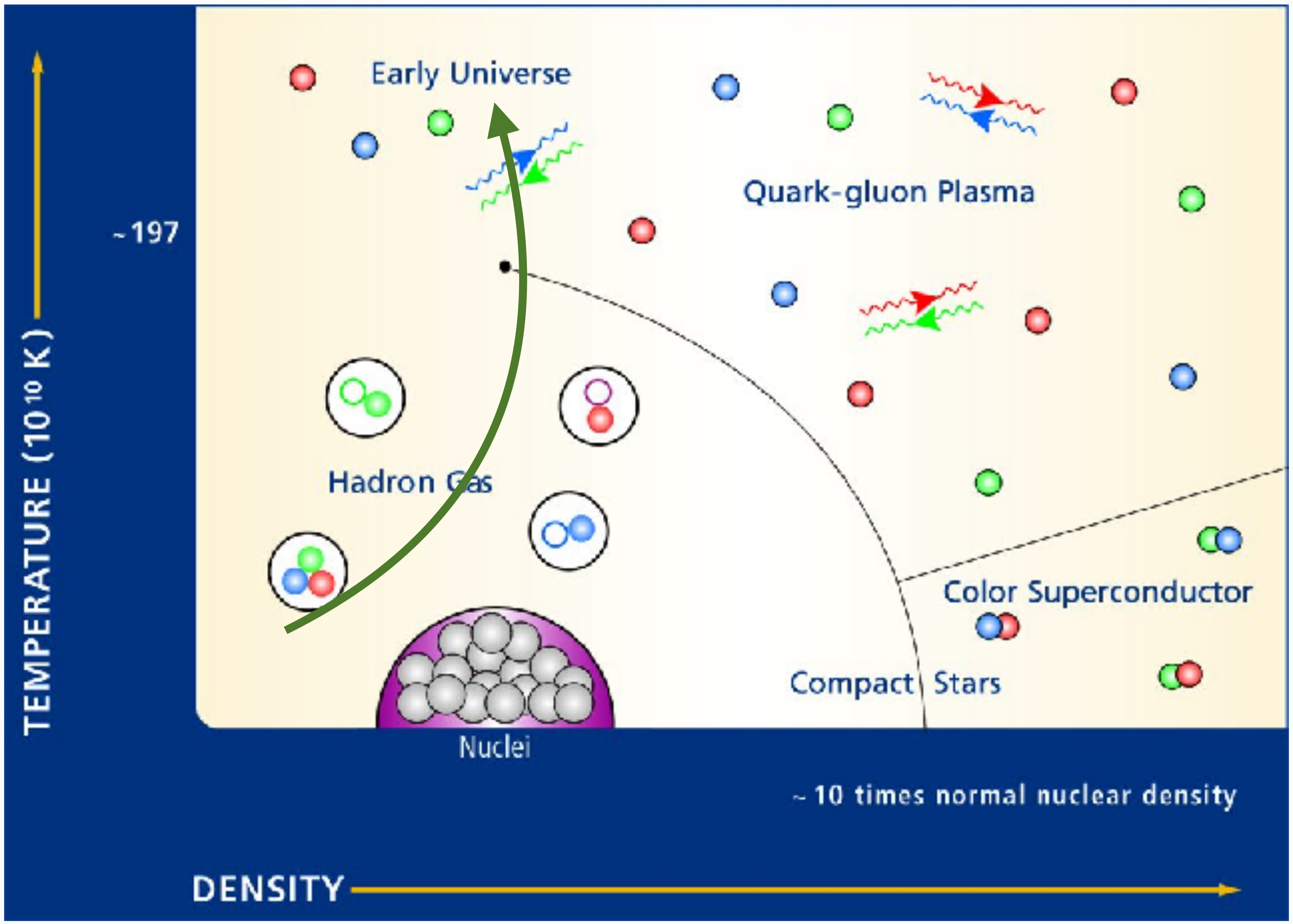

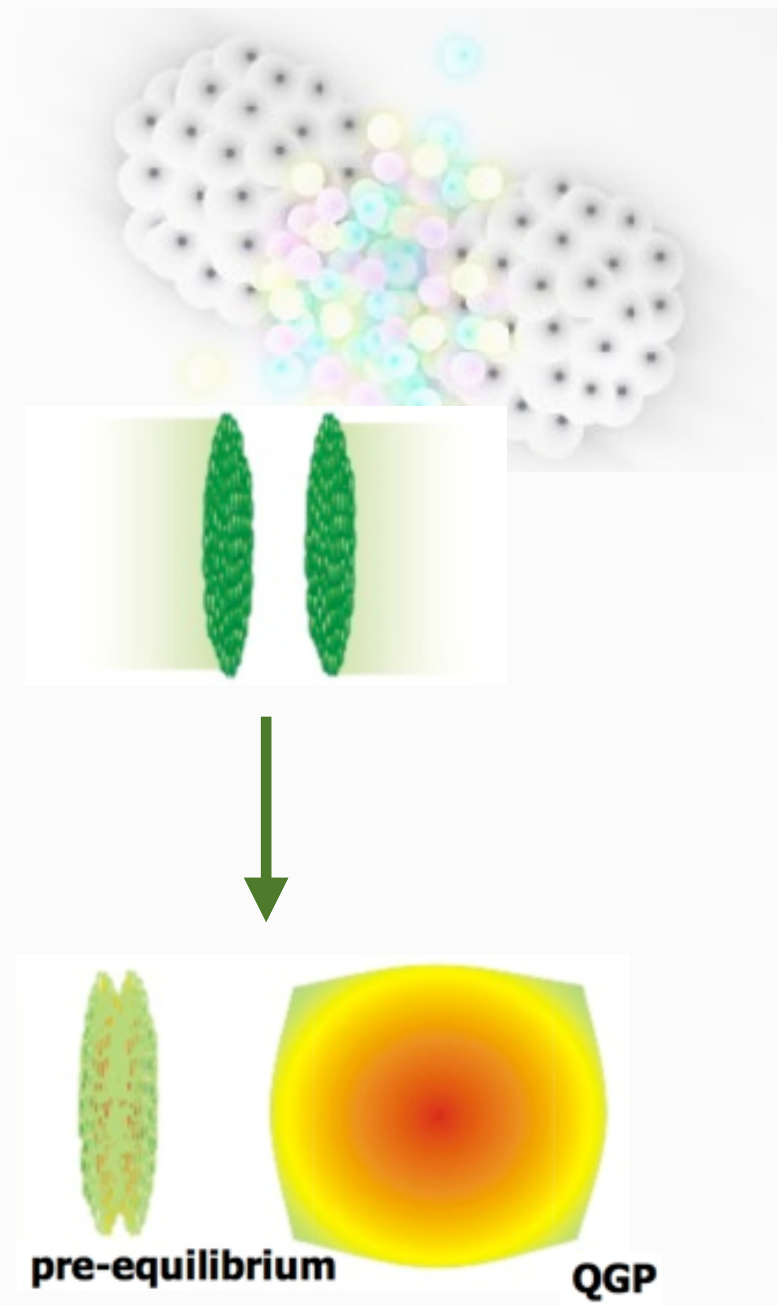

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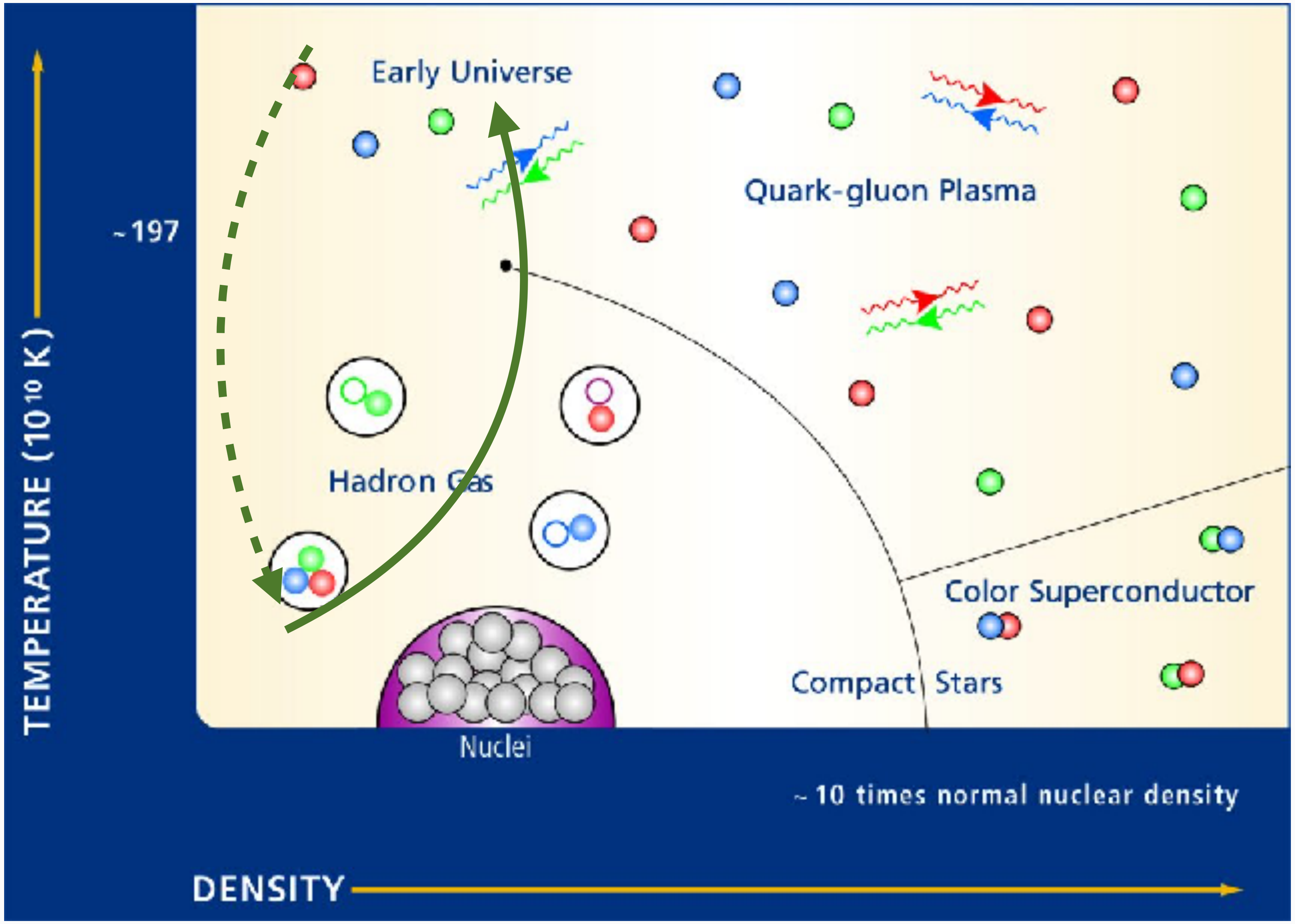

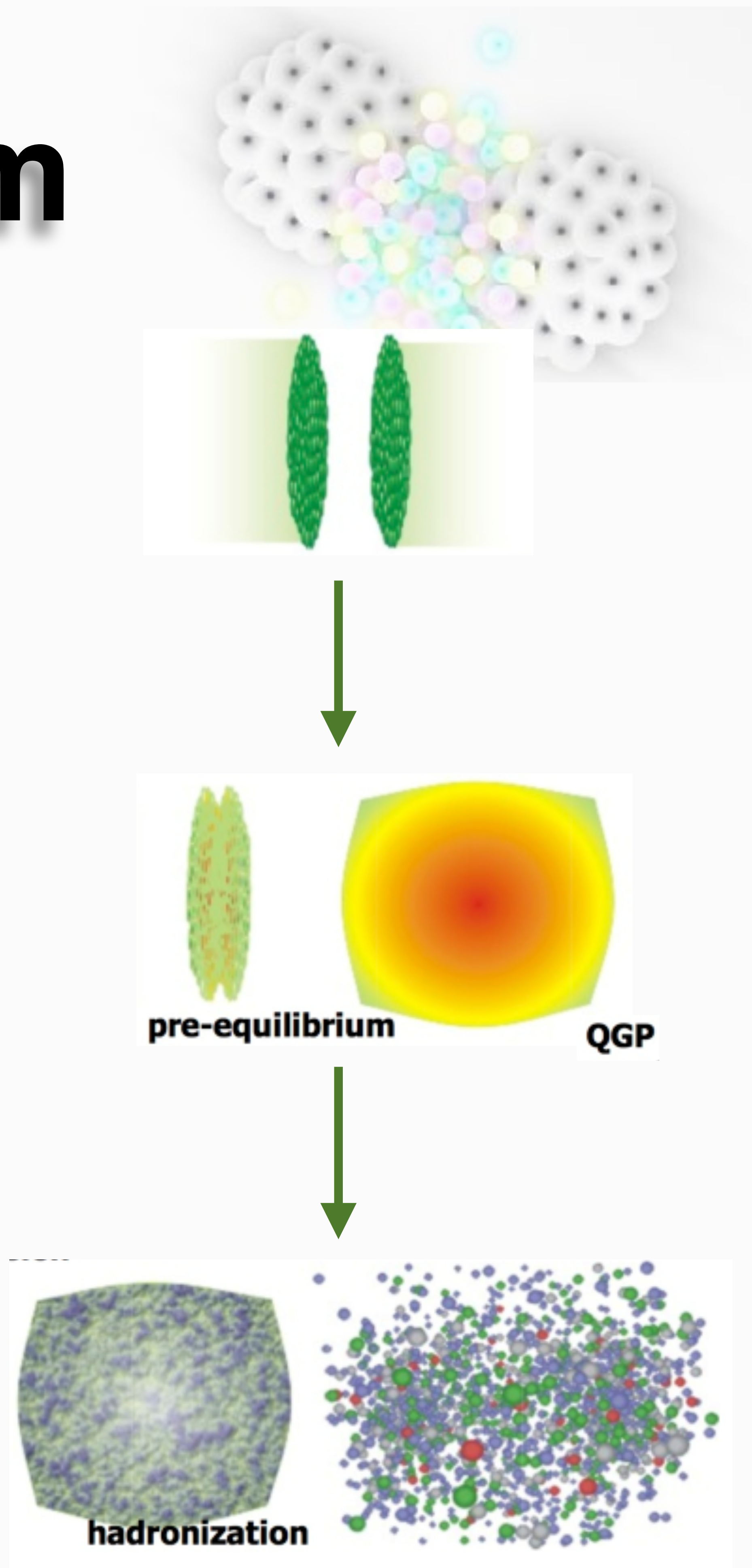

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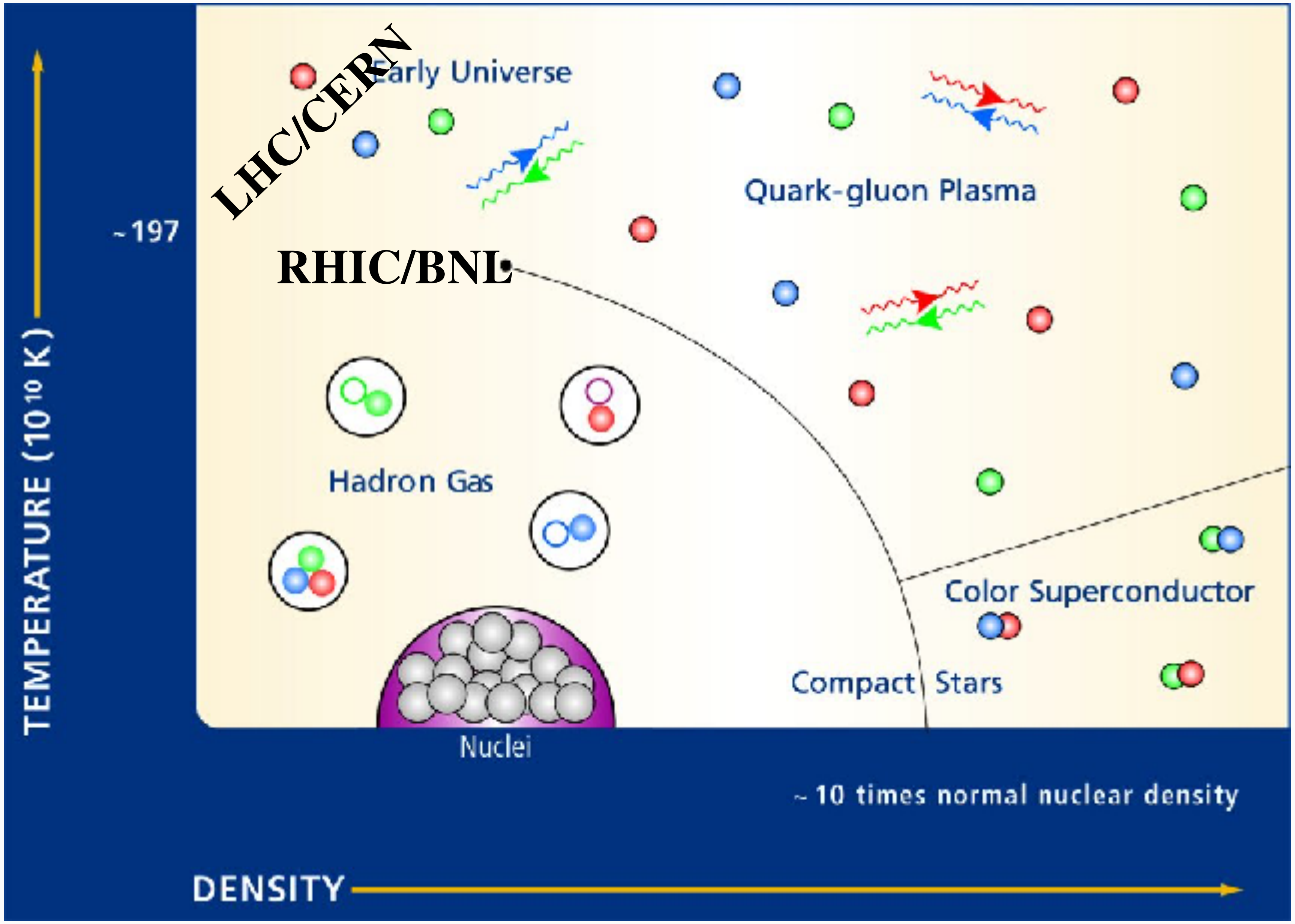

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- Why are quarks confined into hadrons?
- Why are hadrons massive and what is the relation to chiral symmetry breaking?
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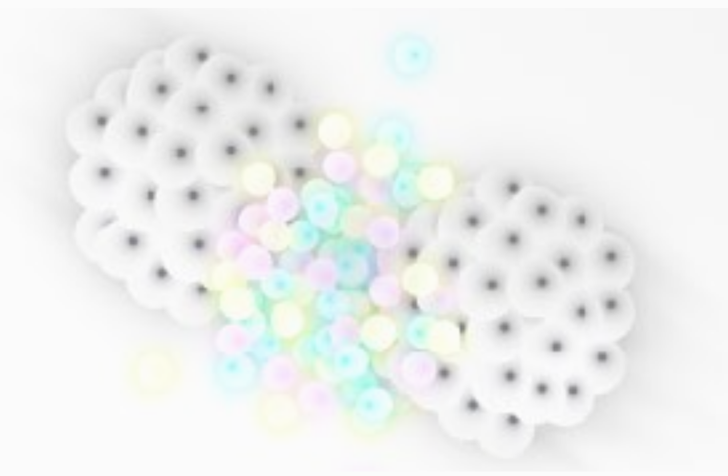

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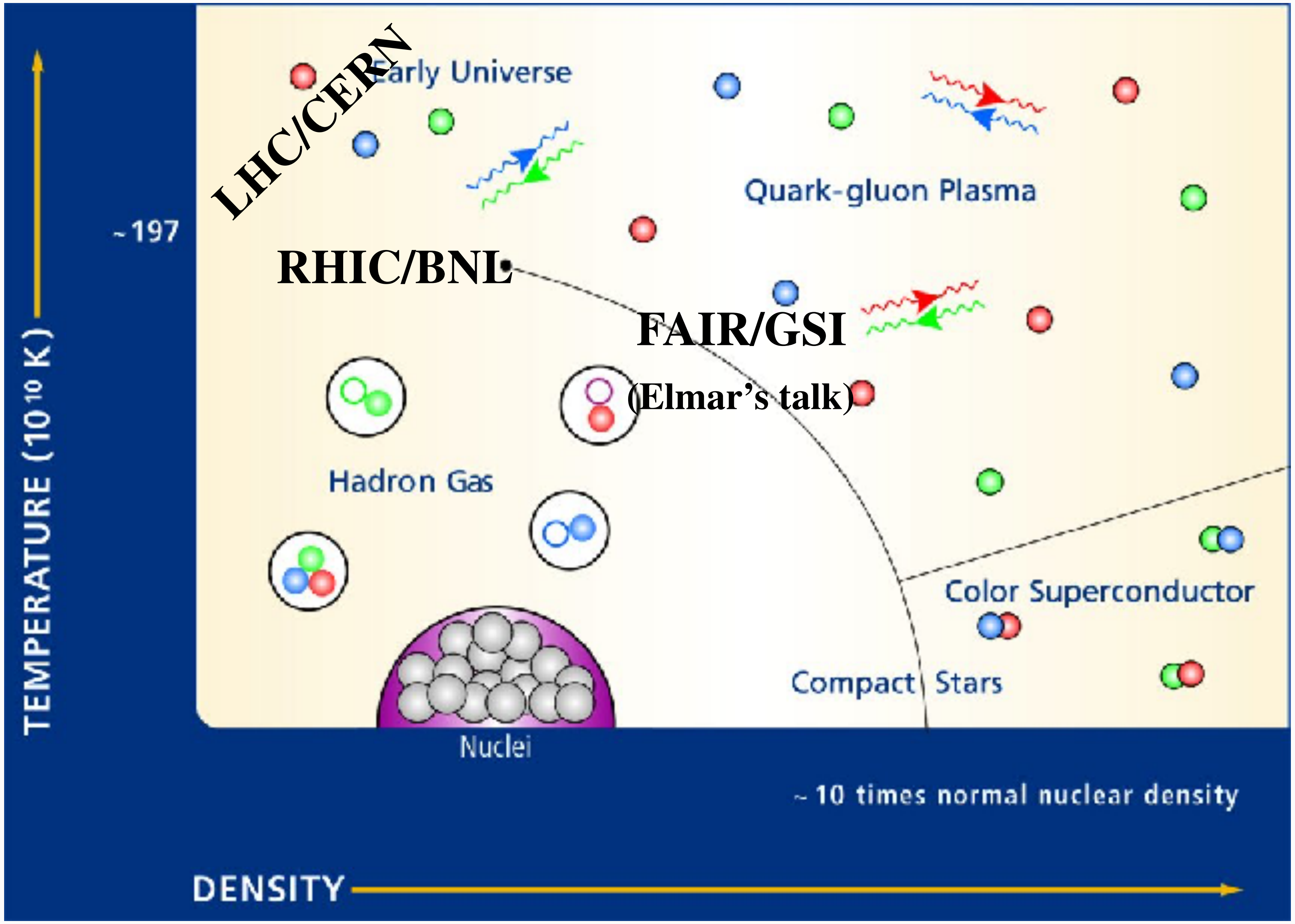

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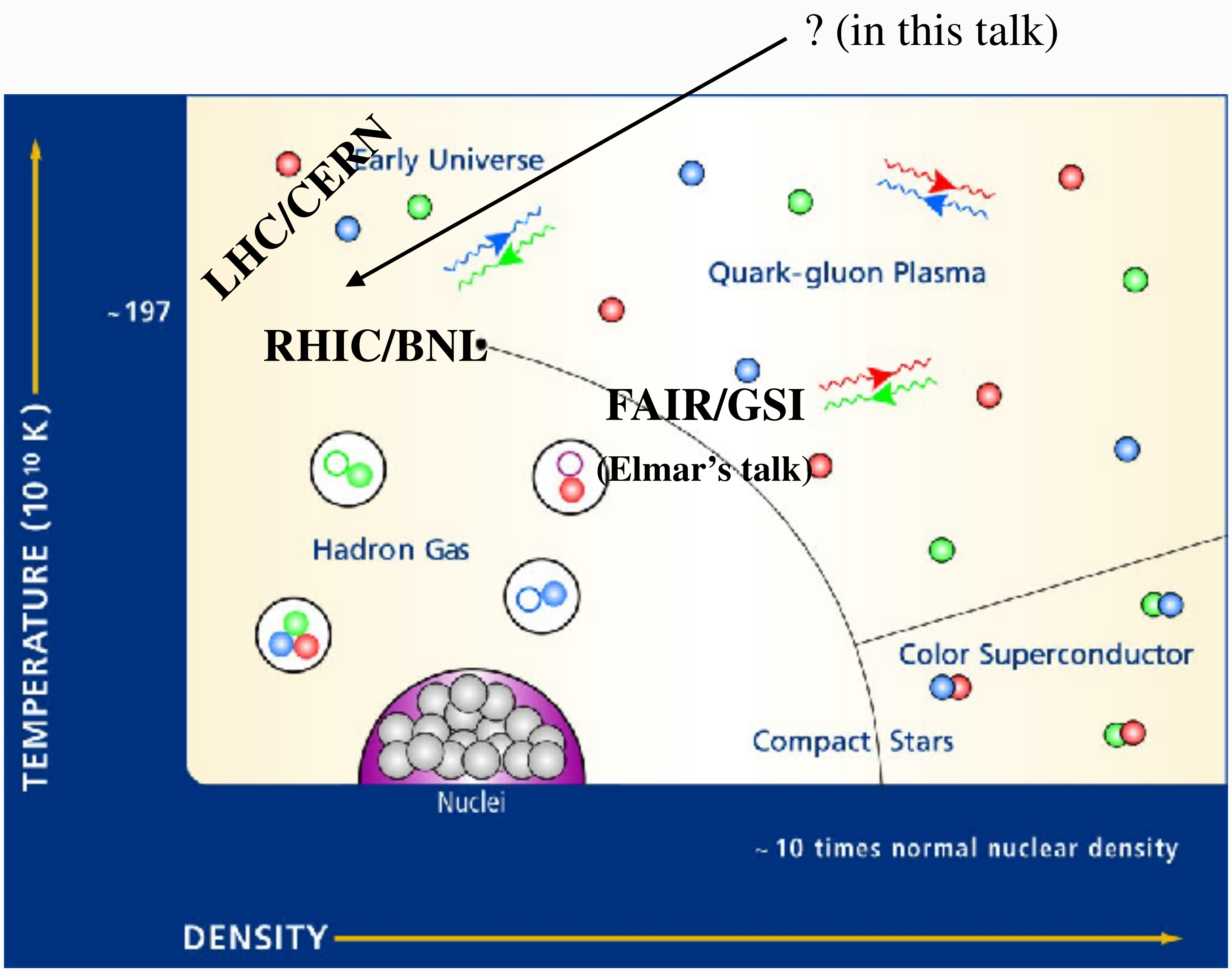

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Probing the QGP

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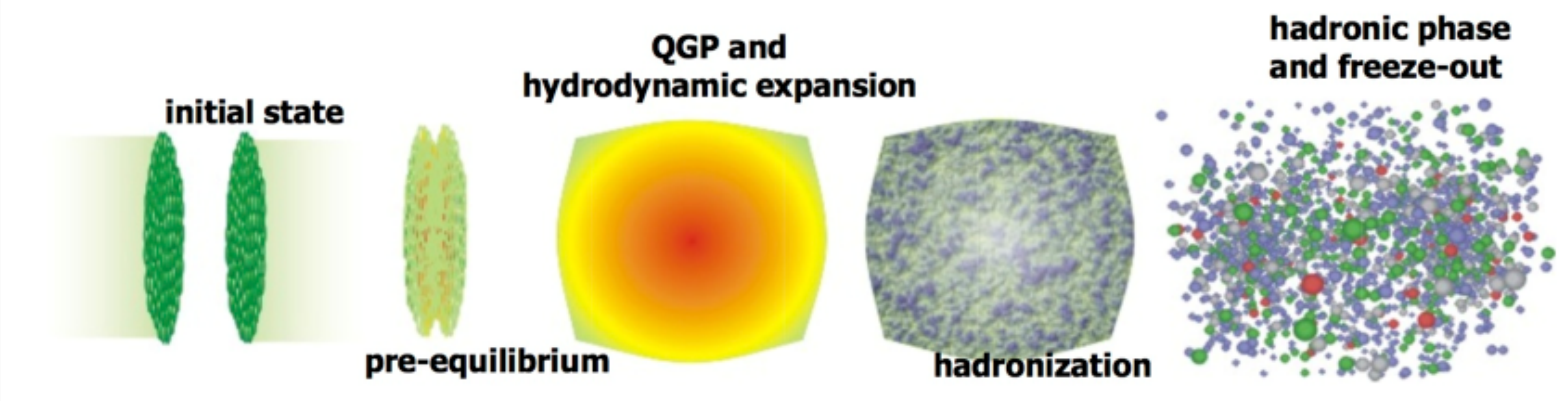

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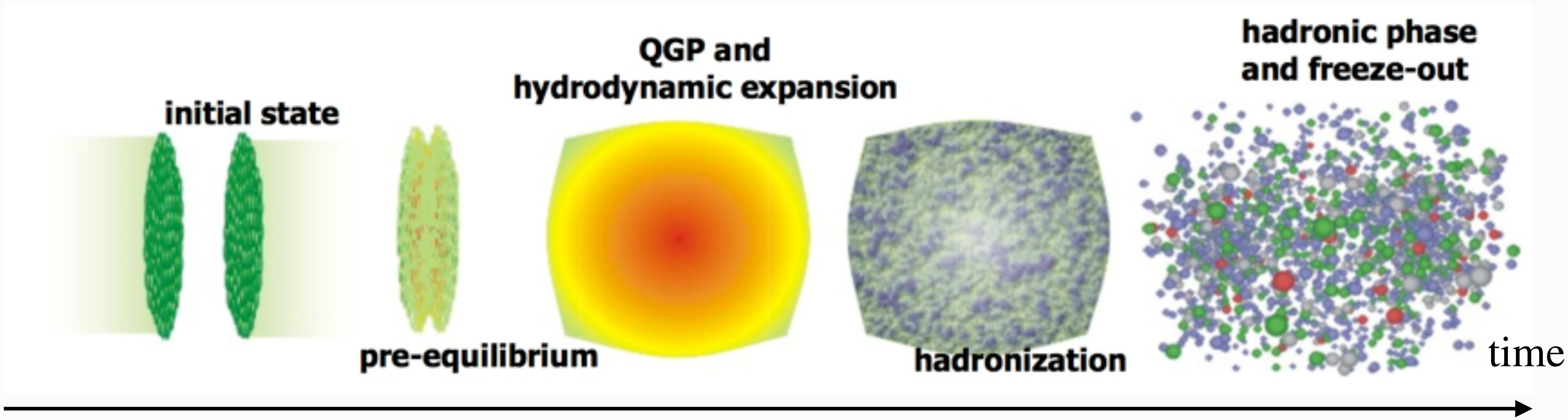

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Very short timescales… QGP probing is done indirectly.

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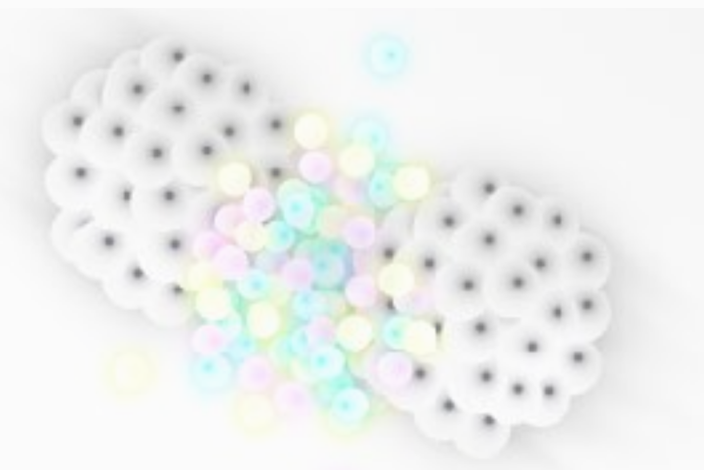

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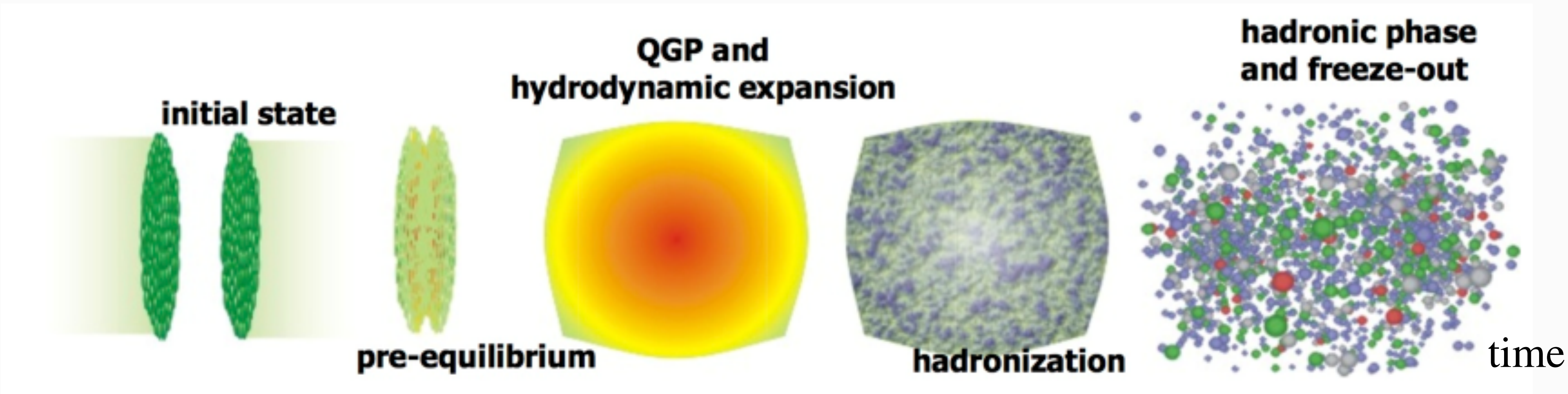

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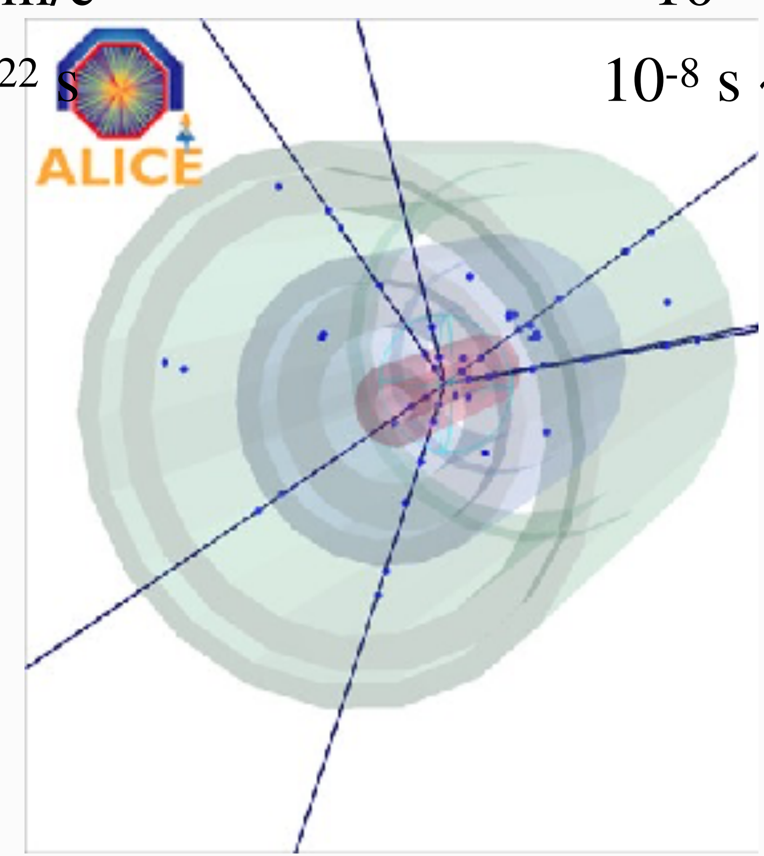

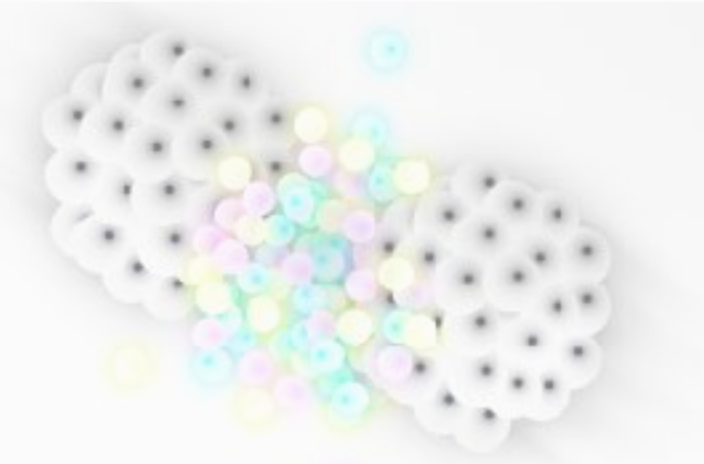

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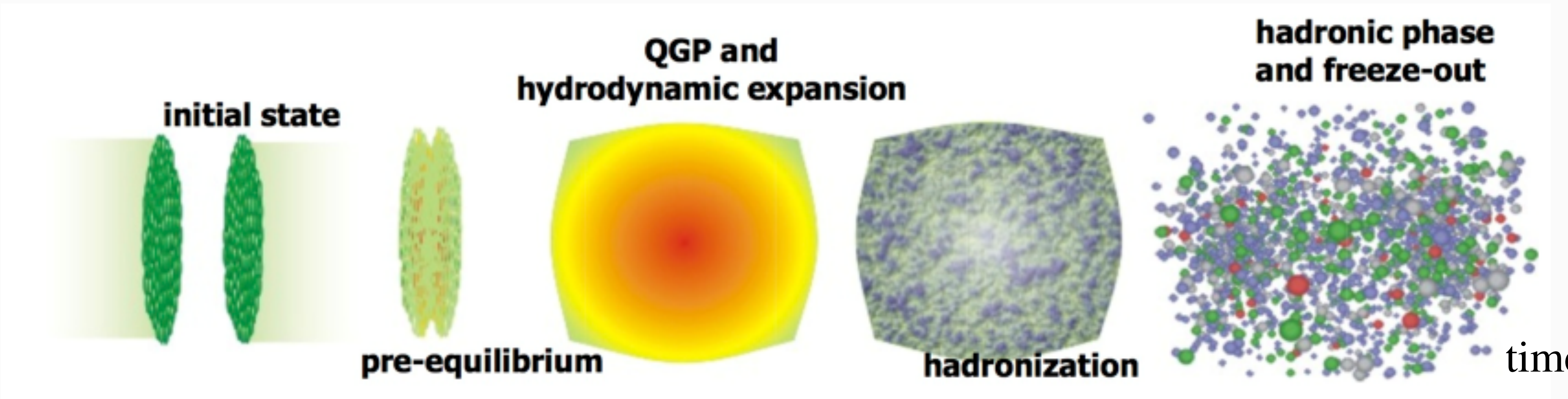

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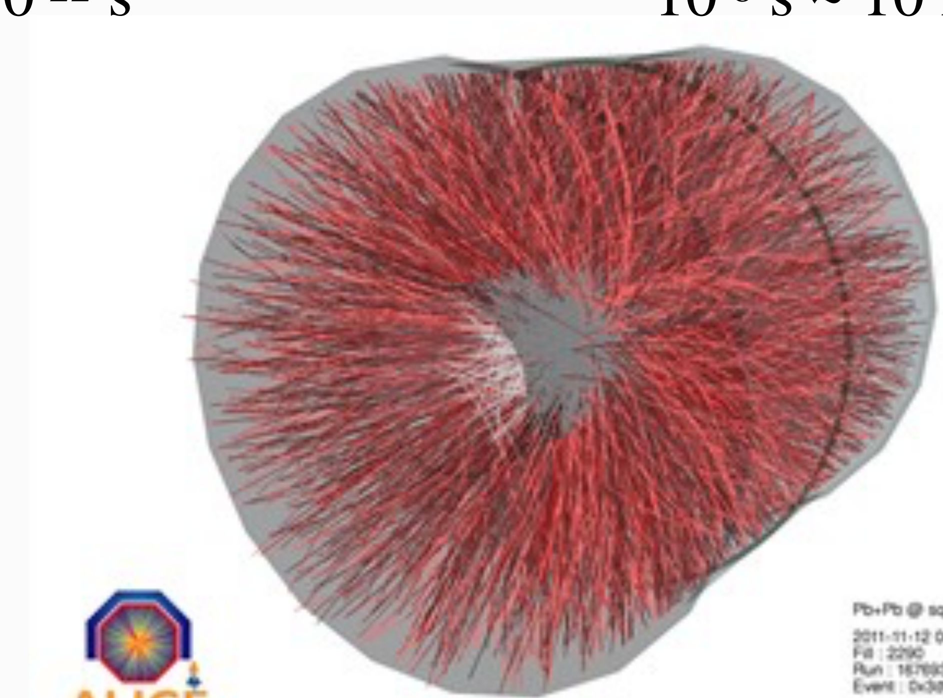

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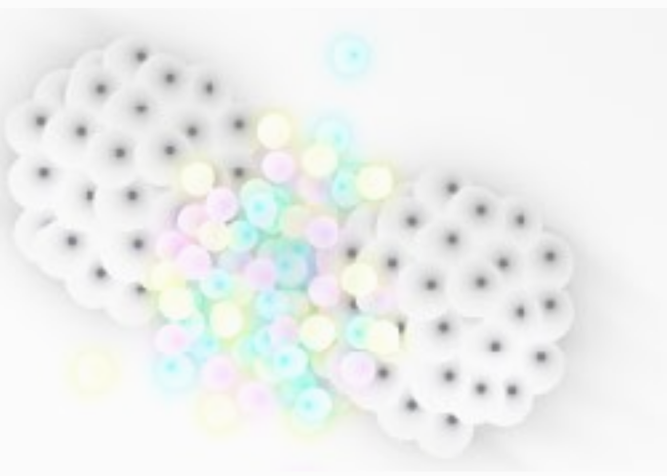

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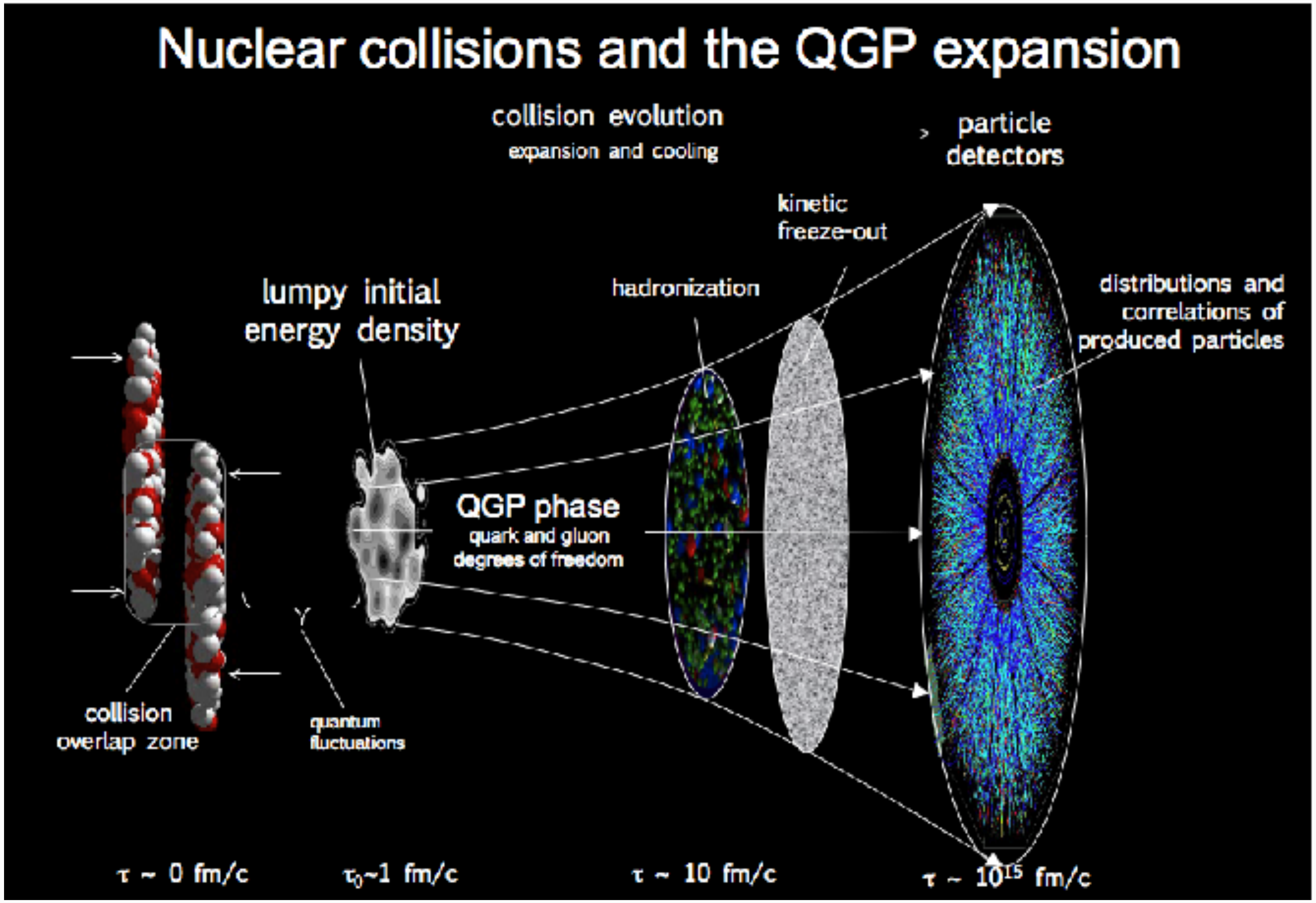

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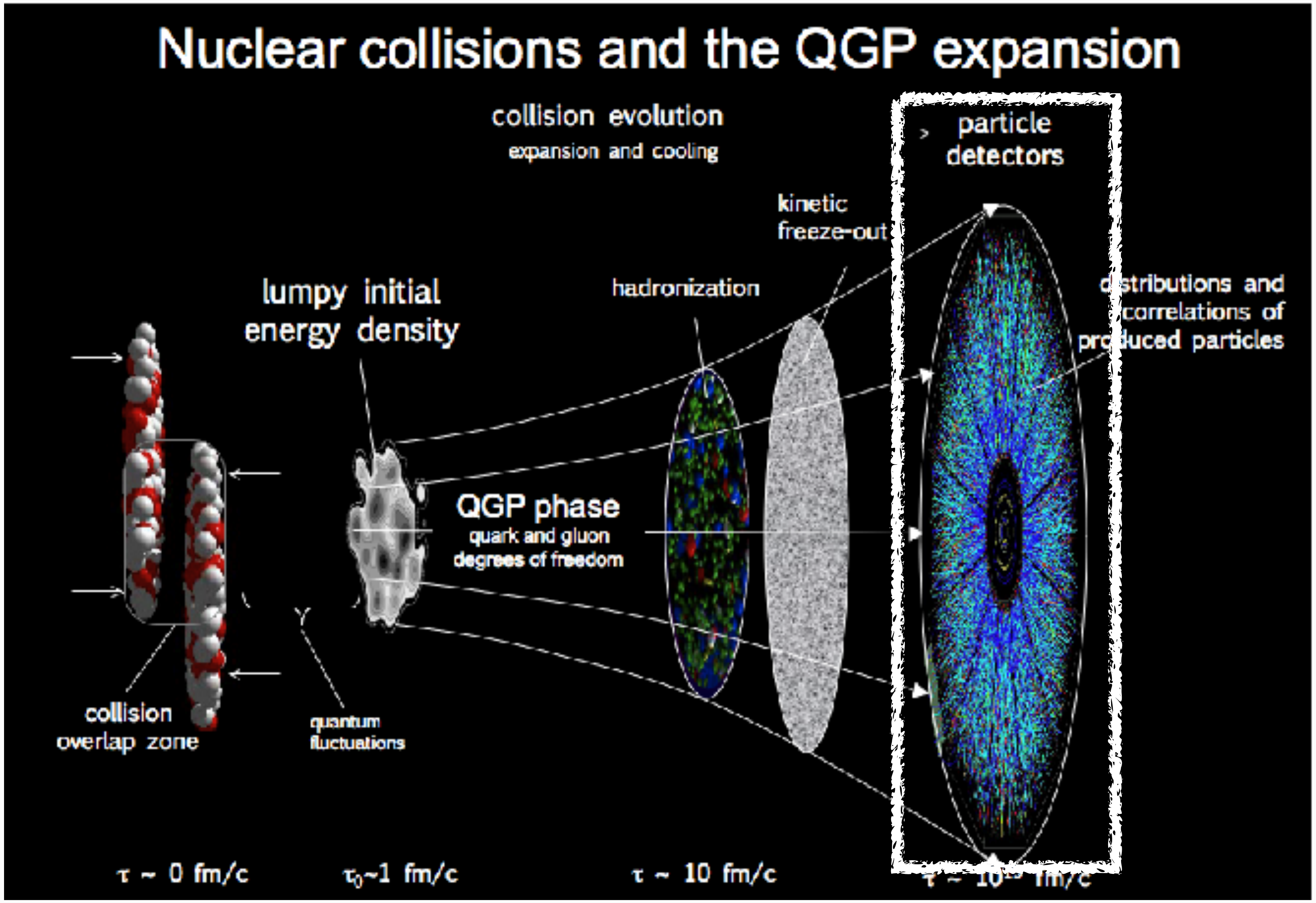
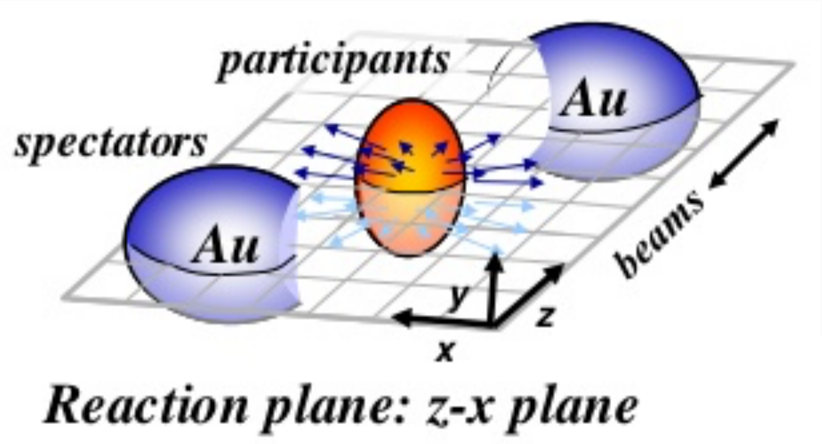


Bulk of particles can give information on the QGP properties (collectivity, viscosity, …)

Soft probes

- Spatial and Momentum distribution of the produced particles
  - Local or large scale collective behaviour?

Try different centrality collisions



(defines azimuthal angle Ψ_R)

Response of the system to initial spatial anisotropy

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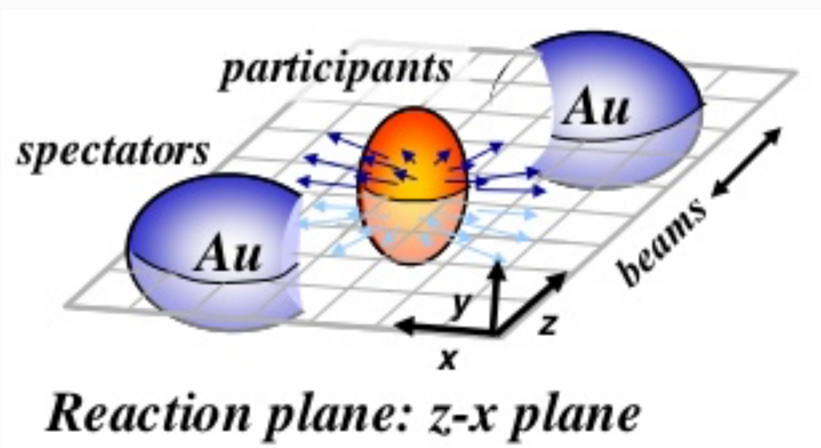

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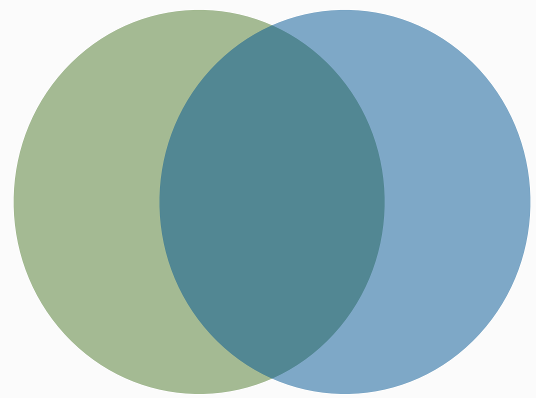

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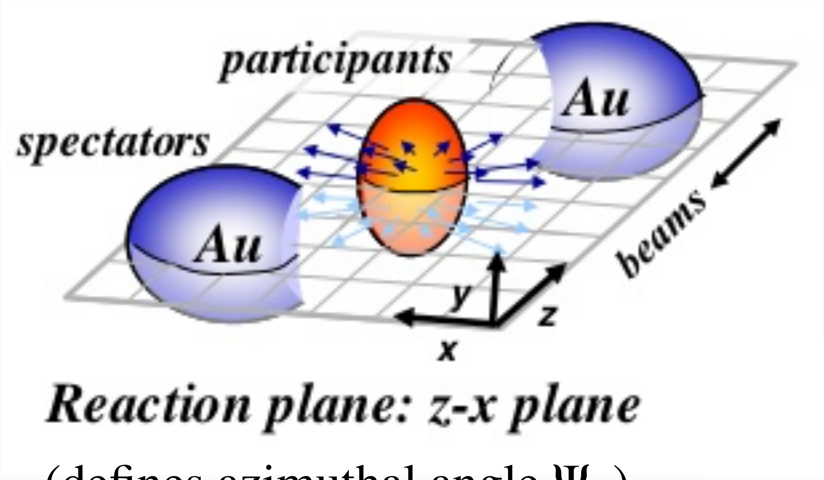

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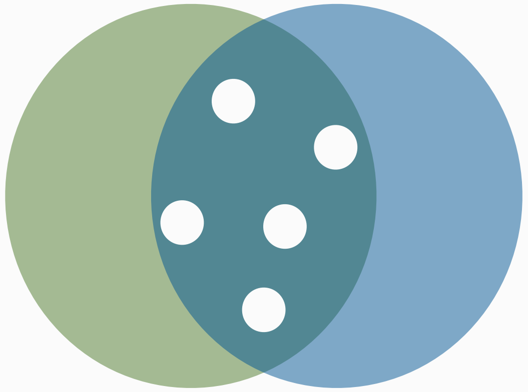

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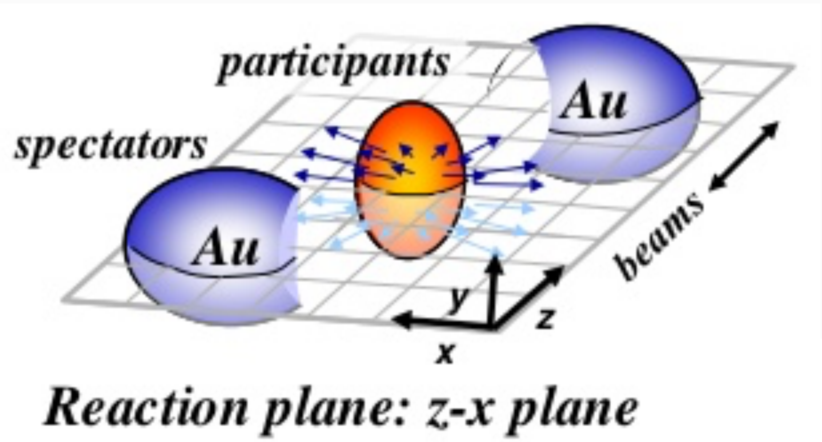

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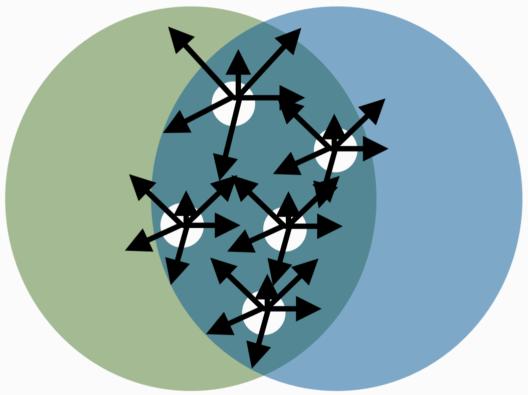

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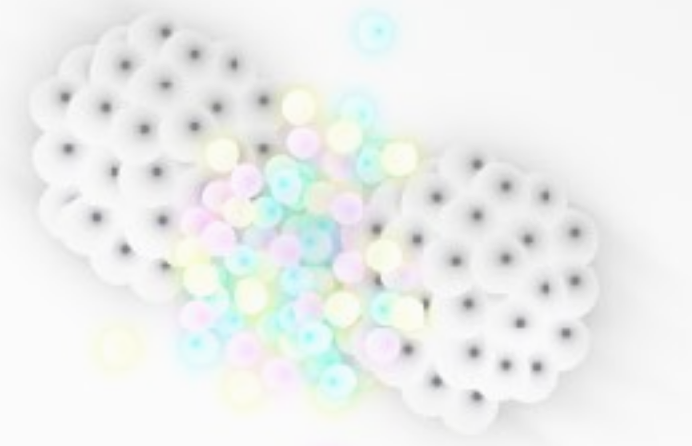

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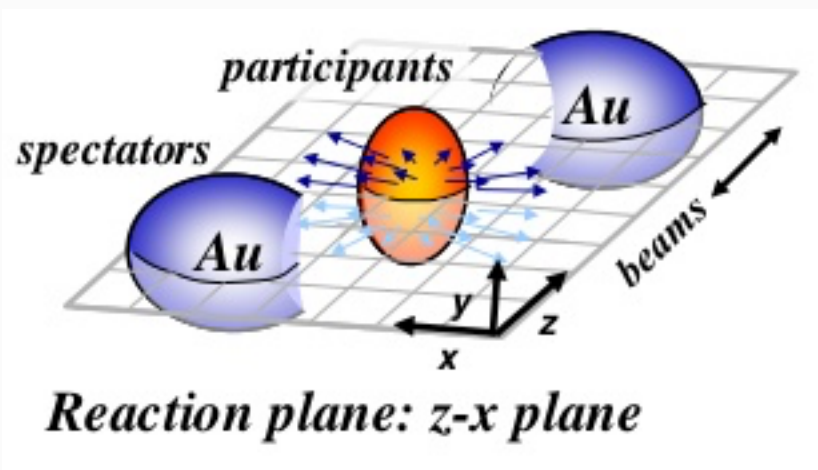

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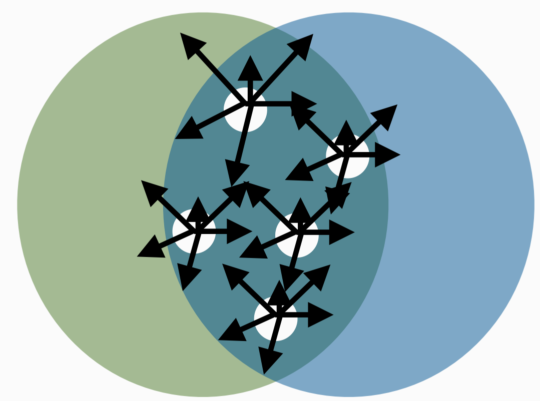

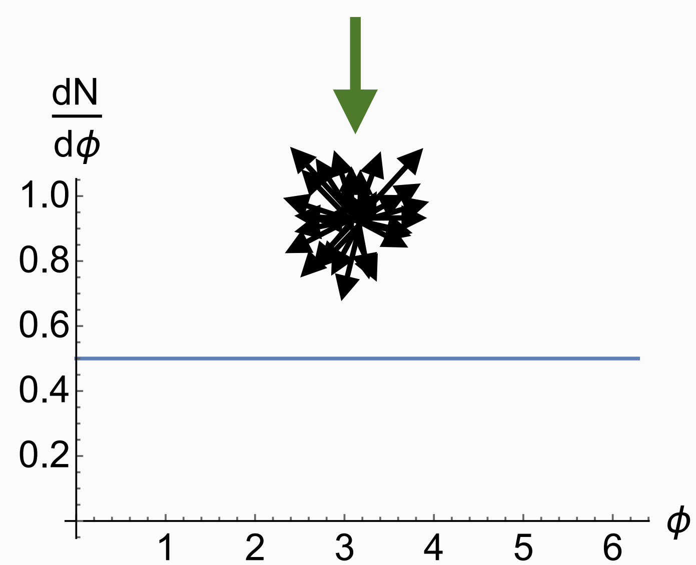

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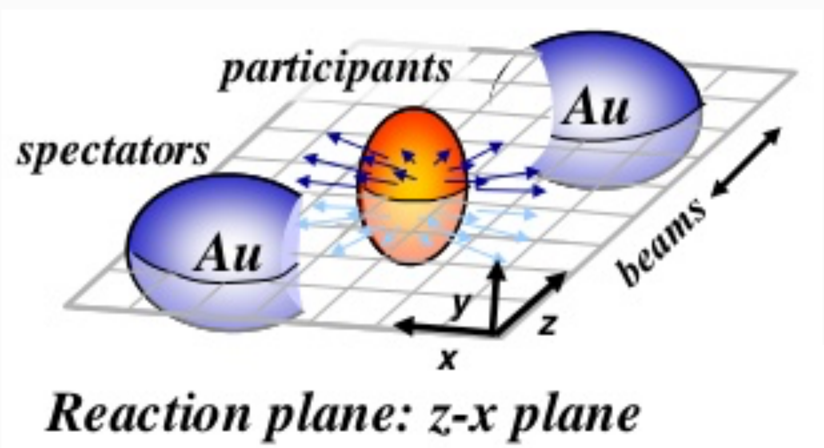

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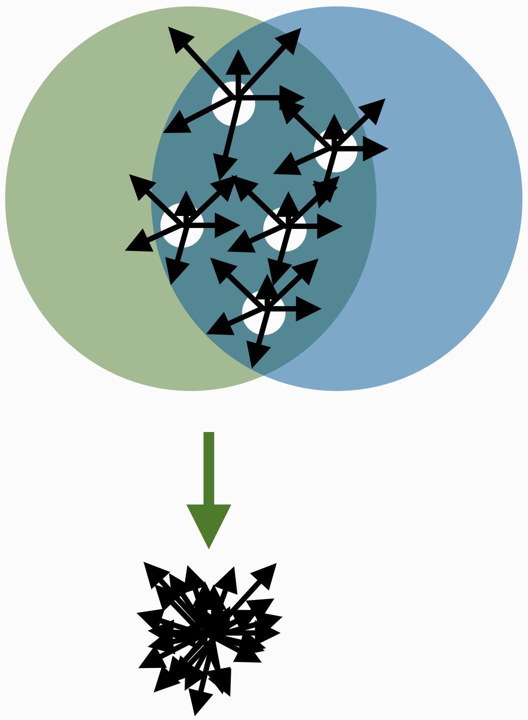

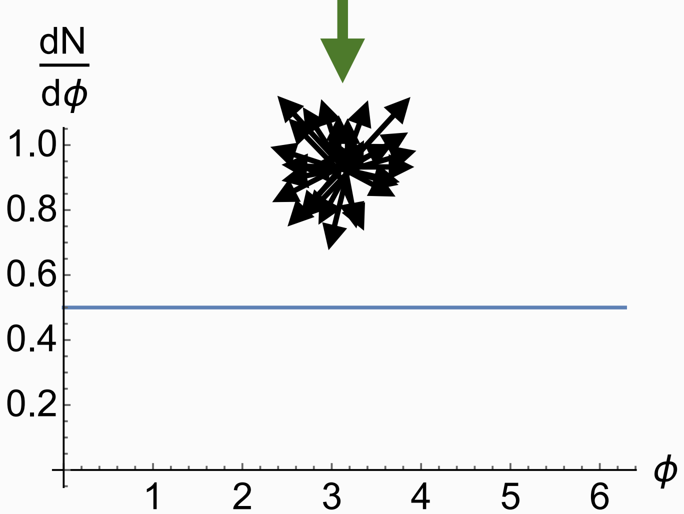

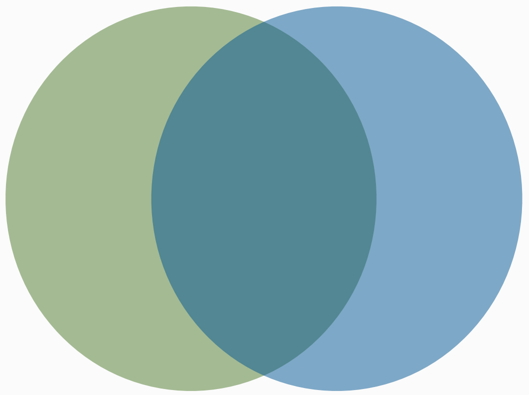

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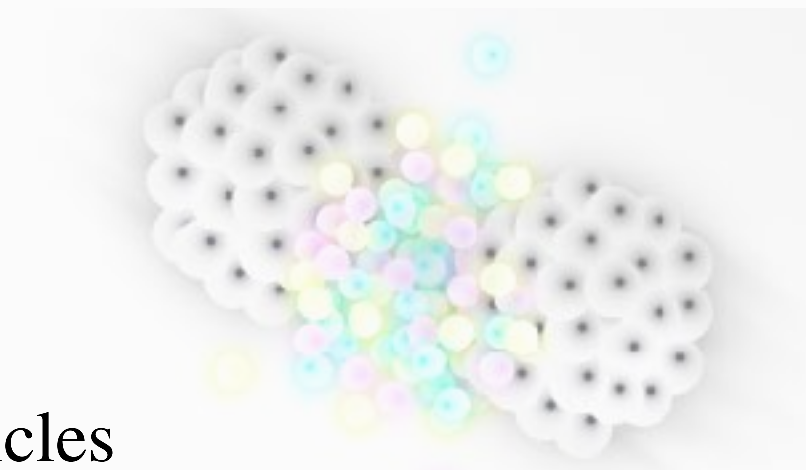

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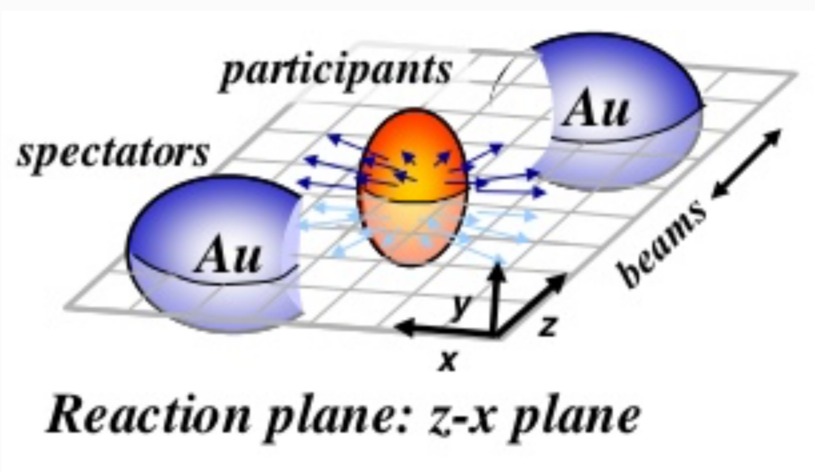

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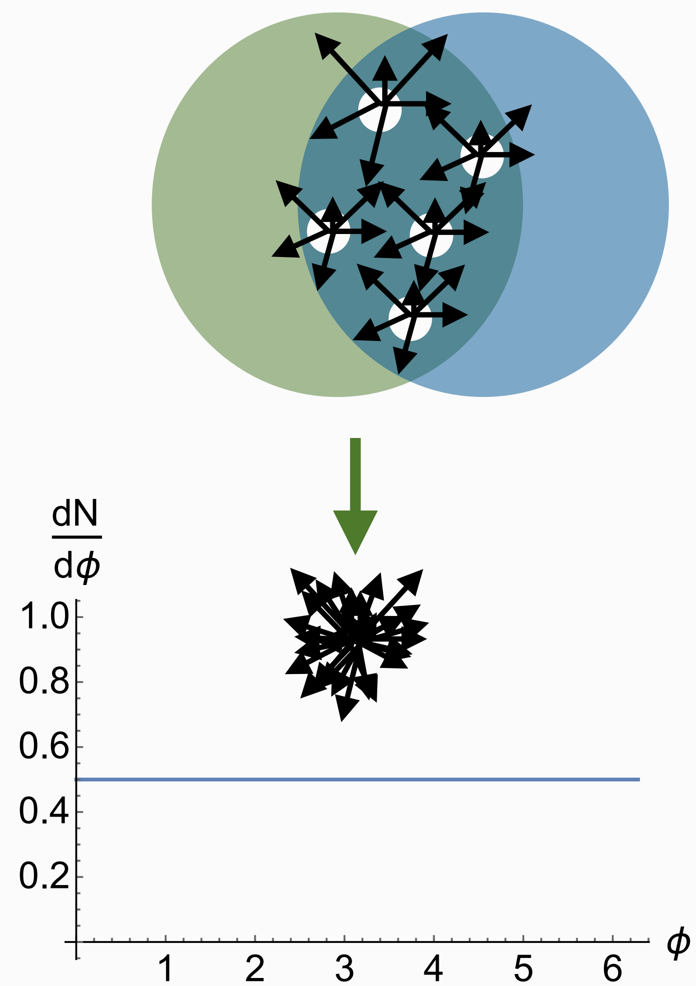
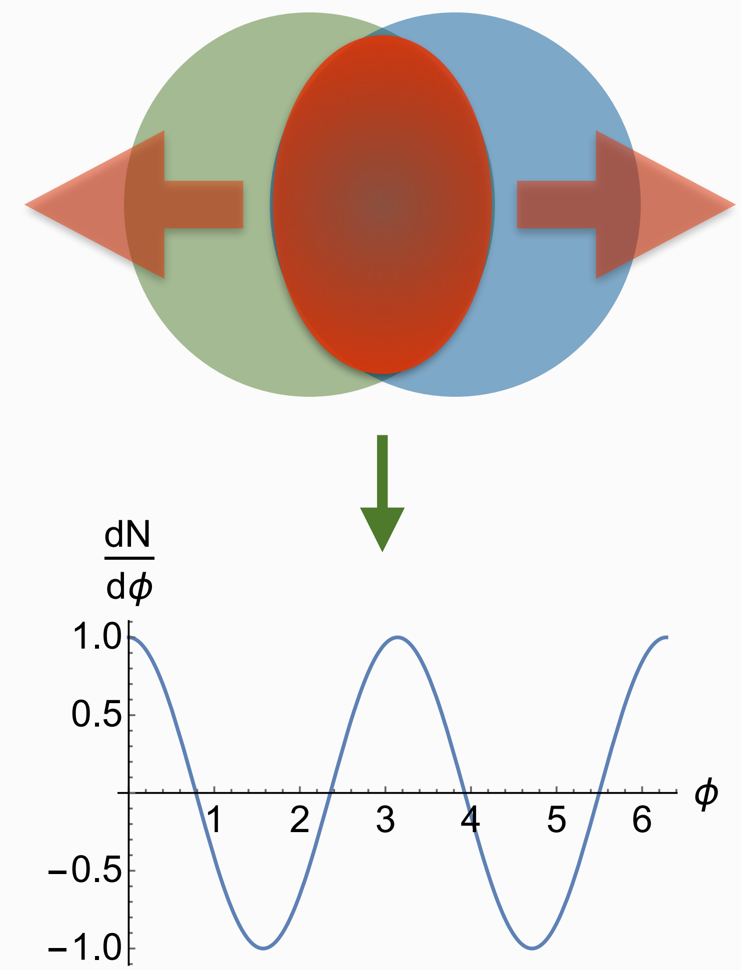


Collective bulk behaviour



Soft probes

- Fourier decomposition in ϕ wrt reaction plane Ψ_R:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum_n v_n \cos\left[n(\phi - \Psi_R)\right]\right)$$

  - Elliptic flow: Second Fourier coefficient (v_2)

$$v_2 = \langle \cos\left[2(\phi - \Psi_R)\right] \rangle$$

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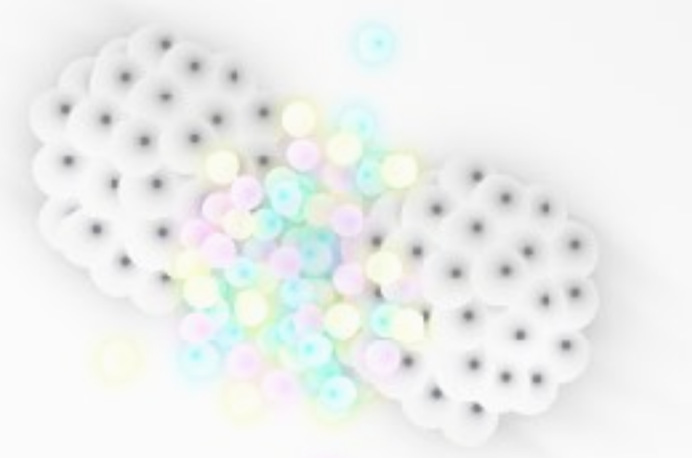

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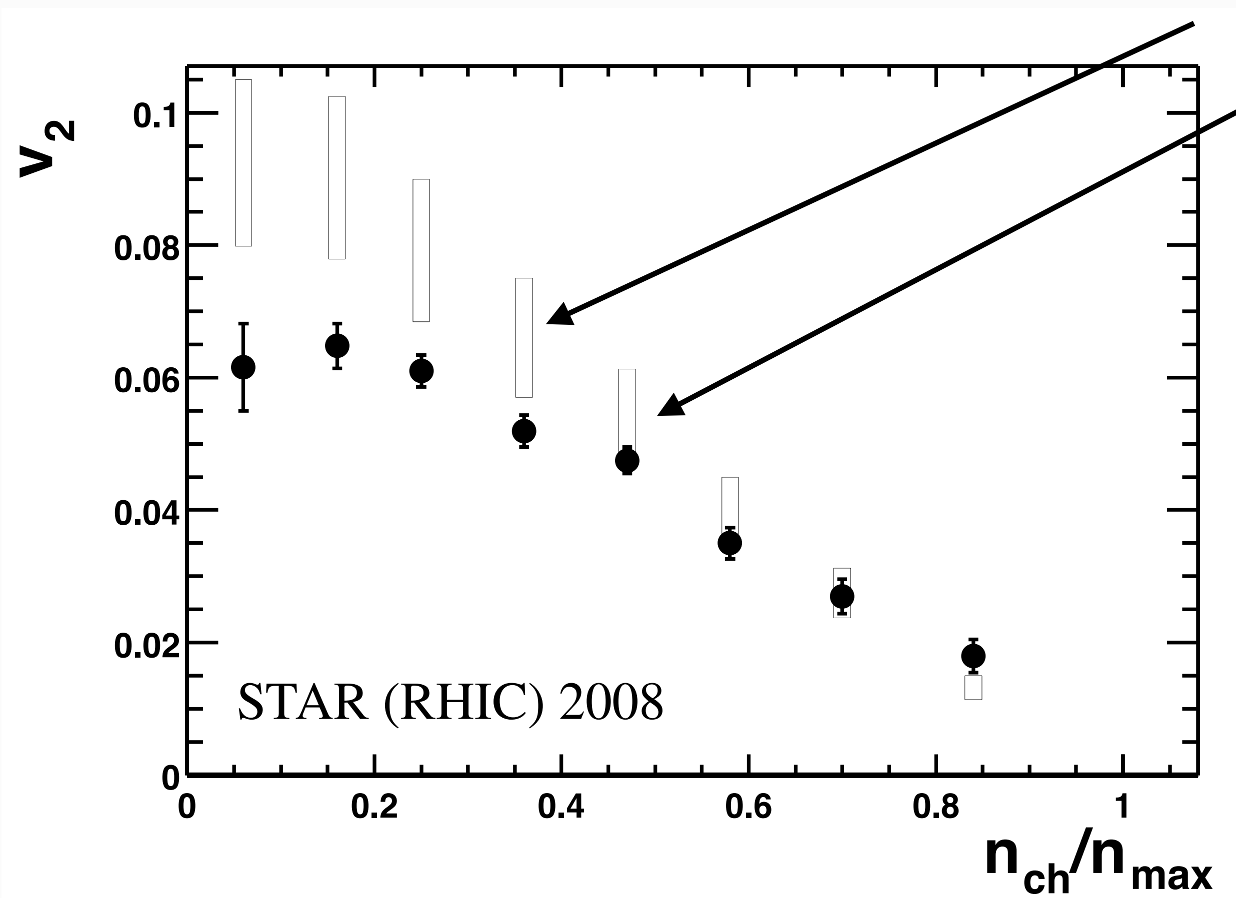


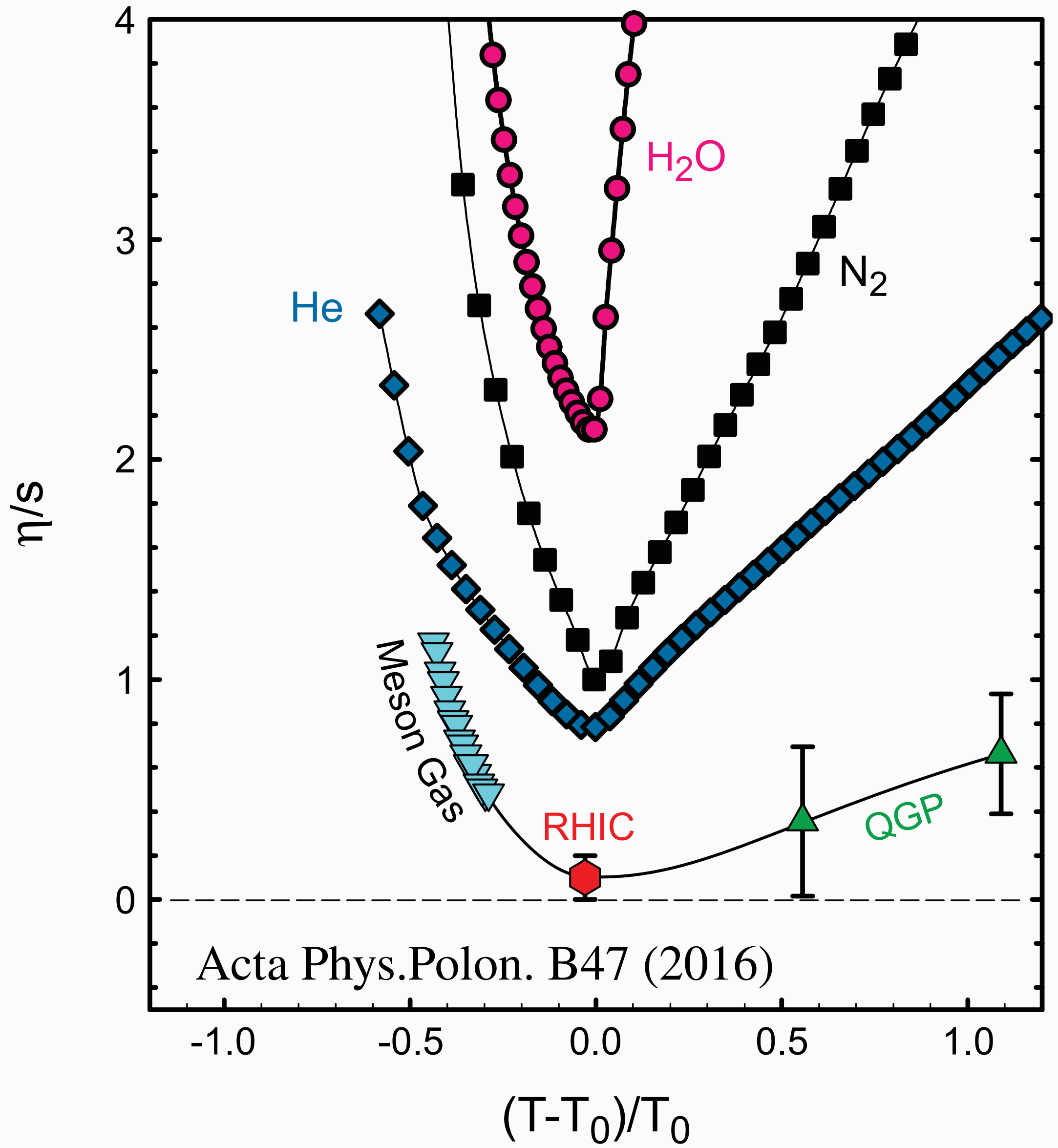
Range of expected values from ideal Hydrodynamics

Seems to behave like an (almost) **ideal fluid**!!

Peripheral ⟷ Central

Soft probes

- Assessing QGP viscosity….
  - Not zero viscosity, but still smallest viscosity so far!



Plasma should be a **strongly coupled fluid**!

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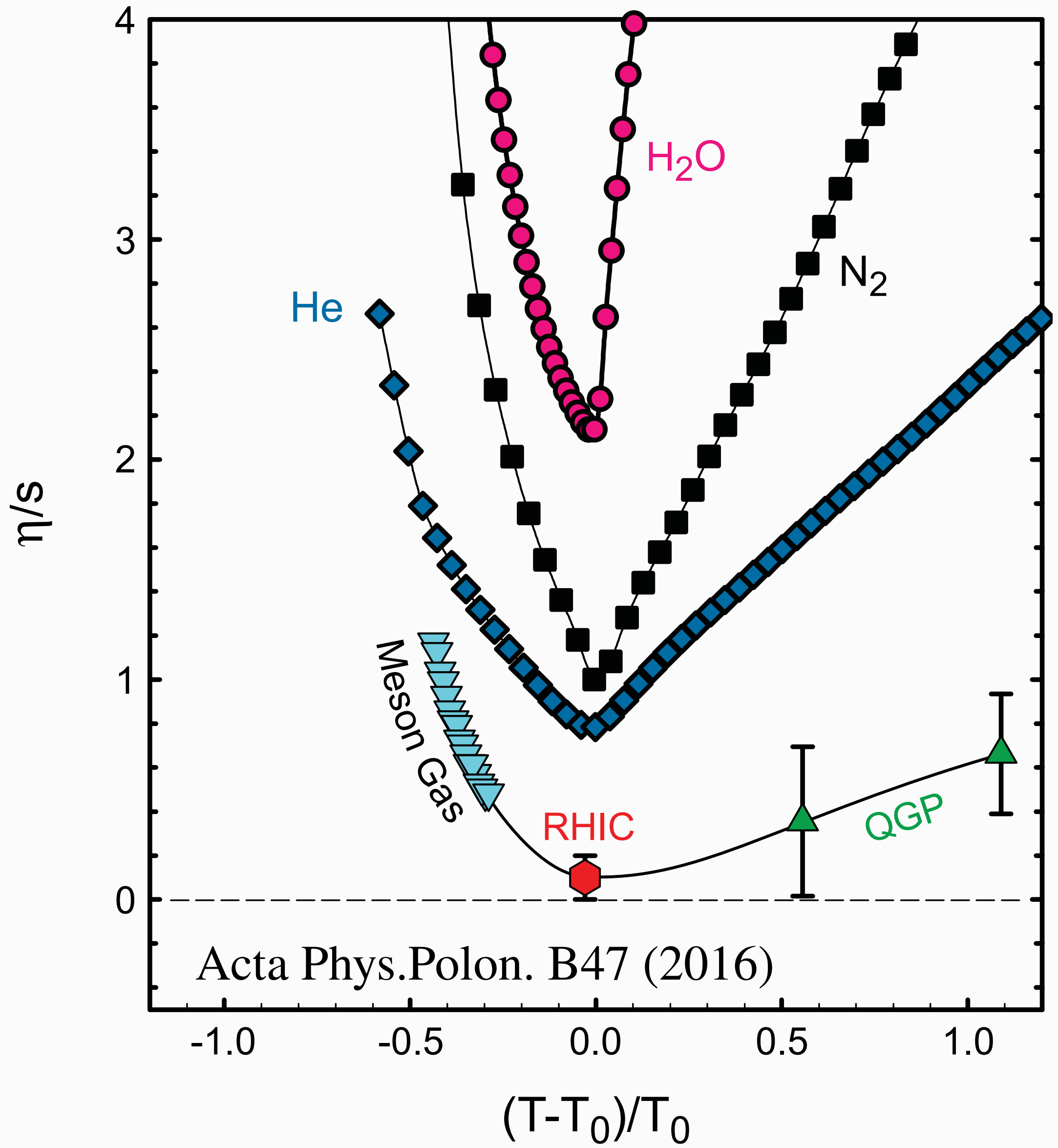

Hydrodynamic able to describe observations 👍

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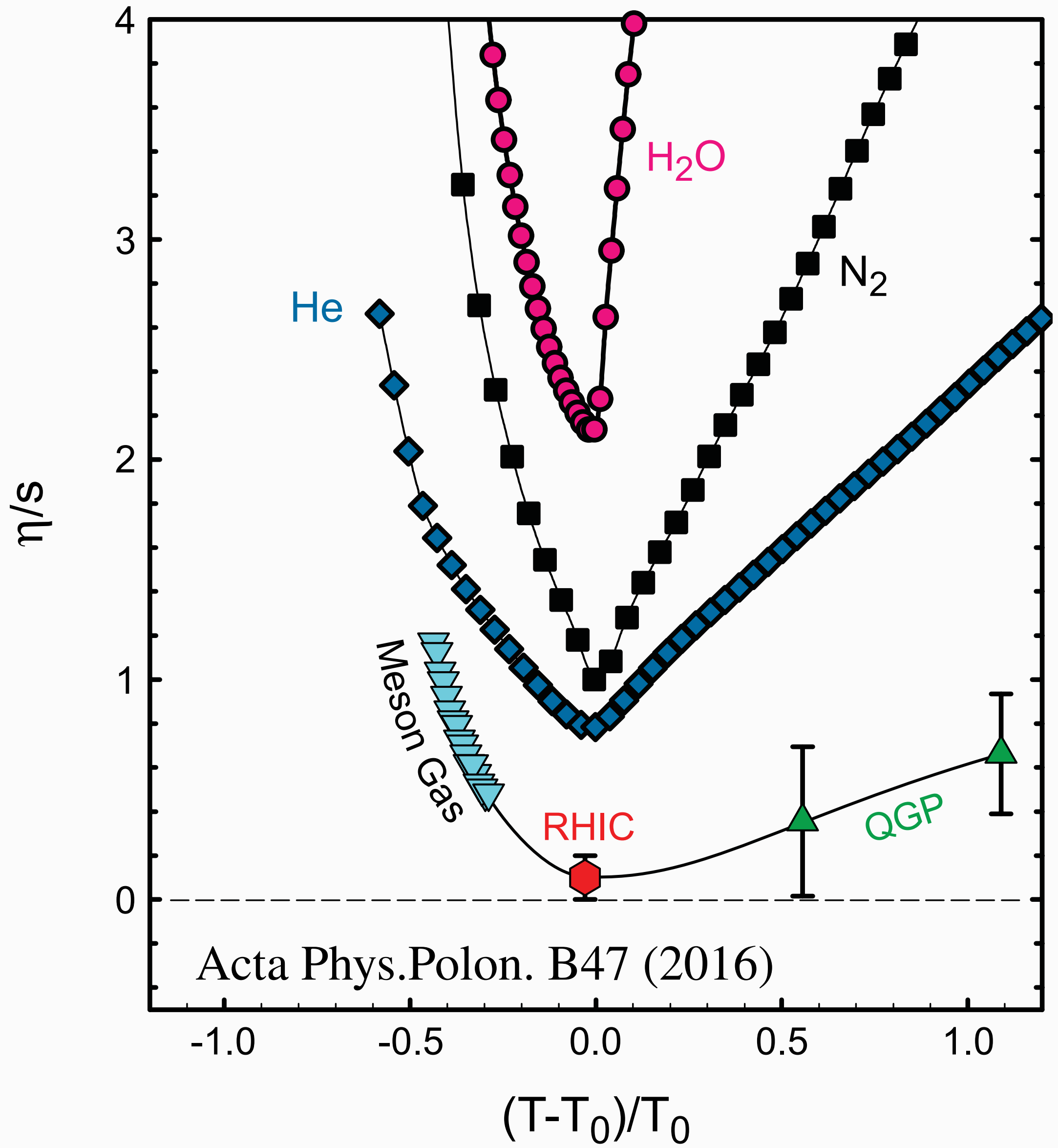

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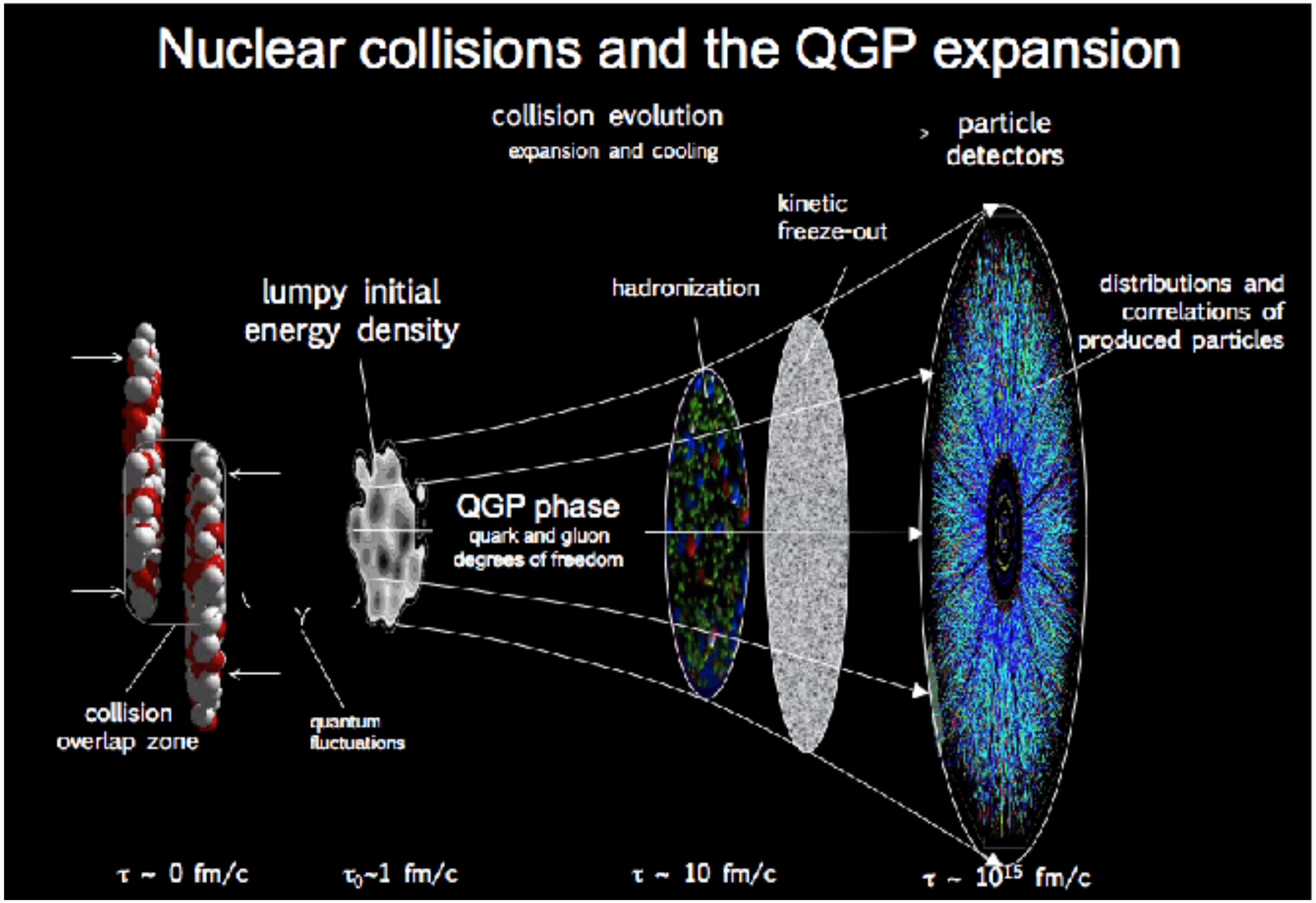
Hydrodynamic able to describe observations 👍

But we want to connect the QGP properties with QCD dynamics…

Probing the QGP

- QGP probes:
  - Produced within the collision



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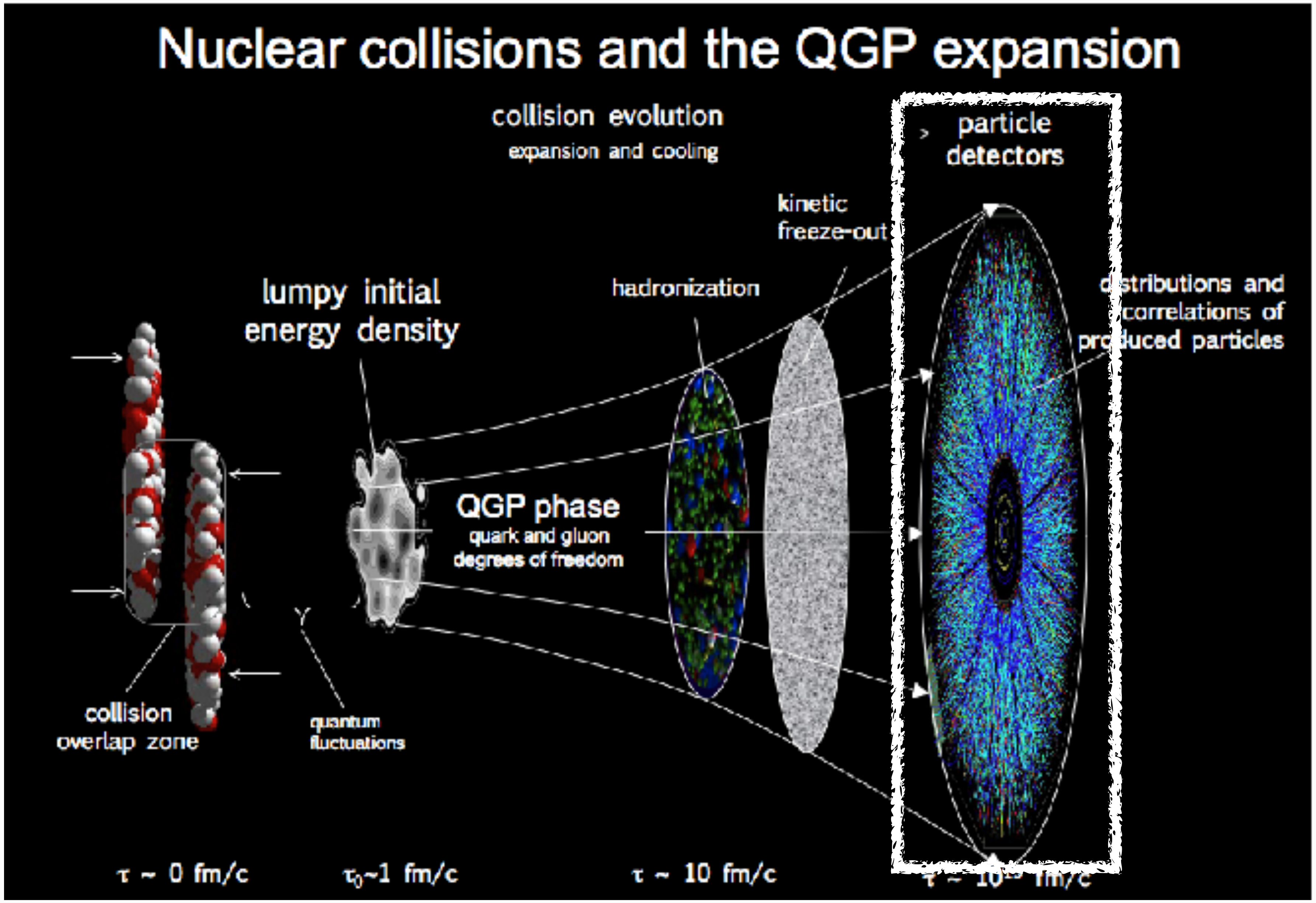

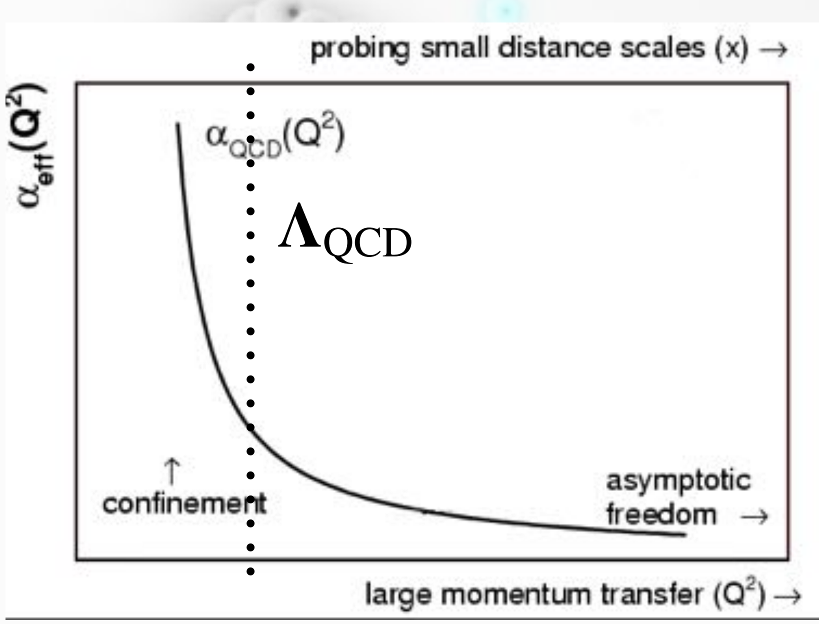

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p_T ~ hundreds MeV (~ Λ_{QCD})

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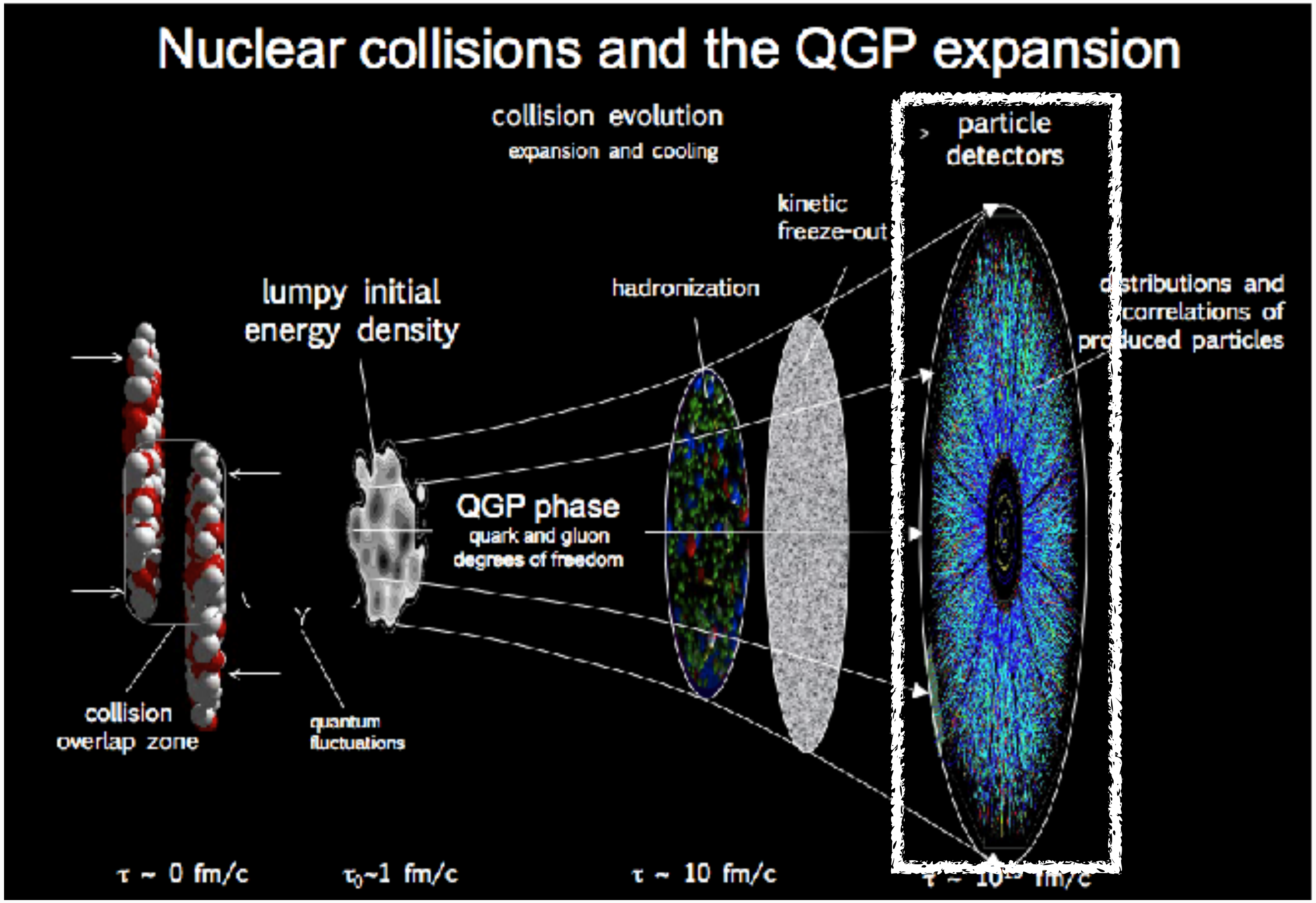

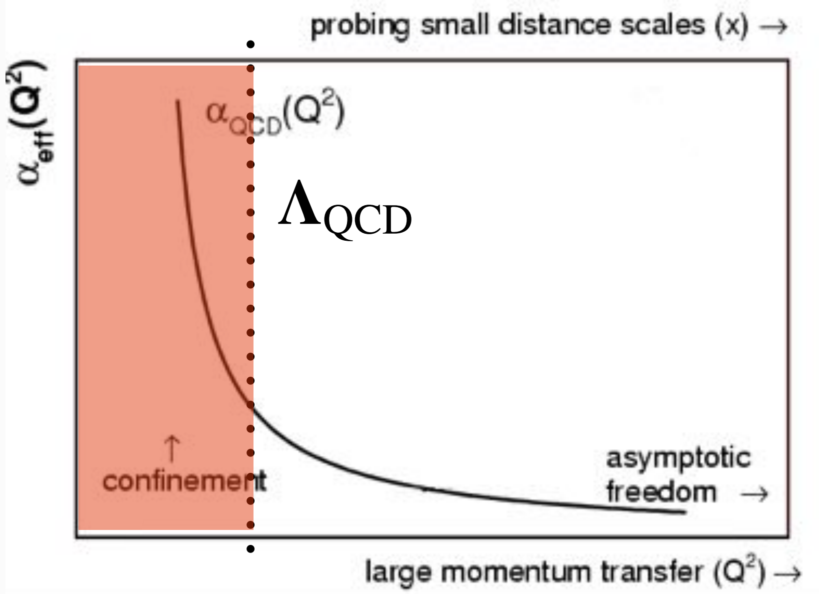

Bulk of particles can give information on the QGP properties (collectivity, viscosity, …)

p_T ~ hundreds MeV (~ Λ_{QCD})

soft probes: non-pQCD

Probing the QGP

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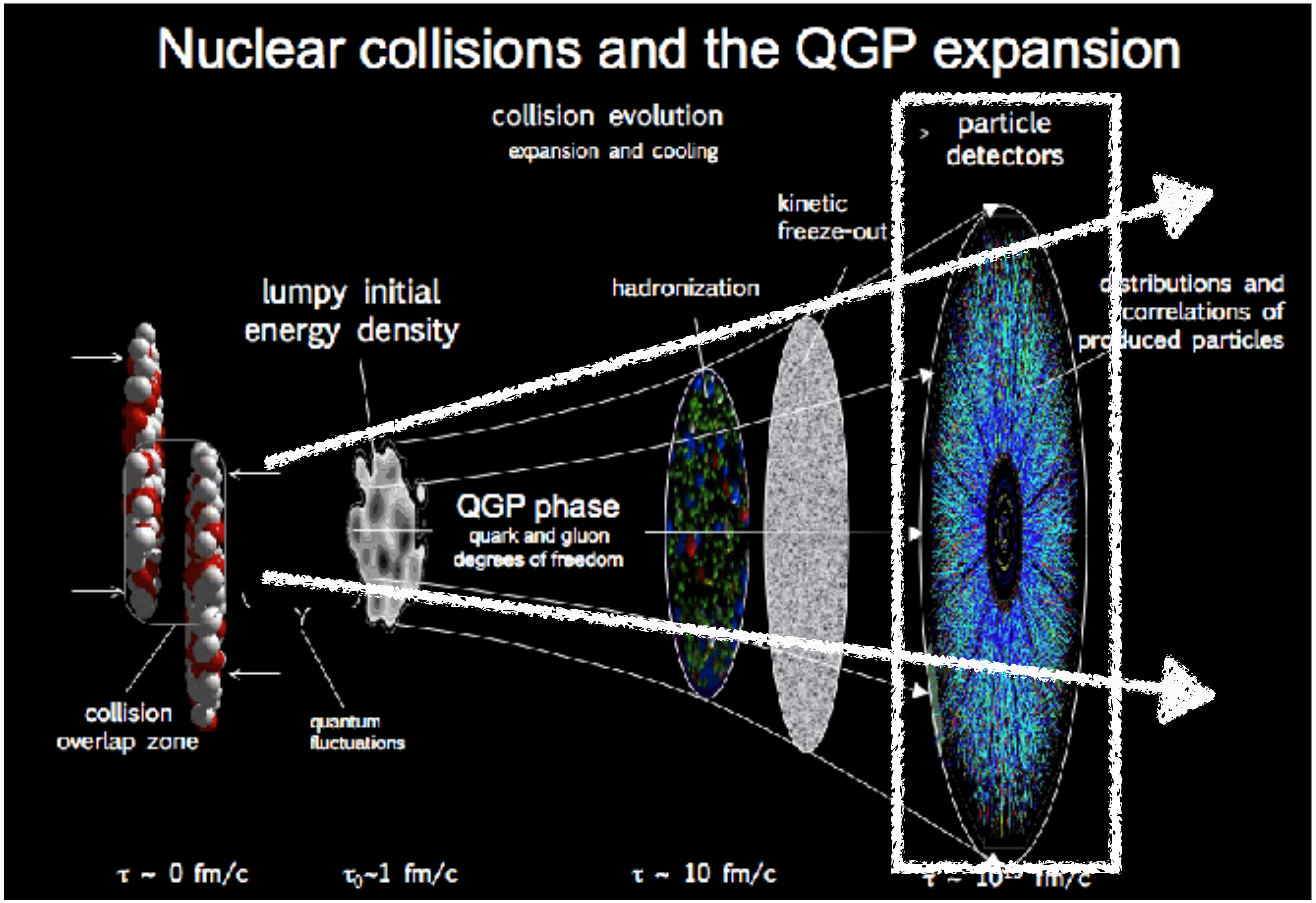

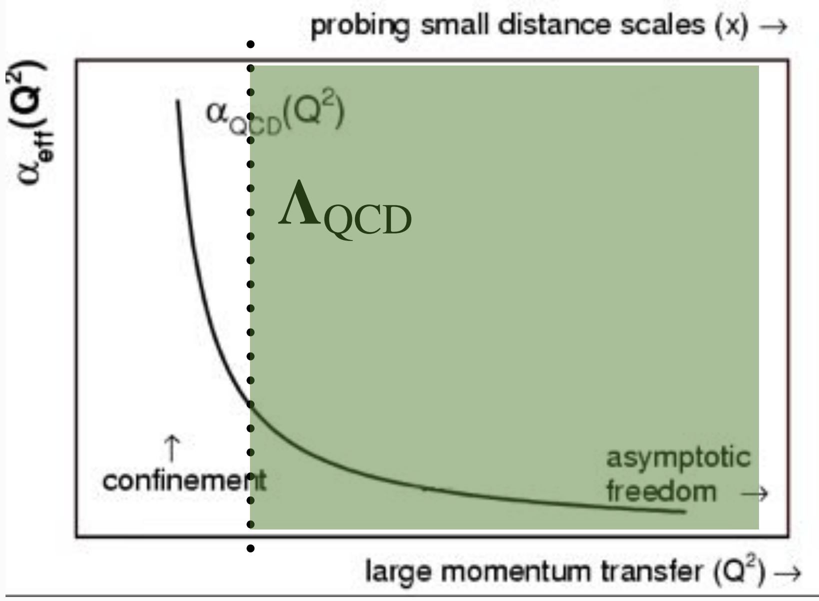

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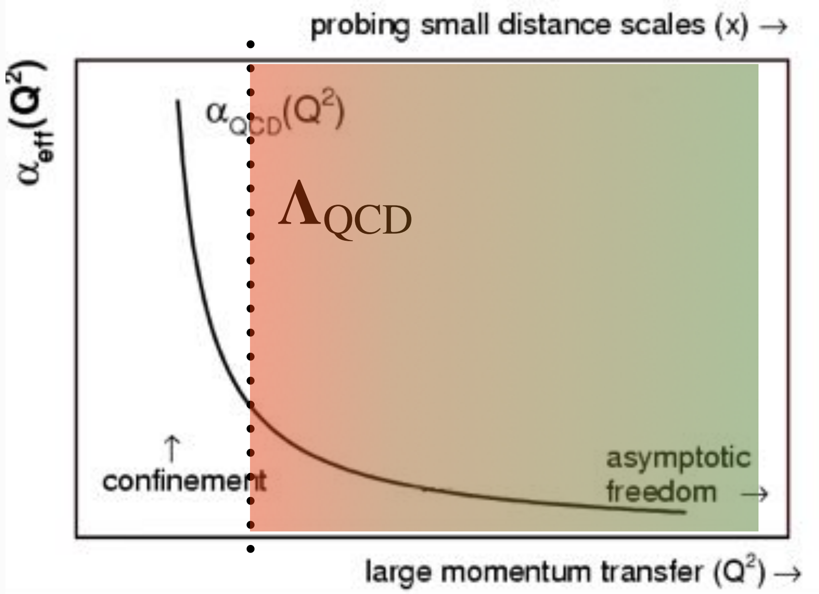

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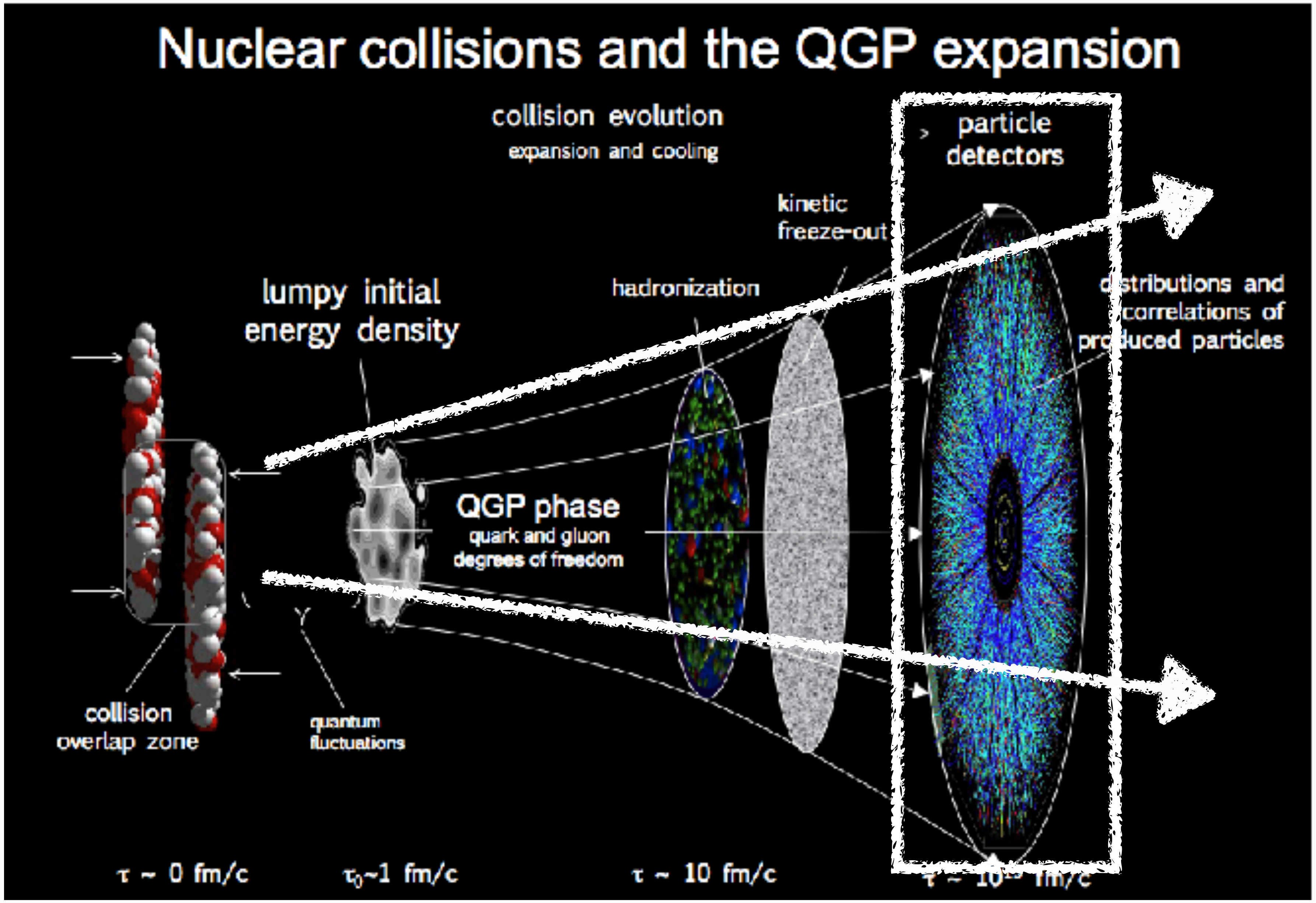

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hard probes: pQCD ?

Hard Probes

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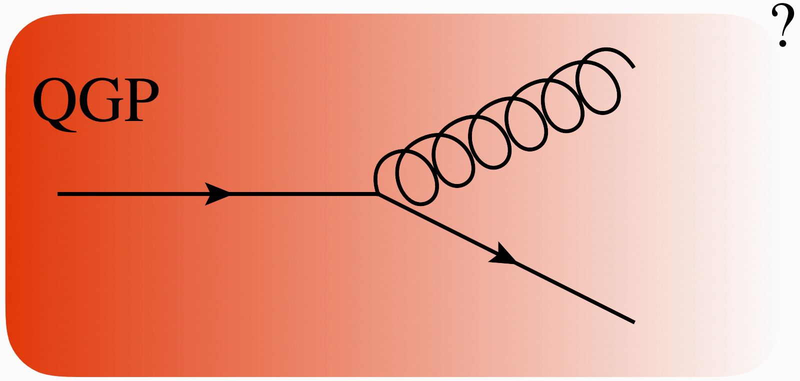

??

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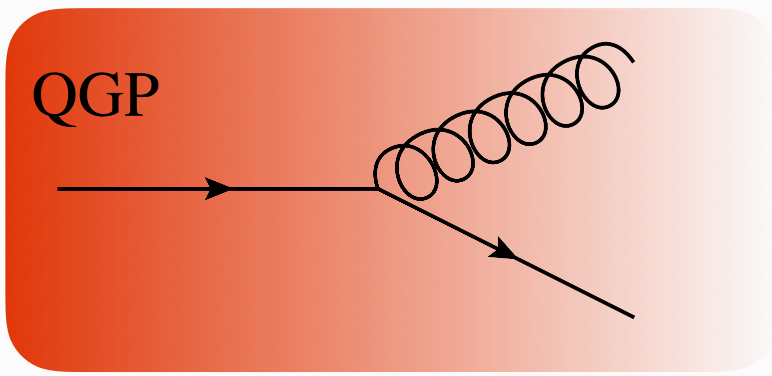
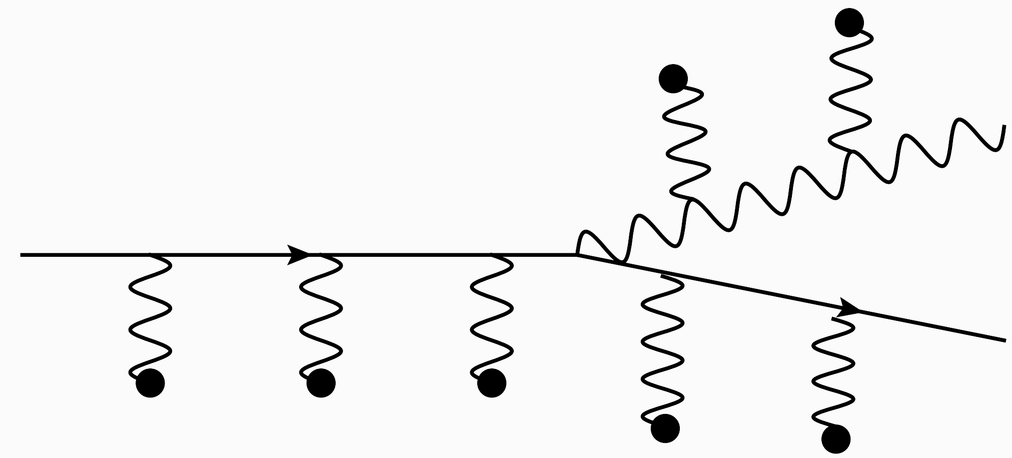


$\Longrightarrow$

QGP = collection of static scattering centres



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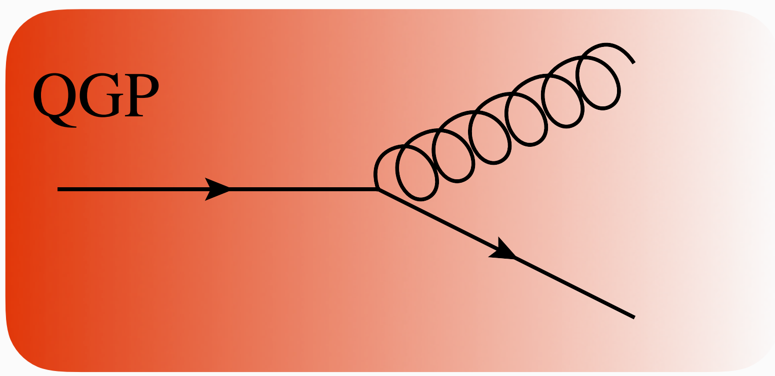

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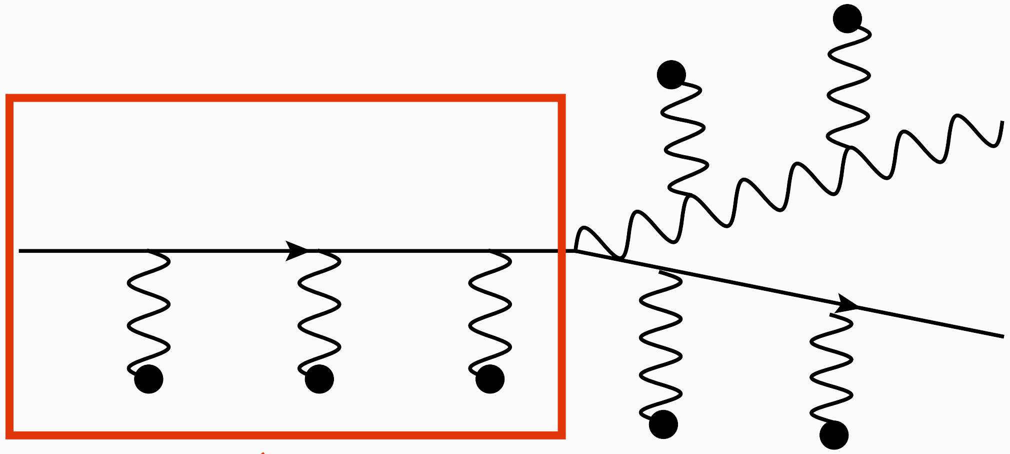

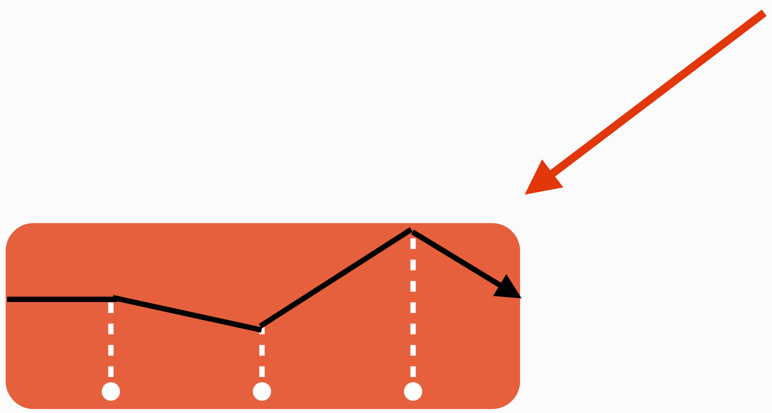

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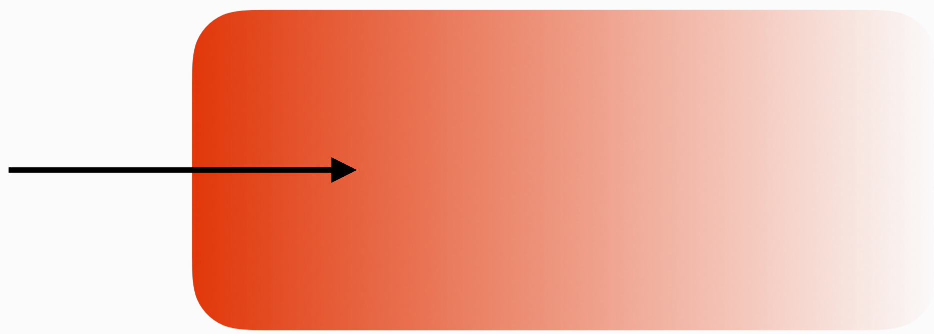
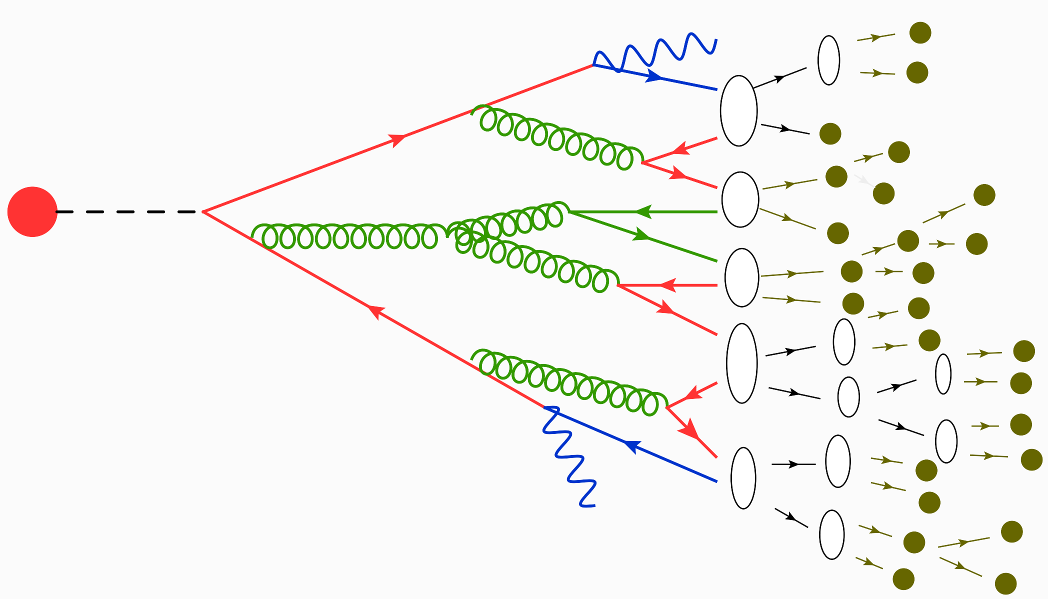
- Jet Quenching pQCD expectations vs Jet Quenching observations





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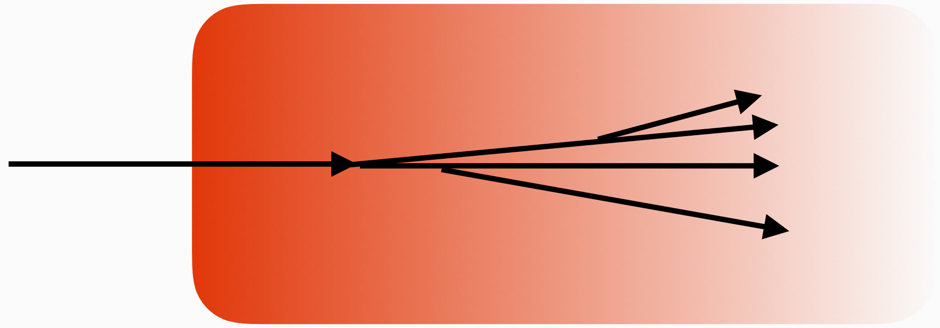

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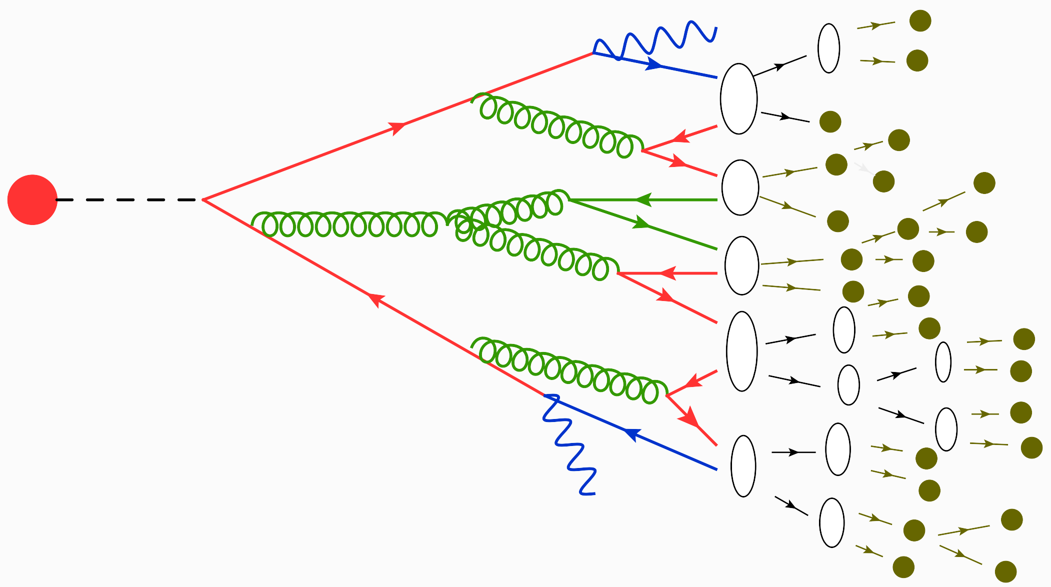

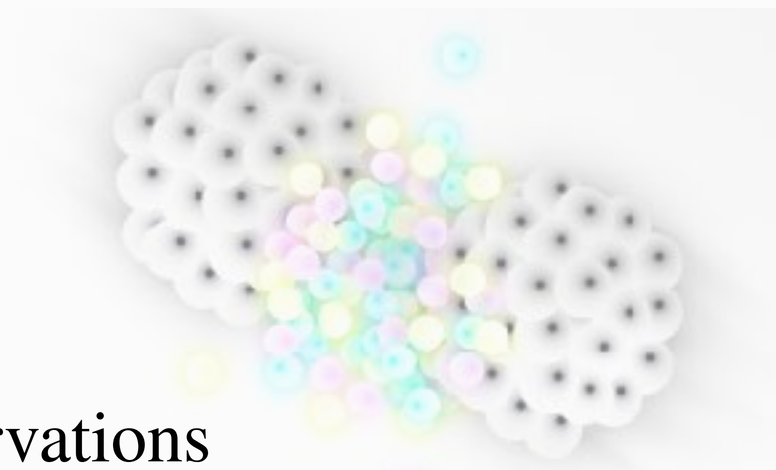

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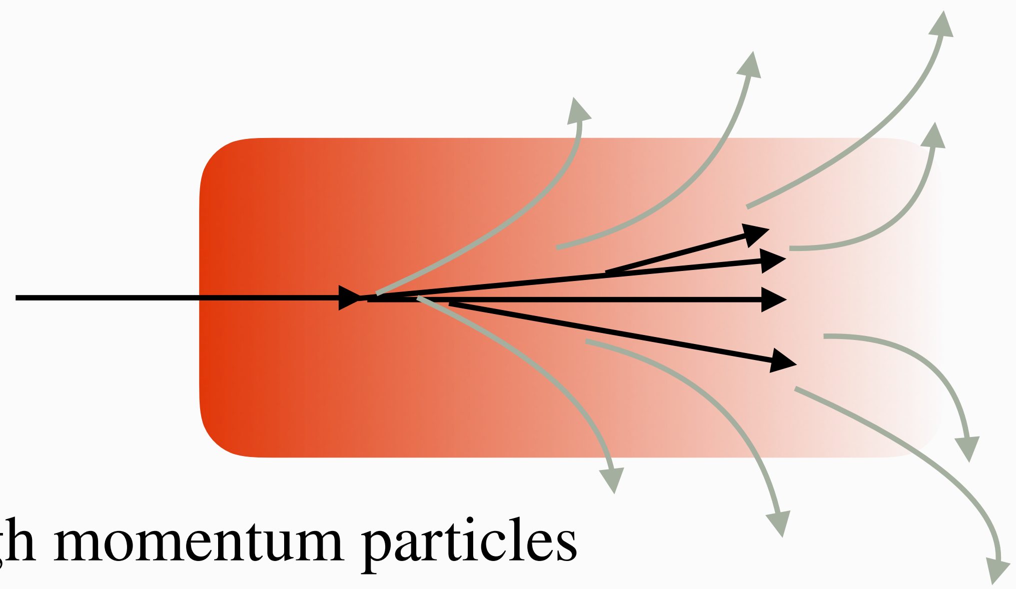

High momentum particles

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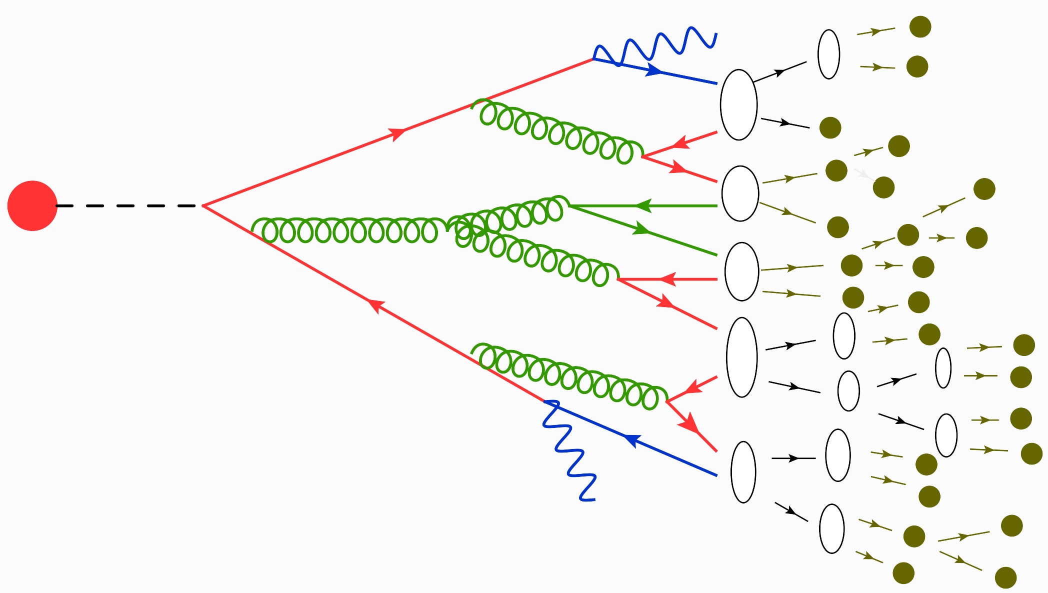
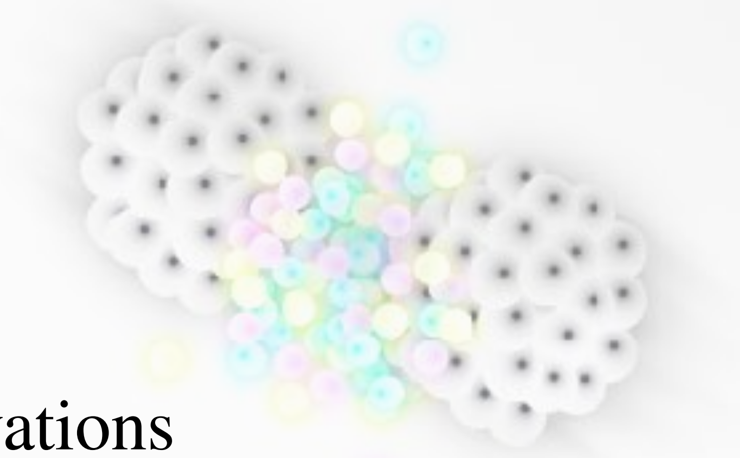
(re-scatter more with the QGP)





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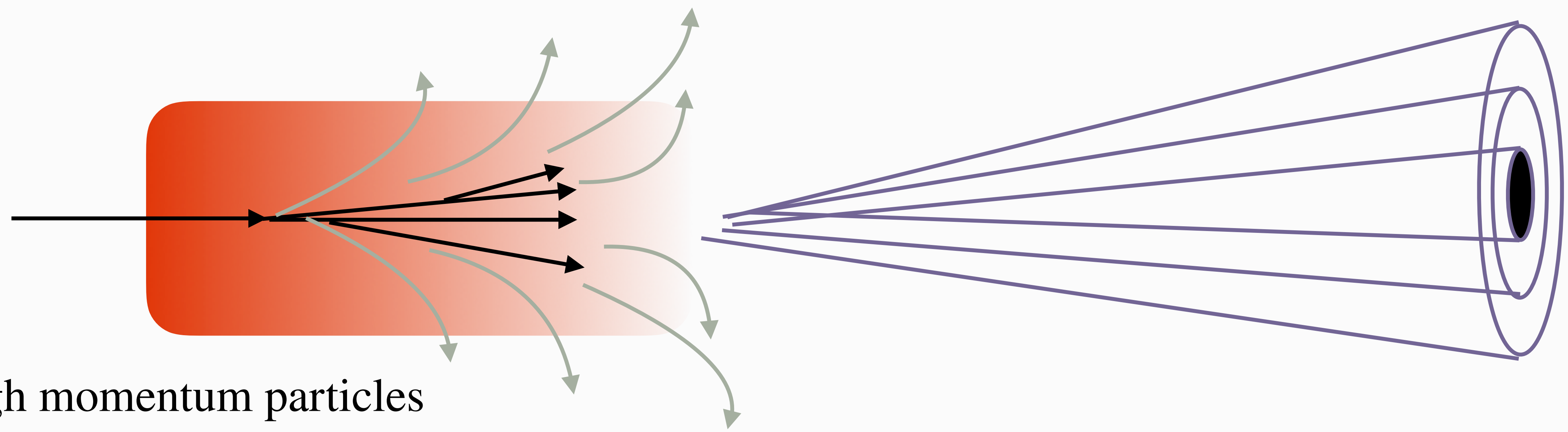

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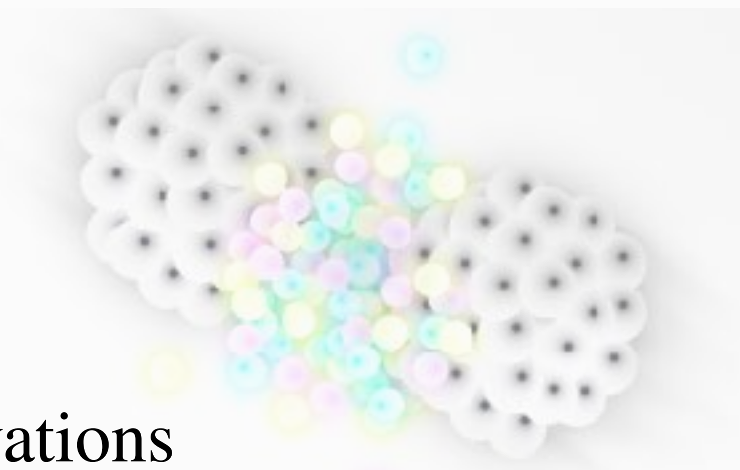

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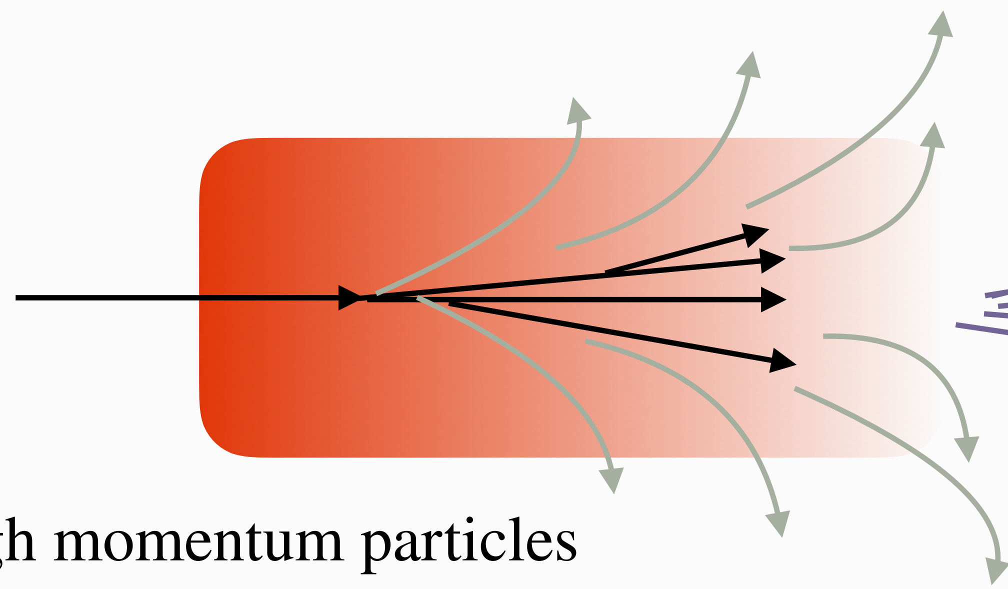

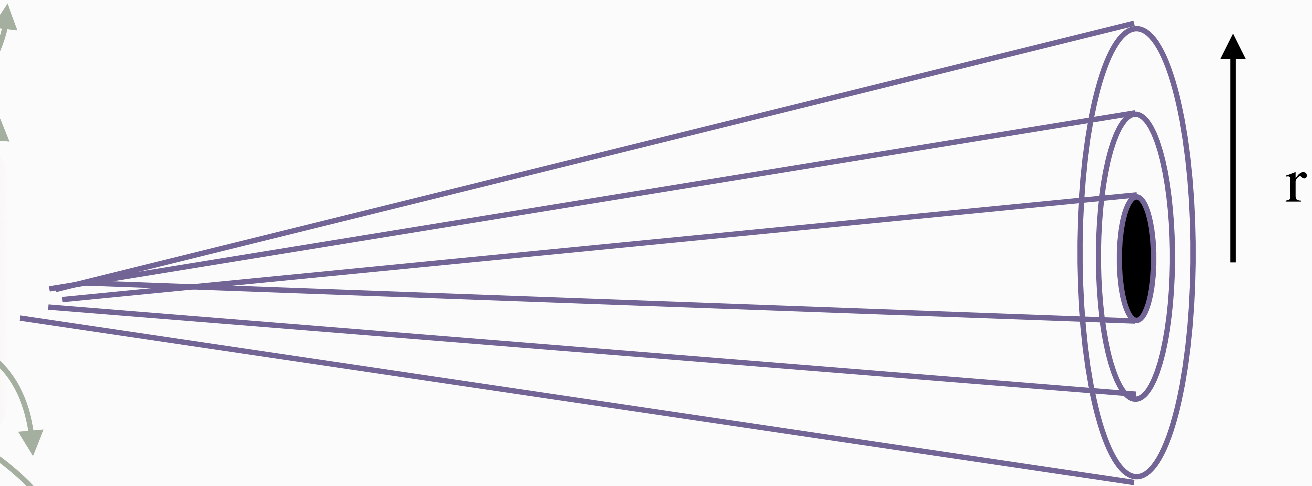

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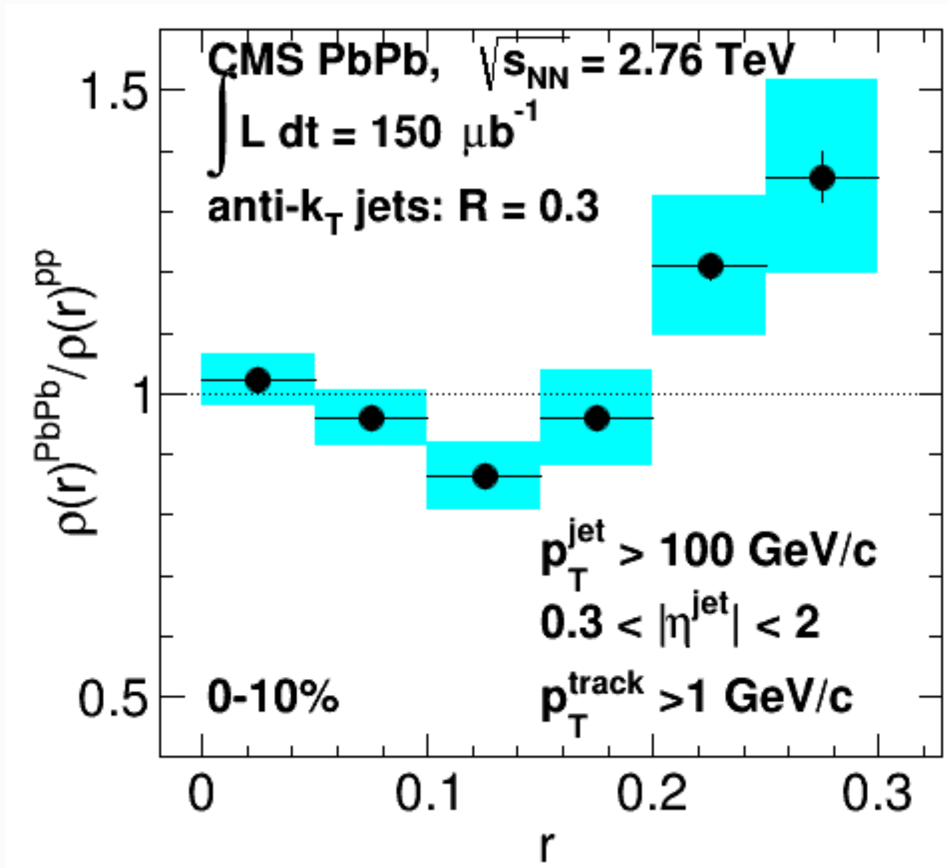

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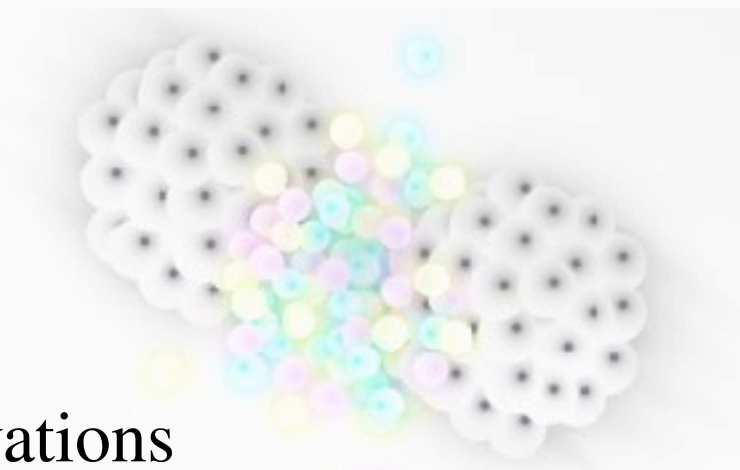

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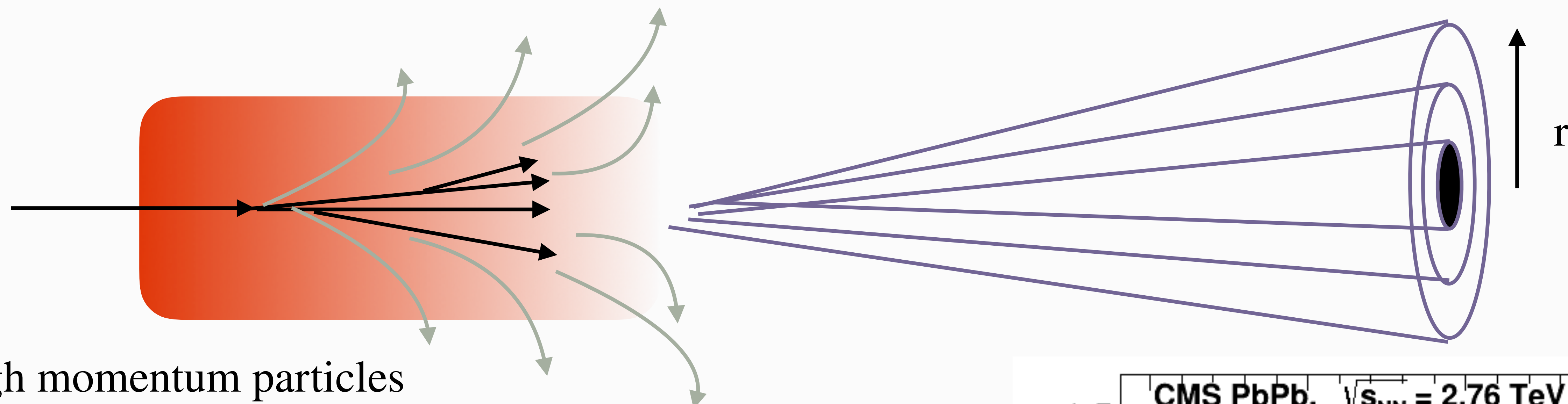

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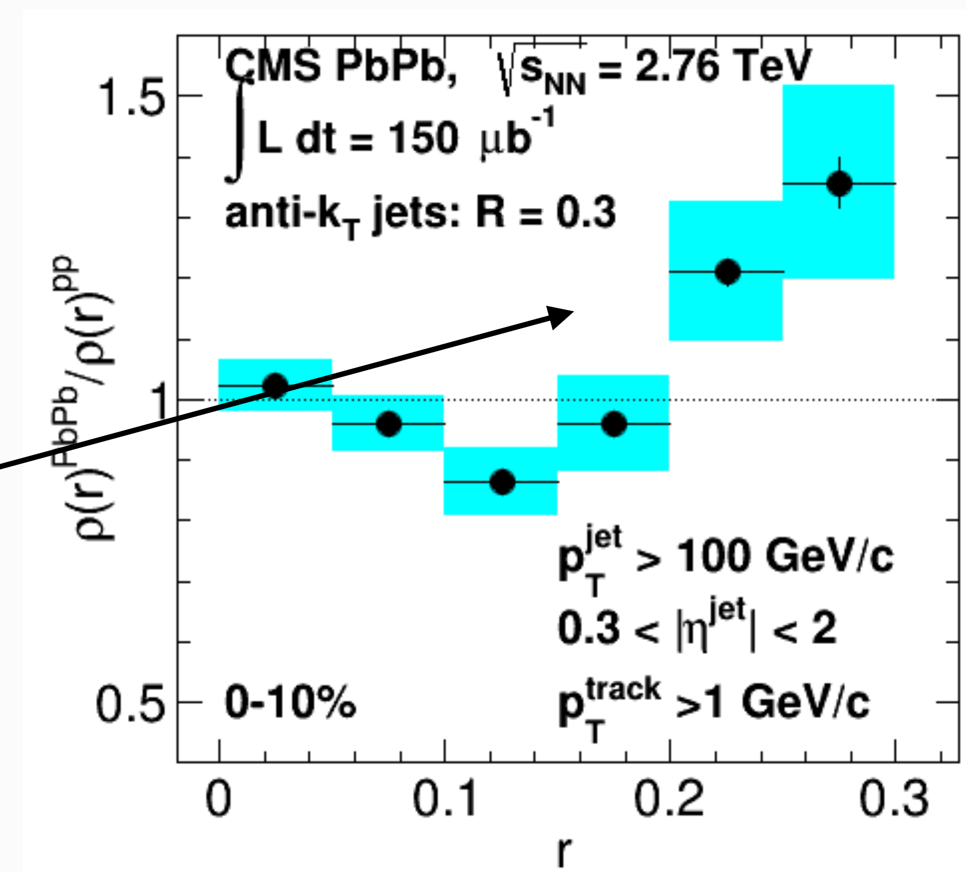

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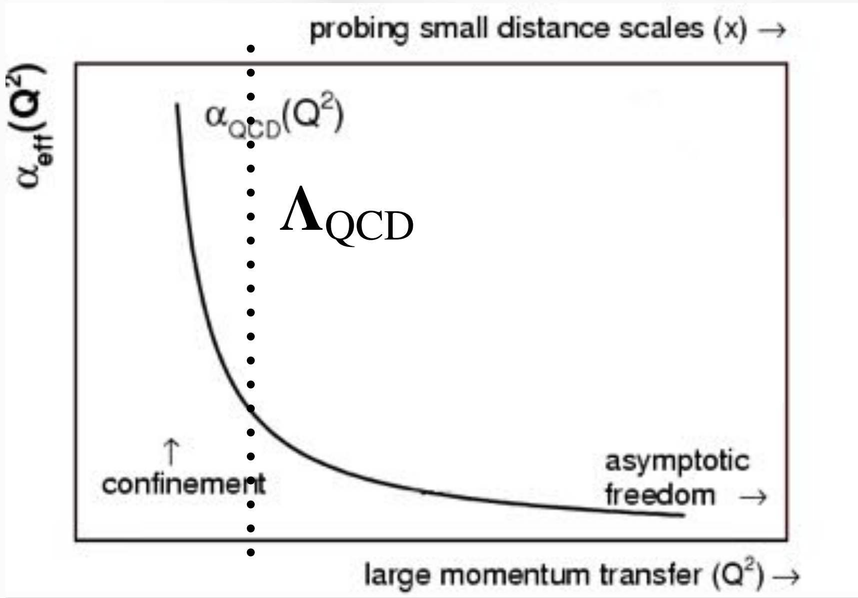

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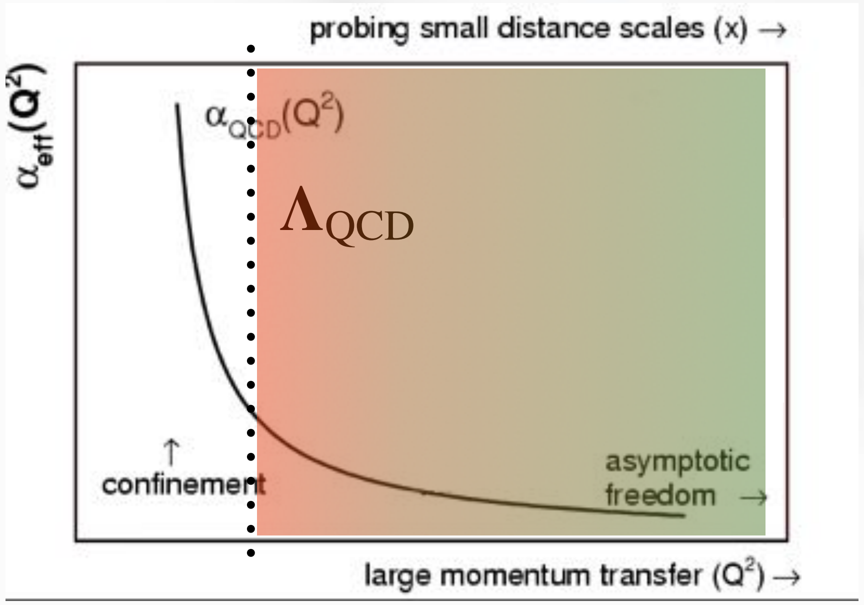

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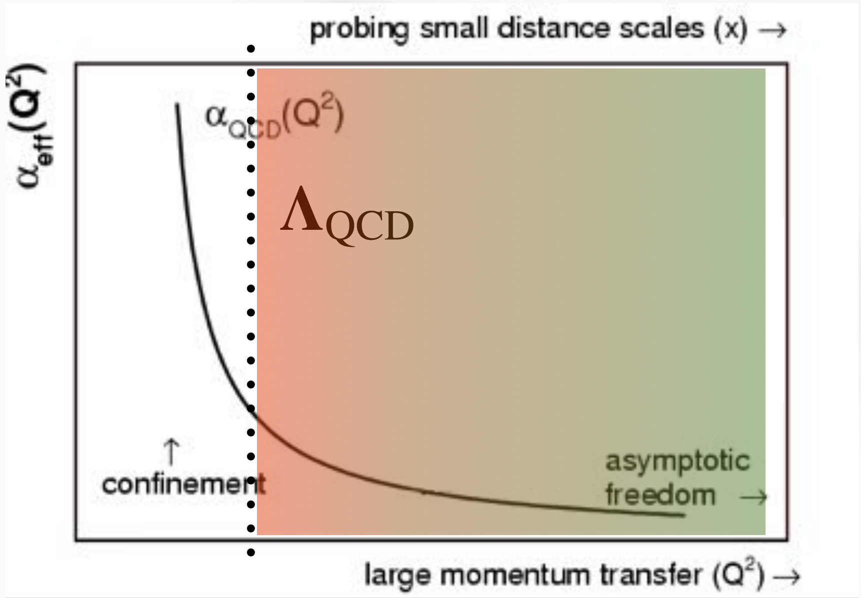

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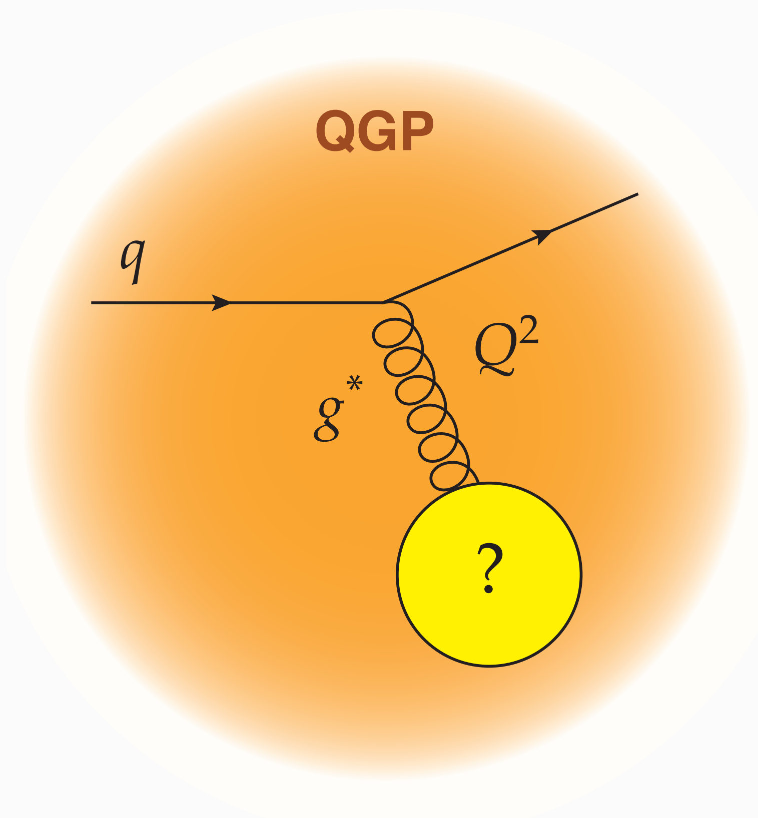

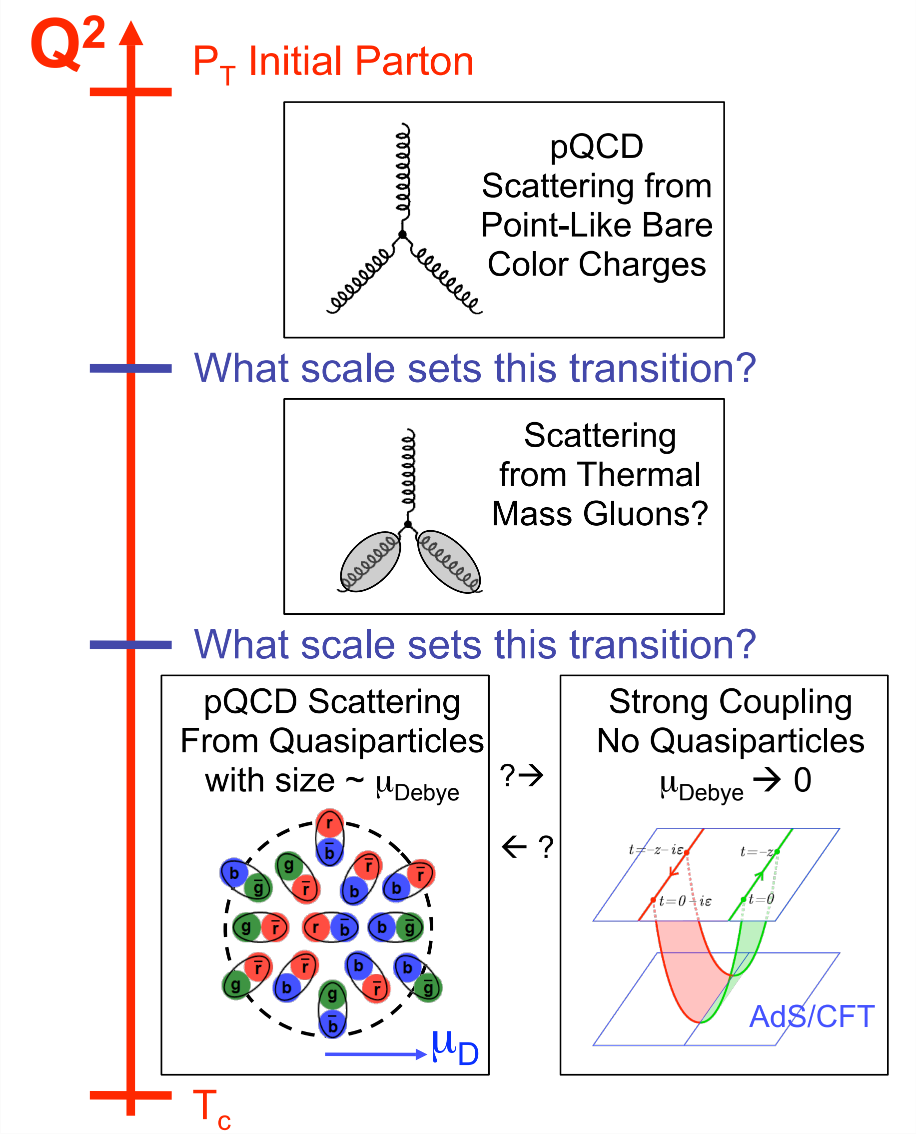

Need to understand QCD dynamics at **<u>all</u>** energy sales!!!

Summary

- QCD = theory of the strong interactions
  - The theory that we know less… theory that we need more!
    - Either as the signal of interest, either as the background for other (B)SM searches

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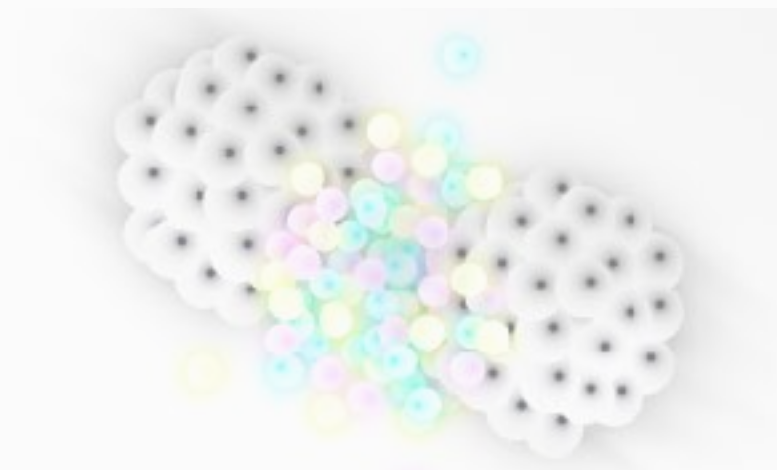

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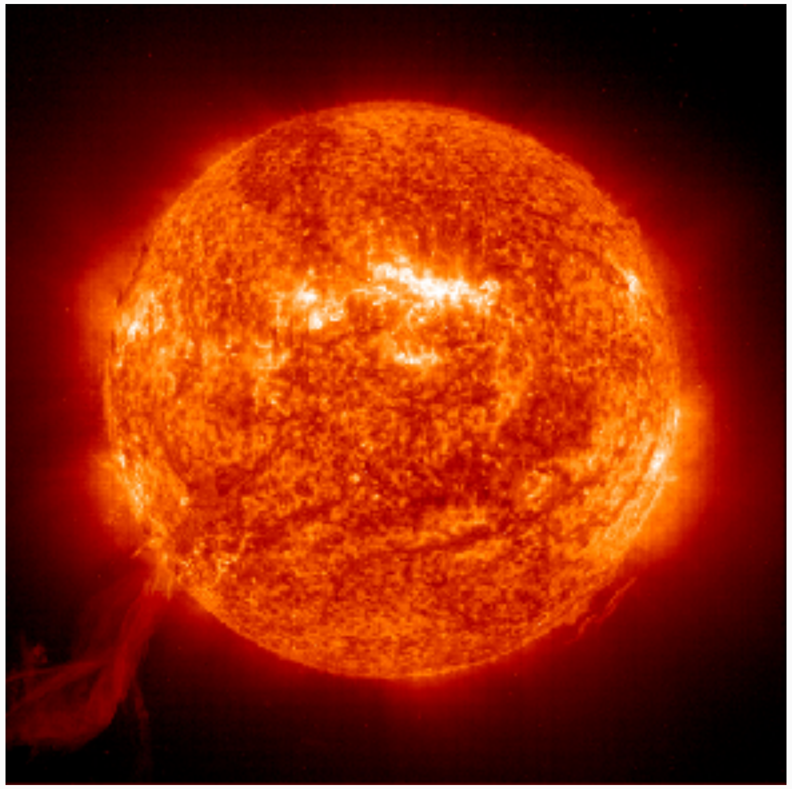

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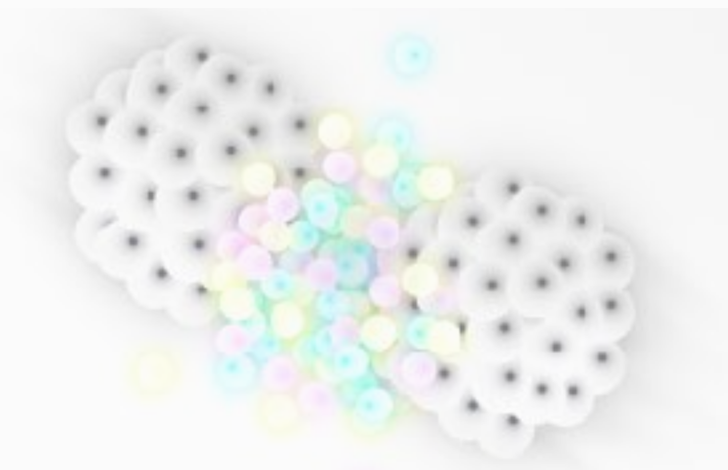

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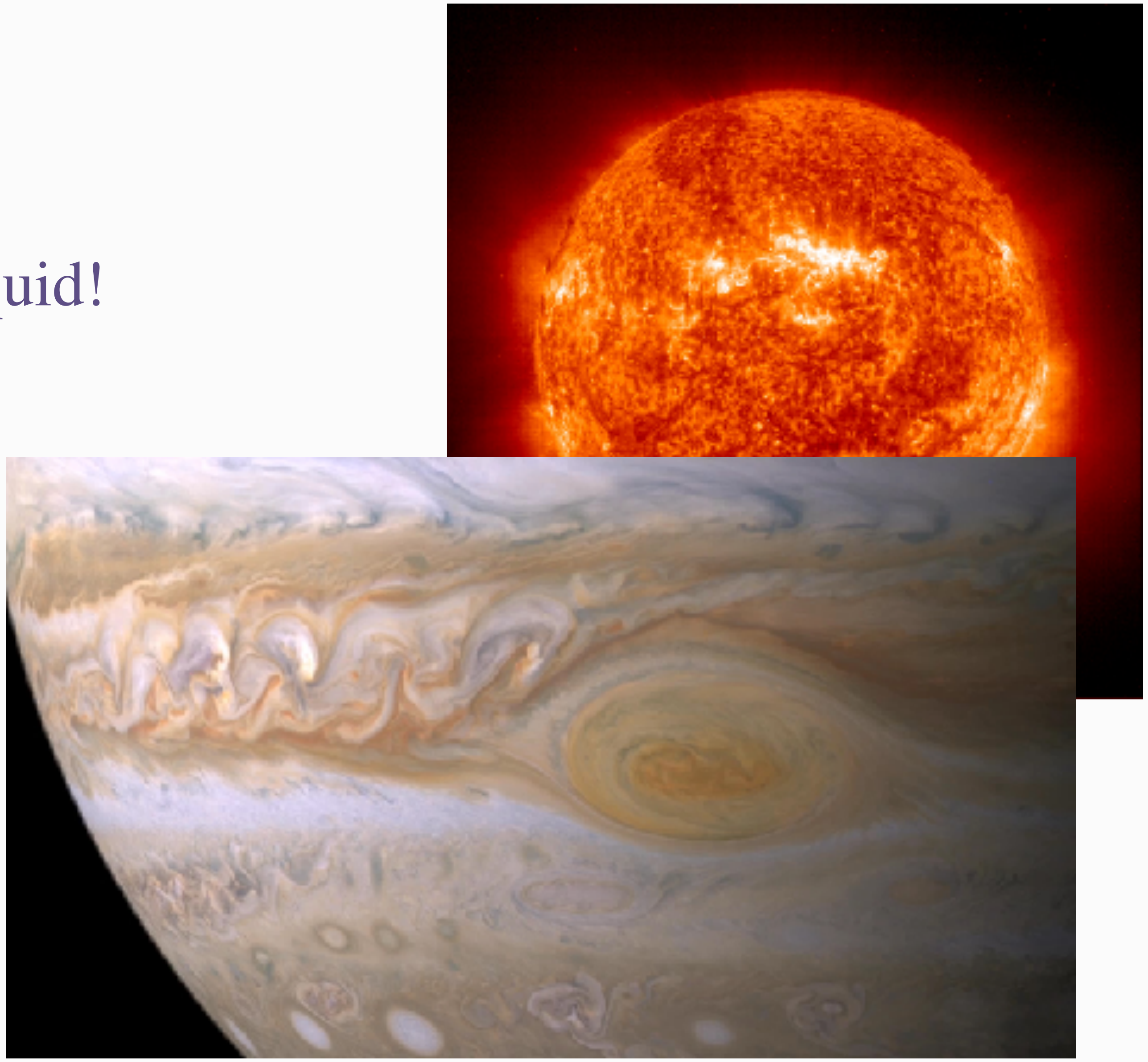

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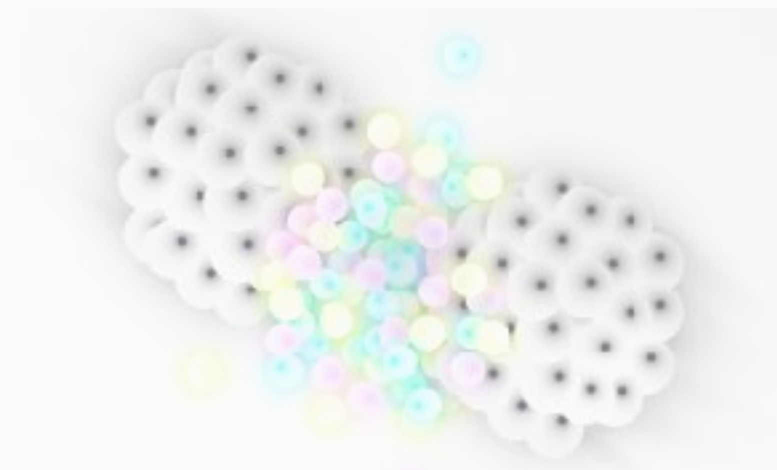

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Testing the boundaries of the QCD theory

Understanding QCD dynamics at all scales

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Check Research Opportunities

(11:00) G. Milhano

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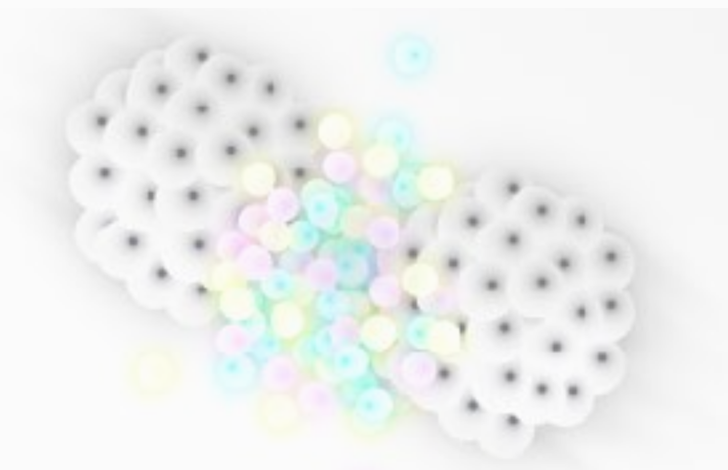

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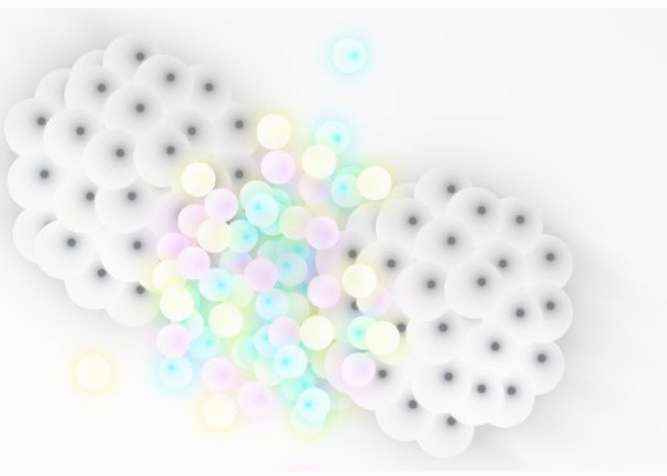
also QCD related:
(9:00) ATLAS, also Heavy-Ions
(11:10-11:40) D. Galaviz and C. Quintans

Backup slides

QCD Phase Diagram



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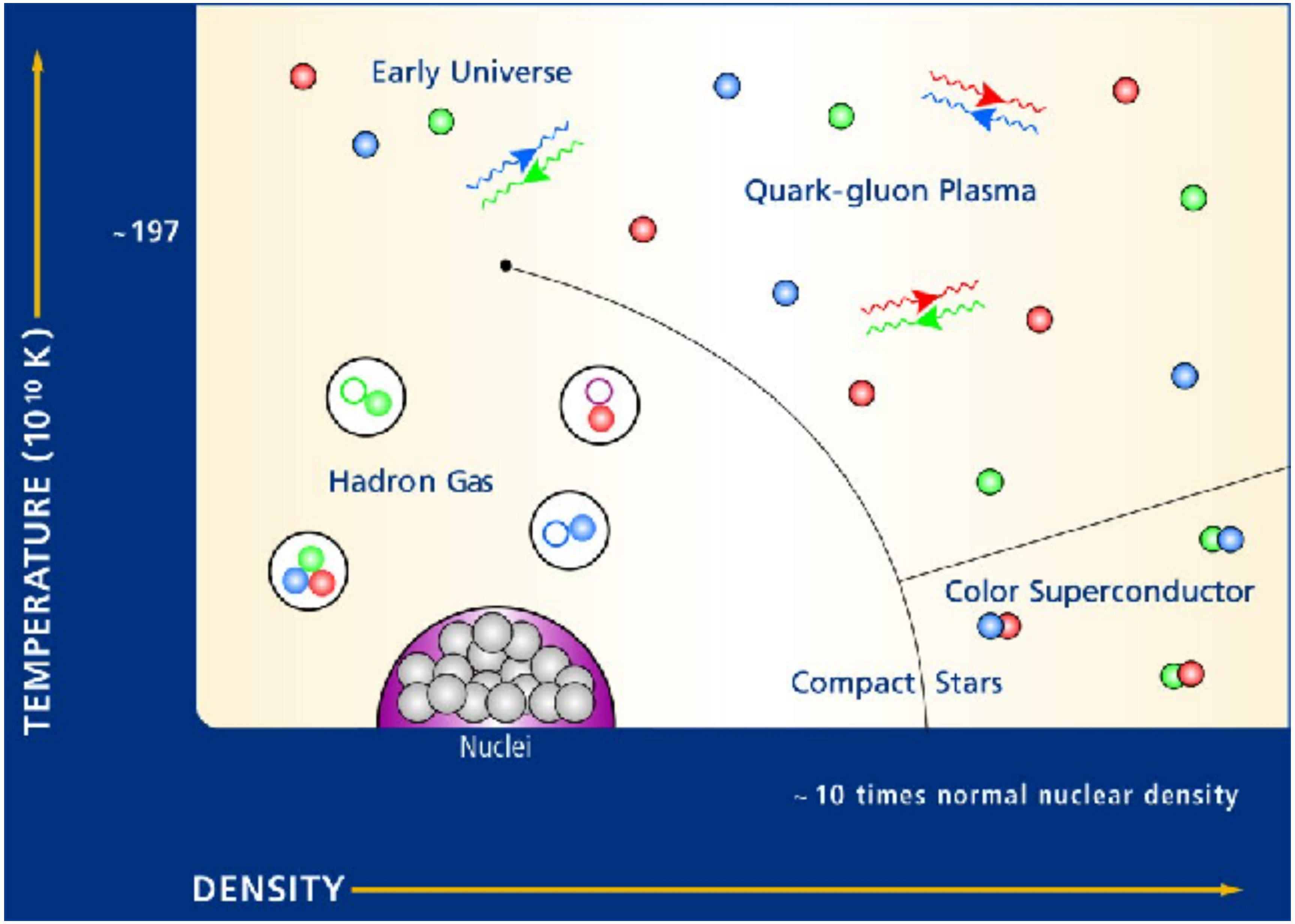

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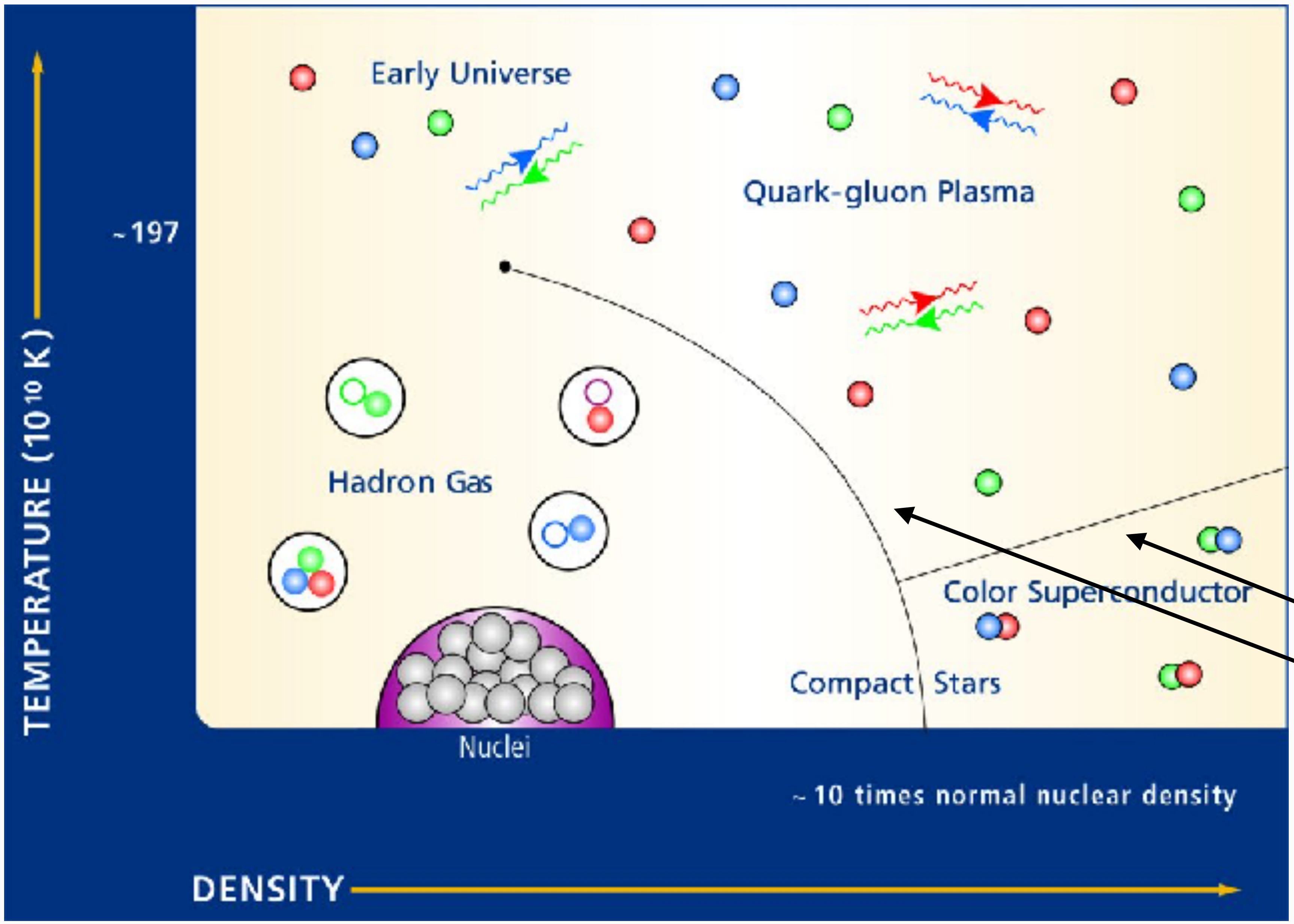

First order phase transition (thermodynamic singularities of the system)

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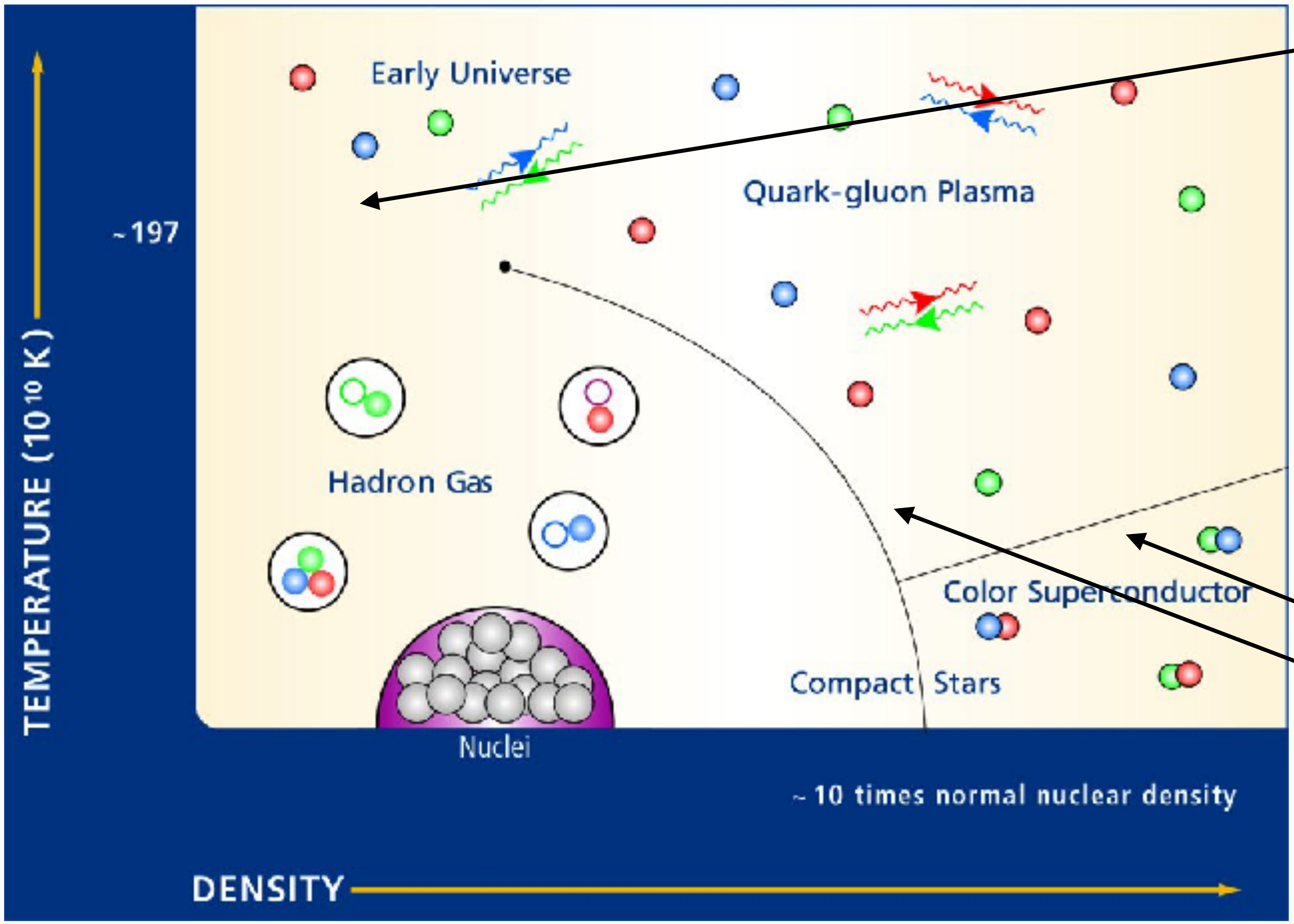

Cross-Over
(second order phase transition)

First order phase transition
(thermodynamic singularities
of the system)

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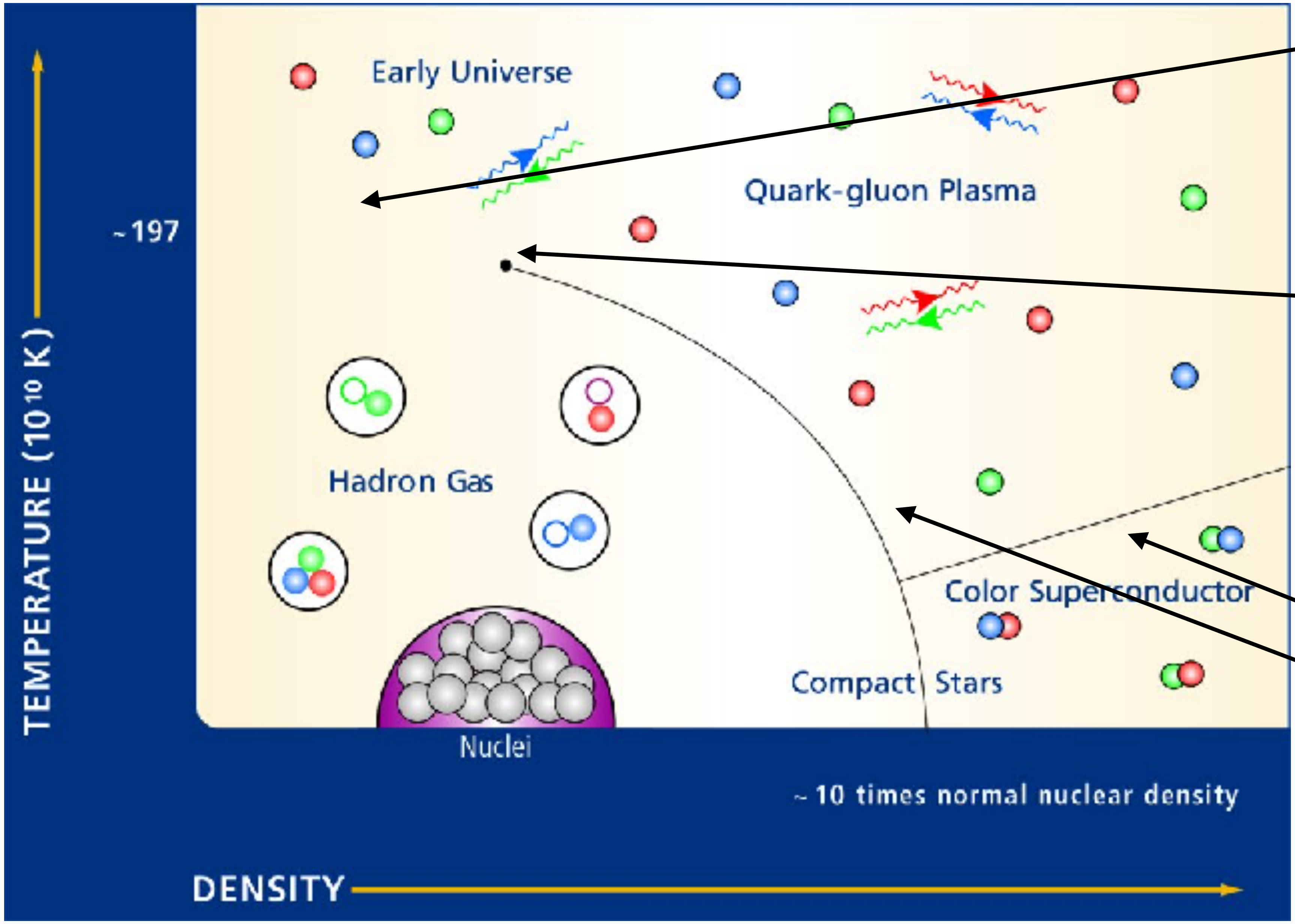

Cross-Over
(second order phase transition)

Critical point (?)

First order phase transition
(thermodynamic singularities
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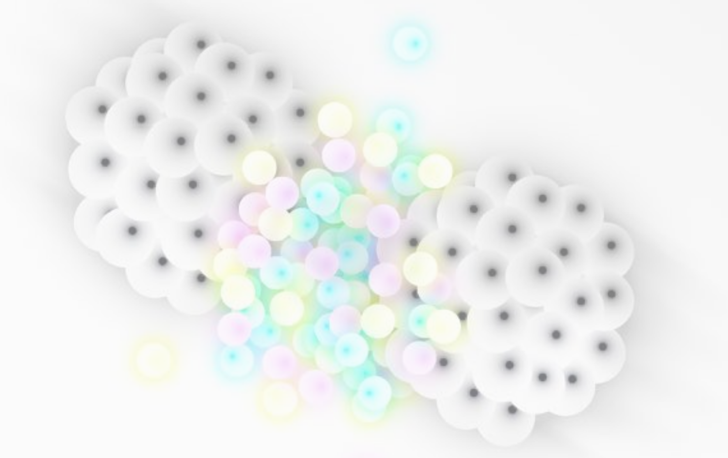
Soft probes



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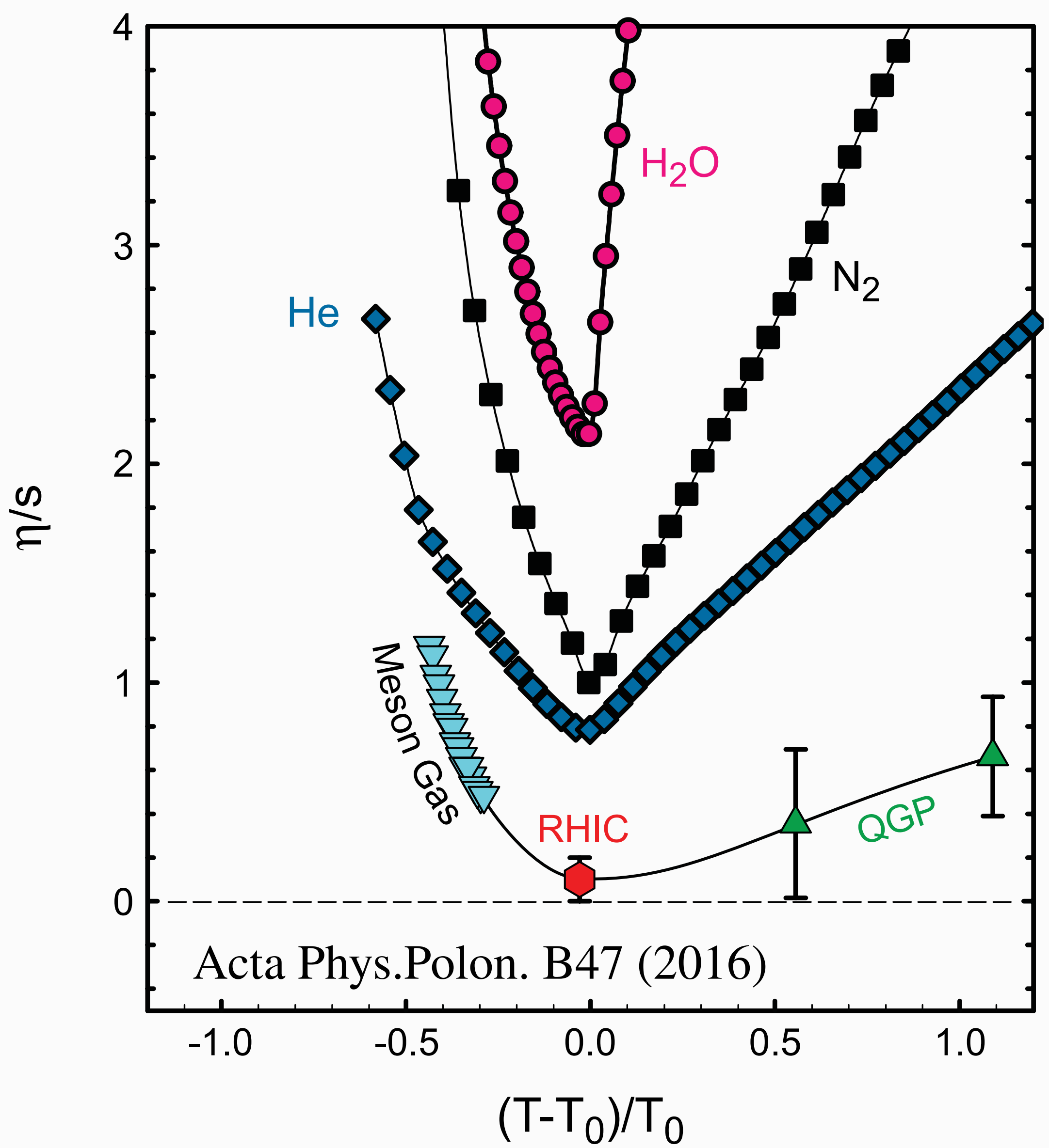

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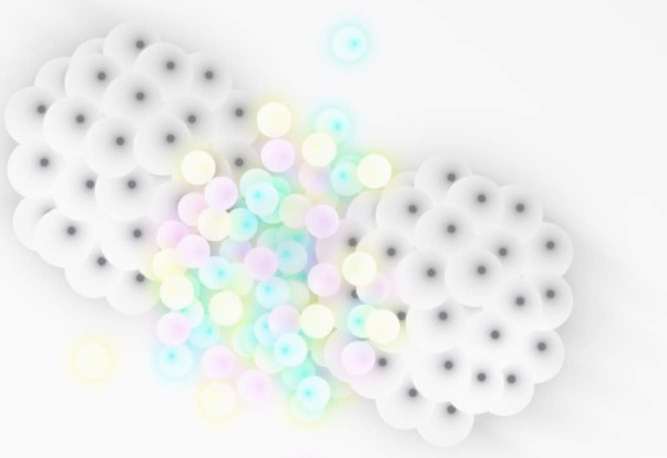

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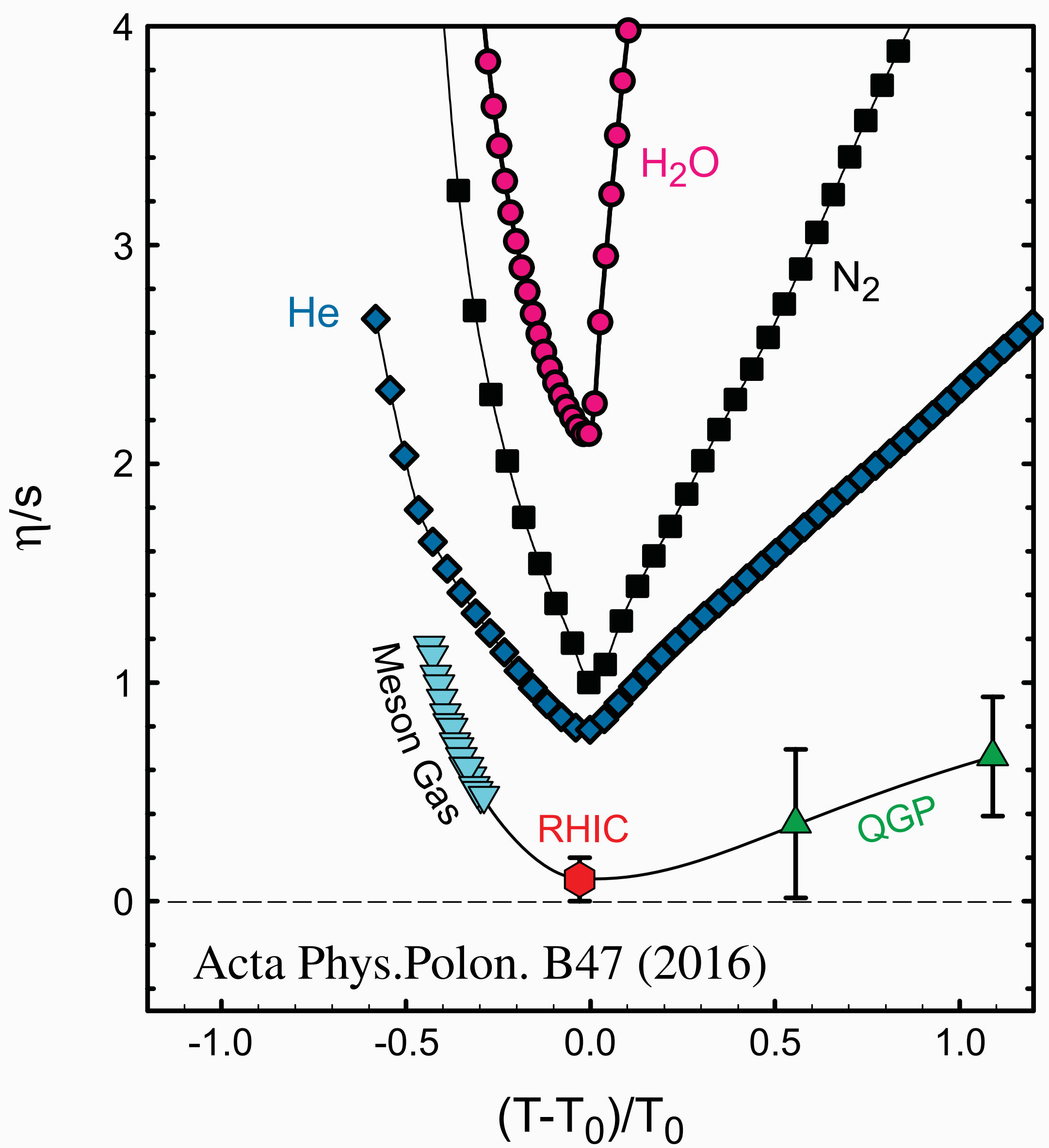

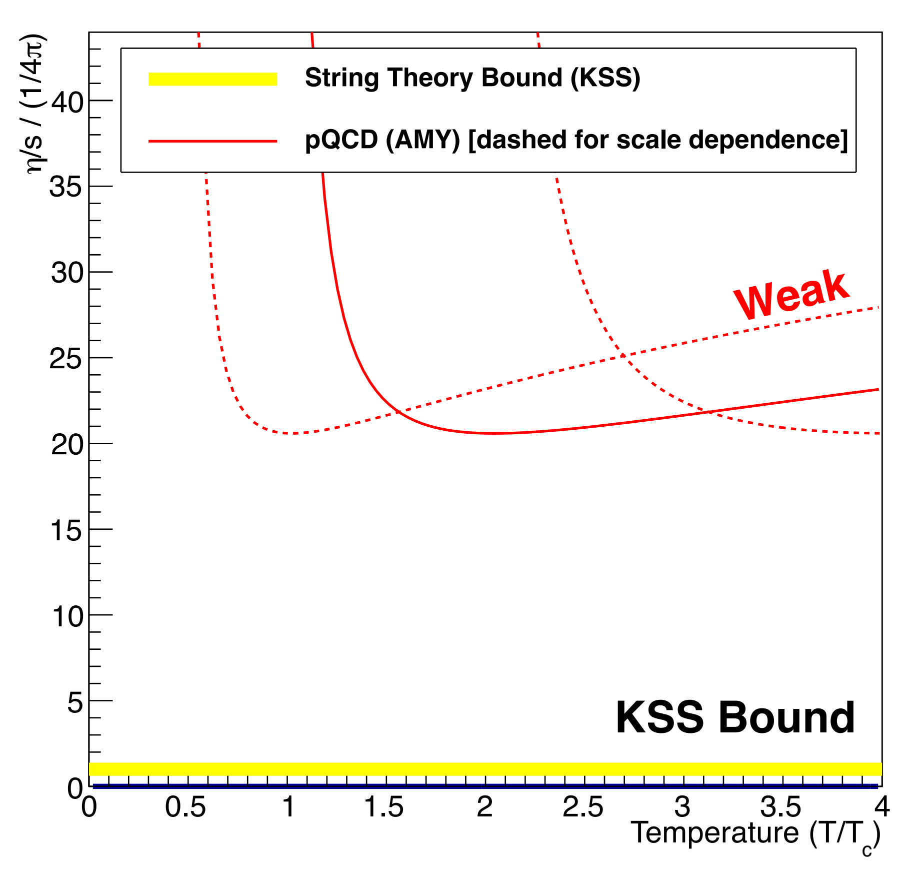

And the plasma should be a **strongly coupled fluid**!

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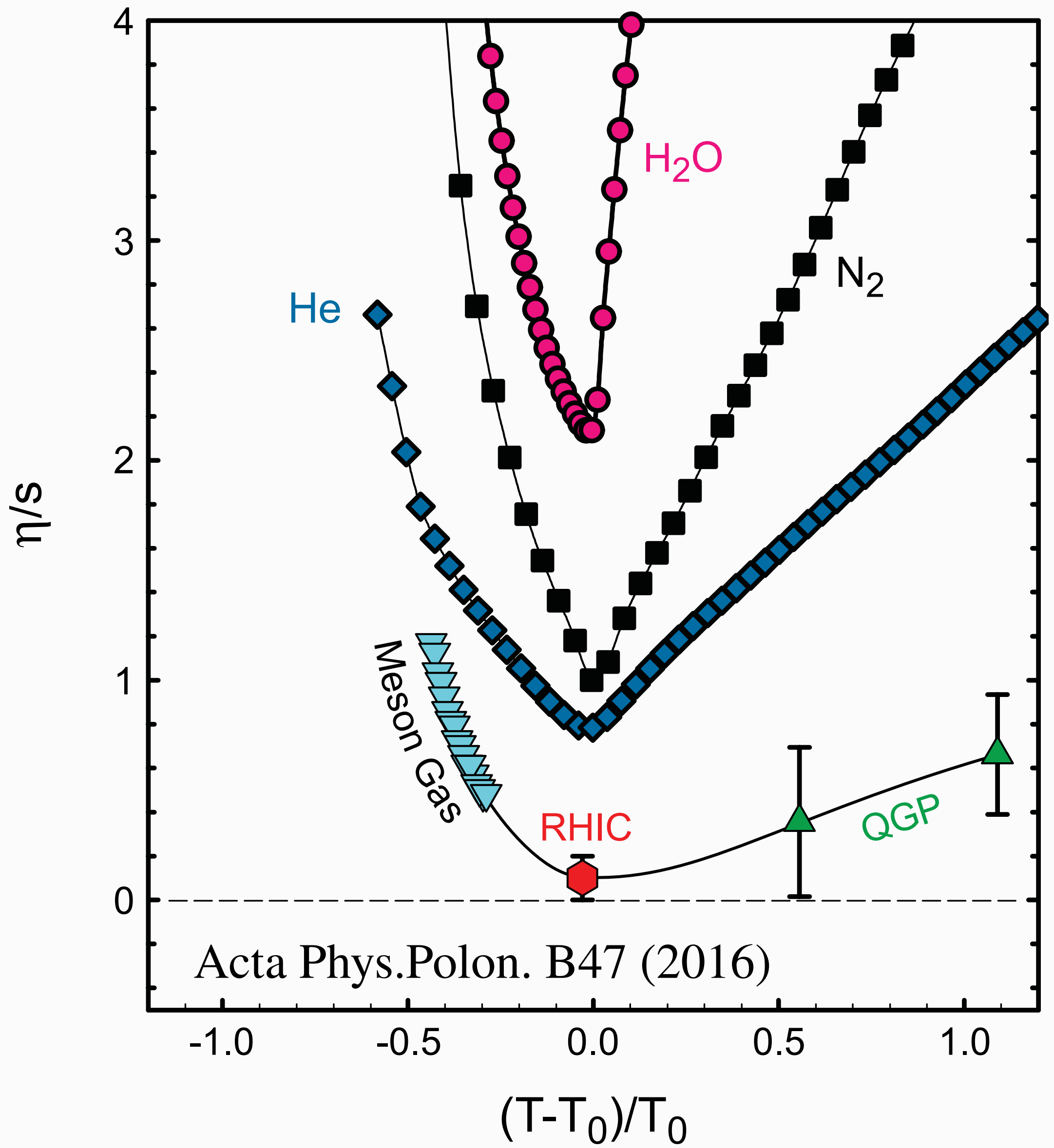

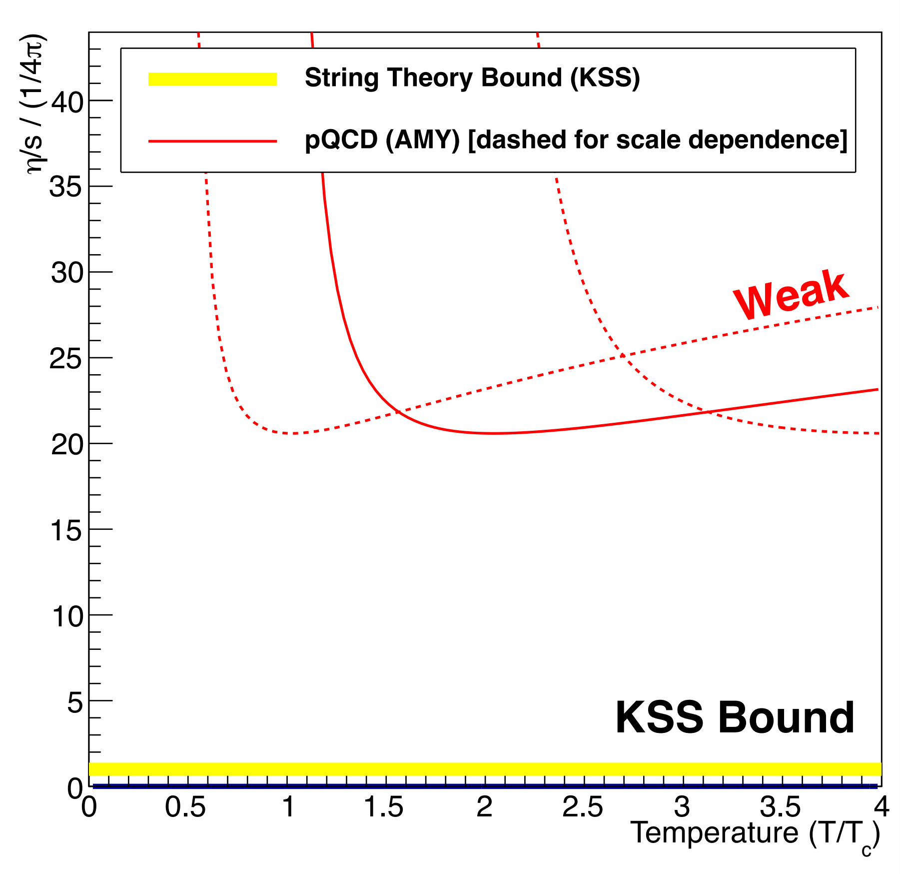

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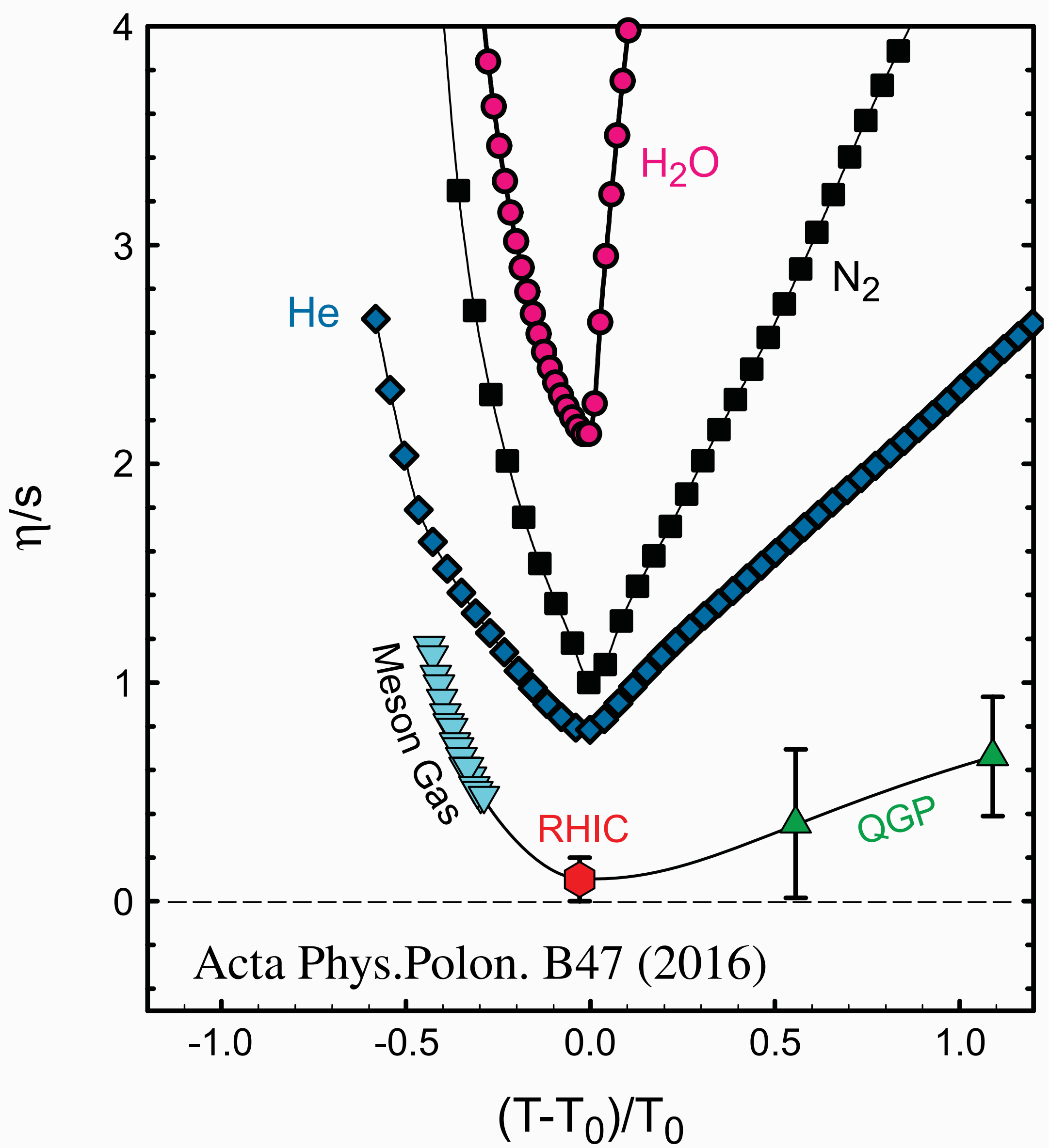

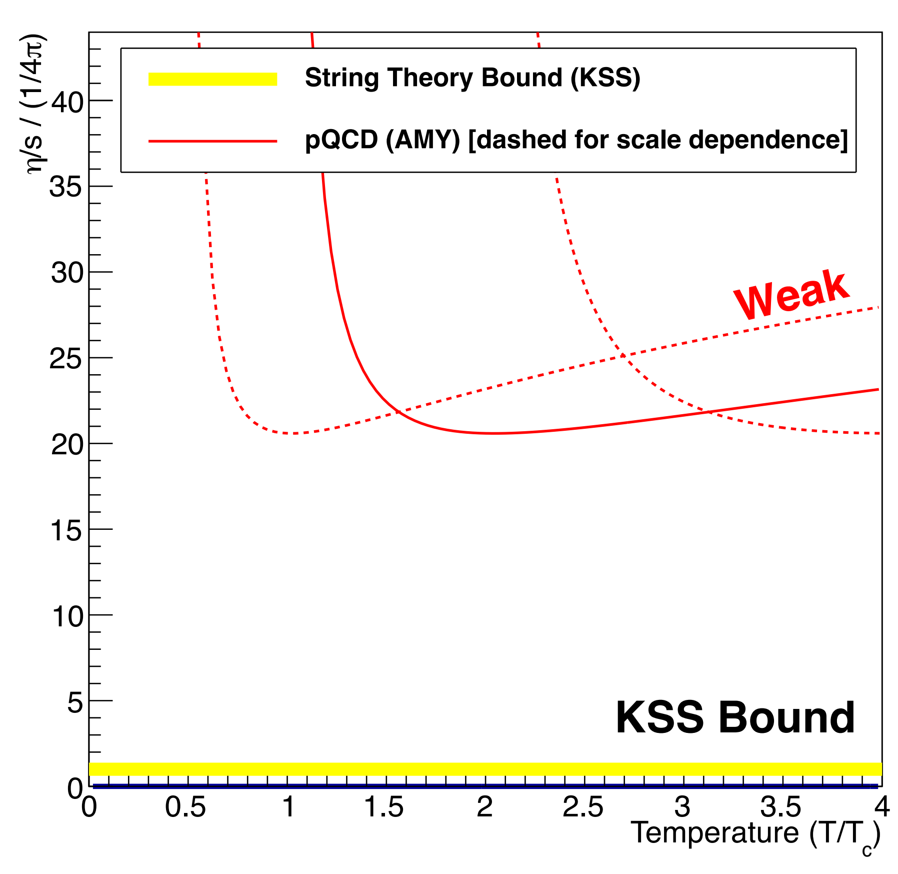

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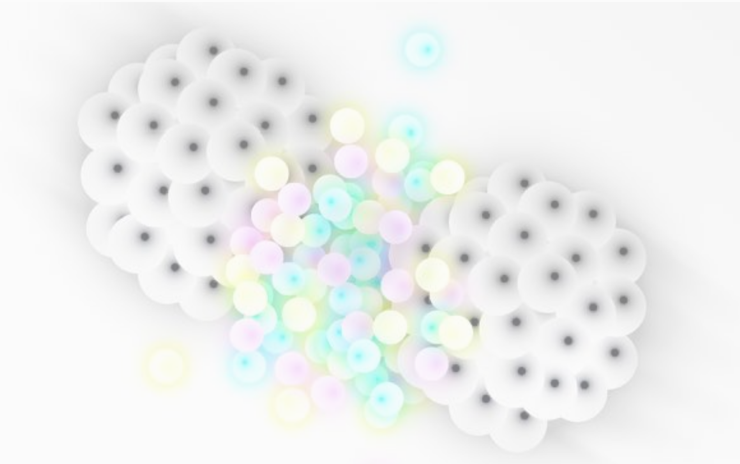
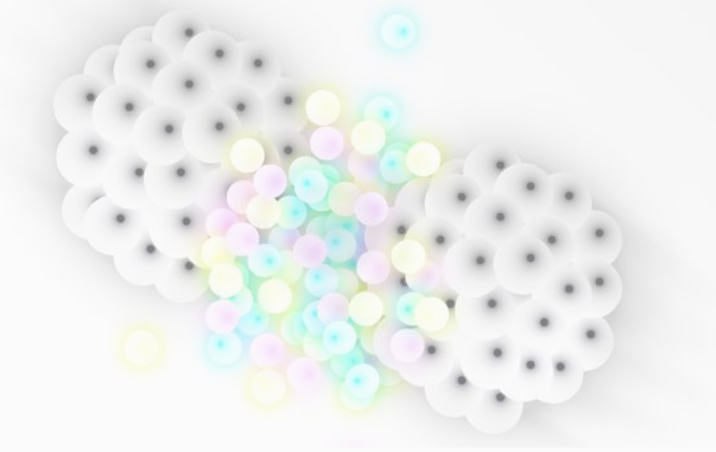
But we want to connect the QGP properties with QCD dynamics…

Hard Probes

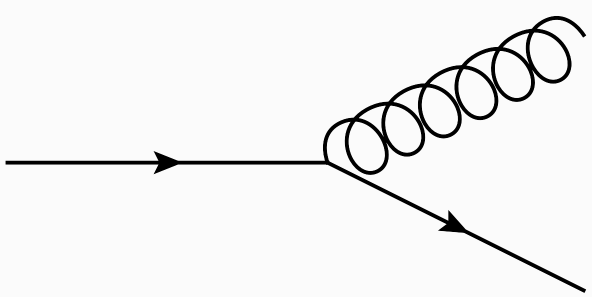


- Jet Quenching:
  - collection of in-medium modifications induced on high momentum objects (particles, jets, …)

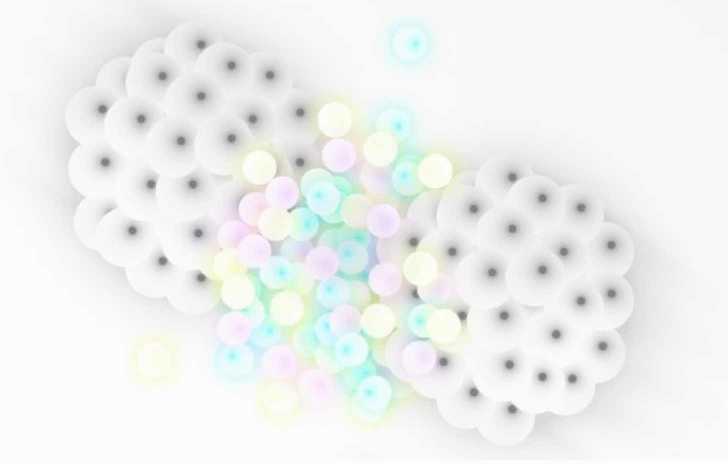
Hard Probes



- Jet Quenching:
  - collection of in-medium modifications induced on high momentum objects (particles, jets, …)



Hard Probes



- Jet Quenching:
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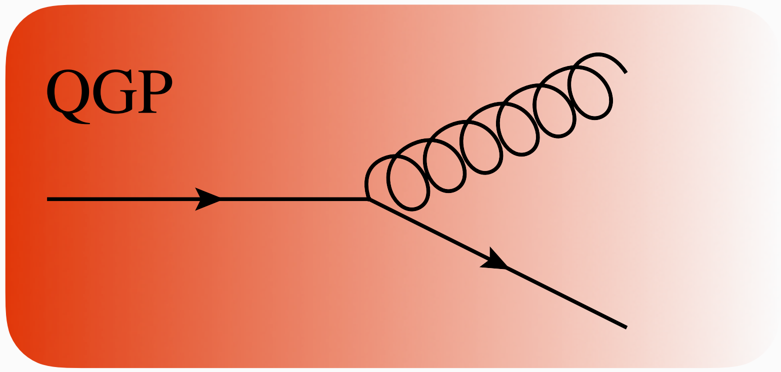

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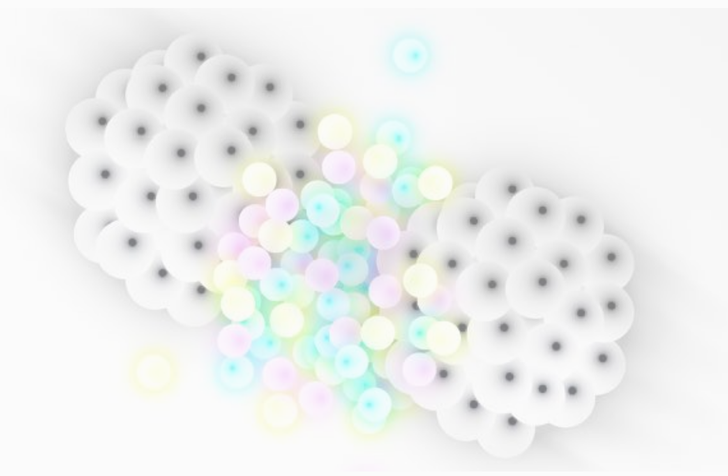
Hard Probes



- Jet Quenching:
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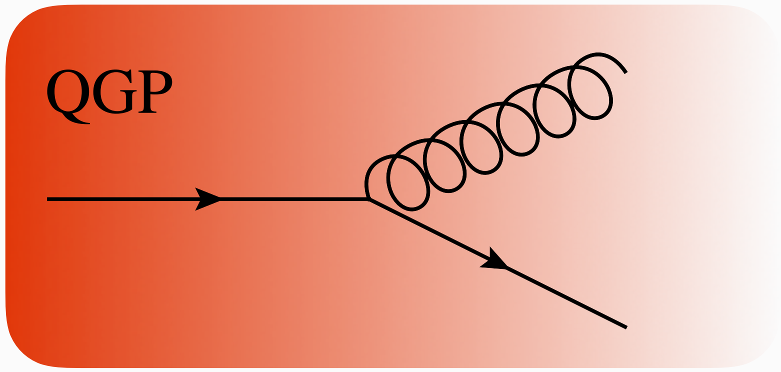

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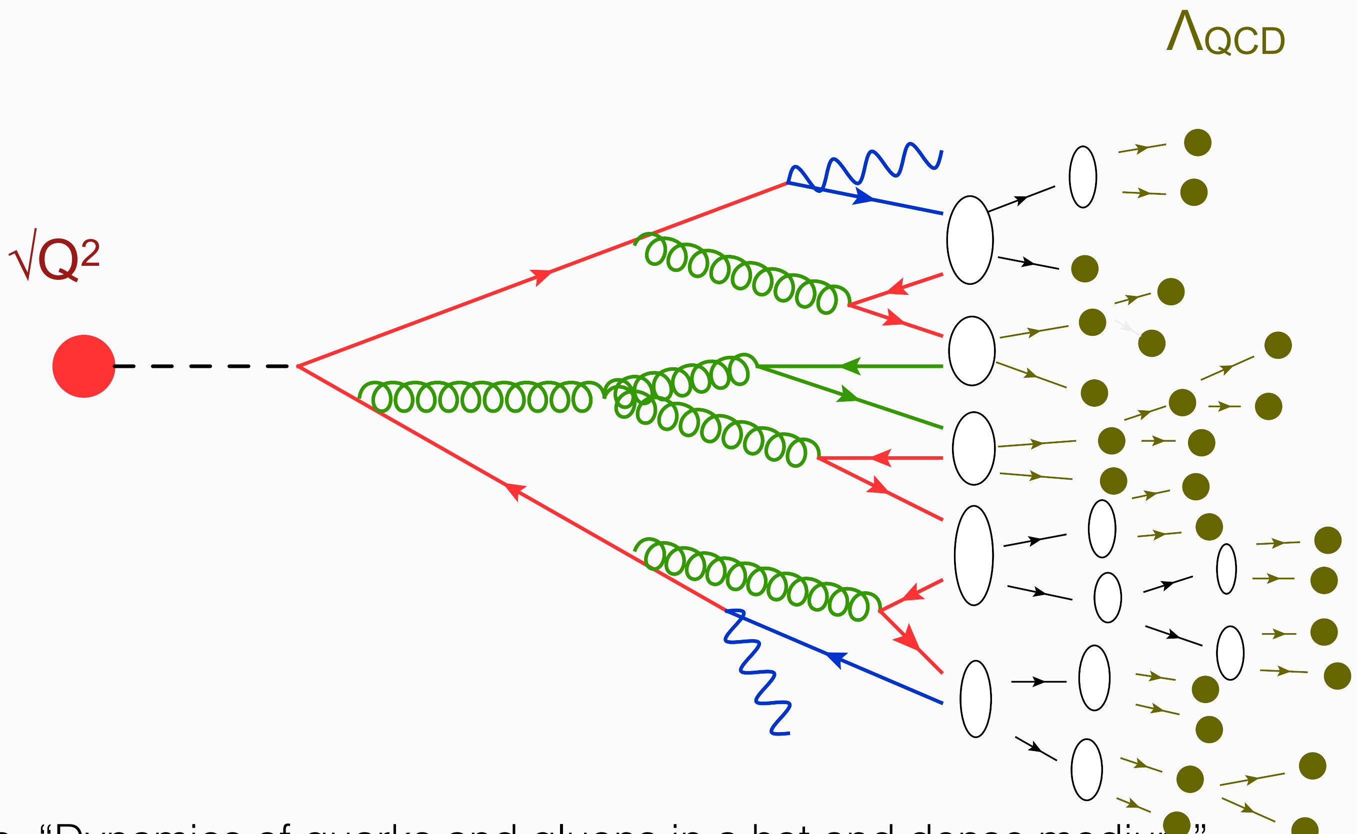
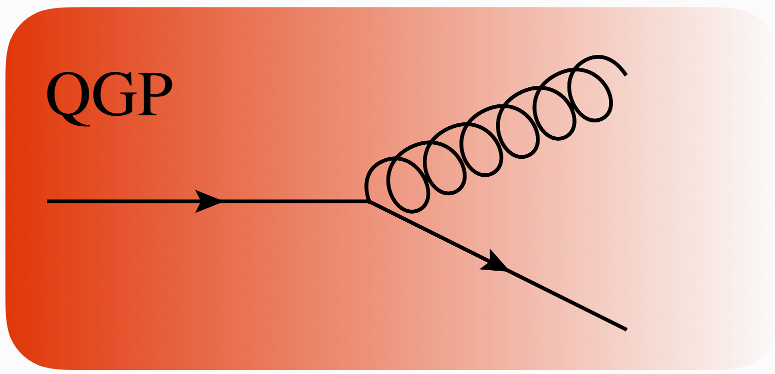


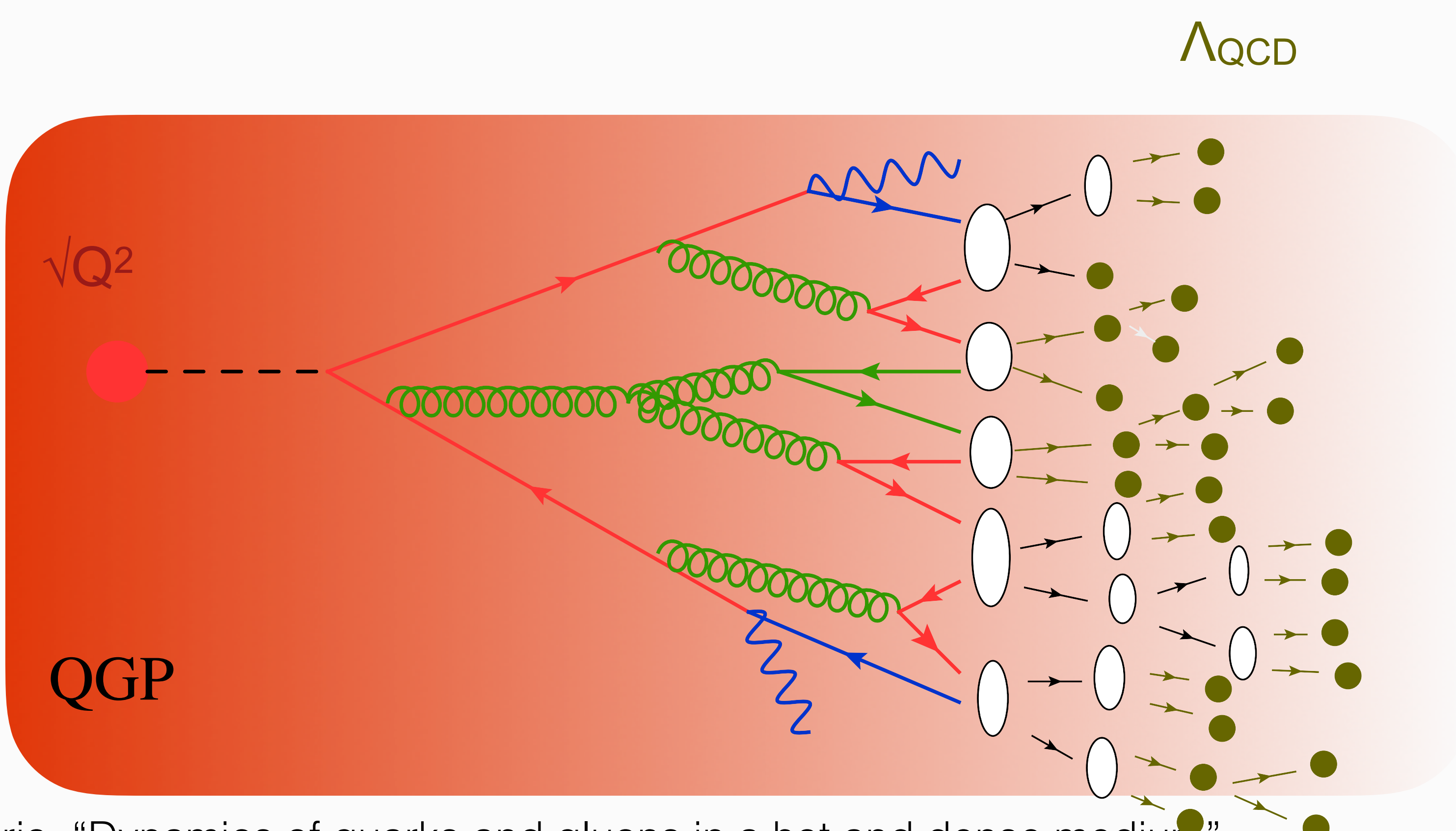
Hard Probes

- Jet Quenching:
  - collection of in-medium modifications induced on high momentum objects (particles, jets, …)



??

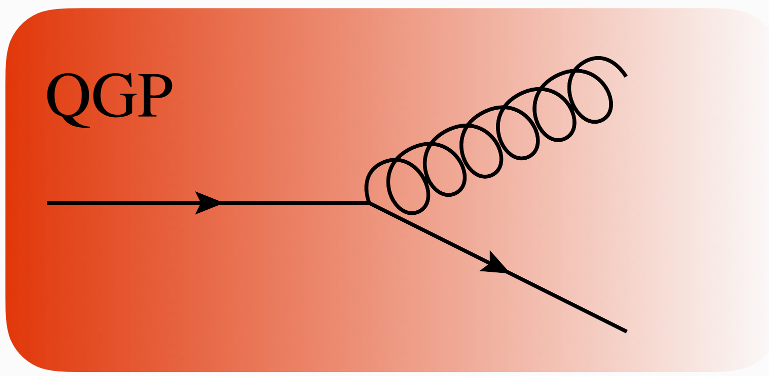
Interference between partonic emissions?



??

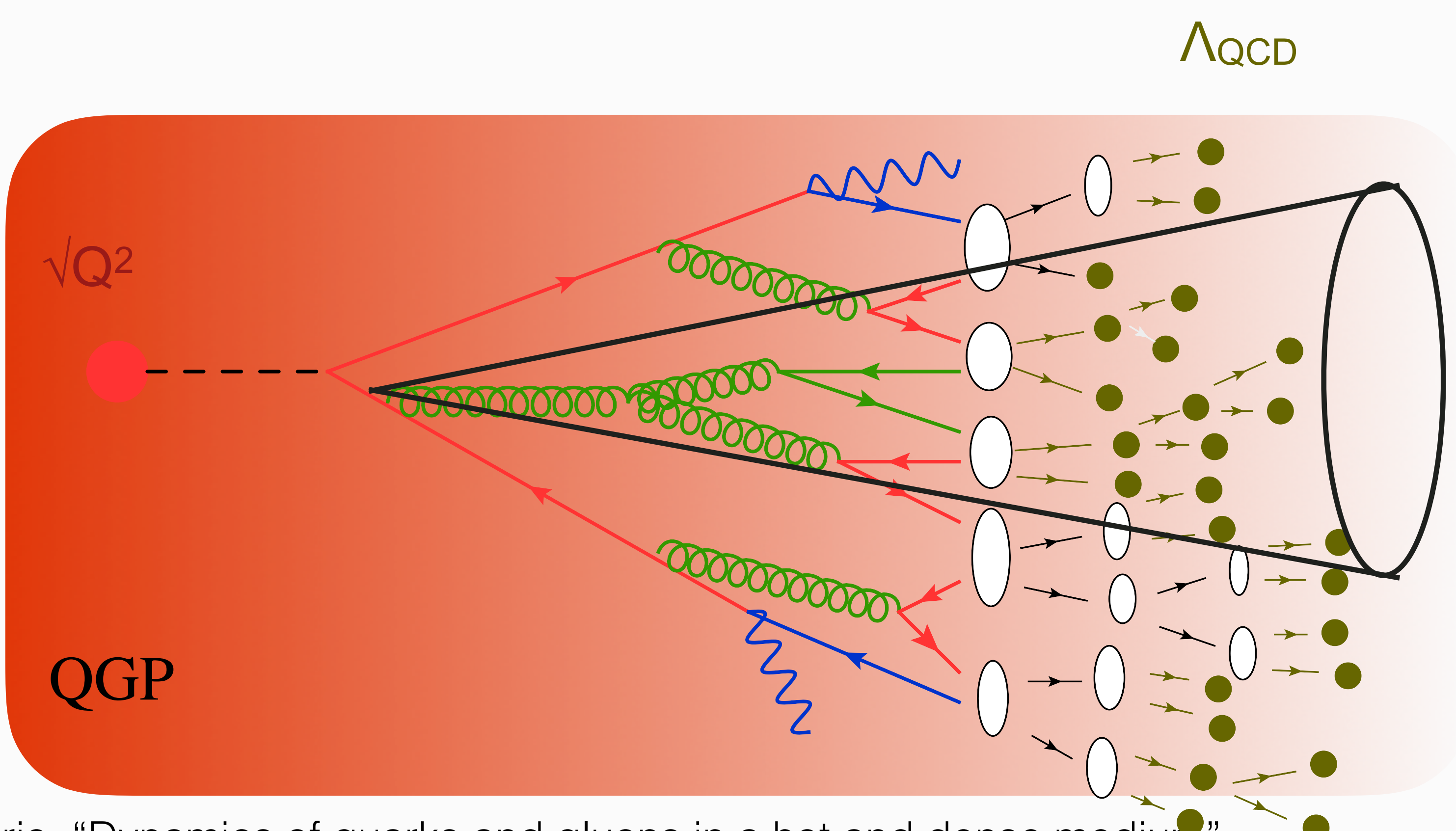
Hard Probes

- Jet Quenching:
  - collection of in-medium modifications induced on high momentum objects (particles, jets, …)



??

Interference between partonic emissions?



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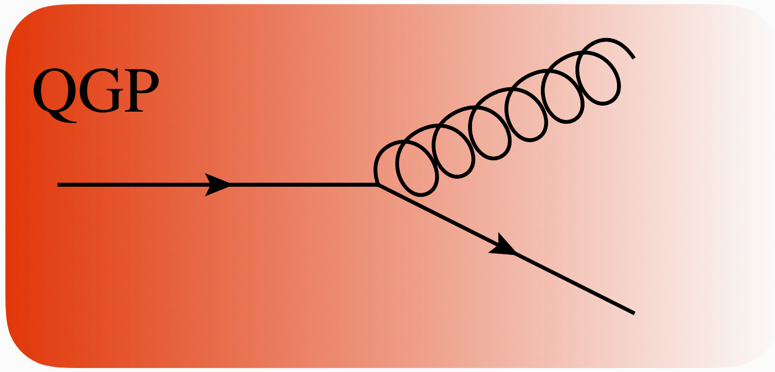
Jets are reconstructed at the level of the final event…

How to distinguish between "medium particles" from "hard scattering particles"?

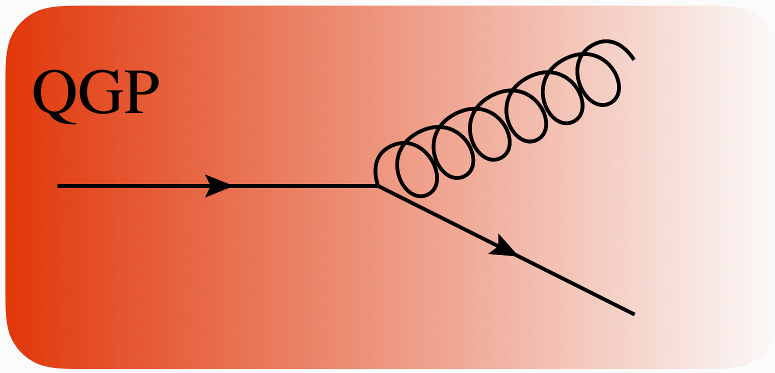
Hard Probes

- Jet Quenching from a pQCD perspective:



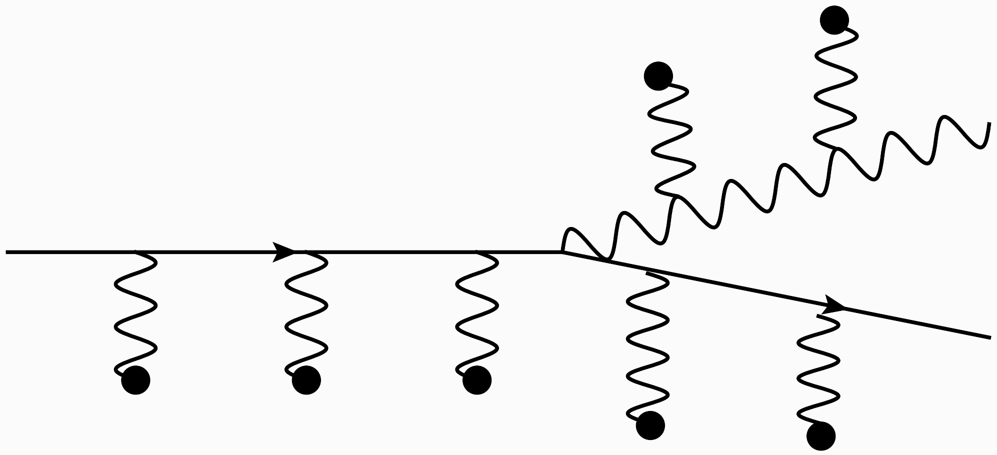
Hard Probes

- Jet Quenching from a pQCD perspective:

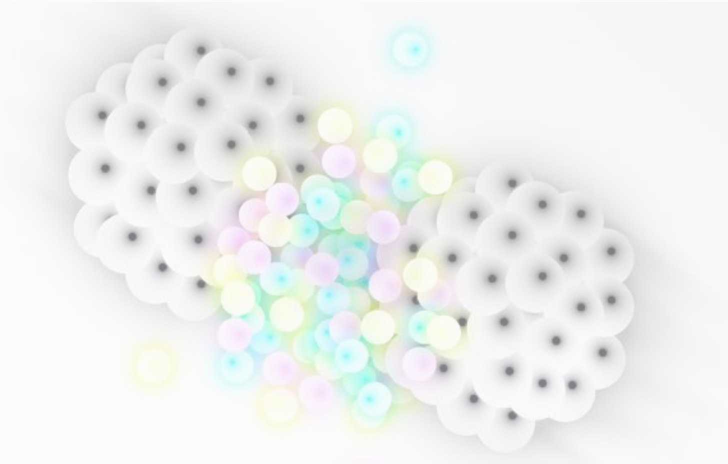


$\Longrightarrow$

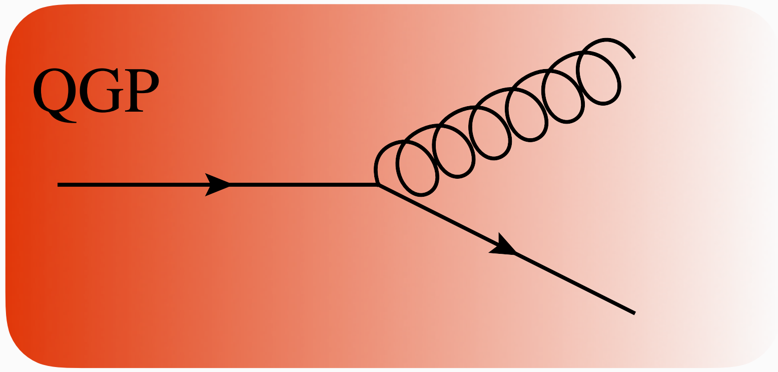
QGP = collection of static scattering centres



Hard Probes



- Jet Quenching from a pQCD perspective:



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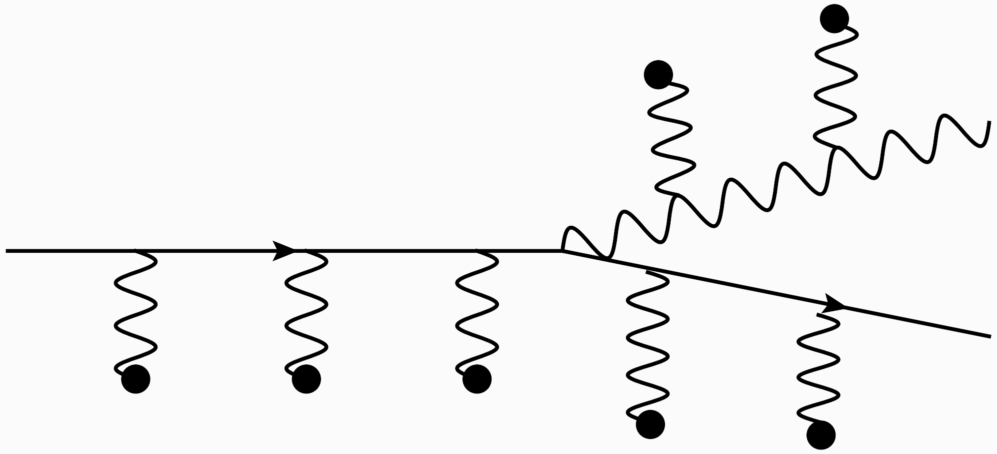
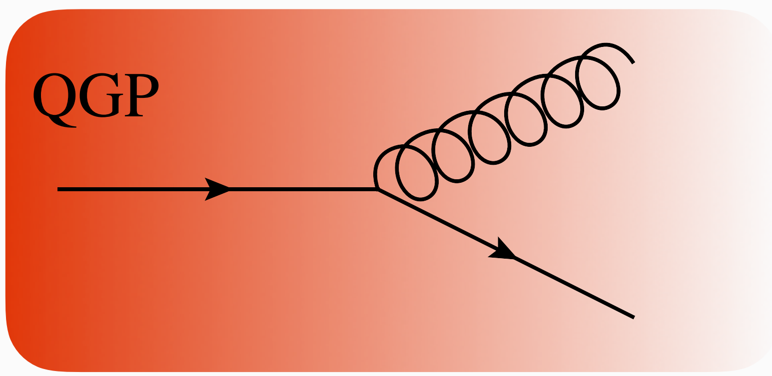


Vacuum QCD Feynman rules: $\Longrightarrow$ In-medium QCD Feynman rules:

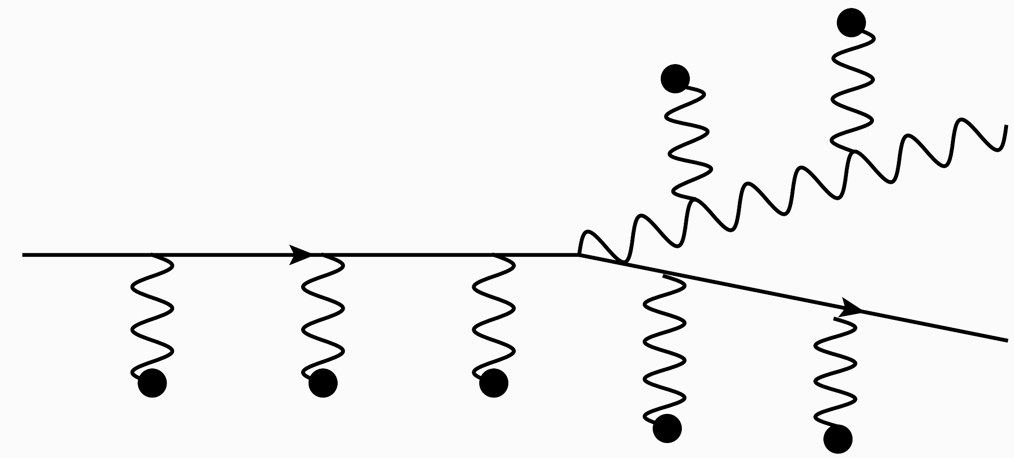
Hard Probes

- Jet Quenching from a pQCD perspective:



$\Longrightarrow$

QGP = collection of static scattering centres

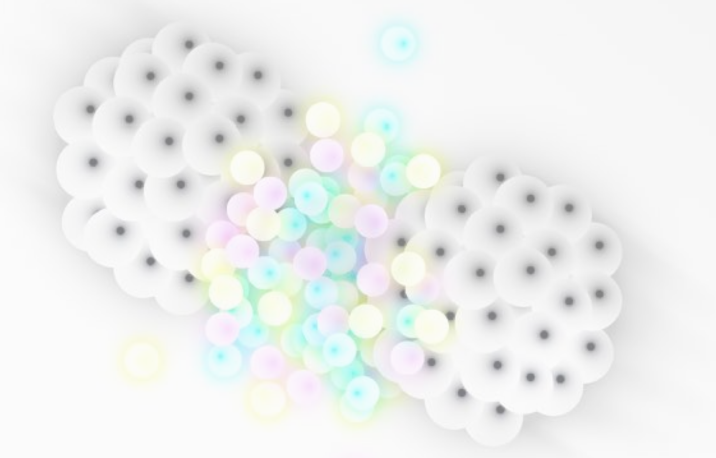


Vacuum QCD Feynman rules:

$\Longrightarrow$

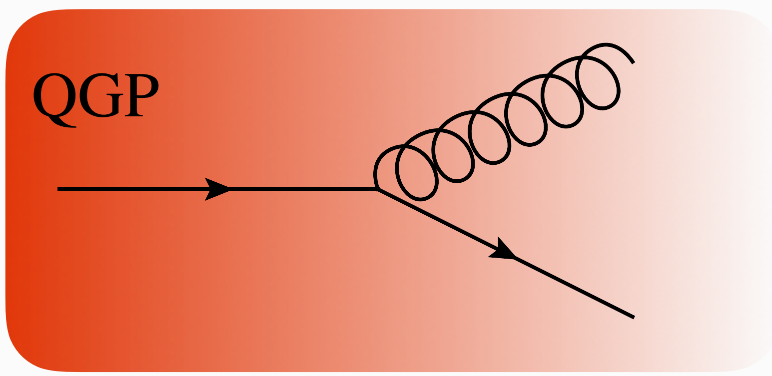
In-medium QCD Feynman rules:

$$= i\delta^{ab}\frac{\not{p}+m}{p^2-m^2+i\varepsilon}$$



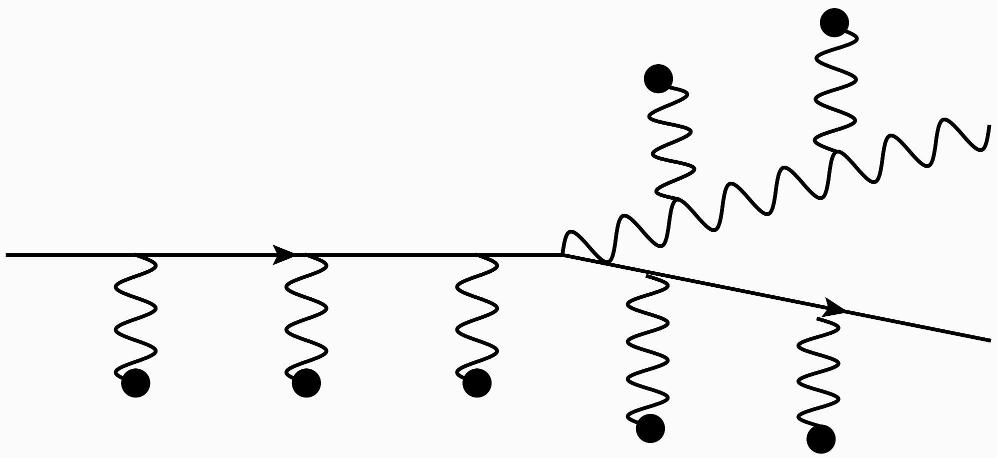
Hard Probes

- Jet Quenching from a pQCD perspective:



$\Longrightarrow$

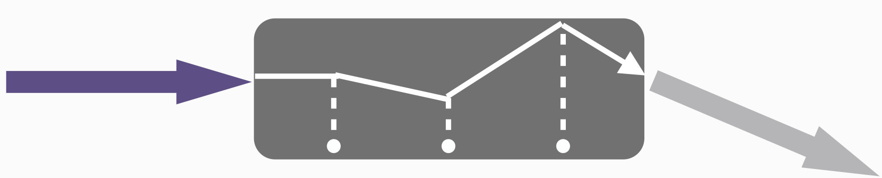
QGP = collection of static scattering centres



Vacuum QCD Feynman rules:

$\Longrightarrow$

In-medium QCD Feynman rules:

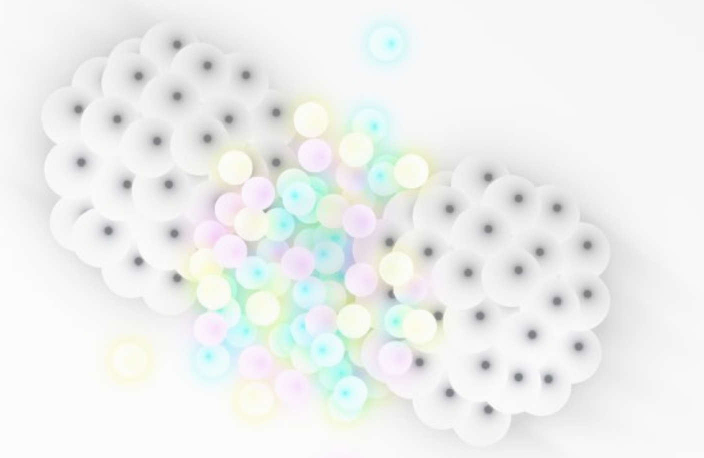


$$= i\delta^{ab}\frac{\not{p}+m}{p^2-m^2+i\varepsilon}$$

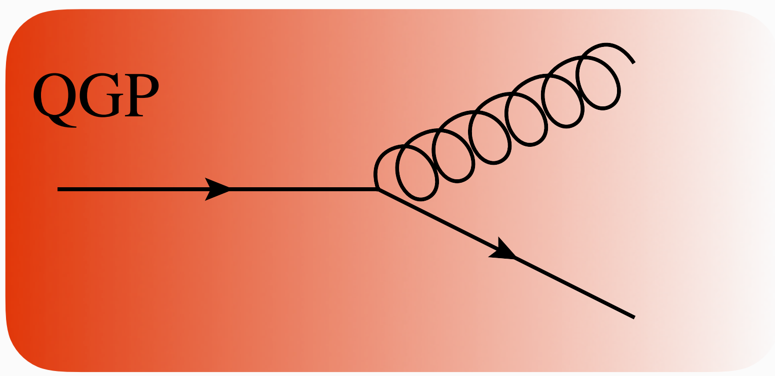
$$G(x_{0+},\mathbf{x_0}_\perp;L_+,\mathbf{x}_\perp|p_+) = \int_{\mathbf{r}_\perp(x_{0+})=\mathbf{x_0}_\perp}^{\mathbf{r}_\perp(L_+)=\mathbf{x}_\perp}\mathcal{D}\mathbf{r}_\perp(\xi)\exp\left\{\frac{ip_+}{2}\int_{x_{0+}}^{L_+}d\xi\,\left(\frac{d\mathbf{r}_\perp}{d\xi}\right)^2\right\} \times W(x_{0+},L_+;\mathbf{r}_\perp(\xi)),$$

$$W(x_{0+},L_+;\mathbf{x}_\perp) = \mathcal{P}\exp\left\{ig\int_{x_{0+}}^{L_+}dx_+A_-(x_+,\mathbf{x}_\perp)\right\}$$

Hard Probes

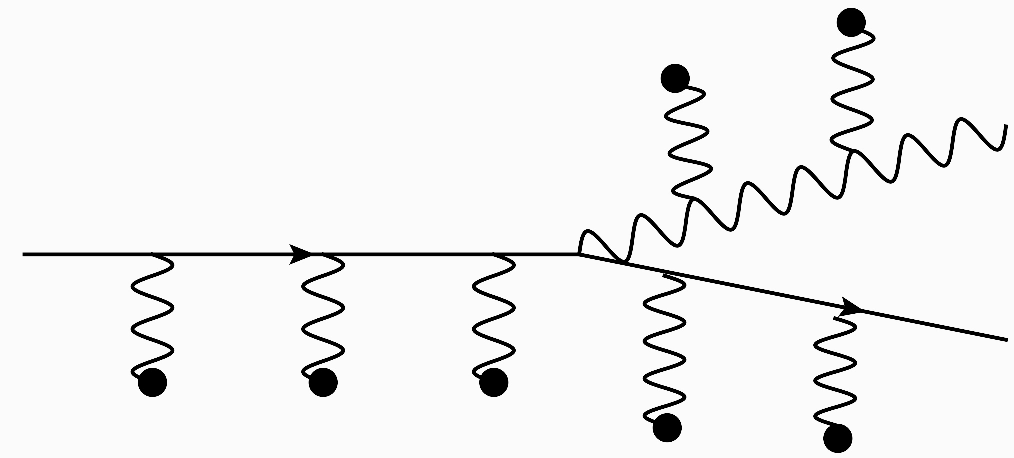


- Jet Quenching from a pQCD perspective:



$\Longrightarrow$

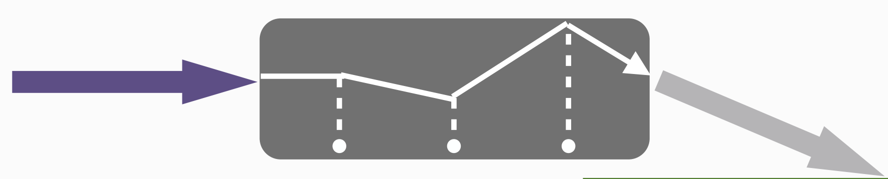
QGP = collection of static scattering centres



Vacuum QCD Feynman rules:

$\Longrightarrow$

In-medium QCD Feynman rules:

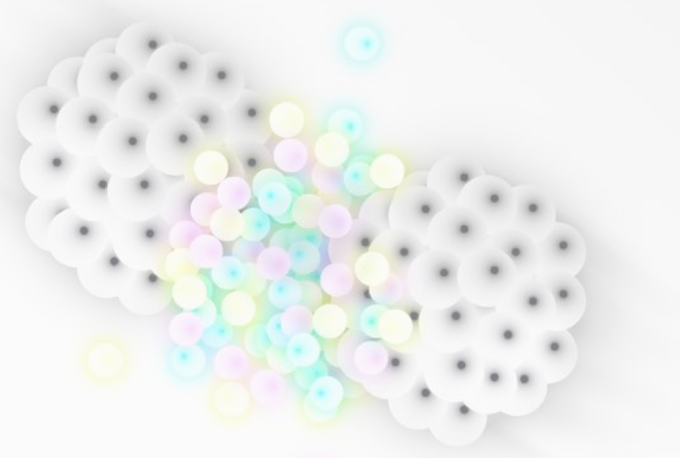


Kinetic description

$$= i\delta^{ab}\frac{\not{p}+m}{p^2-m^2+i\varepsilon}$$

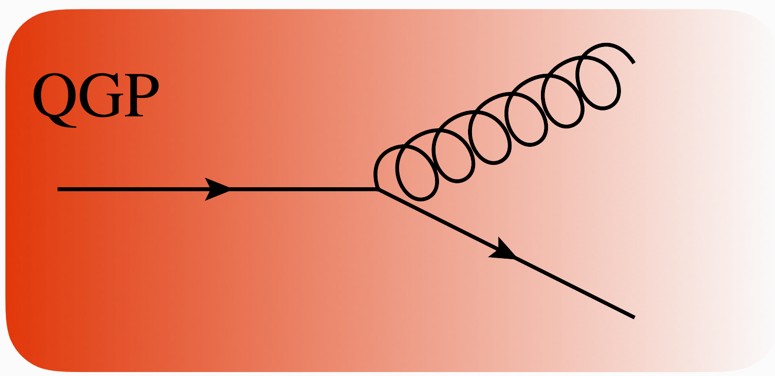
$$G(x_{0+},\mathbf{x_{0}}_\perp;L_+,\mathbf{x}_\perp|p_+) = \boxed{\int_{\mathbf{r}_\perp(x_{0+})=\mathbf{x_0}_\perp}^{\mathbf{r}_\perp(L_+)=\mathbf{x}_\perp} \mathcal{D}\mathbf{r}_\perp(\xi)\exp\left\{\frac{ip_+}{2}\int_{x_{0+}}^{L_+} d\xi\,\left(\frac{d\mathbf{r}_\perp}{d\xi}\right)^2\right\}}$$
$$\times W(x_{0+},L_+;\mathbf{r}_\perp(\xi)),$$

$$W(x_{0+},L_+;\mathbf{x}_\perp) = \mathcal{P}\exp\left\{ig\int_{x_{0+}}^{L_+} dx_+ A_-(x_+,\mathbf{x}_\perp)\right\}$$



Hard Probes

- Jet Quenching from a pQCD perspective:



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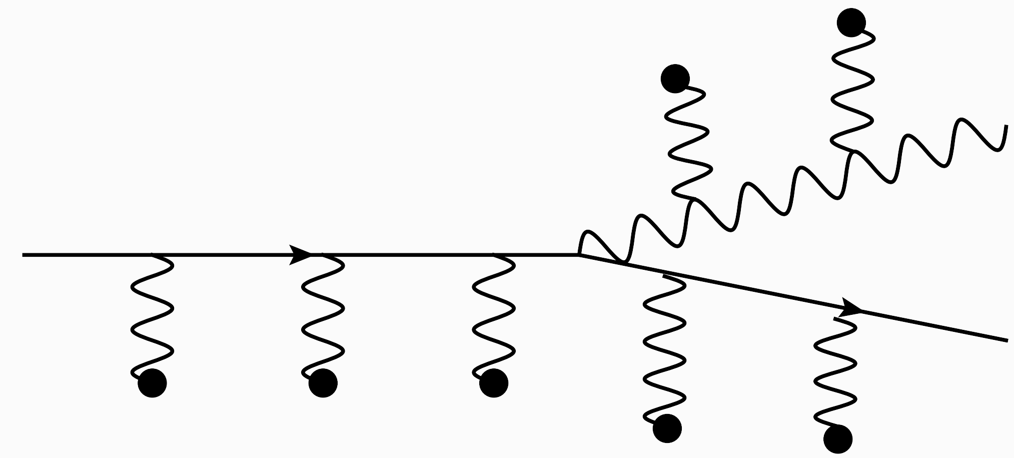
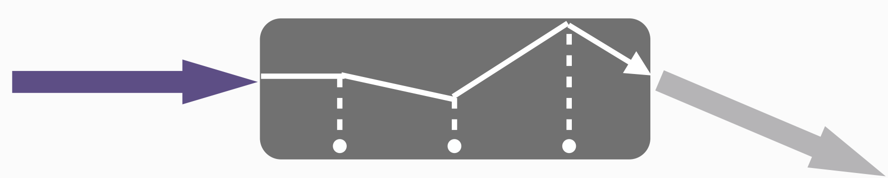
QGP = collection of static scattering centres



Vacuum QCD Feynman rules: $\Longrightarrow$ In-medium QCD Feynman rules:

$\longrightarrow$

$$= i\delta^{ab}\frac{\not{p}+m}{p^2-m^2+i\varepsilon}$$

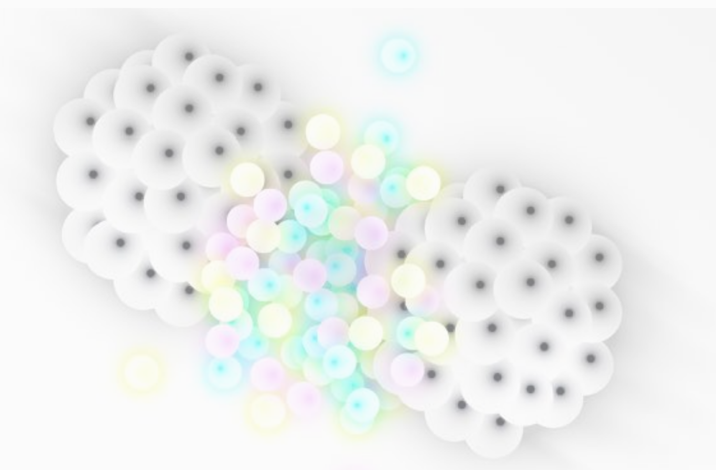


Colour change description

$$G(x_{0+},\mathbf{x_0}_\perp;L_+,\mathbf{x}_\perp|p_+) = \int_{\mathbf{r}_\perp(x_{0+})=\mathbf{x_0}_\perp}^{\mathbf{r}_\perp(L_+)=\mathbf{x}_\perp} \mathcal{D}\mathbf{r}_\perp(\xi)\exp\left\{\frac{ip_+}{2}\int_{x_{0+}}^{L_+} d\xi\,\left(\frac{d\mathbf{r}_\perp}{d\xi}\right)^2\right\}$$

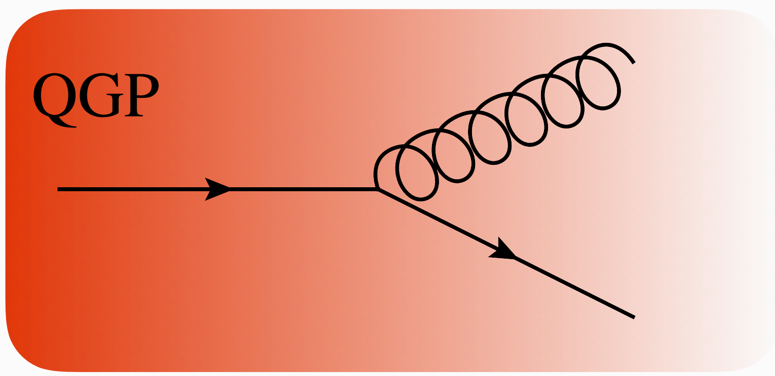
$$\times W(x_{0+},L_+;\mathbf{r}_\perp(\xi)),$$

$$W(x_{0+},L_+;\mathbf{x}_\perp) = \mathcal{P}\exp\left\{ig\int_{x_{0+}}^{L_+} dx_+ A_-(x_+,\mathbf{x}_\perp)\right\}$$



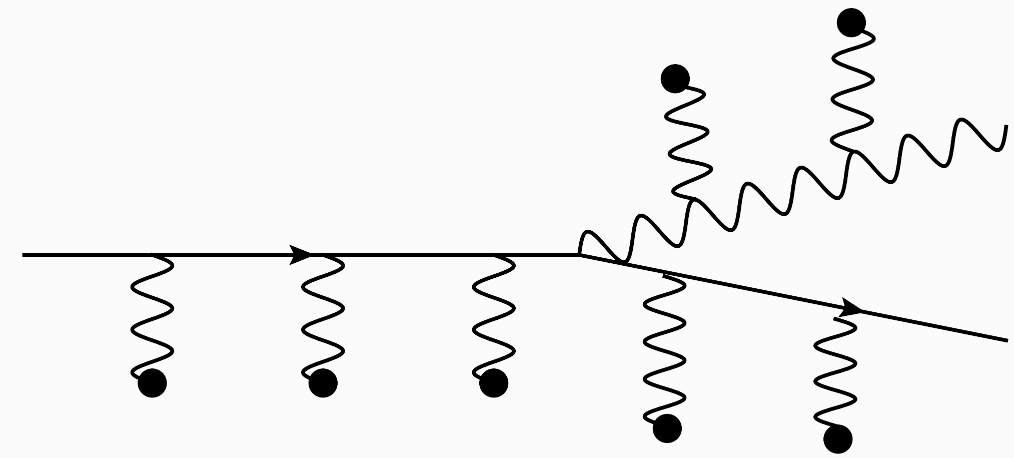
Hard Probes

- Jet Quenching from a pQCD perspective:

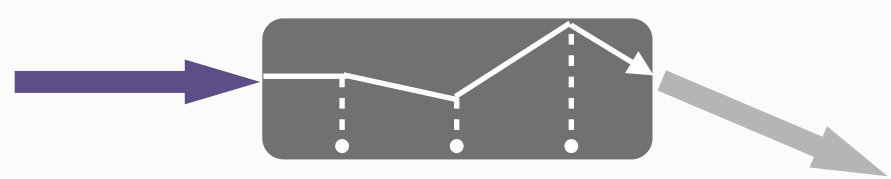


$\Longrightarrow$

QGP = collection of static scattering centres



Vacuum QCD Feynman rules: $\Longrightarrow$ In-medium QCD Feynman rules:



$$= i\delta^{ab}\frac{\not{p}+m}{p^2-m^2+i\varepsilon}$$

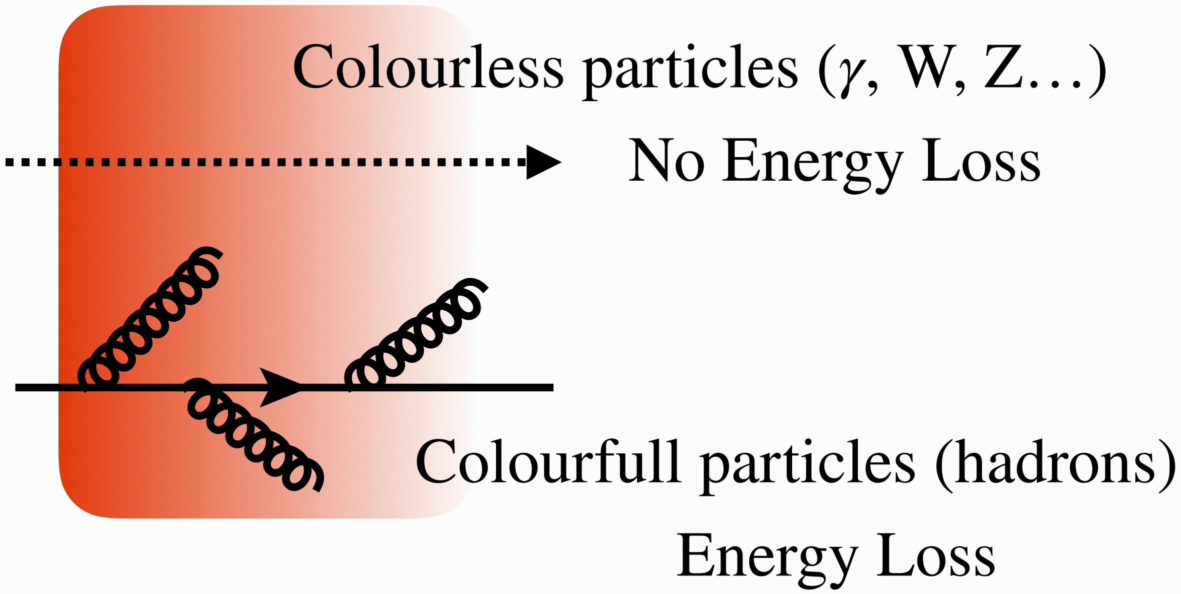
$$G(x_{0+},\mathbf{x_0}_\perp;L_+,\mathbf{x}_\perp|p_+)=\int_{\mathbf{r}_\perp(x_{0+})=\mathbf{x_0}_\perp}^{\mathbf{r}_\perp(L_+)=\mathbf{x}_\perp}\mathcal{D}\mathbf{r}_\perp(\xi)\exp\left\{\frac{ip_+}{2}\int_{x_{0+}}^{L_+}d\xi\left(\frac{d\mathbf{r}_\perp}{d\xi}\right)^2\right\}$$
$$\times W(x_{0+},L_+;\mathbf{r}_\perp(\xi)),$$

(...)

$$W(x_{0+},L_+;\mathbf{x}_\perp)=\mathcal{P}\exp\left\{ig\int_{x_{0+}}^{L_+}dx_+A_-(x_+,\mathbf{x}_\perp)\right\}$$

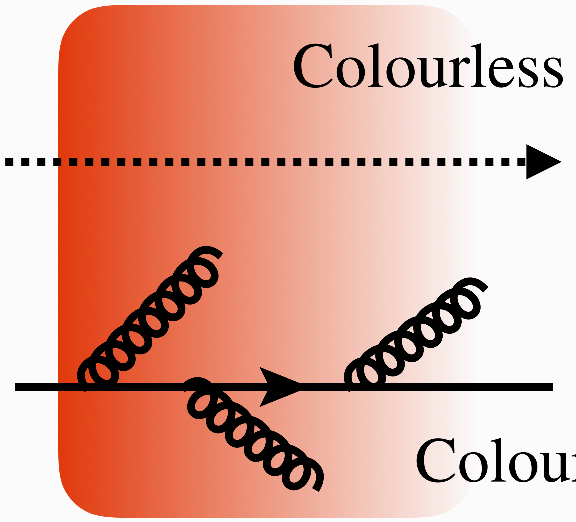
Hard Probes

- Jet Quenching pQCD expectations



Hard Probes

- Jet Quenching pQCD expectations vs Jet Quenching observations:

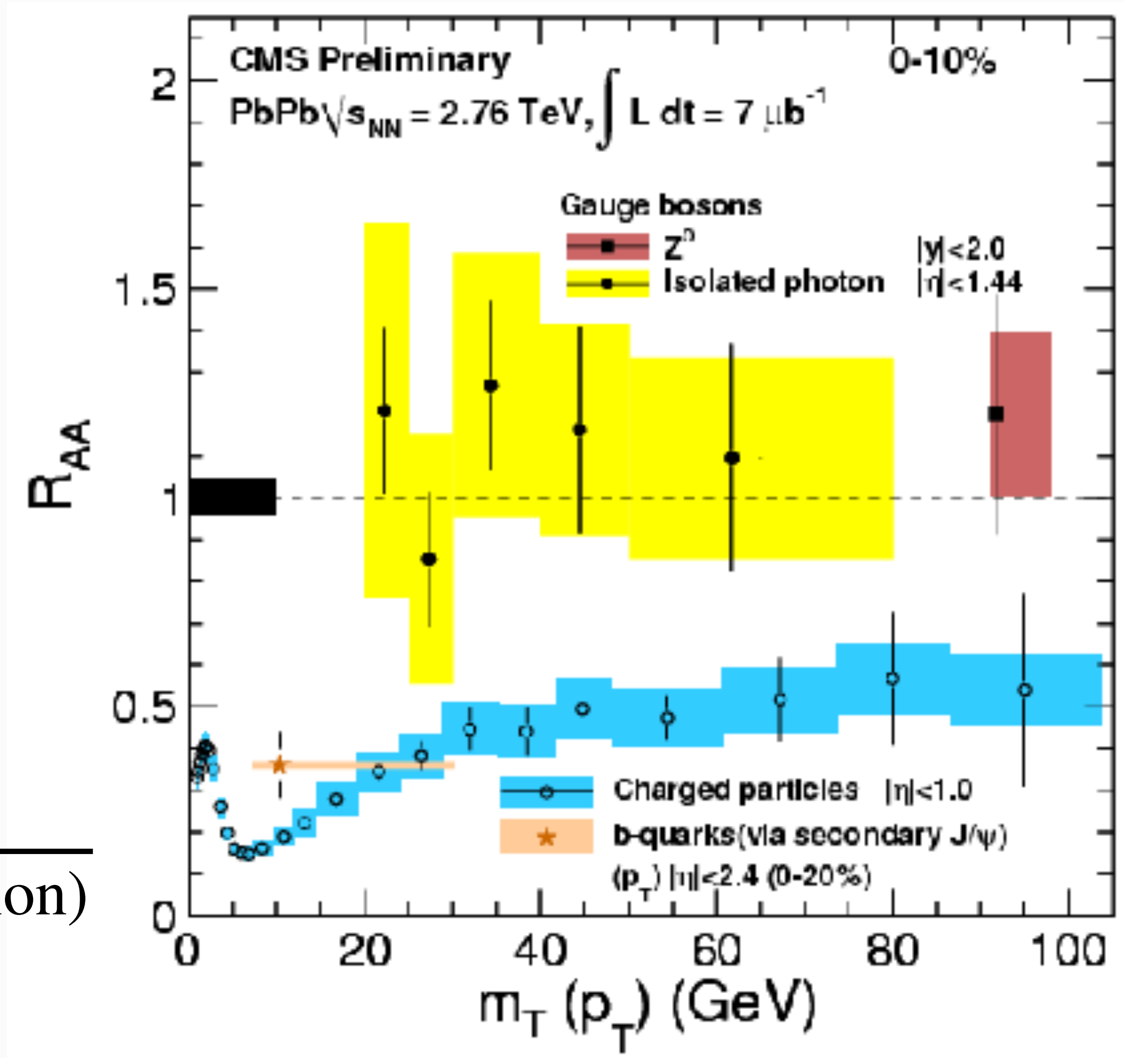


Colourless particles (γ, W, Z…)

No Energy Loss

Colourfull particles (hadrons)

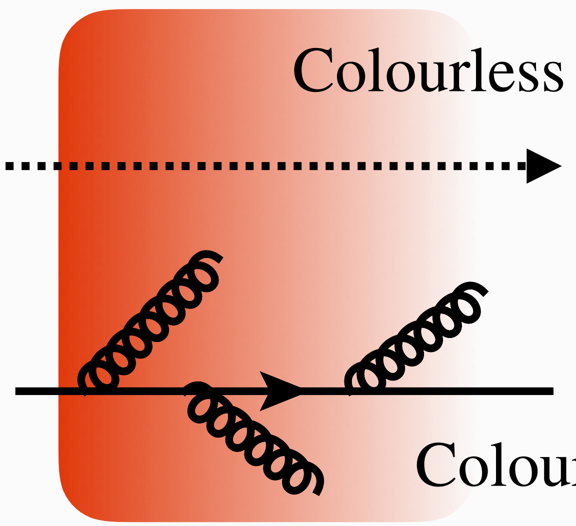
Energy Loss



$$R_{AA} = \frac{\text{\# Particles in PbPb}}{\text{(\# Particles in pp) x (\#pp collisions in a PbPb collision)}}$$

Hard Probes

- Jet Quenching pQCD expectations vs Jet Quenching observations:



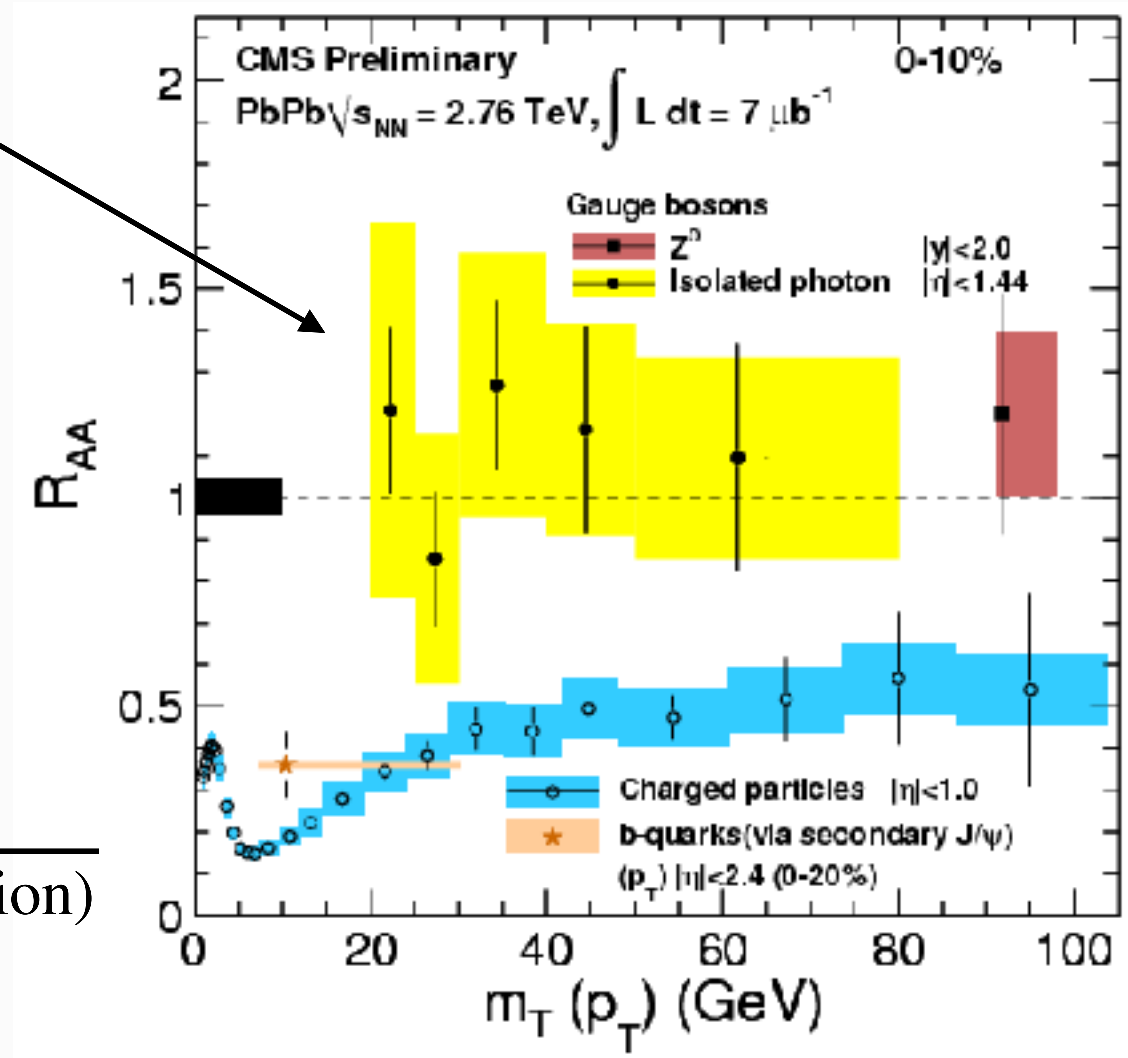
Colourless particles (γ, W, Z…)

No Energy Loss

Colourfull particles (hadrons)

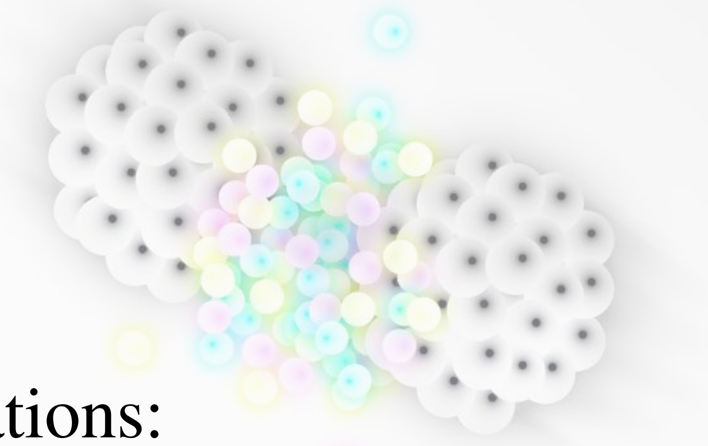
Energy Loss

$R_{AA} = 1$

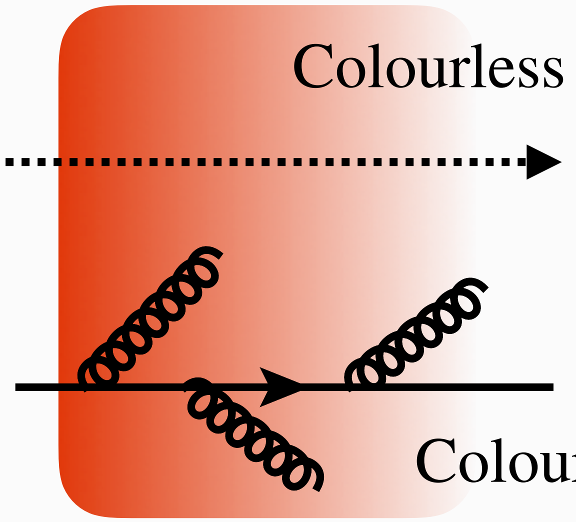


$$R_{AA} = \frac{\text{\# Particles in PbPb}}{(\text{\# Particles in pp}) \times (\text{\#pp collisions in a PbPb collision})}$$

Hard Probes



- Jet Quenching pQCD expectations vs Jet Quenching observations:



Colourless particles (γ, W, Z…)

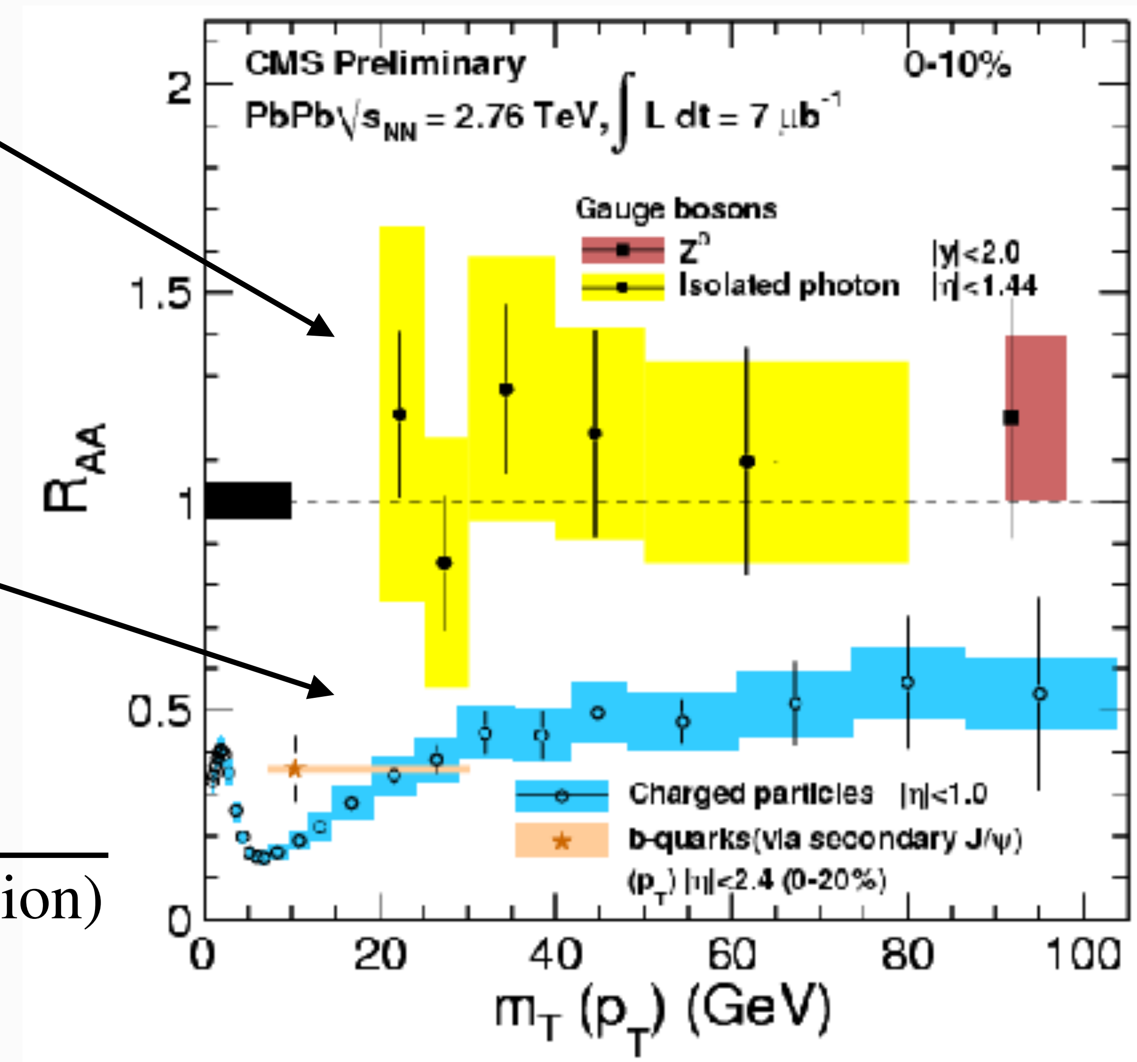
No Energy Loss

Colourfull particles (hadrons)

Energy Loss

$R_{AA} = 1$

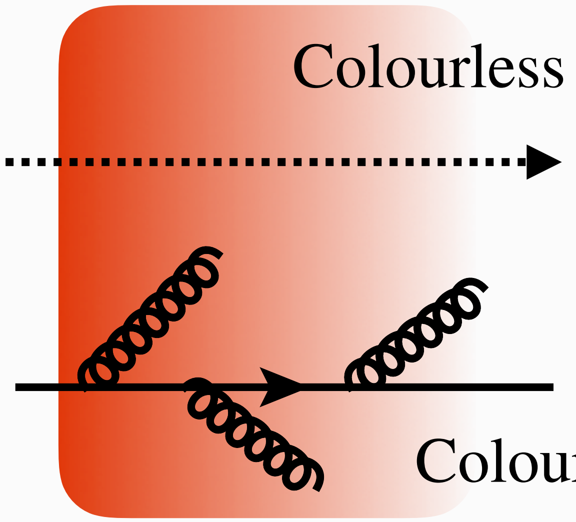
$R_{AA} < 1$



$$R_{AA} = \frac{\text{\# Particles in PbPb}}{\text{(\# Particles in pp) x (\#pp collisions in a PbPb collision)}}$$

Hard Probes

- Jet Quenching pQCD expectations vs Jet Quenching observations:



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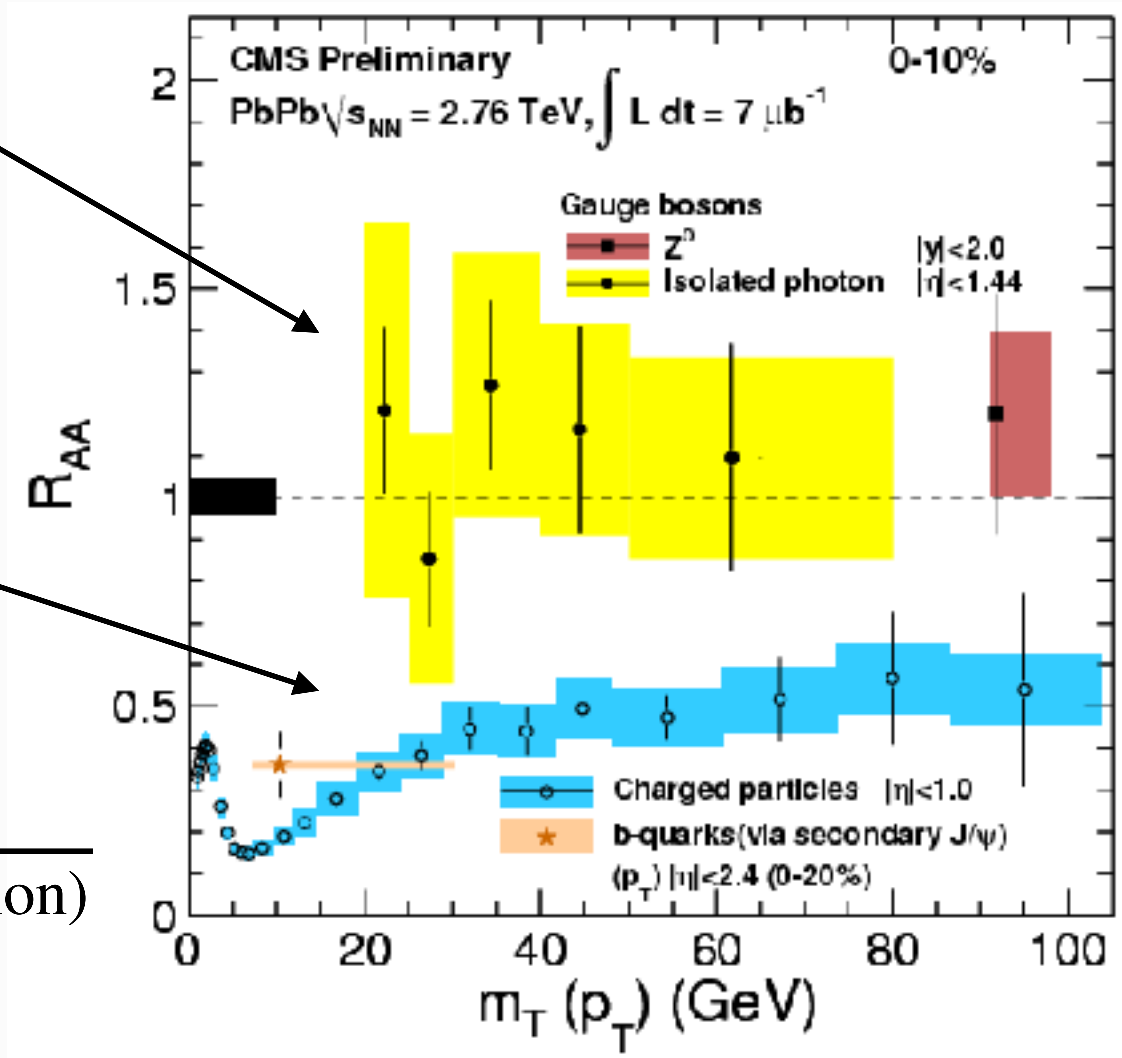

$$R_{AA} = \frac{\text{\# Particles in PbPb}}{\text{(\# Particles in pp) x (\#pp collisions in a PbPb collision)}}$$

<u>QCD</u> *dynamics* but also <u>QGP</u> *properties*:

Amount of suppression can be used to characterise the medium density