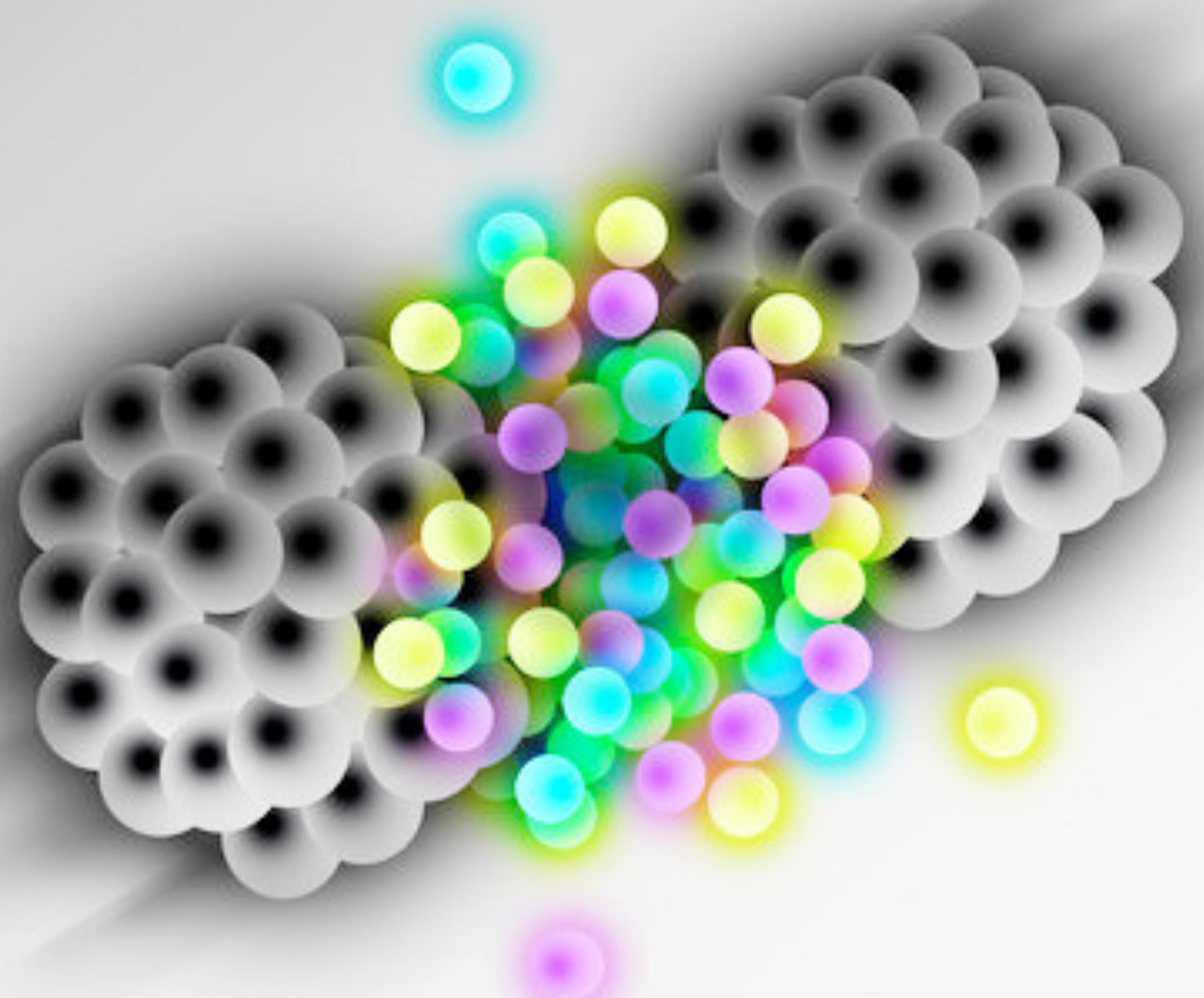
QCD & Heavy-Ions Phenomenology



Liliana Apolinário

LIP

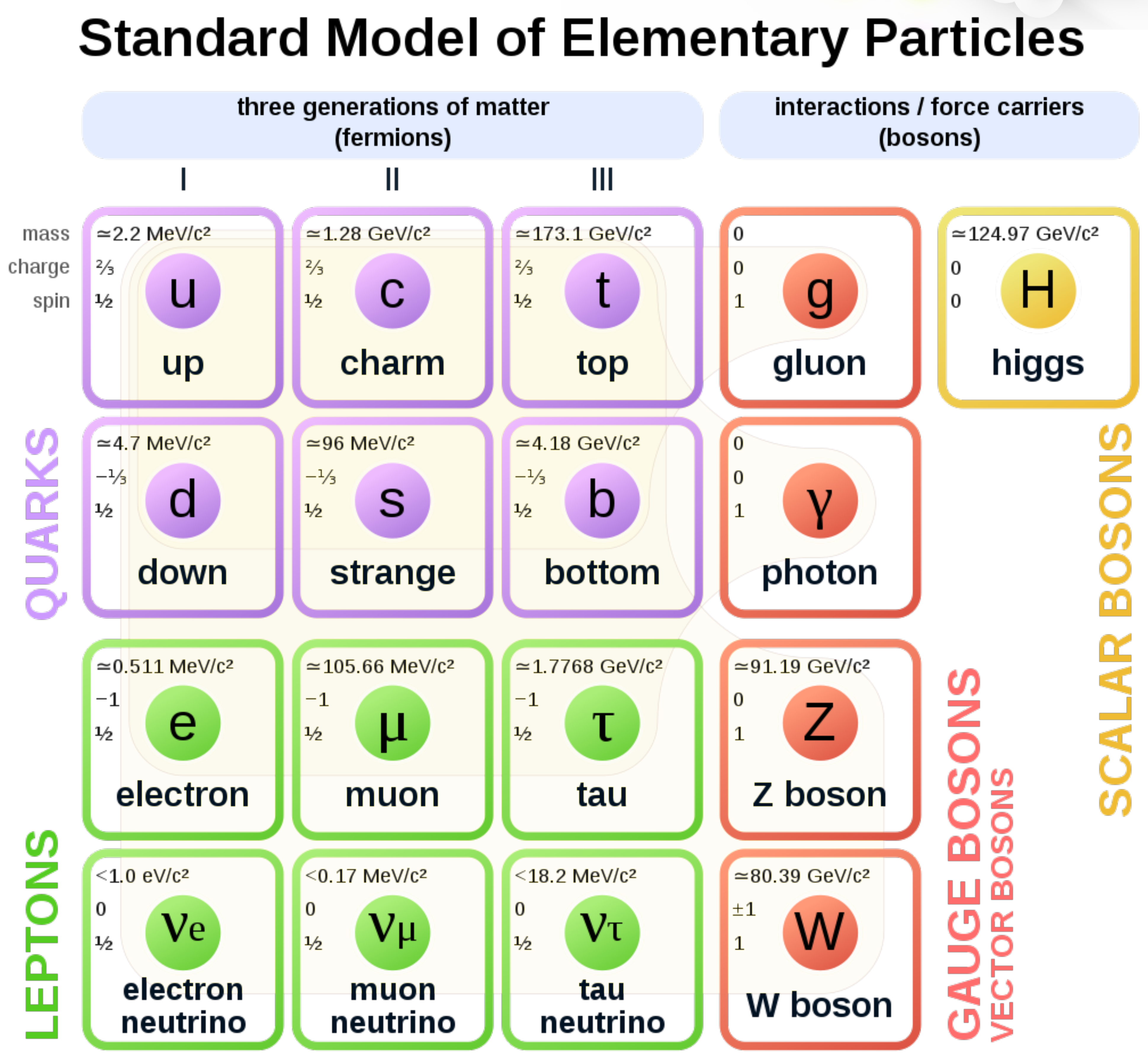
TÉCNICO LISBOA

LIP, July 2020

LIP Internship Program

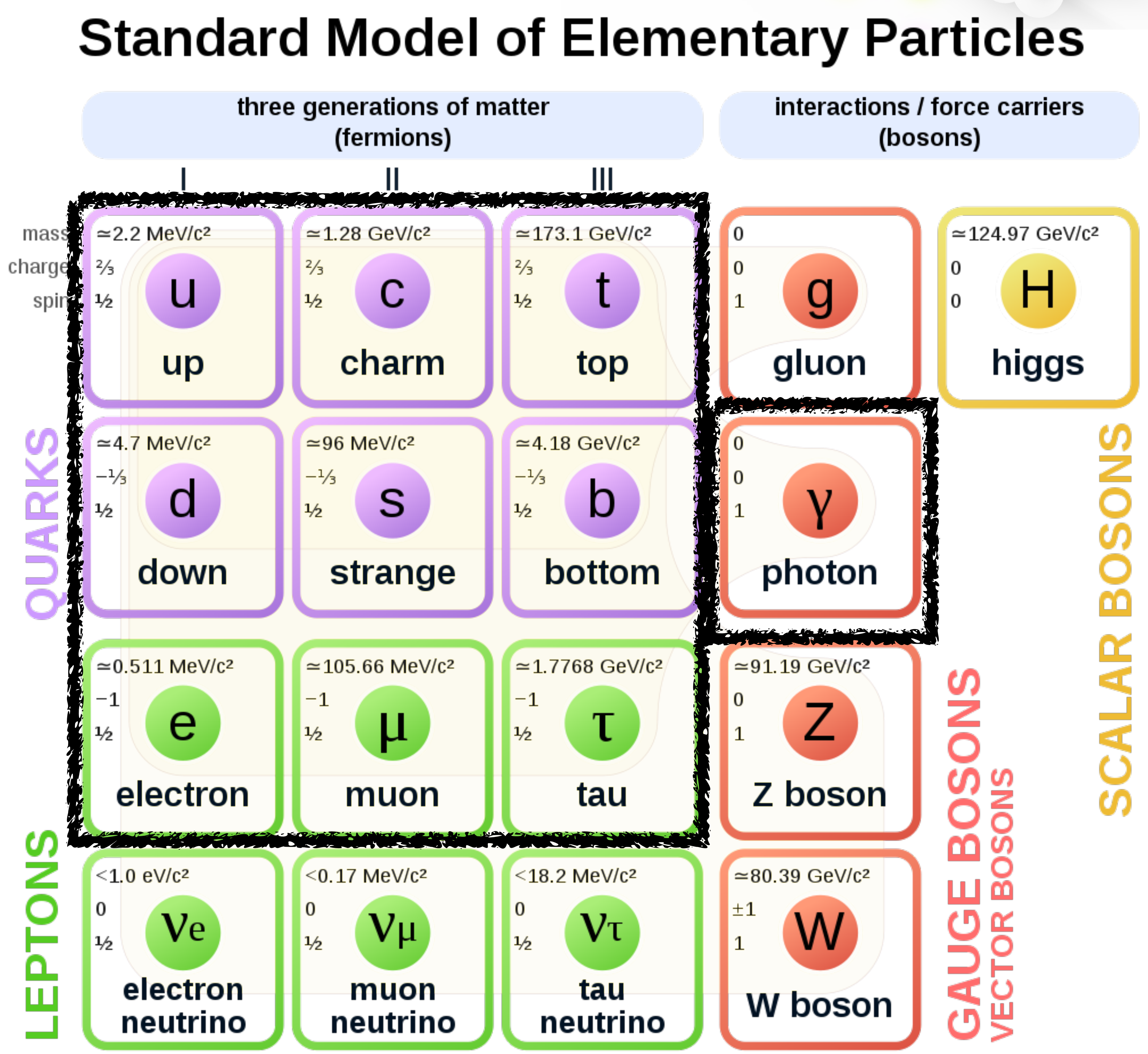
Standard Model: Recap

- Gauge Bosons ("Force carriers")



Standard Model: Recap

- Gauge Bosons ("Force carriers")
- Example: Quantum Electrodynamics (QED)
  - Electrons, muons,… with electric charge (+/-)
  - Photon: neutral particle



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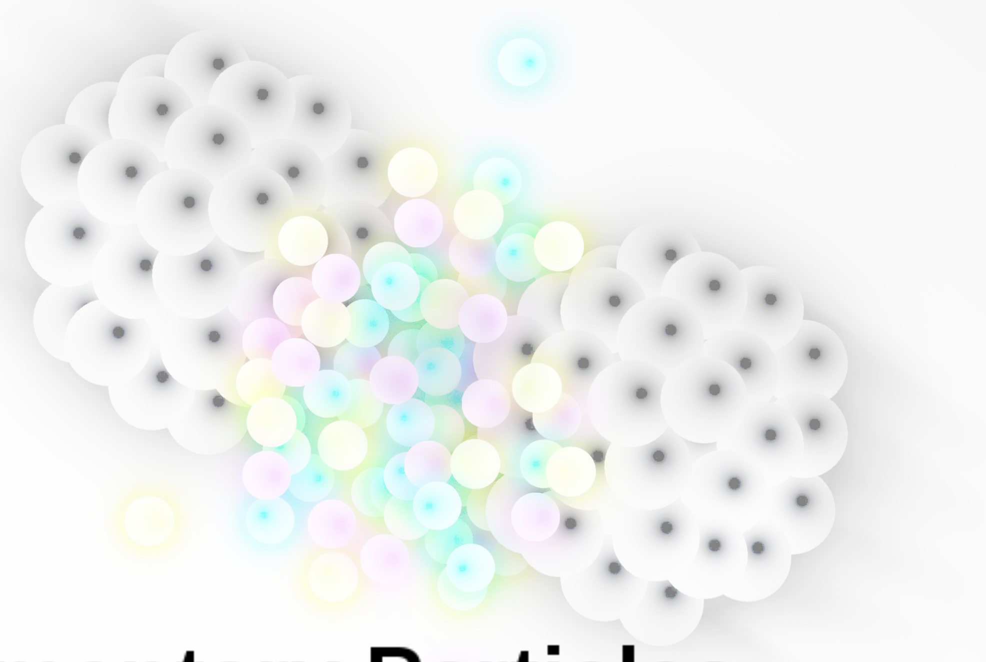
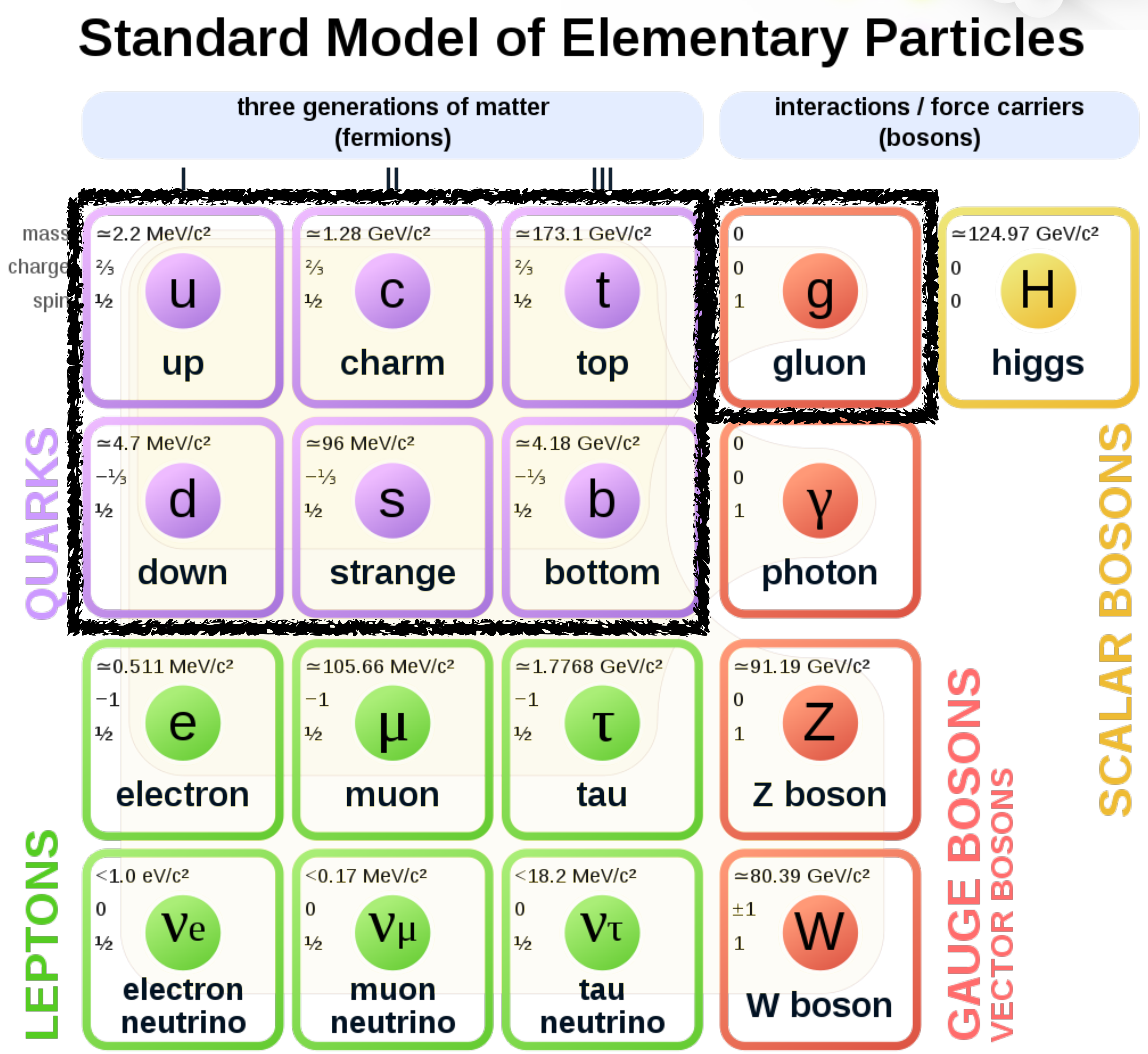
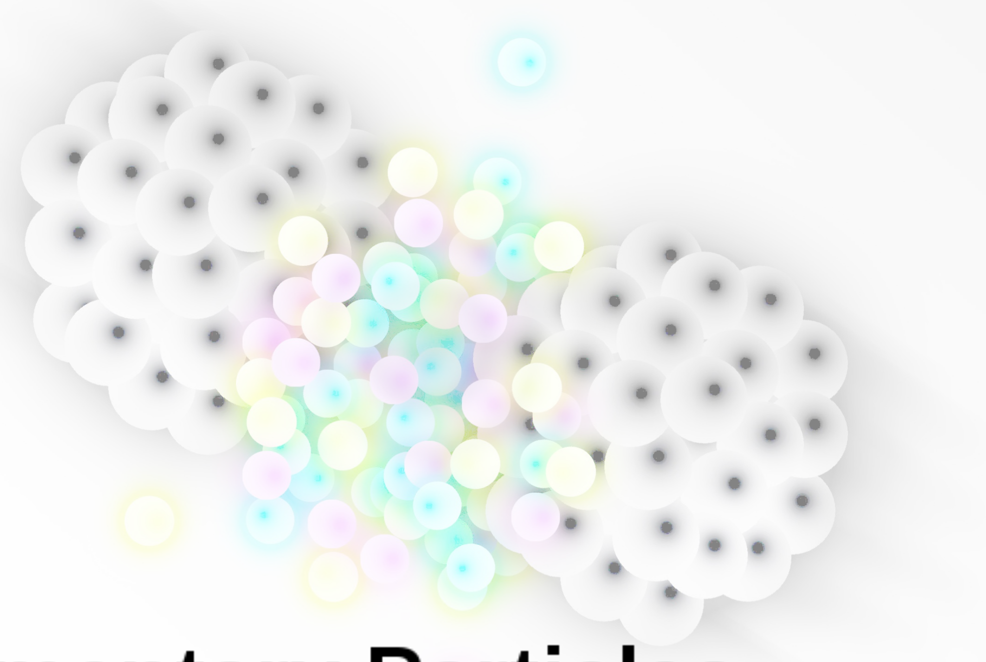


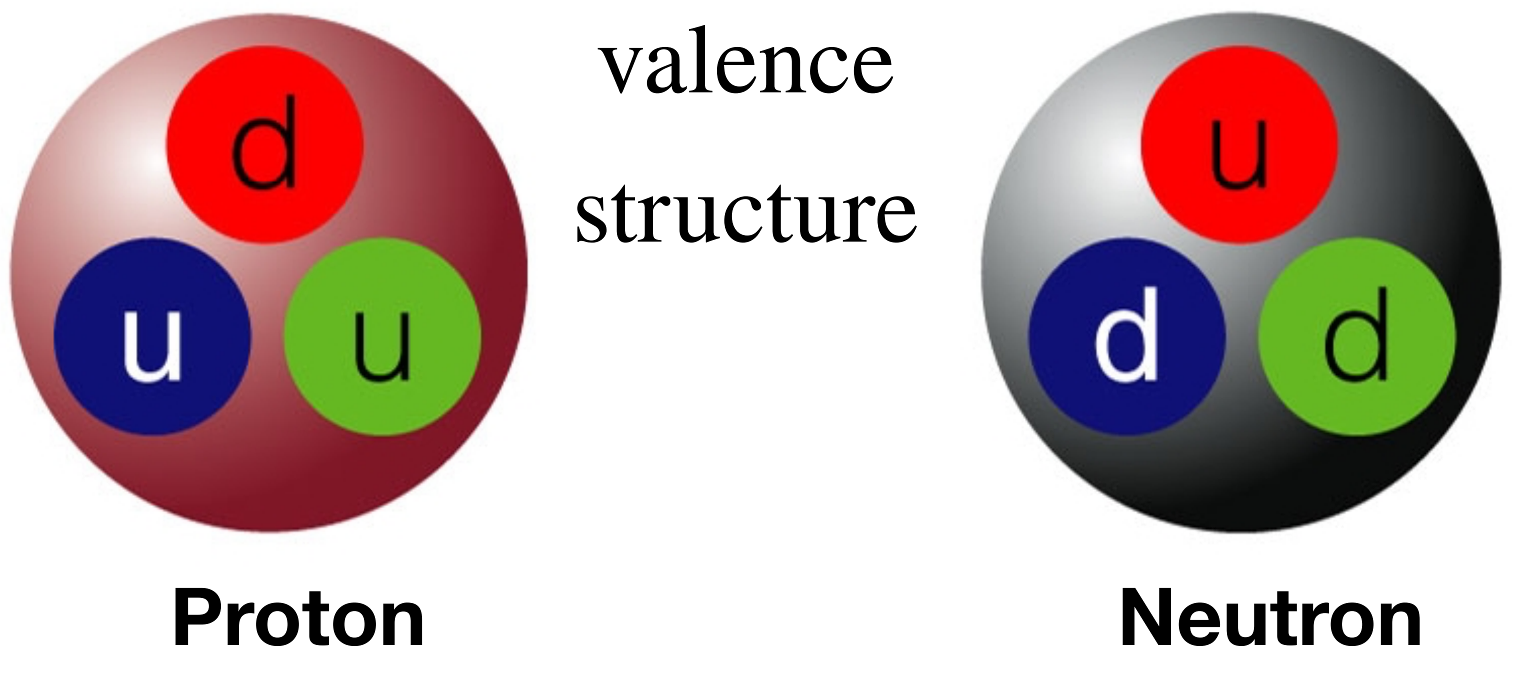
- Gauge Bosons ("Force carriers")
- Example: Quantum Electrodynamics (QED)
  - Electrons, muons,… with electric charge (+/-)
  - Photon: neutral particle
- Example: Quantum Chromodynamics (QCD)
  - Quarks with 1 color charge (RGB)
  - Gluon: with "~2" color charges ($R\bar{R}$, $G\bar{G}$, $B\bar{B}$)

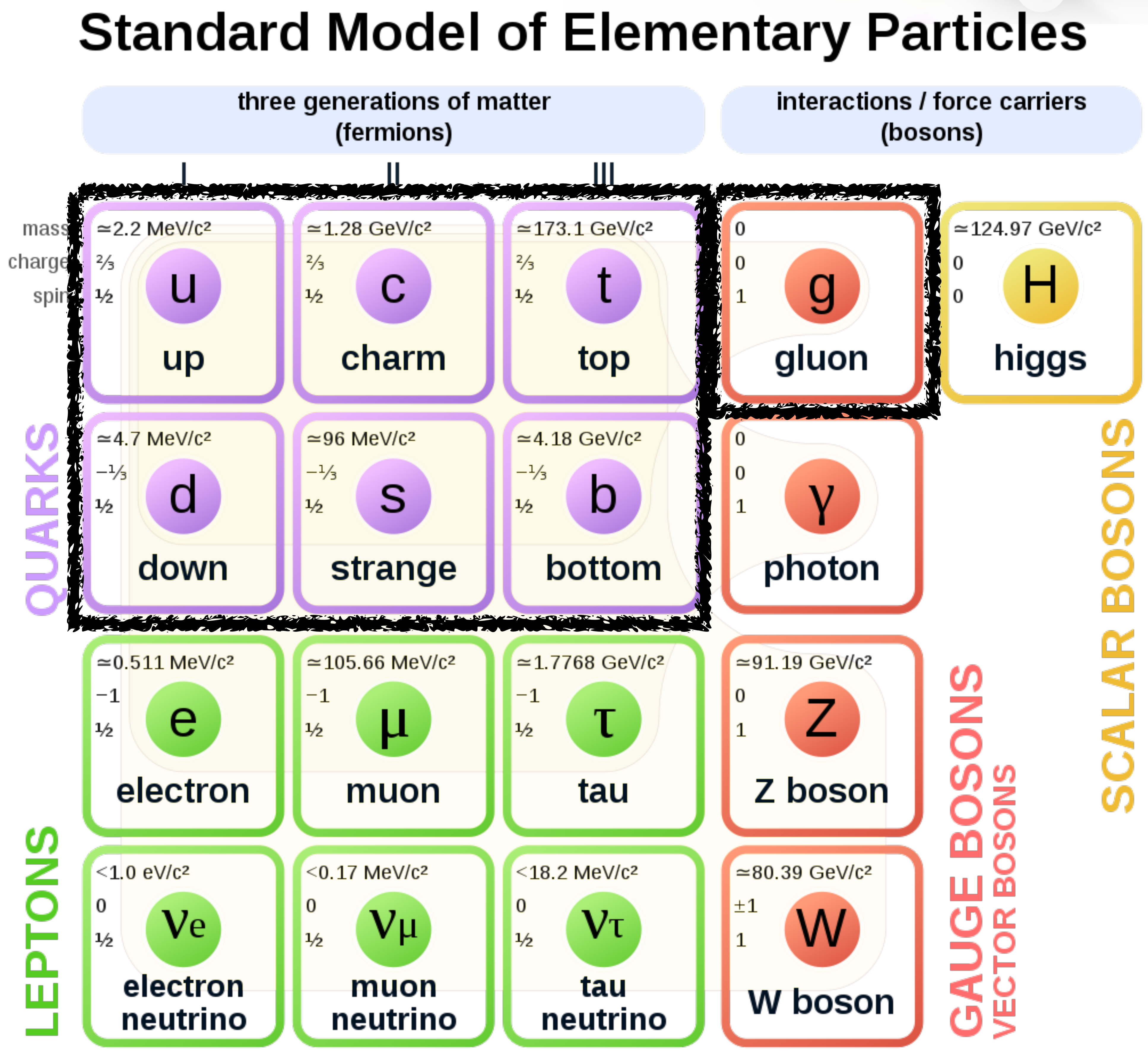


Standard Model: Recap



- Higgs: mass to elementary particles
- QCD: contributes largely to the mass of composite particles (mesons, baryons,…)





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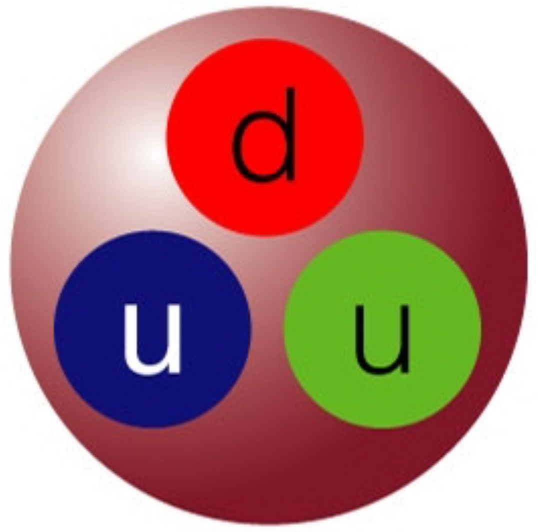
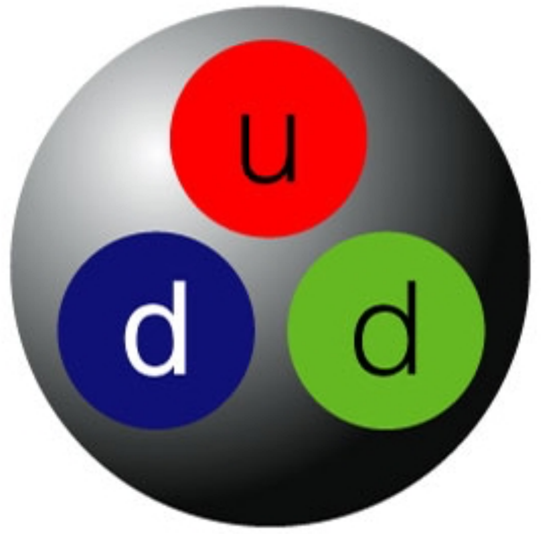


Proton

valence structure

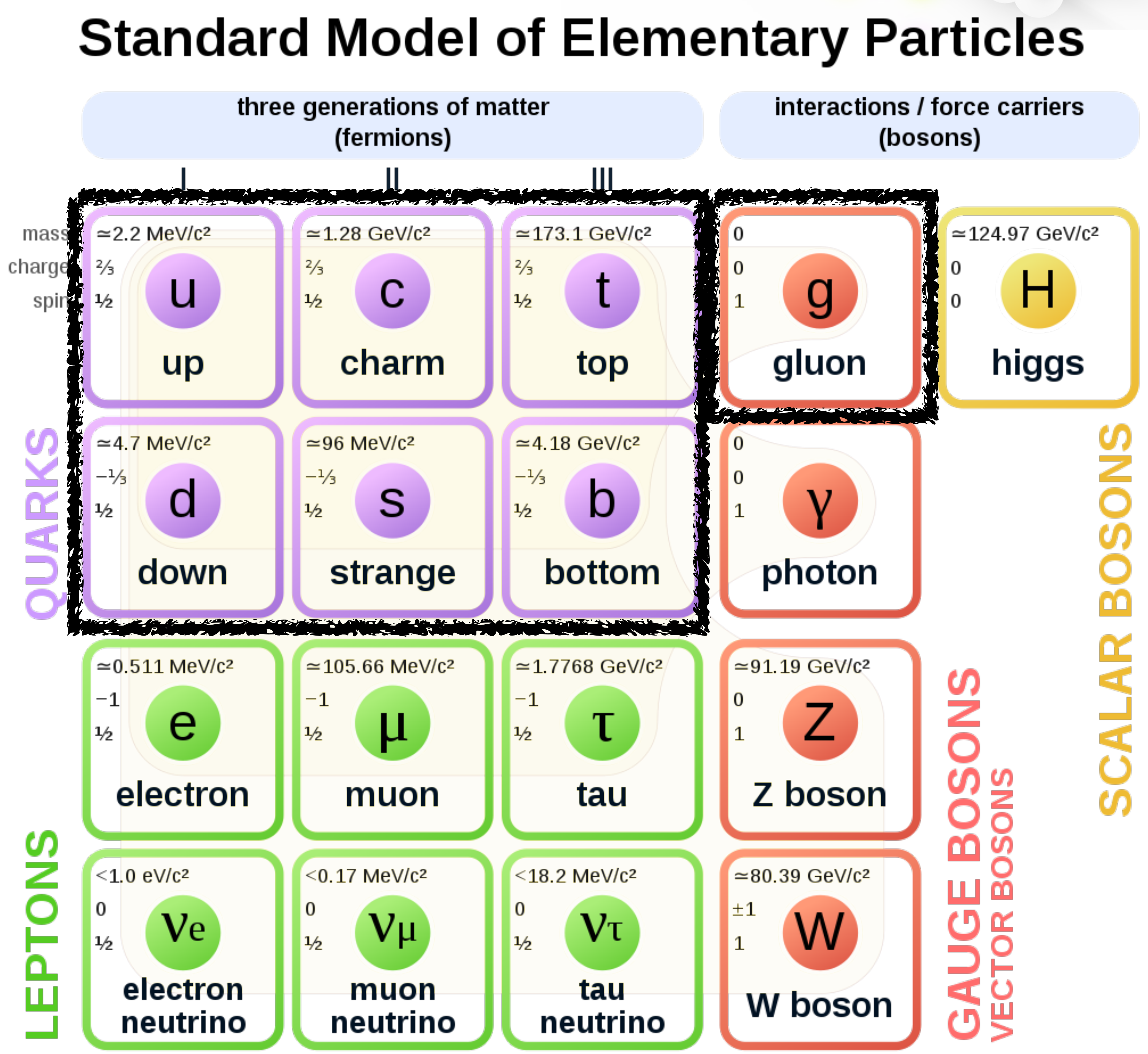


Neutron

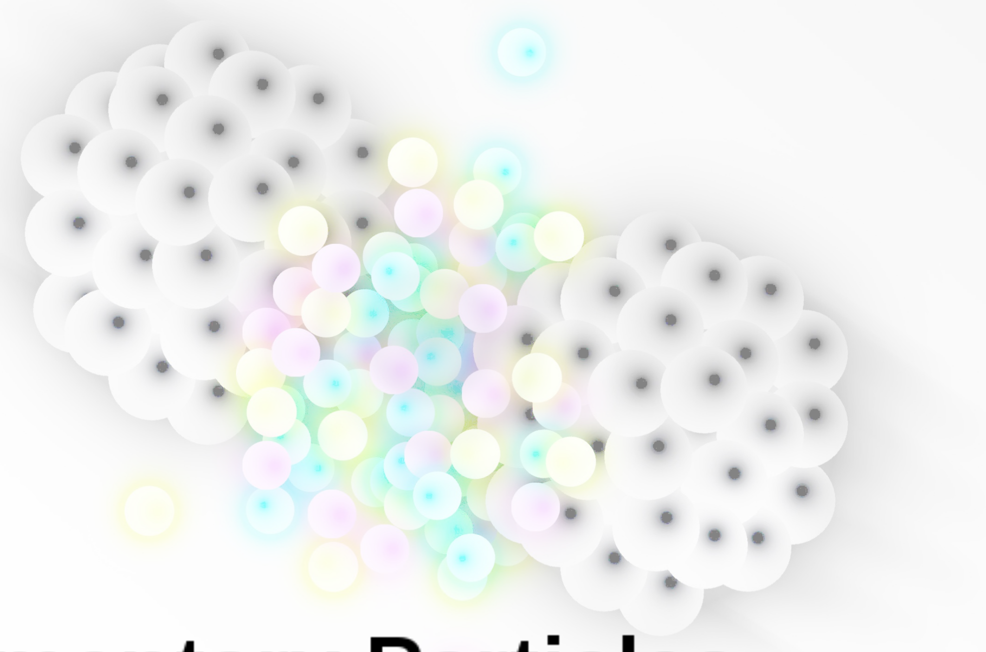
$\ni \{u, d, \ldots, g\}$

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

0.2% mass



Standard Model: Recap



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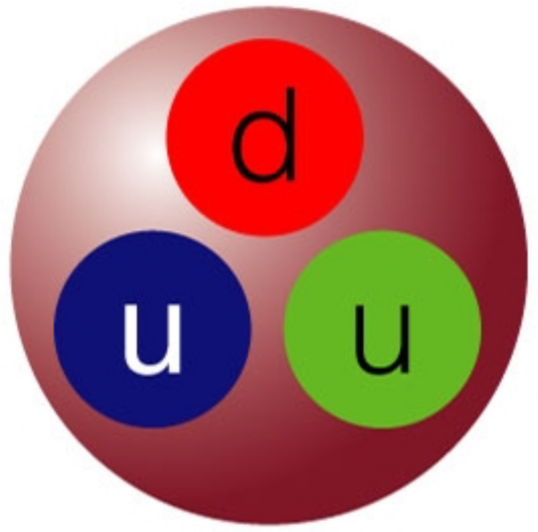

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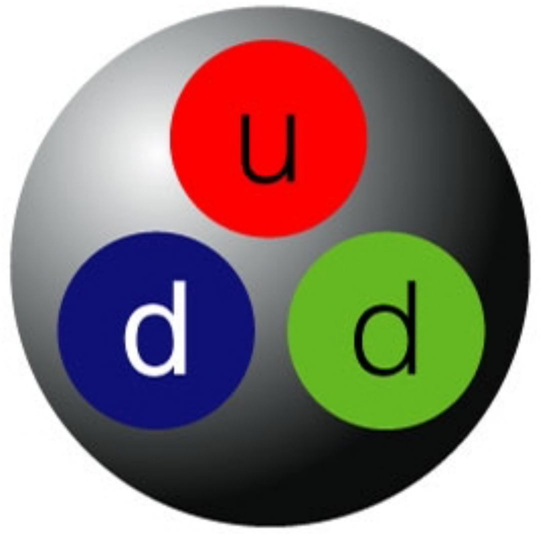


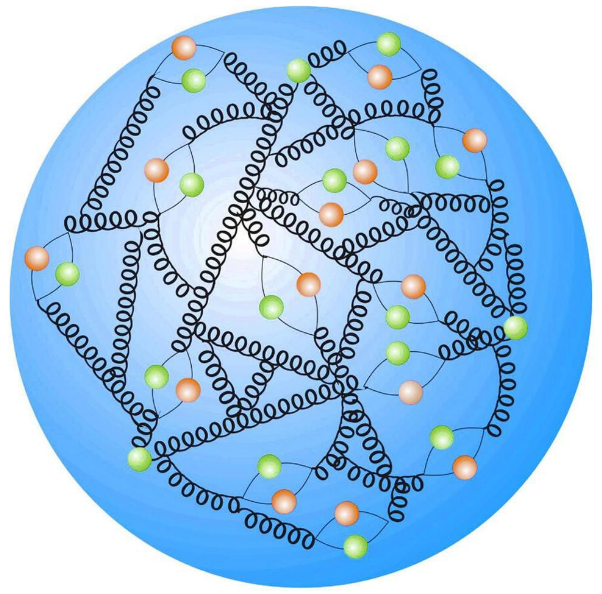
Neutron

$\ni$ {u, d, …, g}

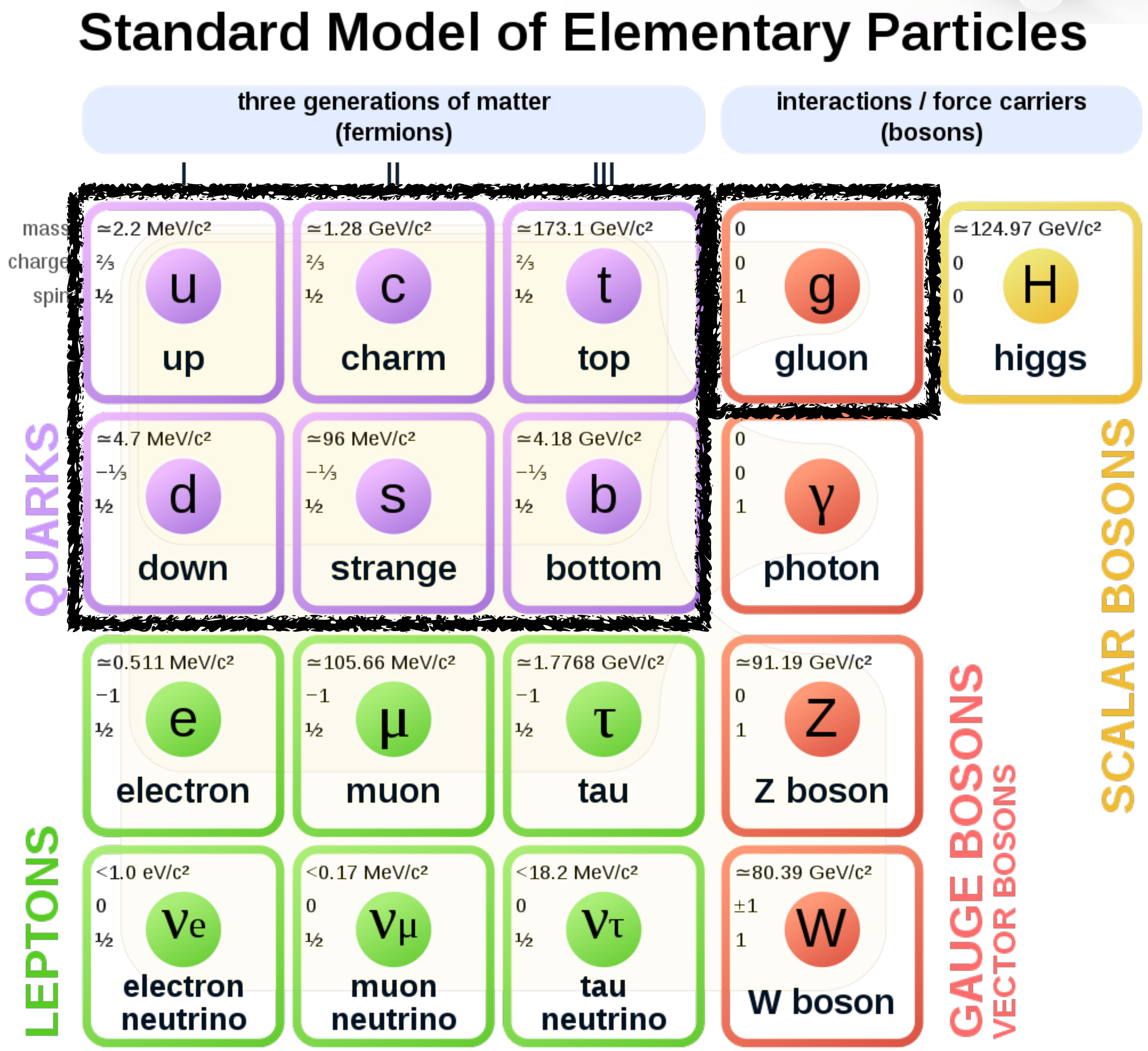
$\neq$ {u, d, …, g}

0.2% mass

(more realistic) proton structure



valence + sea (quarks and gluons)
100% mass



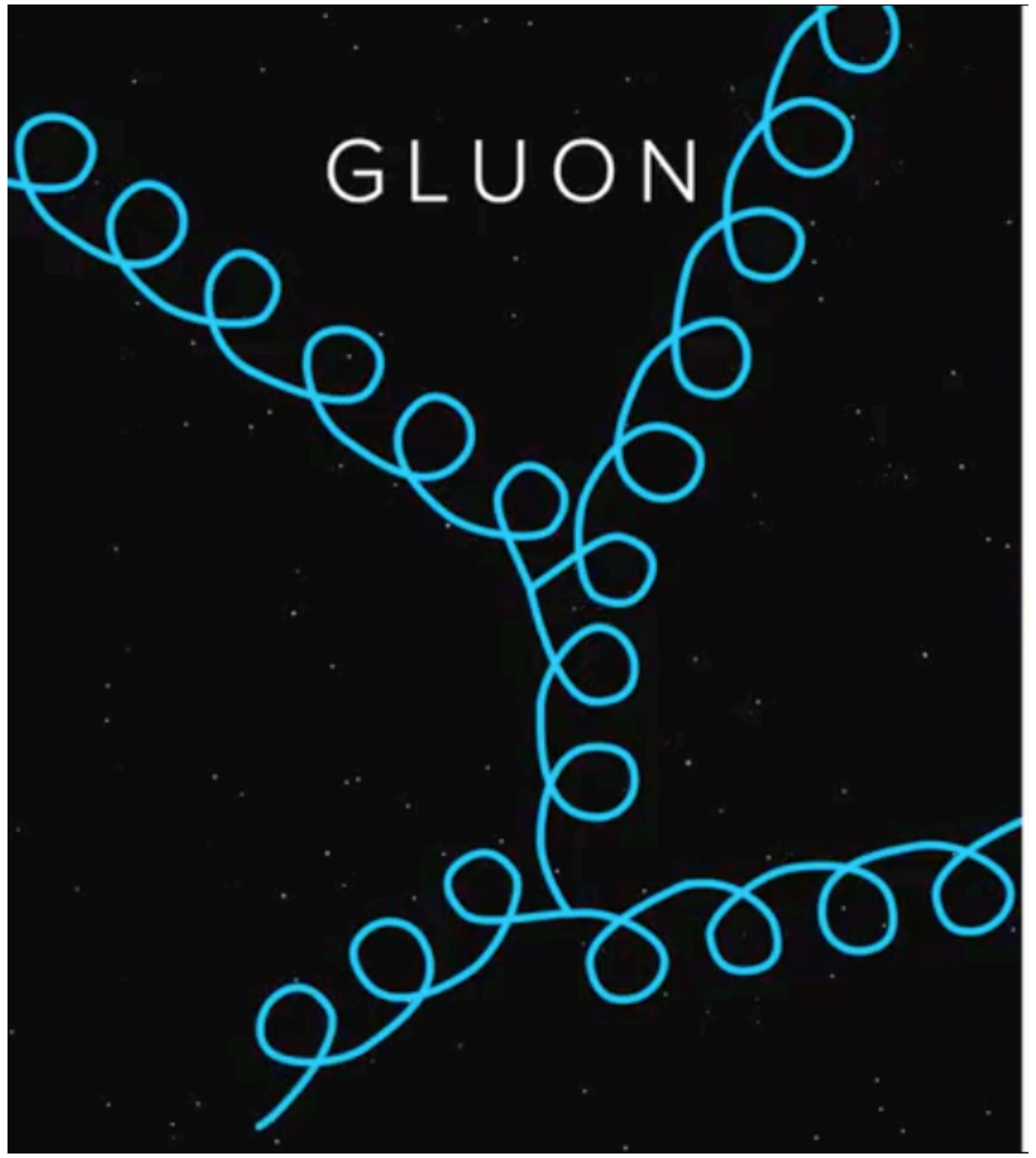
QED vs QCD

- Quantum Electrodynamics

Photons do not have electric charge

- Quantum Chromodynamics

Gluons are colourful



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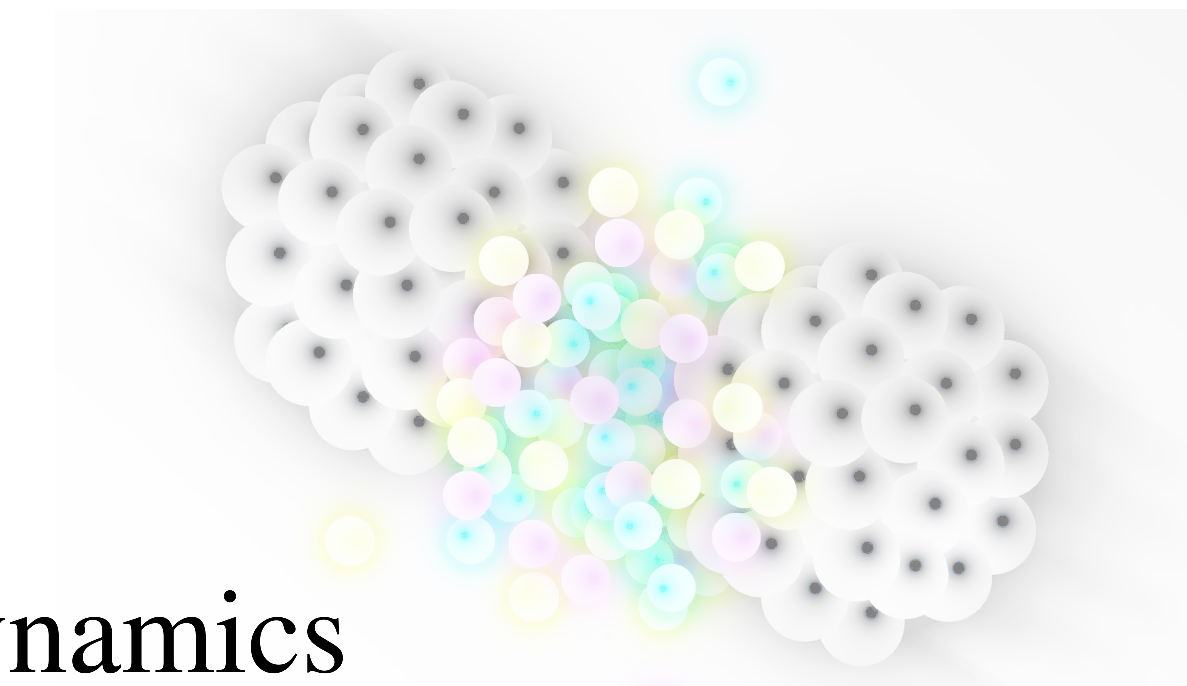
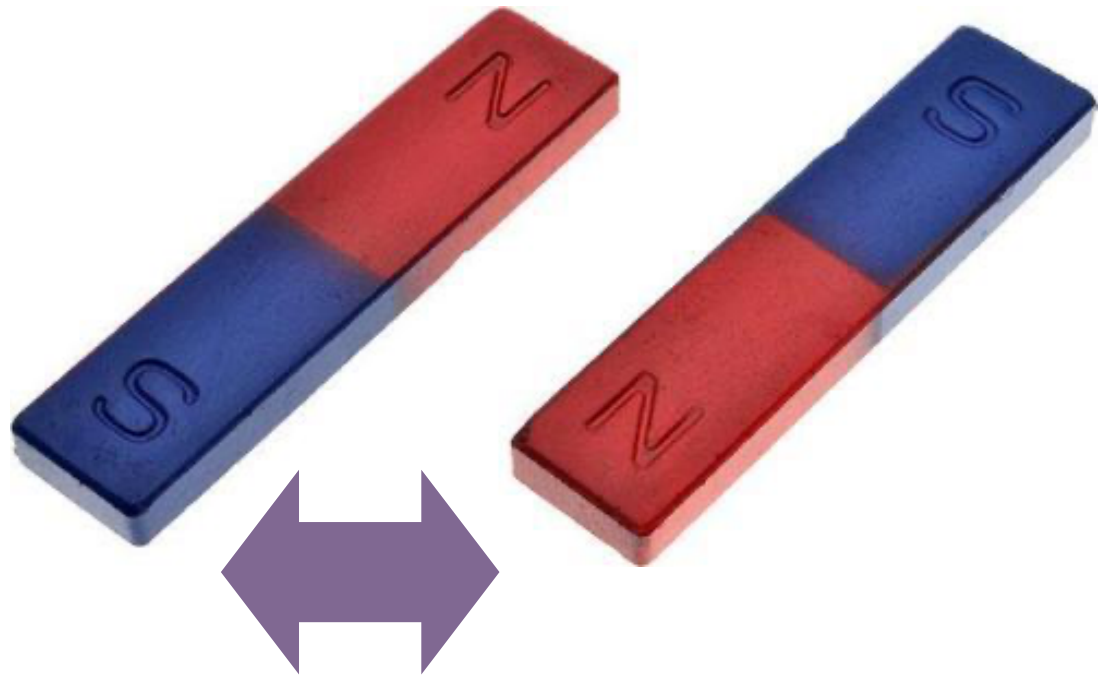


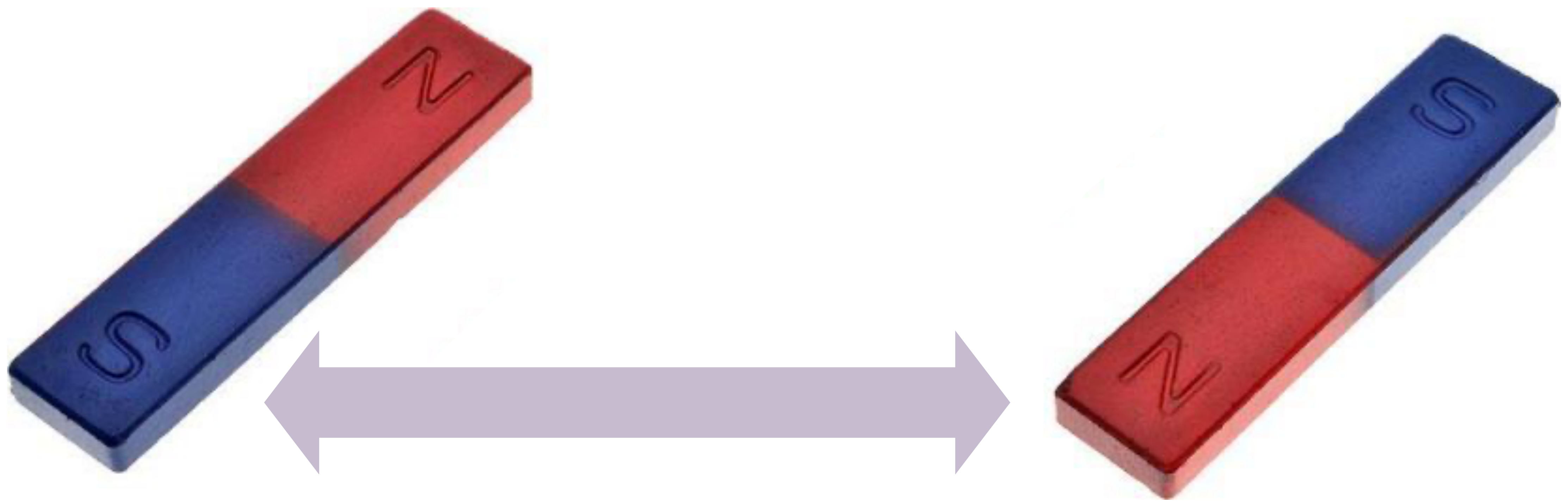
- Quantum Electrodynamics

Photons do not have electric charge

Larger attraction



Smaller attraction



- Quantum Chromodynamics

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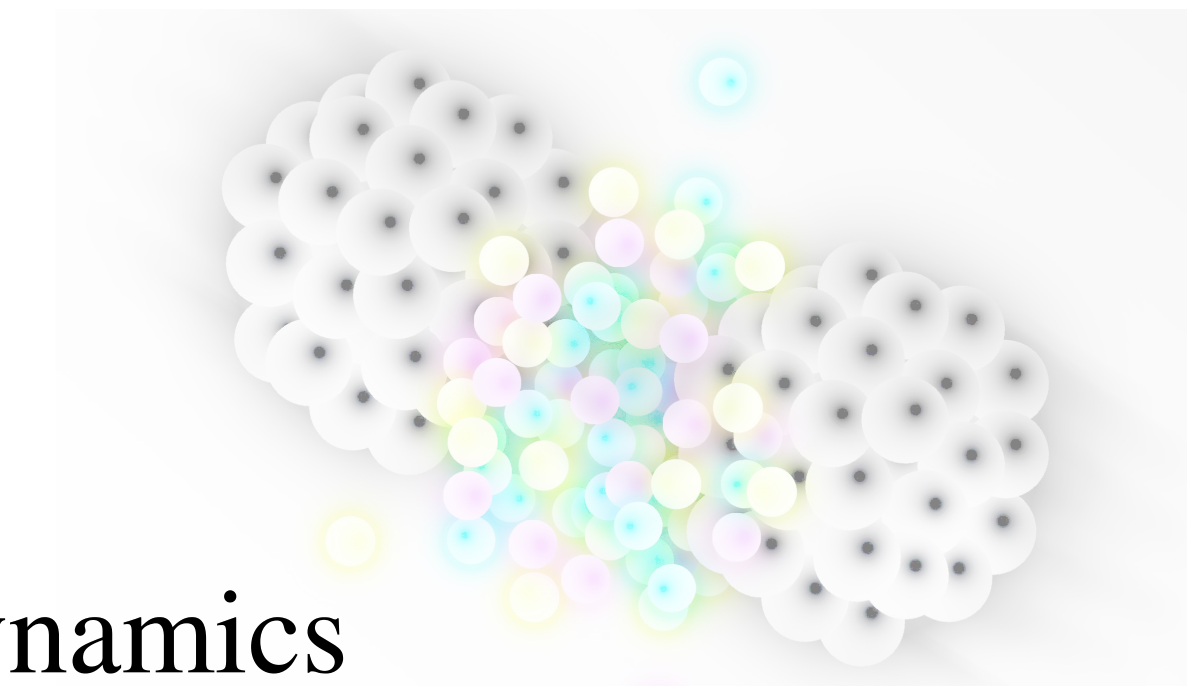
QED vs QCD



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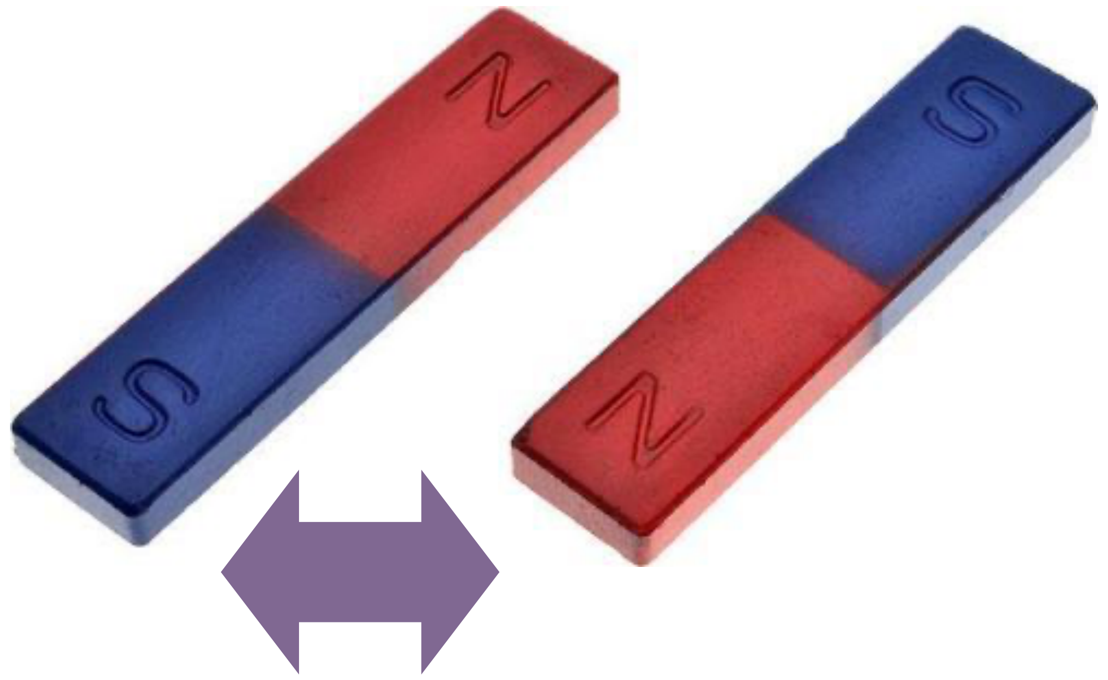

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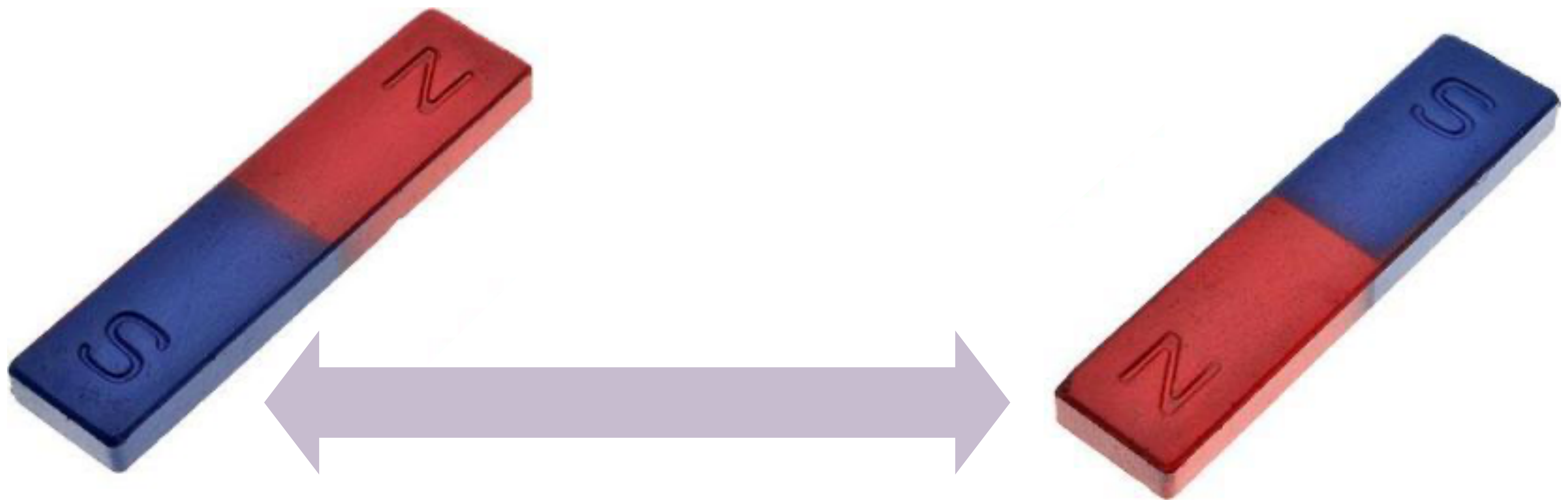

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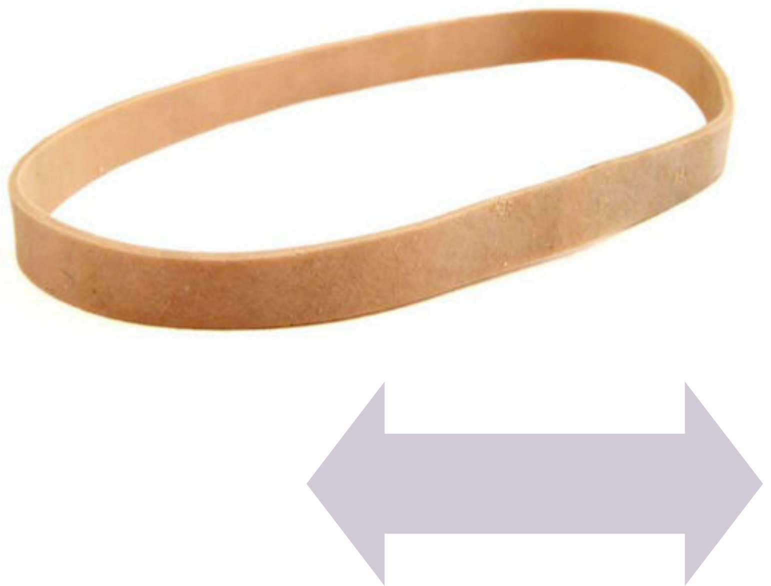
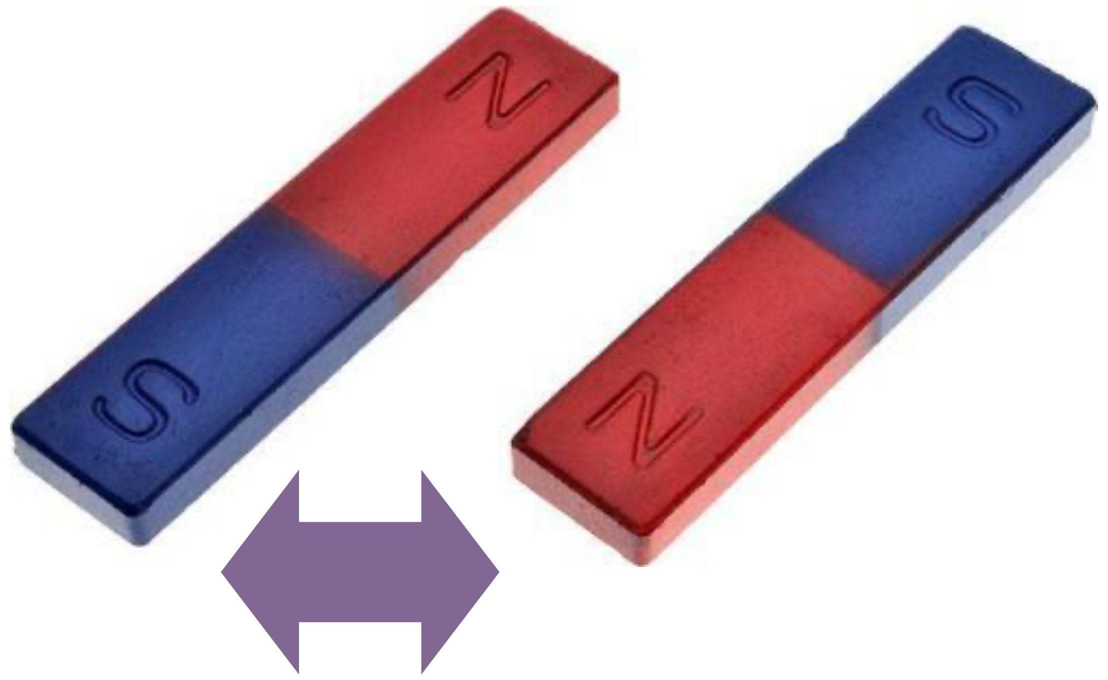


QED vs QCD

- Quantum Electrodynamics
- Quantum Chromodynamics = **Strong Force**

Photons do not have electric charge

Larger attraction



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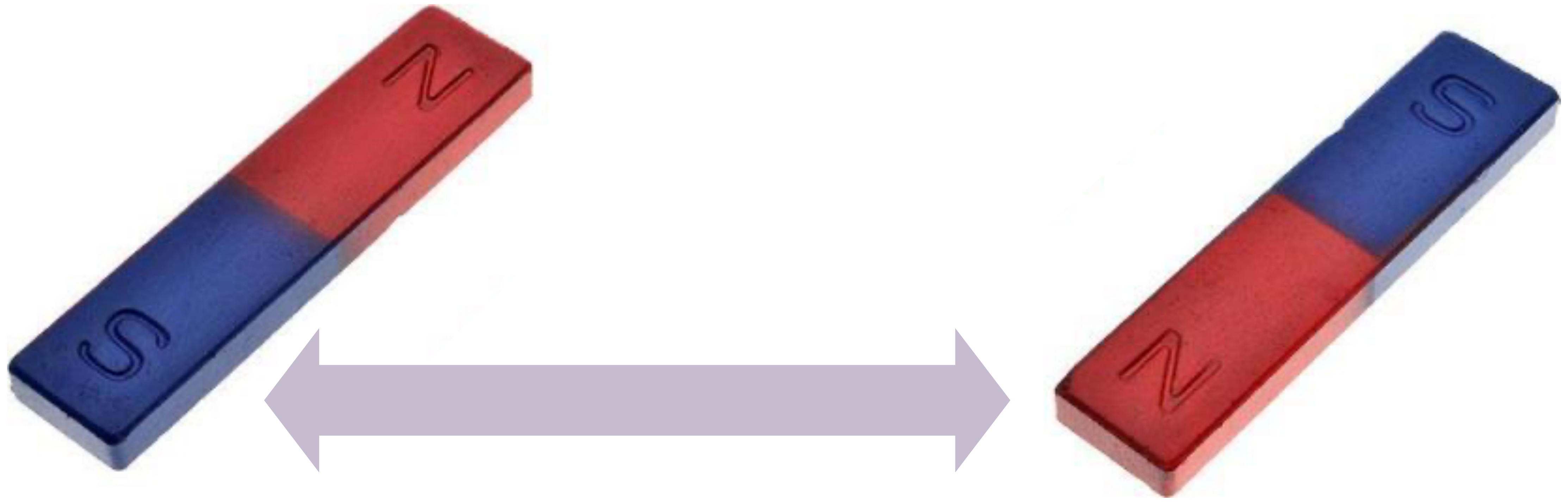

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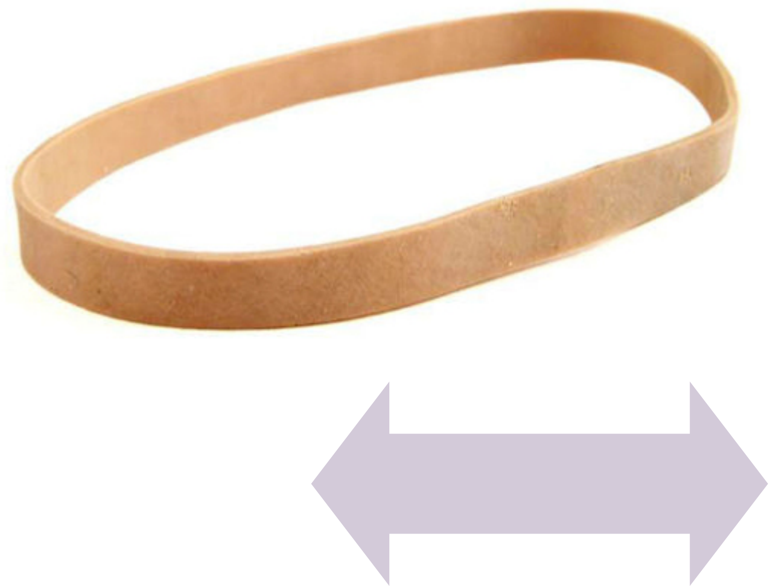

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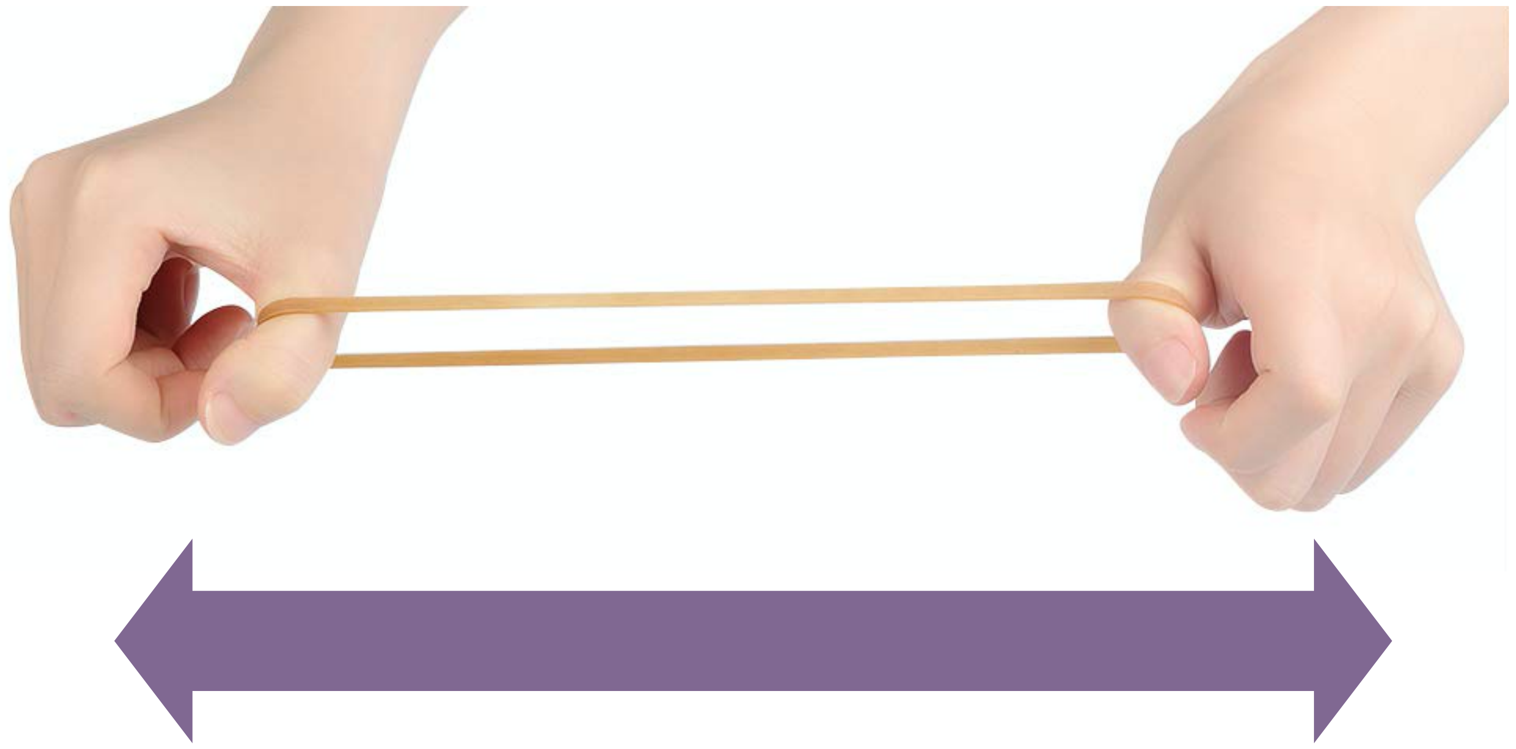
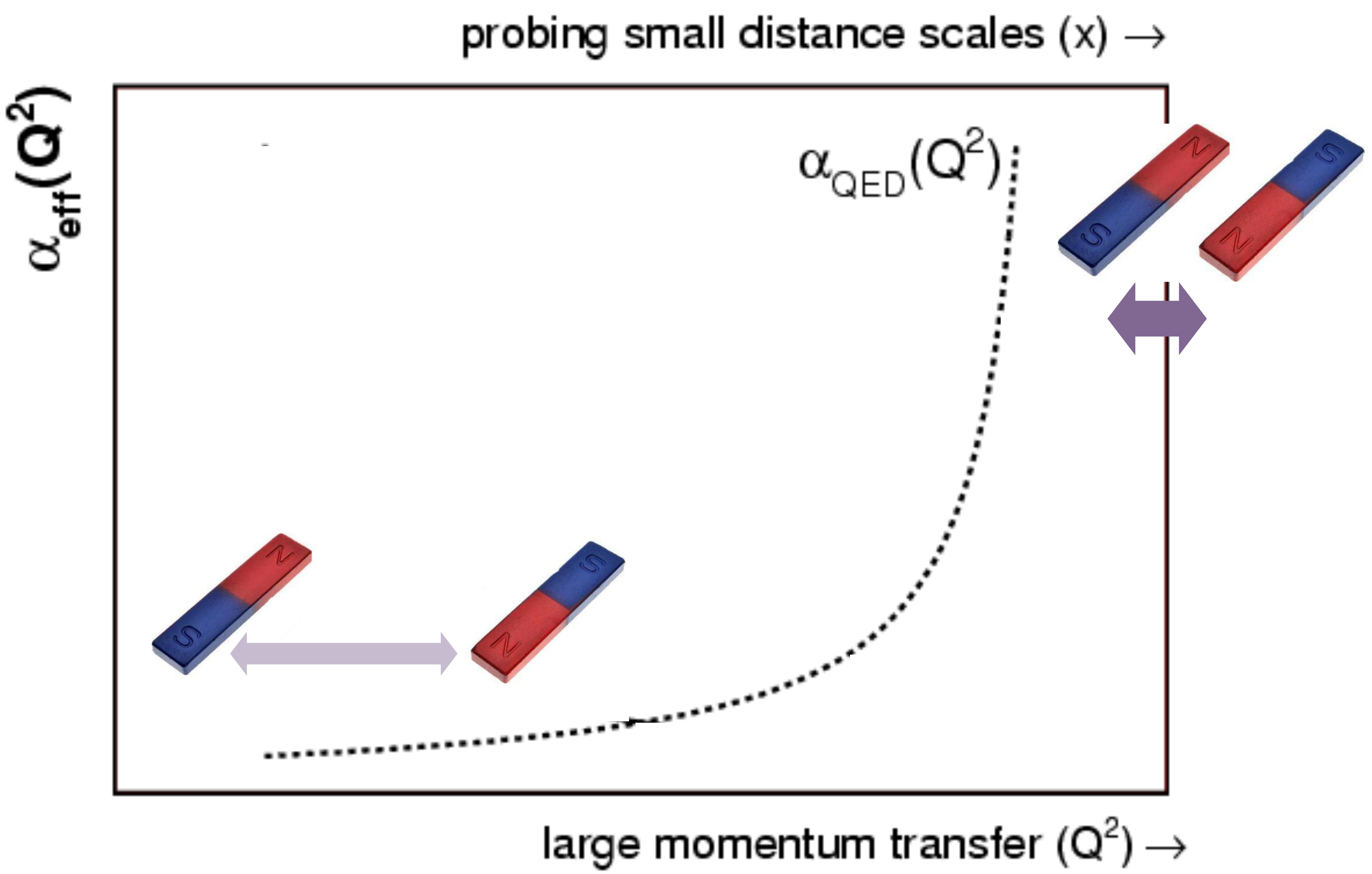
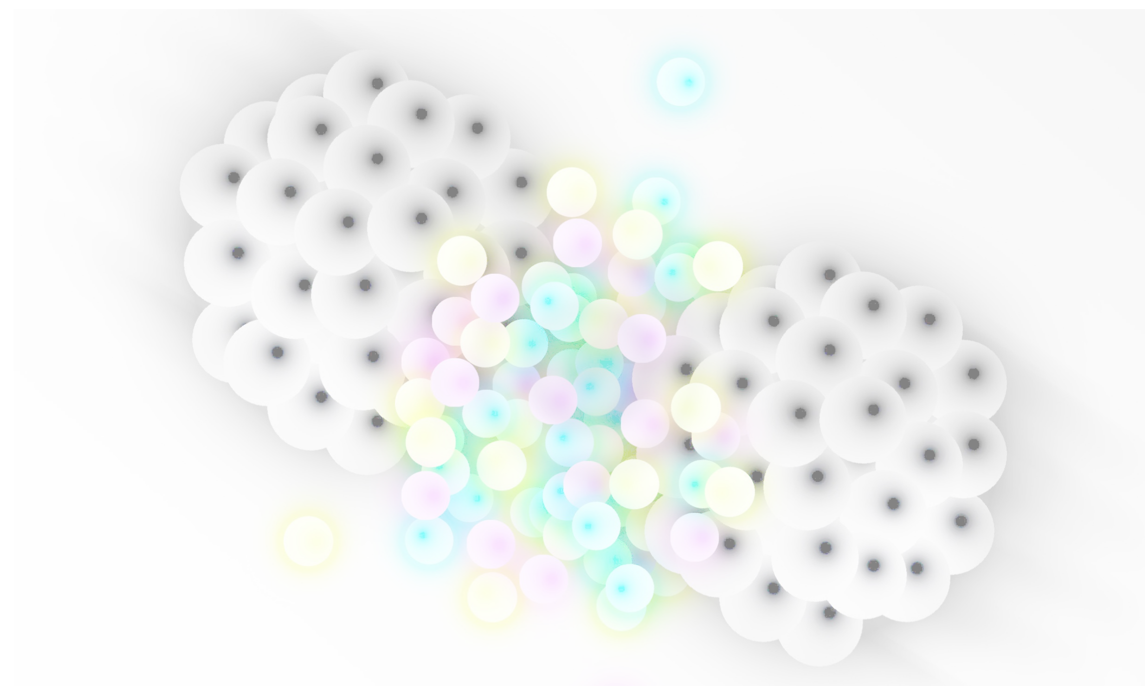


Coupling Constant

- Interaction strength given by α_{QED} and α_{QCD}



Large distances ⟵⟶ **Small distances**



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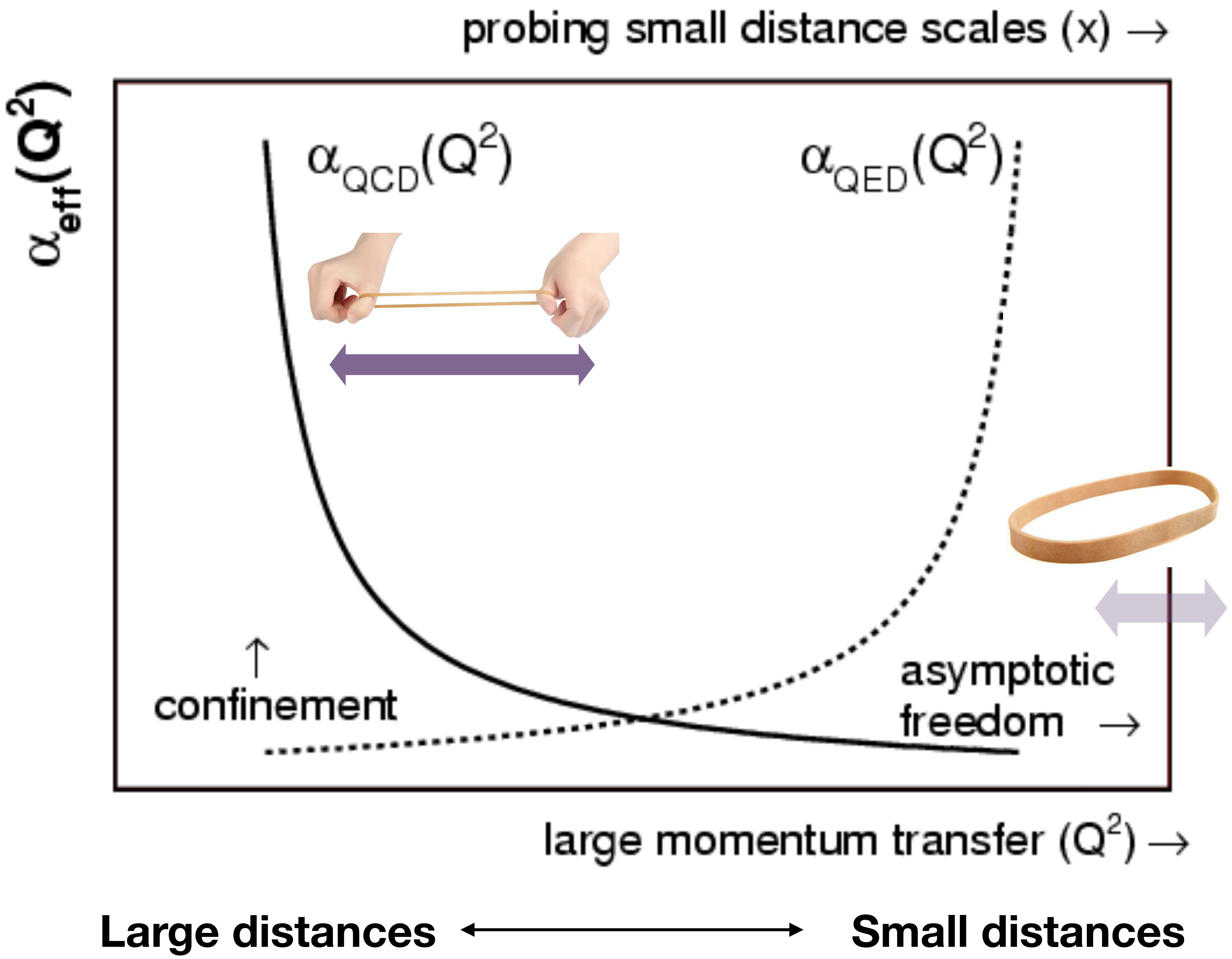

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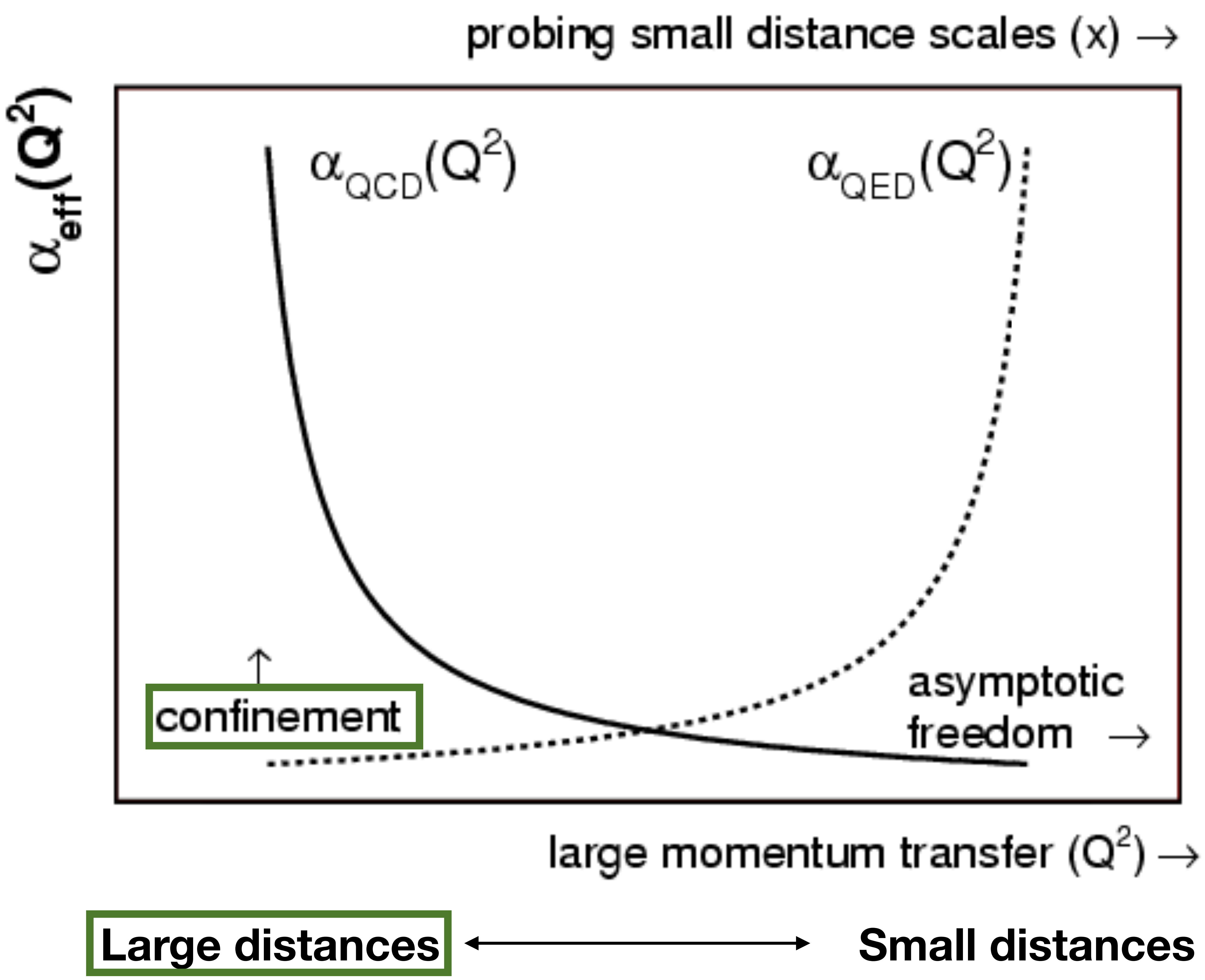
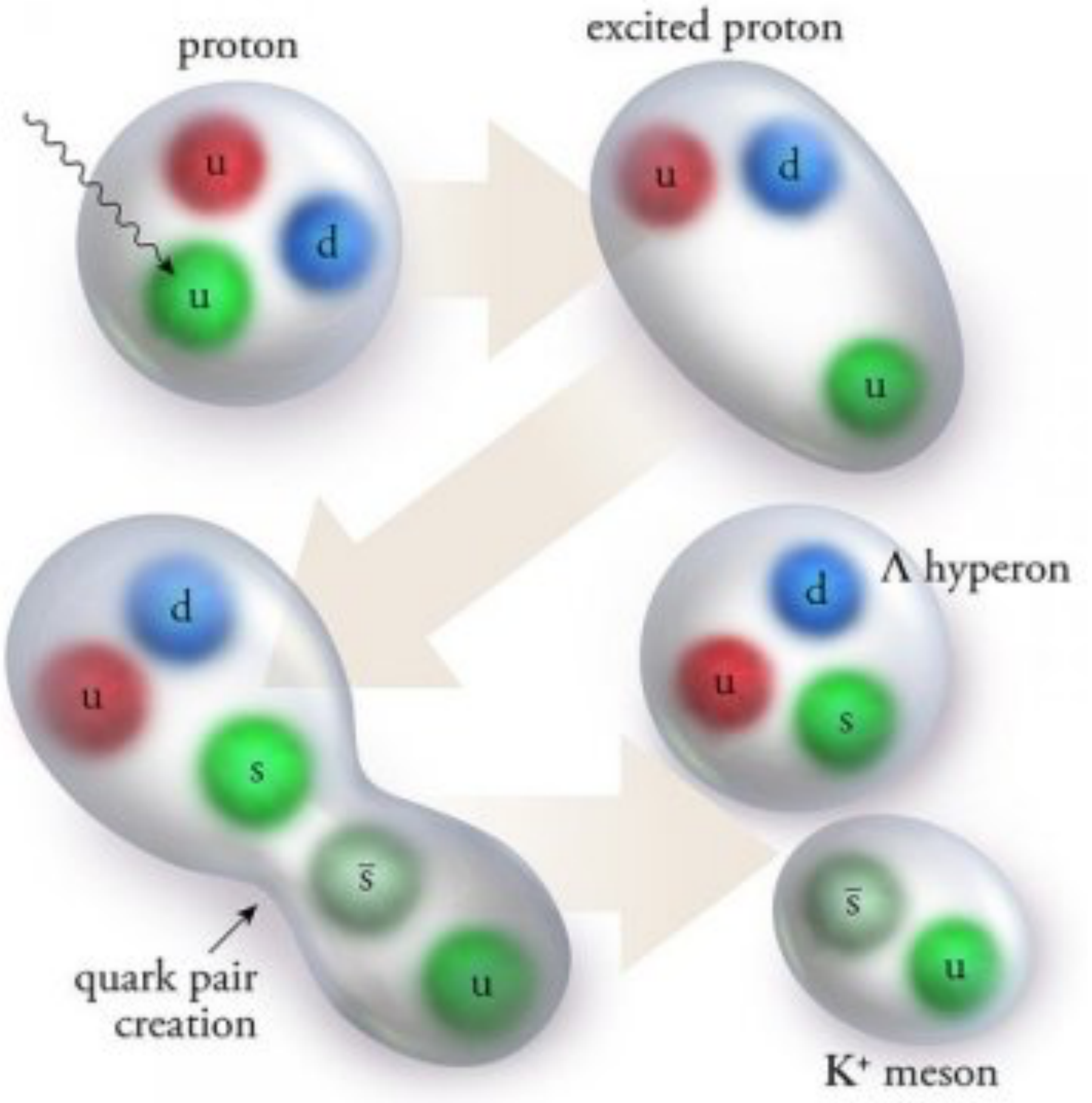


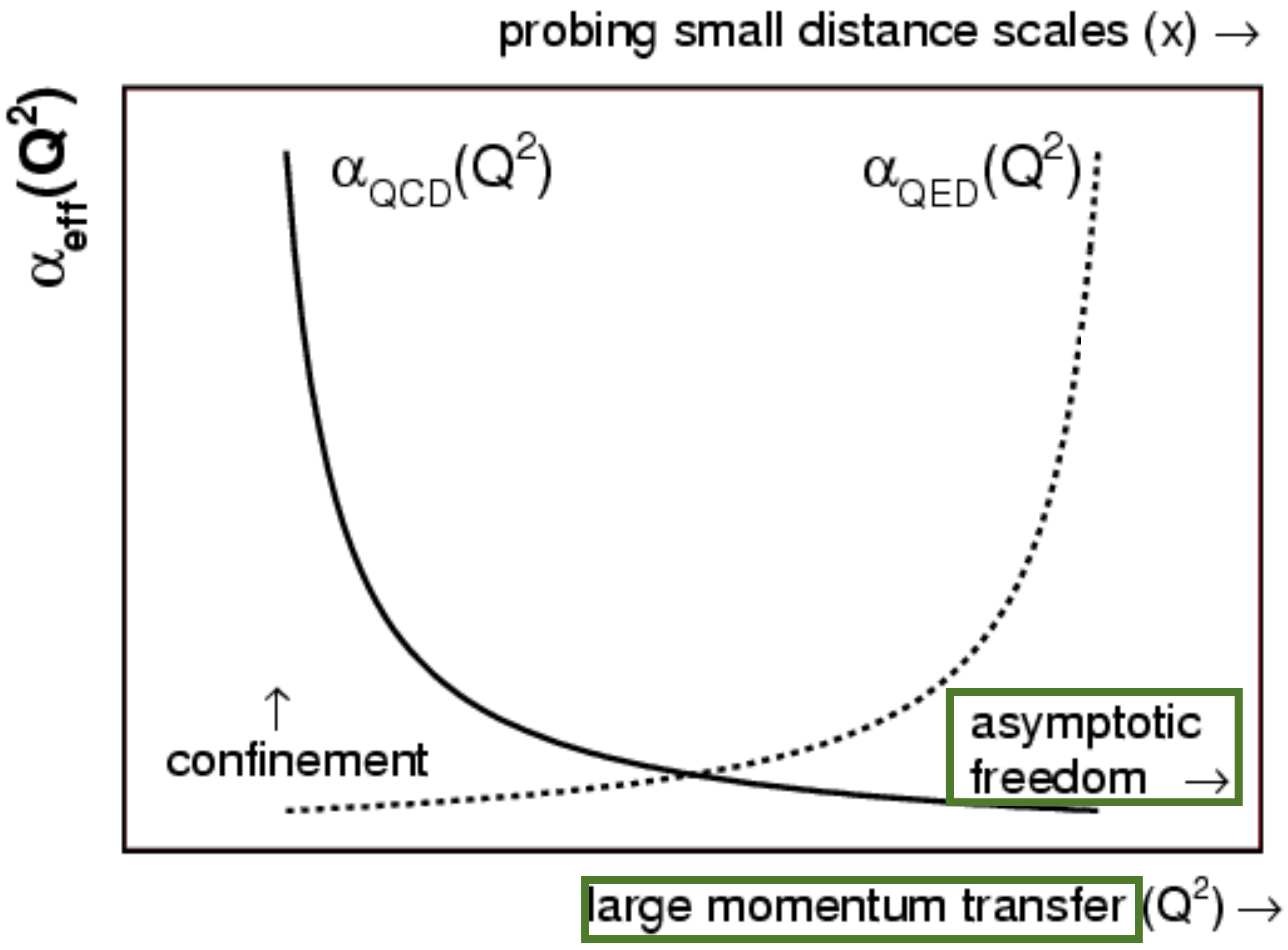
Confinement:



Coupling Constant

- Interaction strength given by α_{QED} and α_{QCD}

Asymptotic freedom



Large distances ⟷ **Small distances**

QCD Lagrangian within perturbation theory!

➜ perturbative QCD (pQCD)

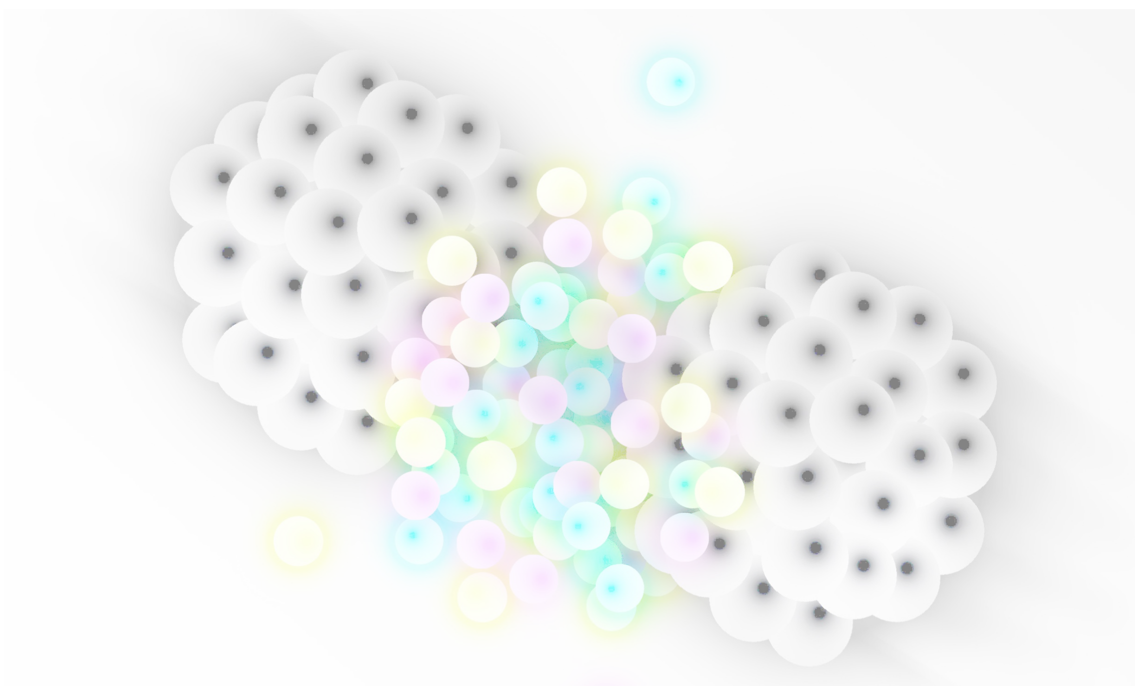
Example: Taylor Series of $f(x)$

$$f(a)+\frac{f'(a)}{1!}(x-a)+\frac{f''(a)}{2!}(x-a)^2+\frac{f'''(a)}{3!}(x-a)^3+\cdots,$$

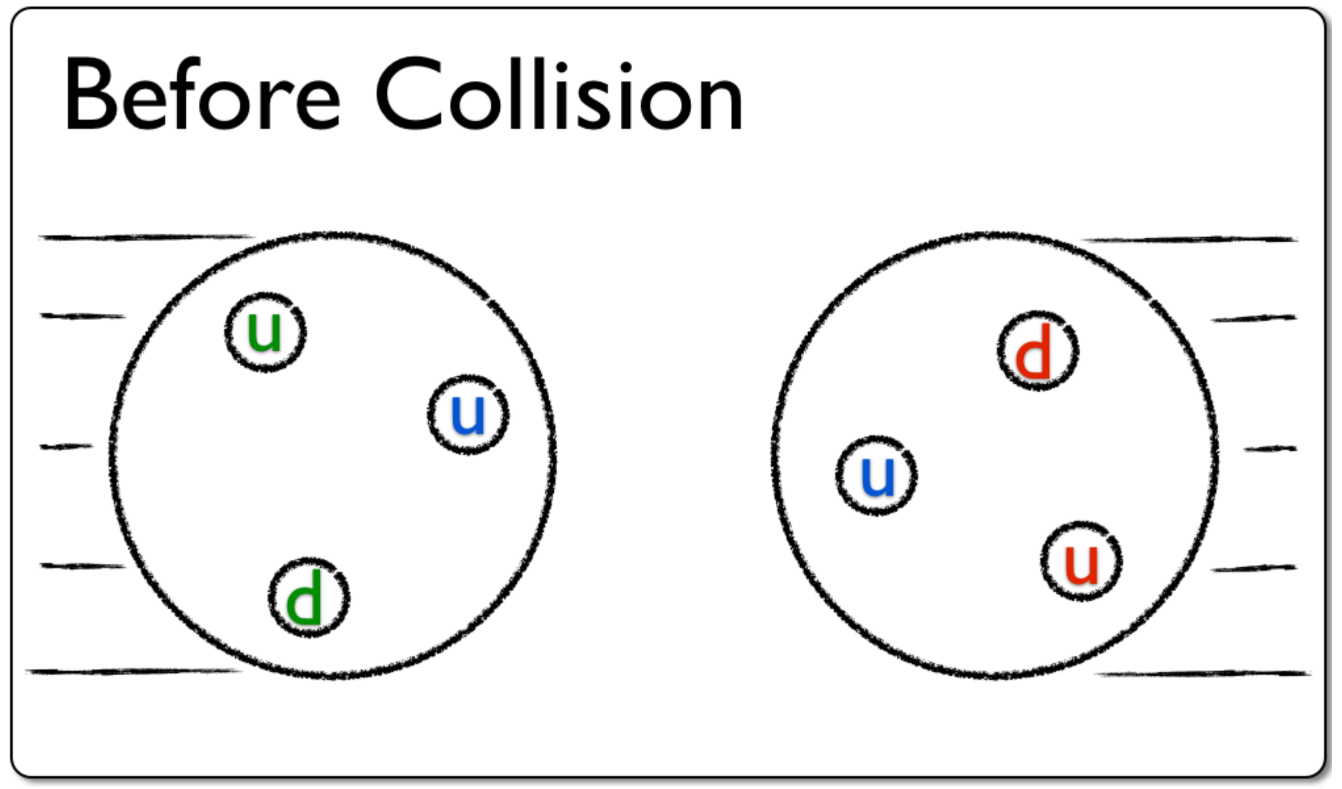
$$\sin(x)\approx x-\frac{x^3}{3!}+\frac{x^5}{5!}-\frac{x^7}{7!}.$$

Higher order terms can be neglected for x << 1

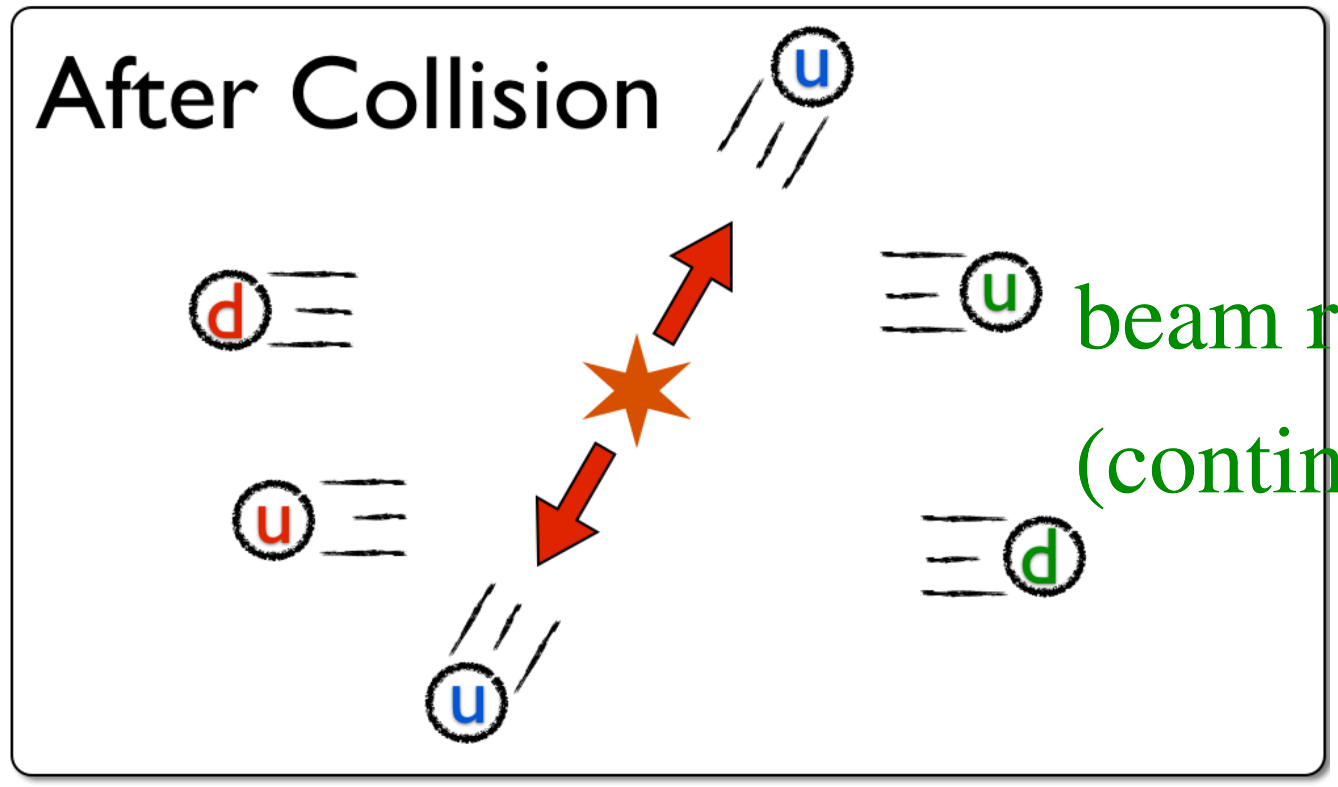
QCD Parton Shower



- Process with a large momentum transfer:



High momentum quarks
(in the transverse direction)



beam remnant
(continue in the beam direction)

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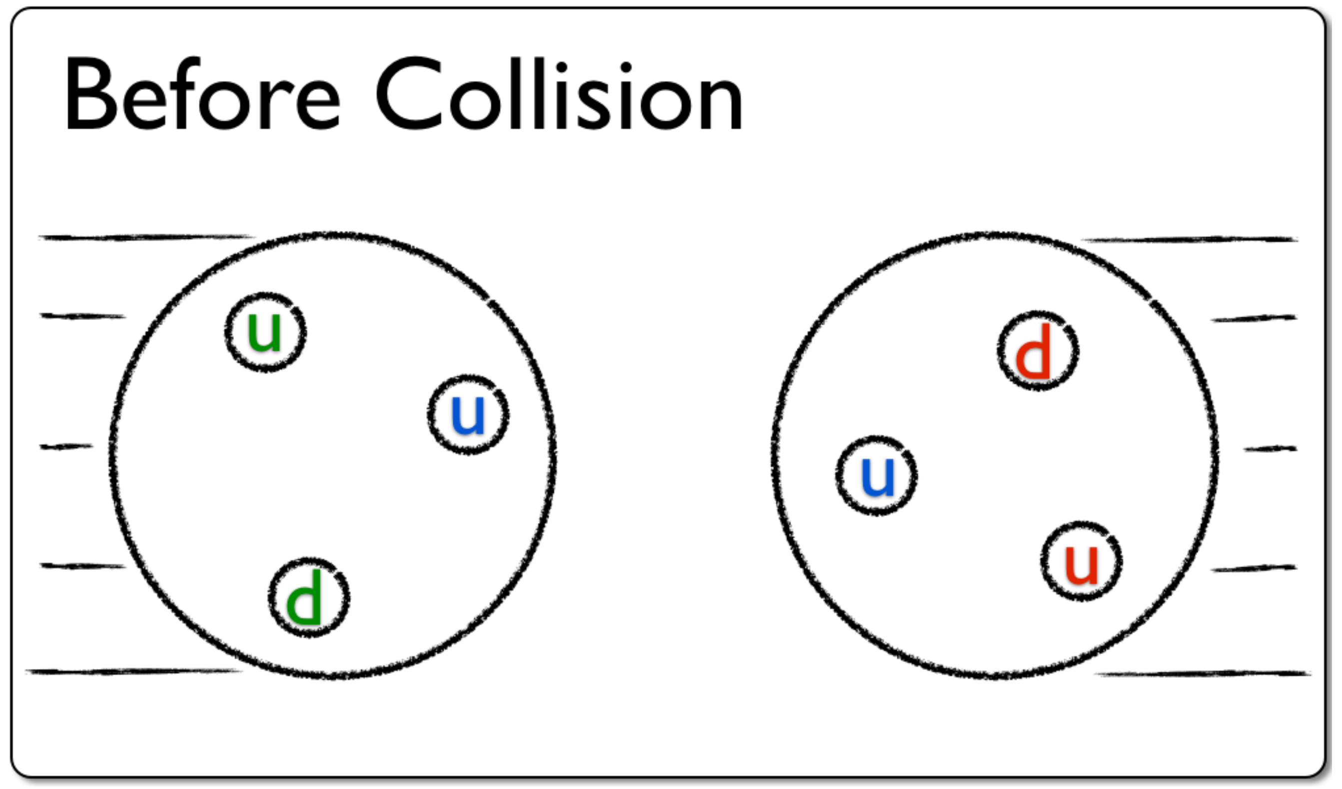

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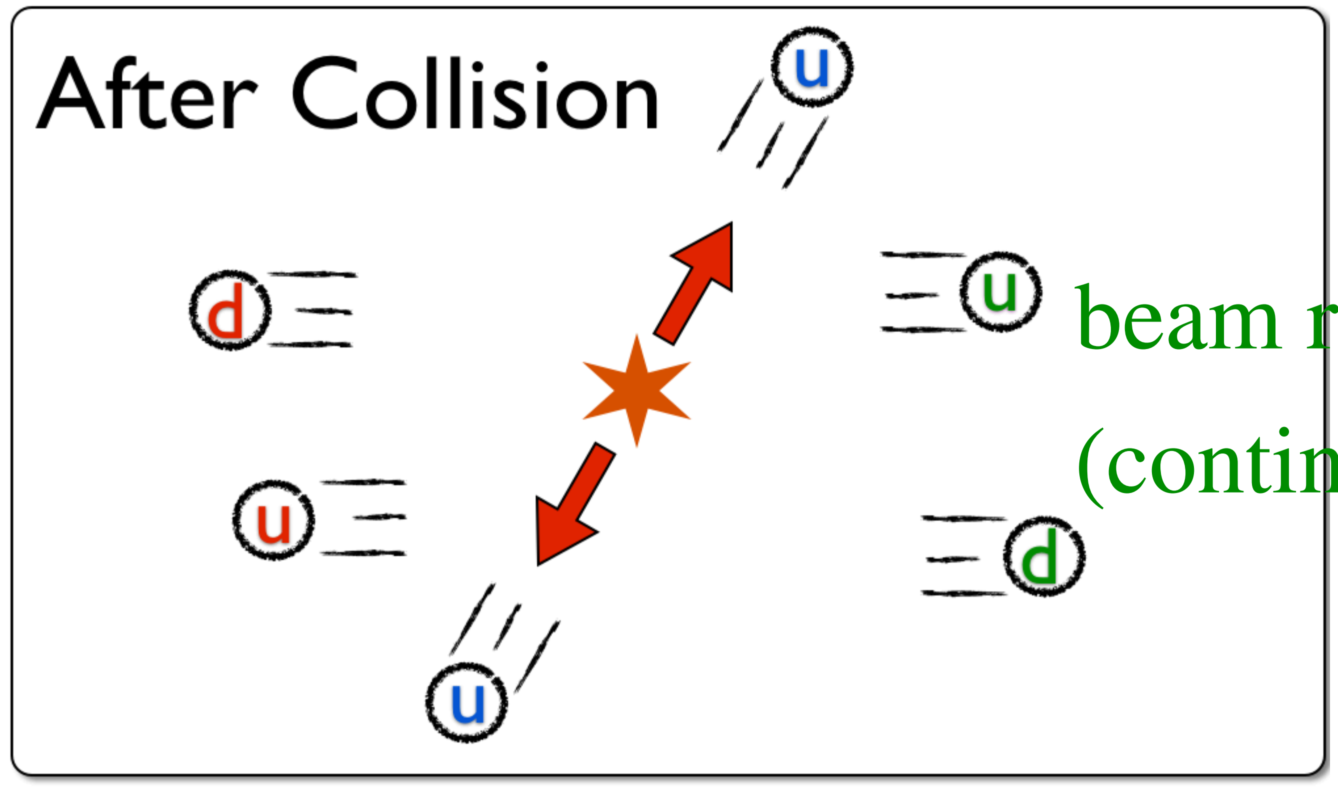

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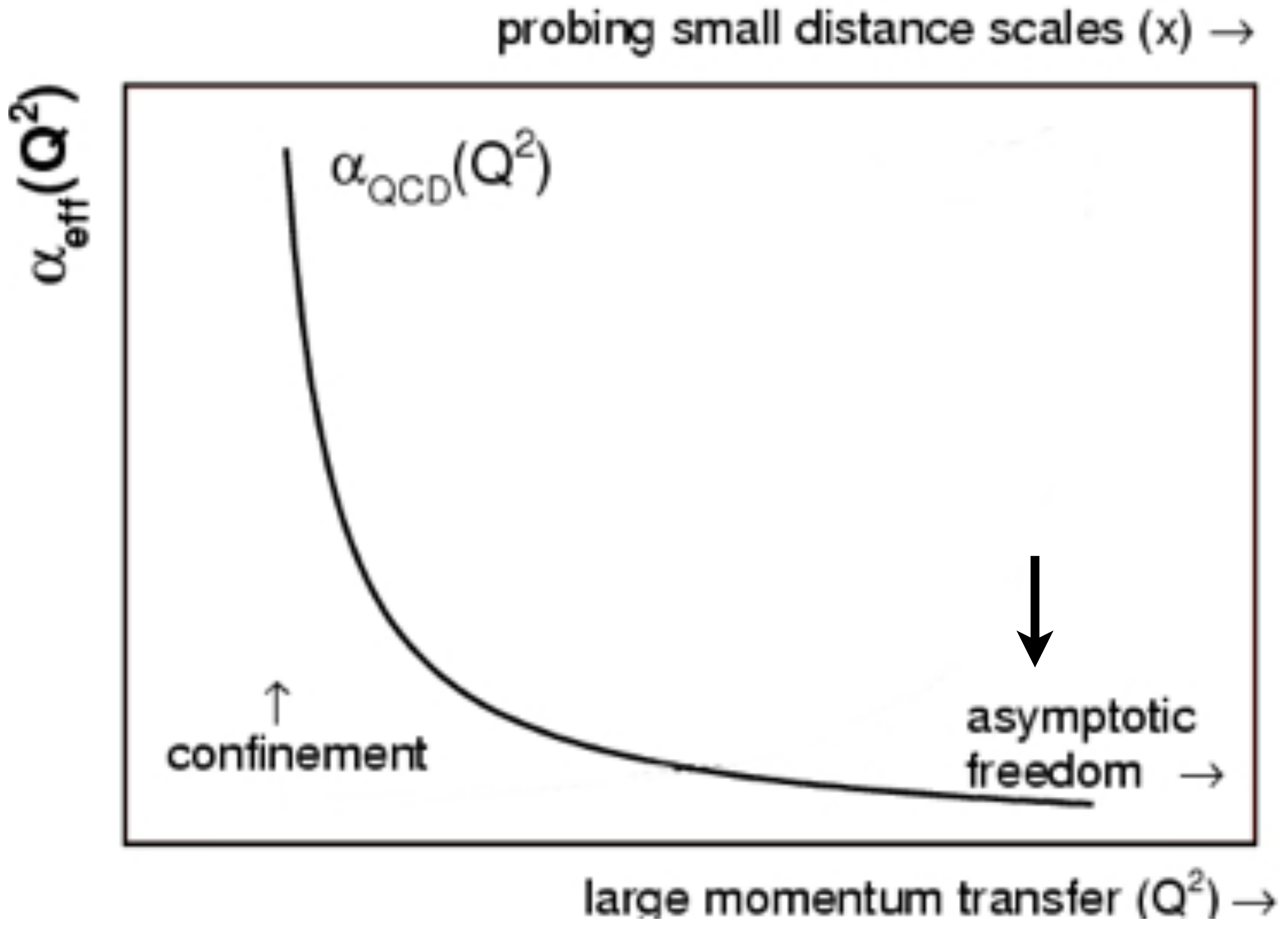

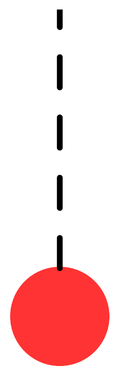

Hard scattering

QCD Parton Shower

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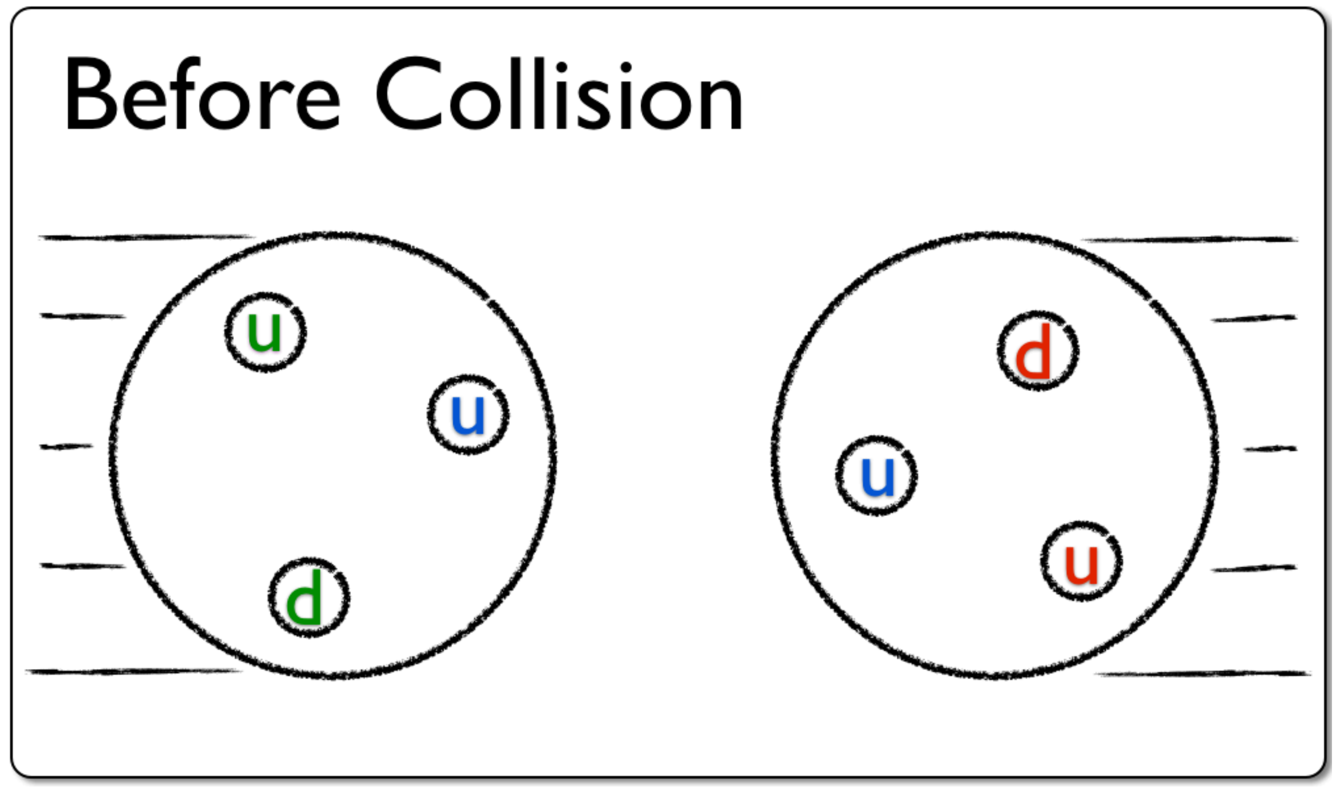

High momentum quarks

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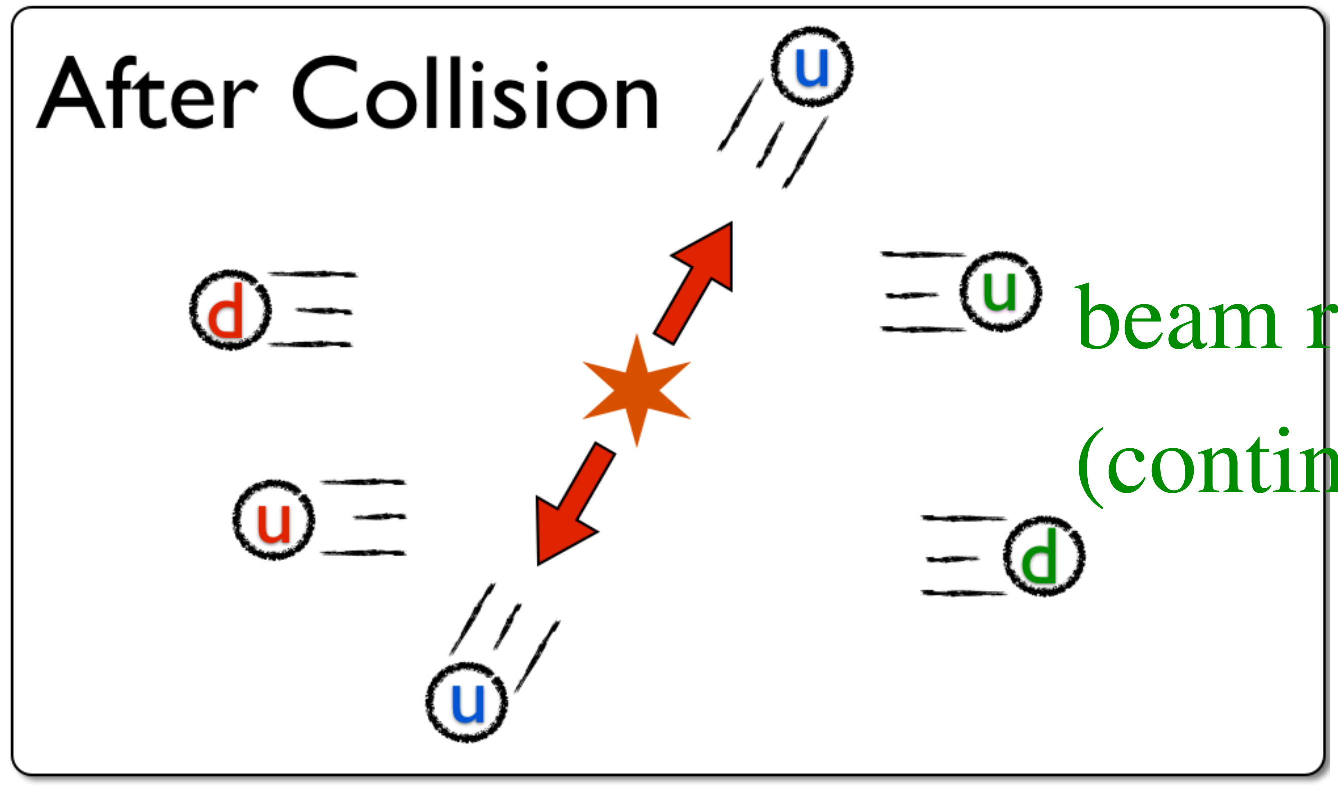

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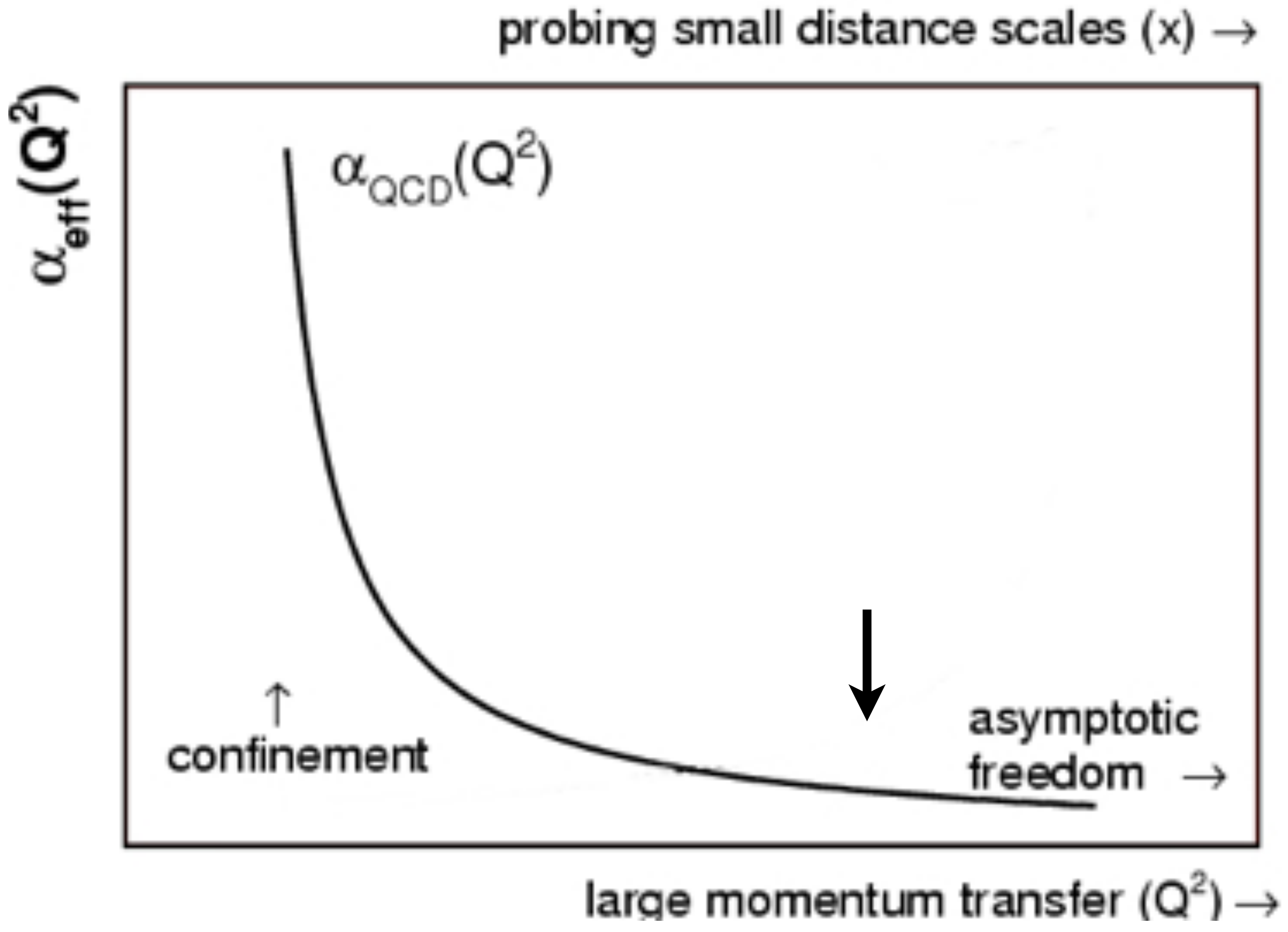

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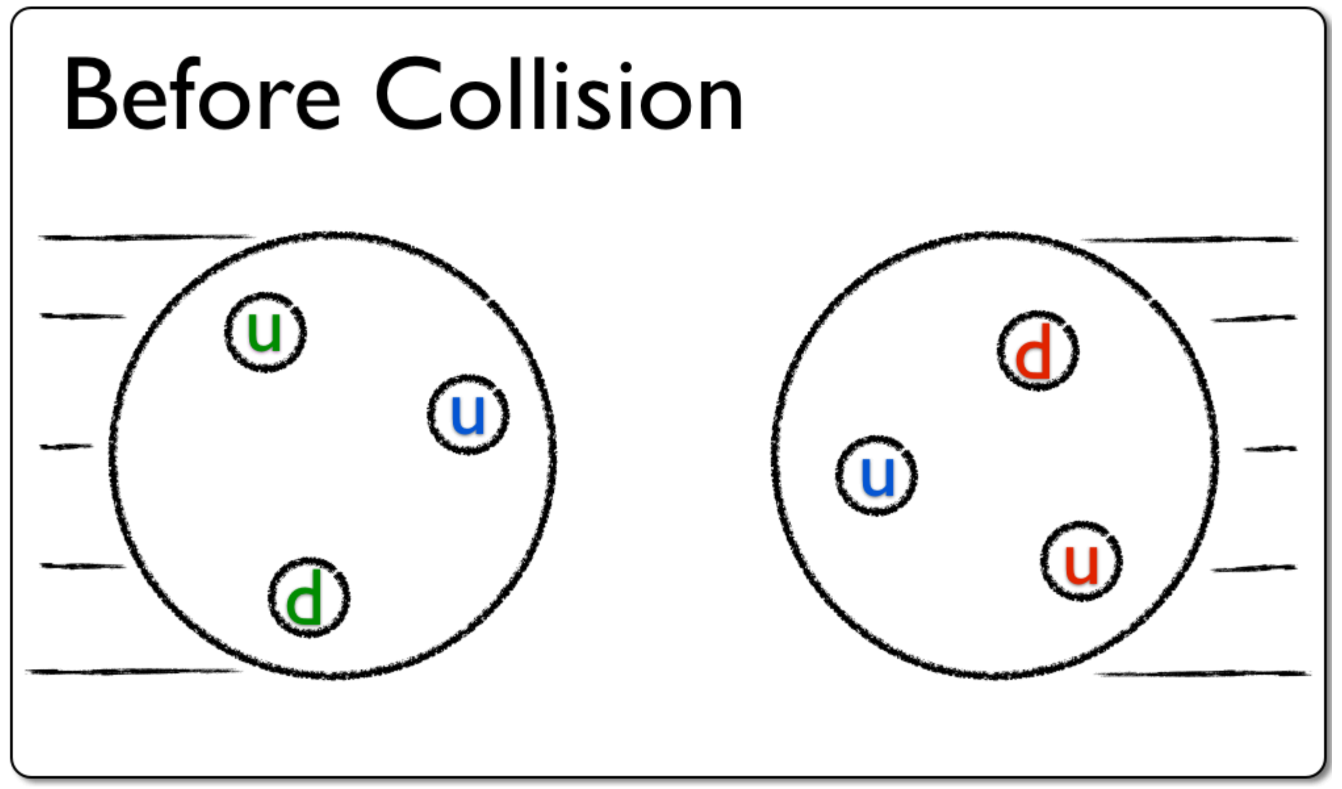

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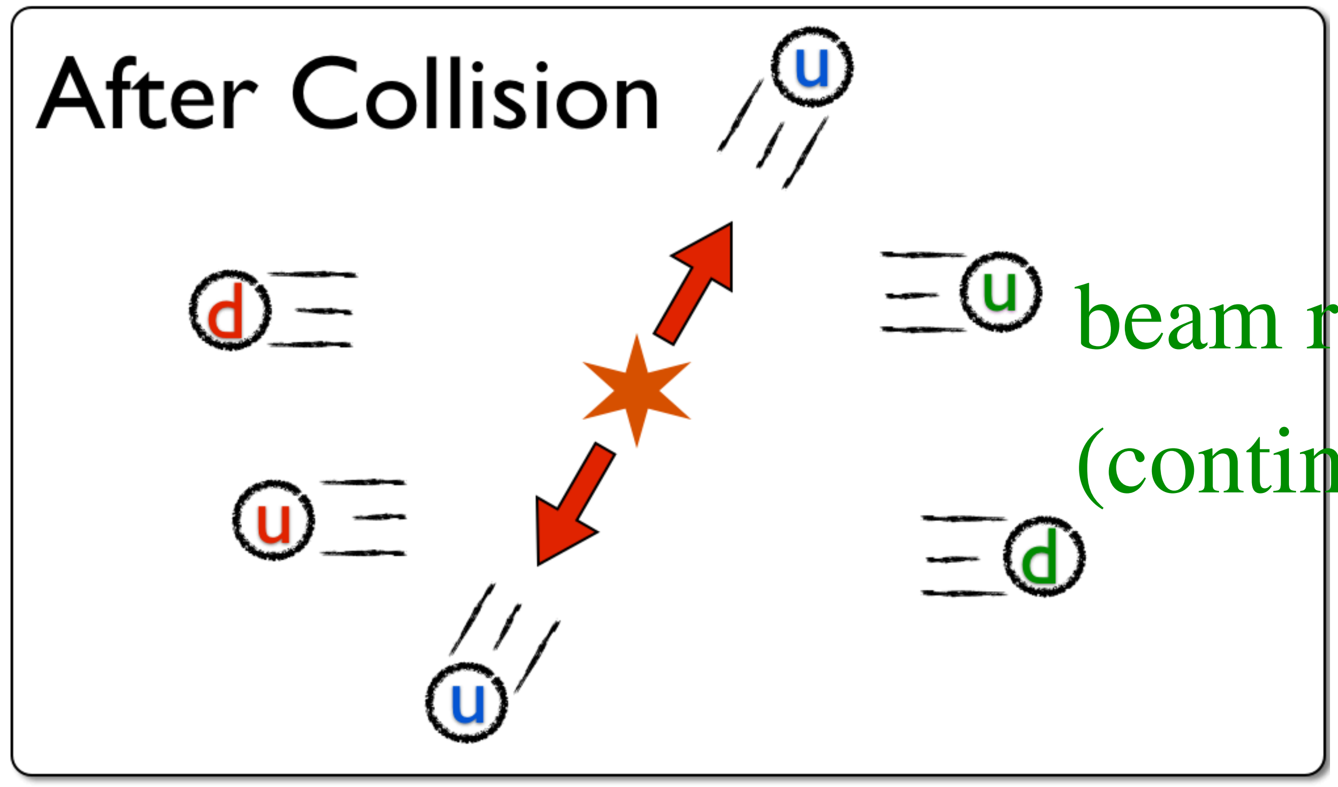

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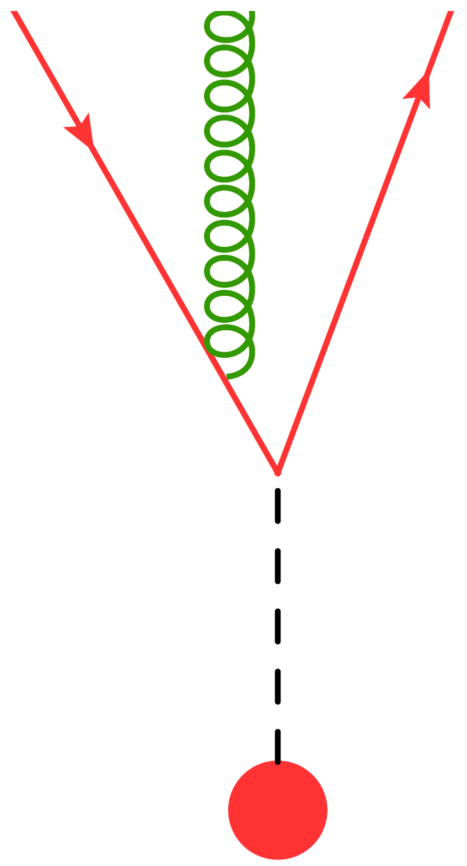

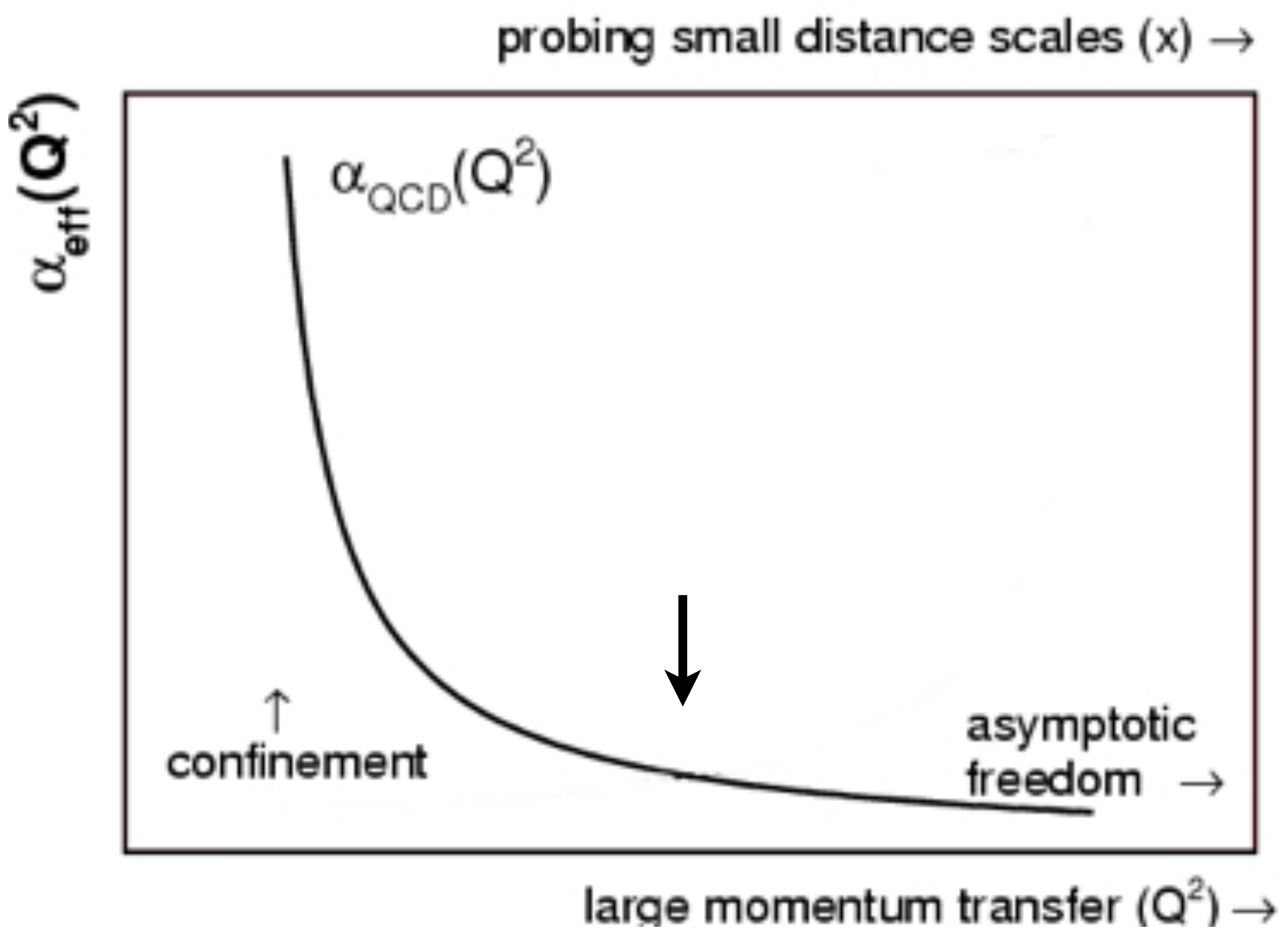

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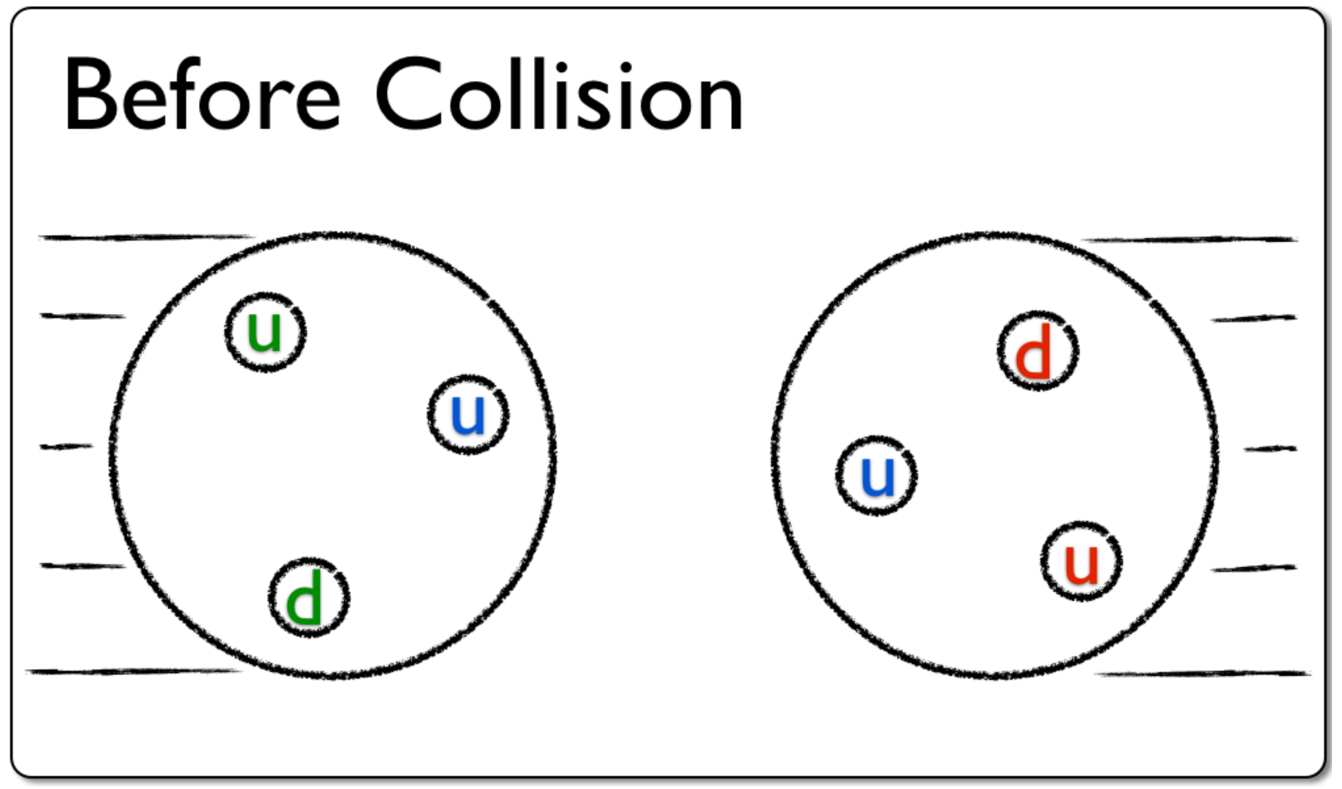

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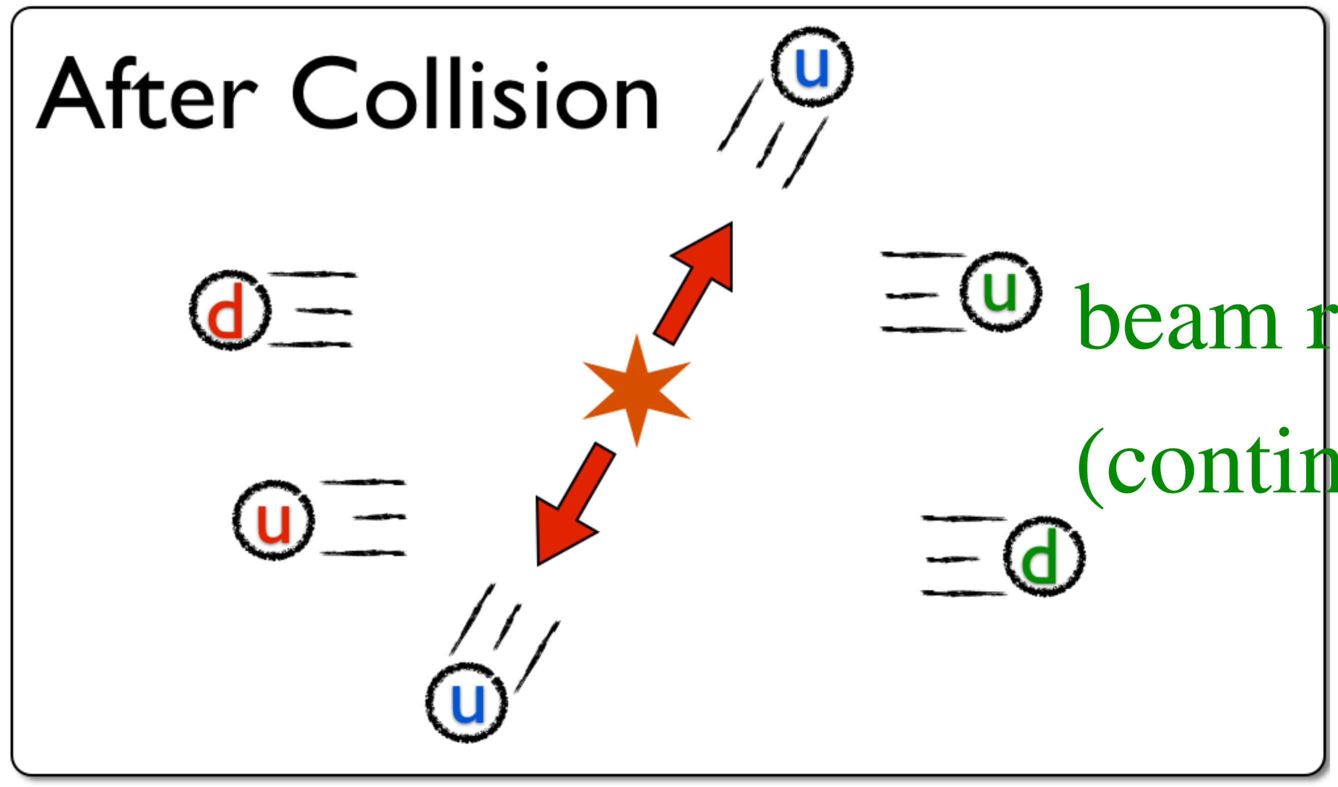

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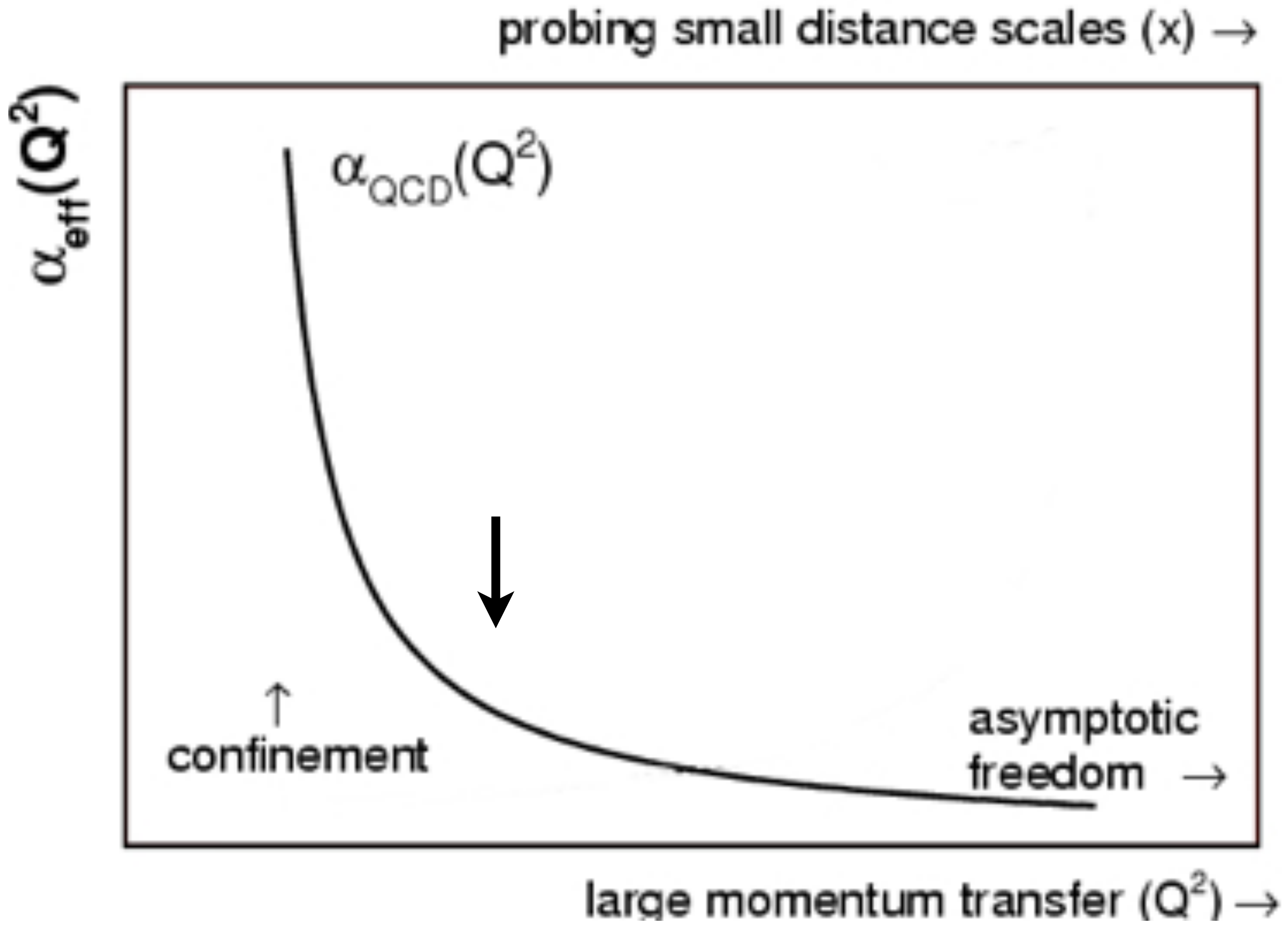

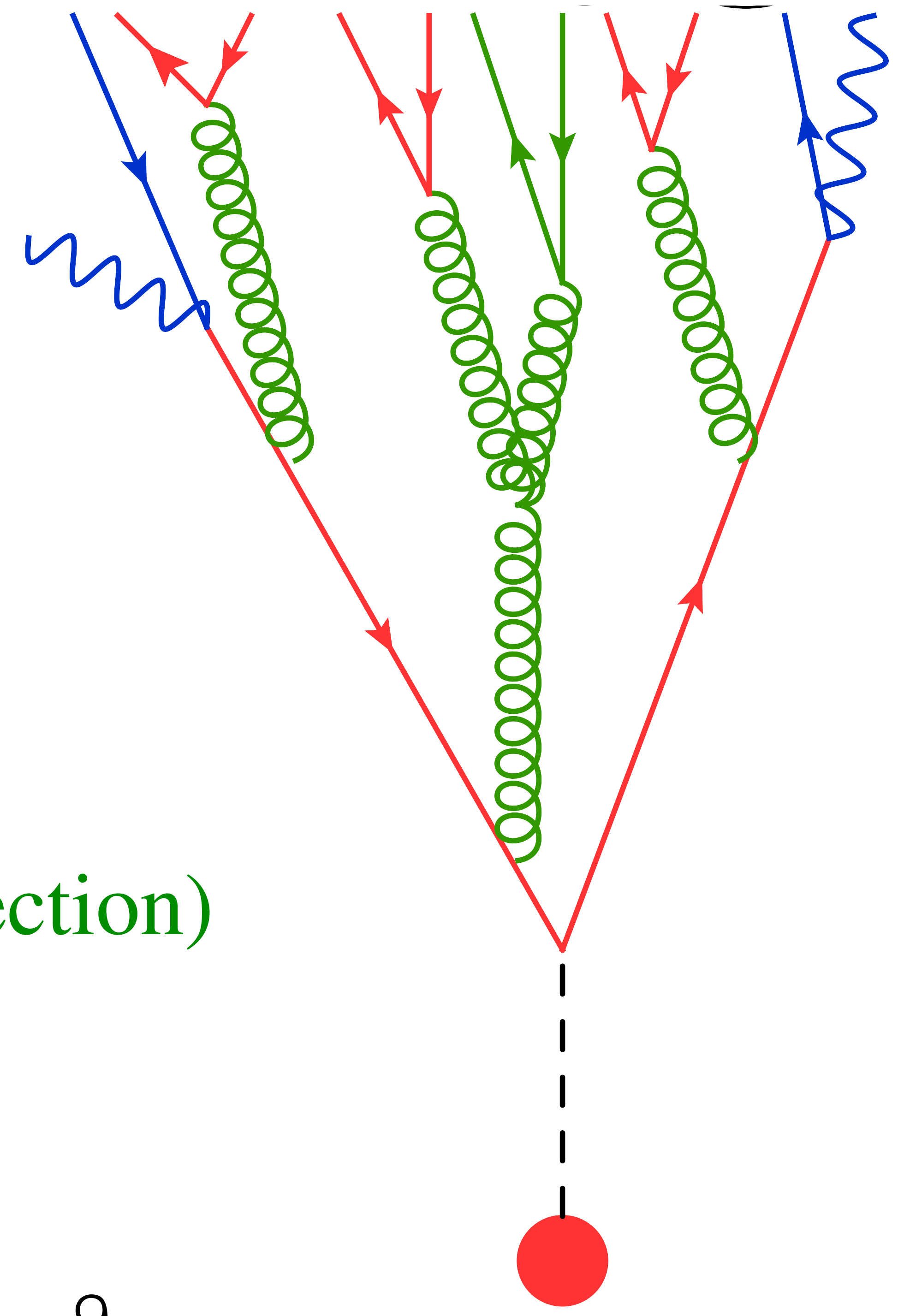

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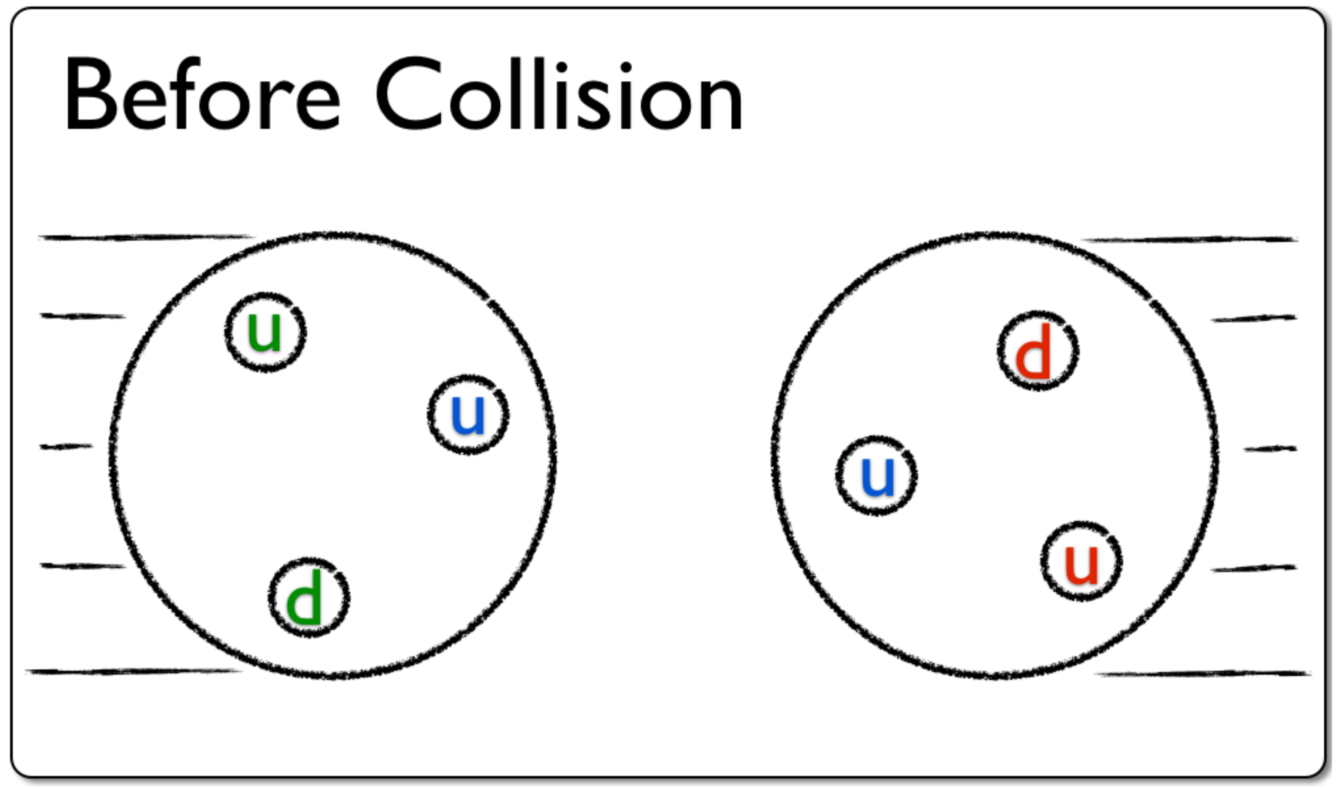

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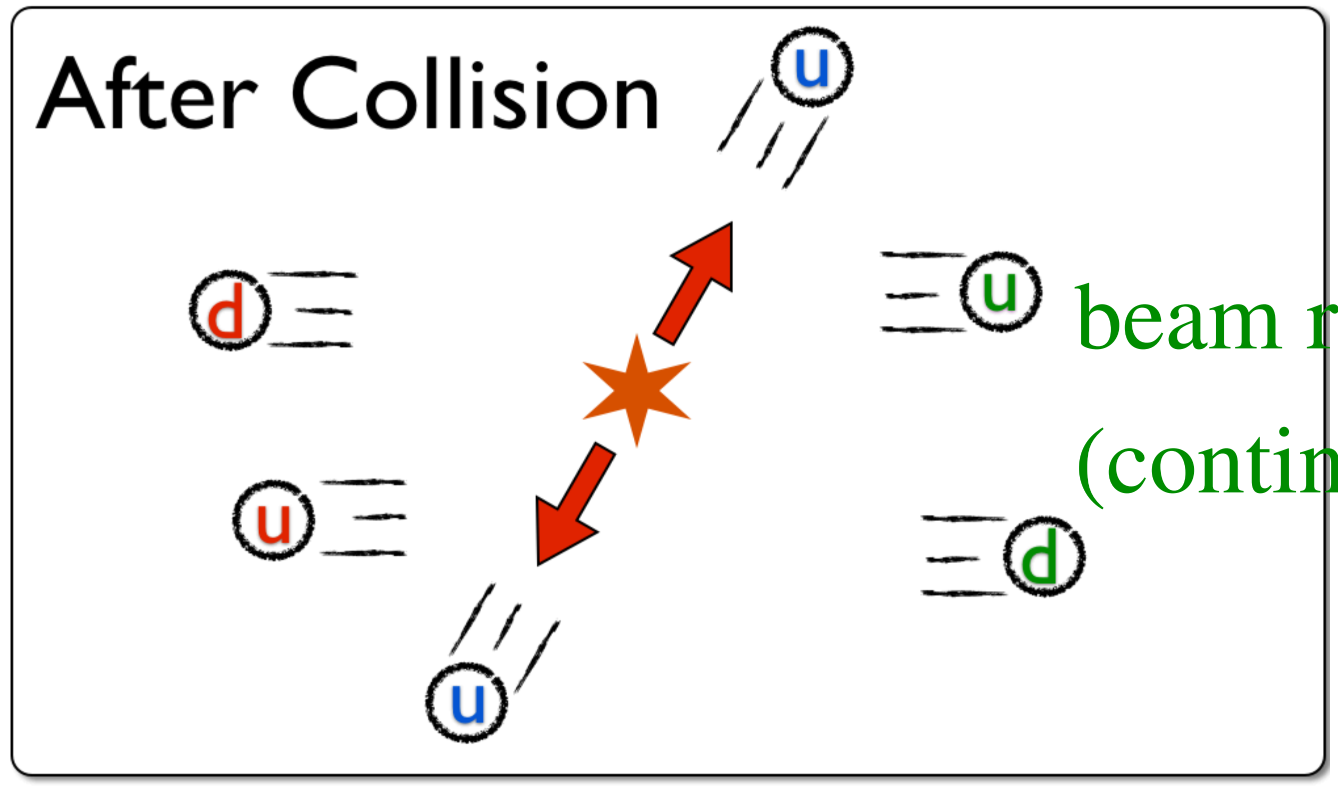
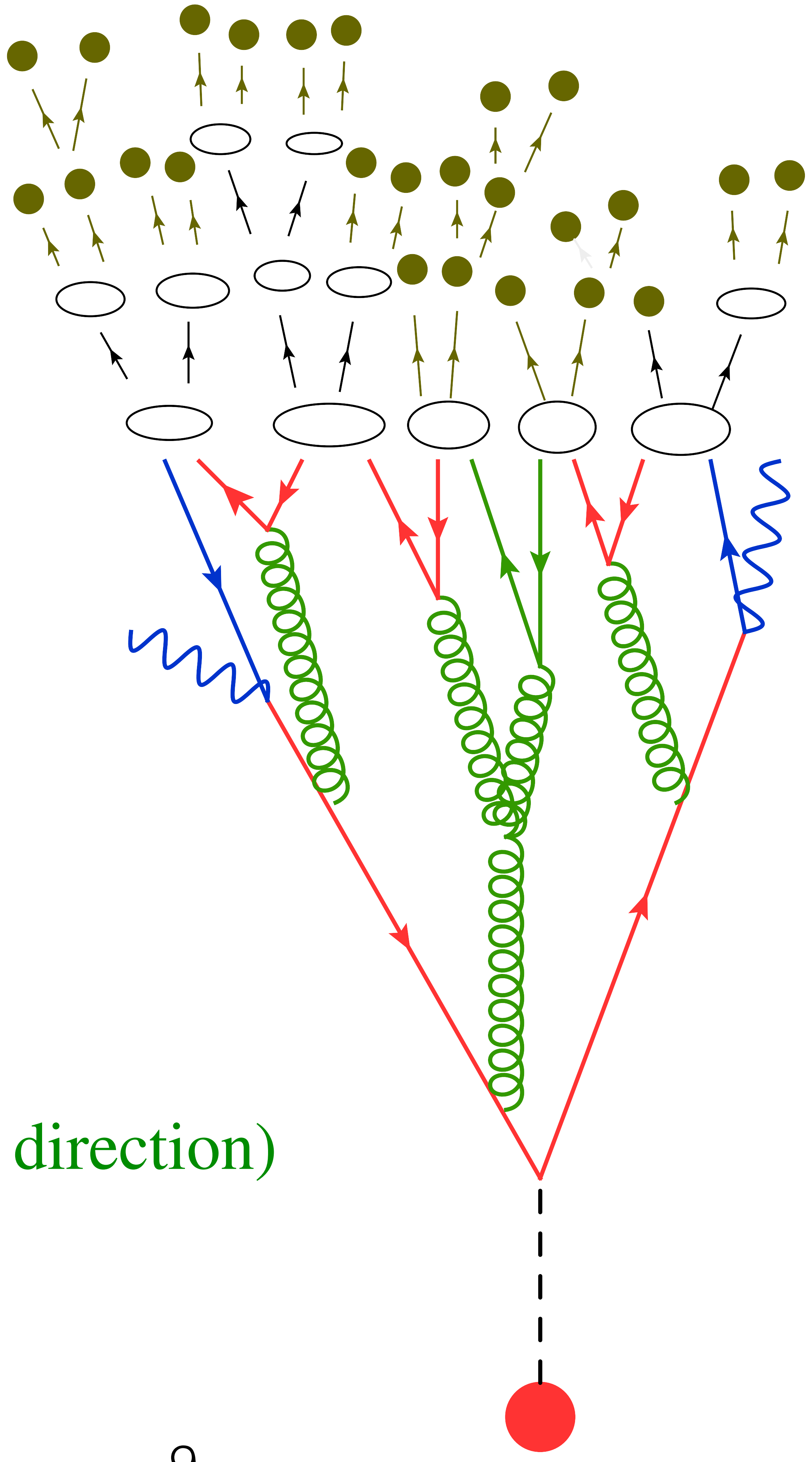


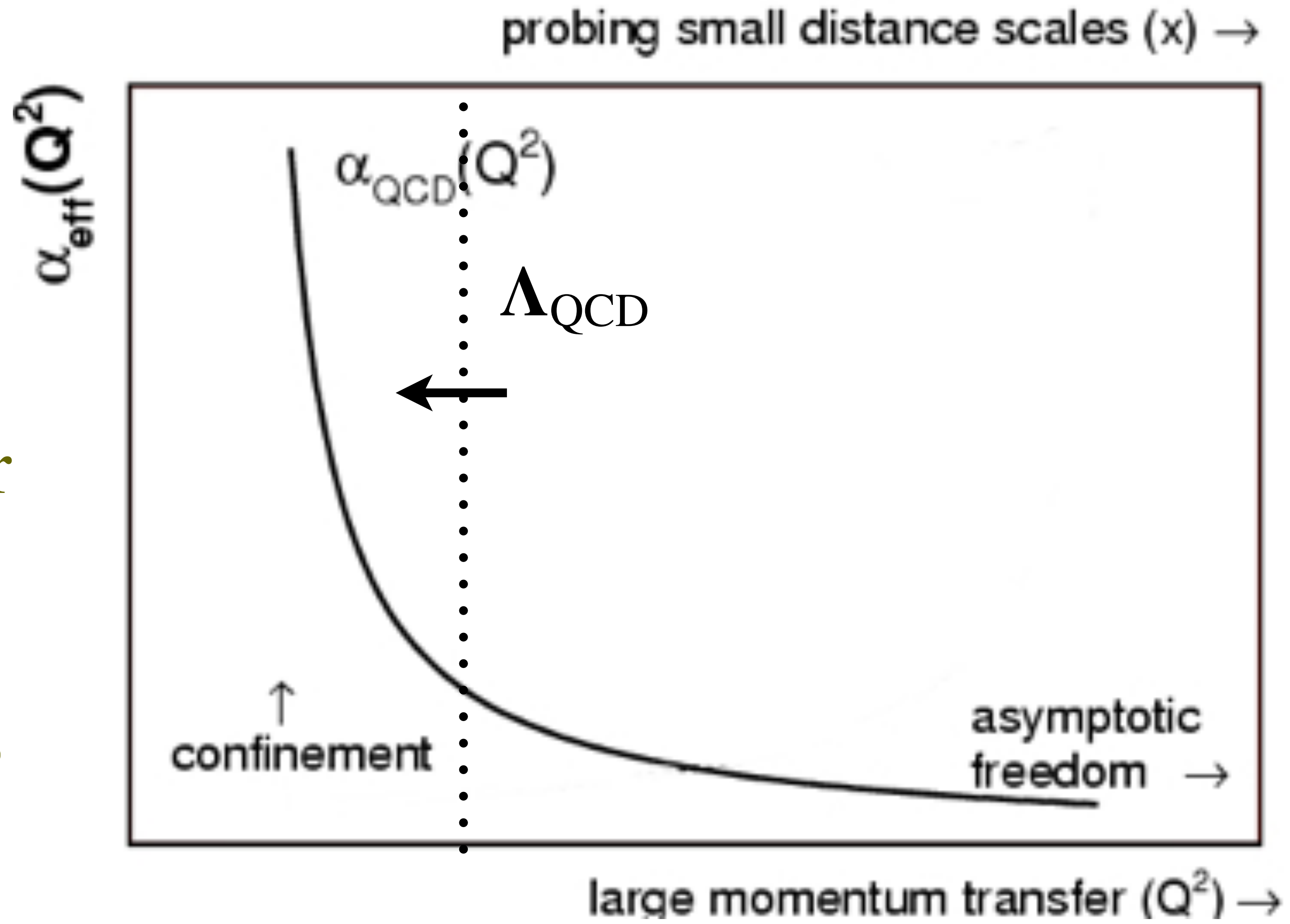
beam remnant

(continue in the beam direction)

Particles @ detector

Λ_{QCD}





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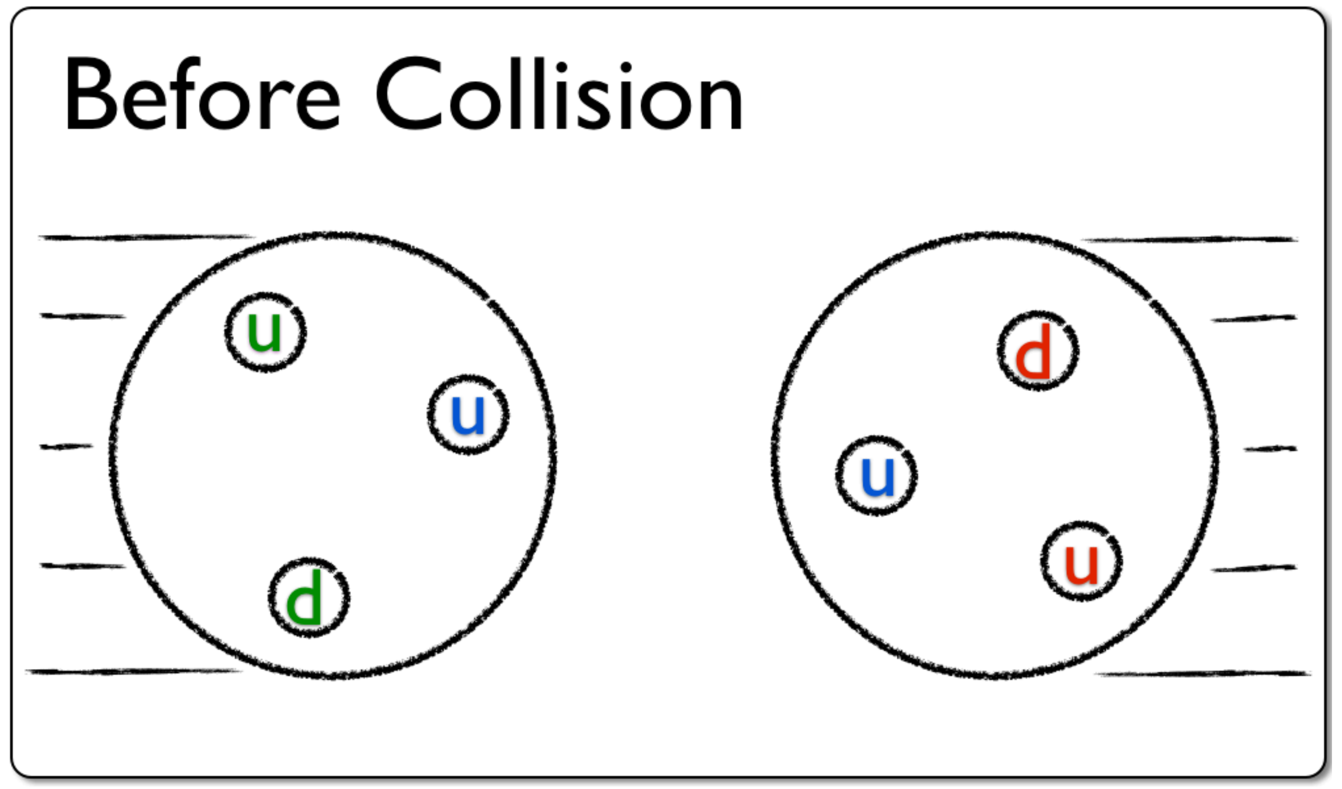

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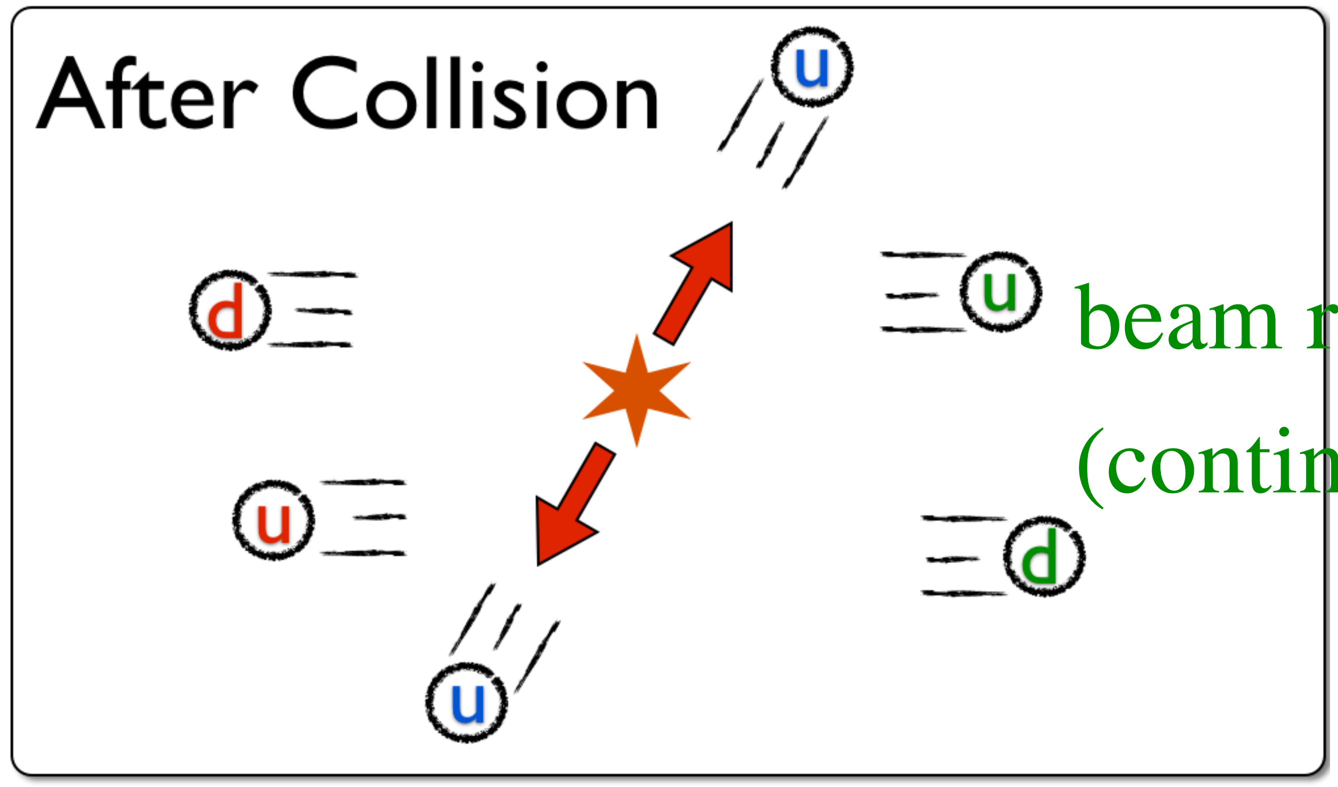

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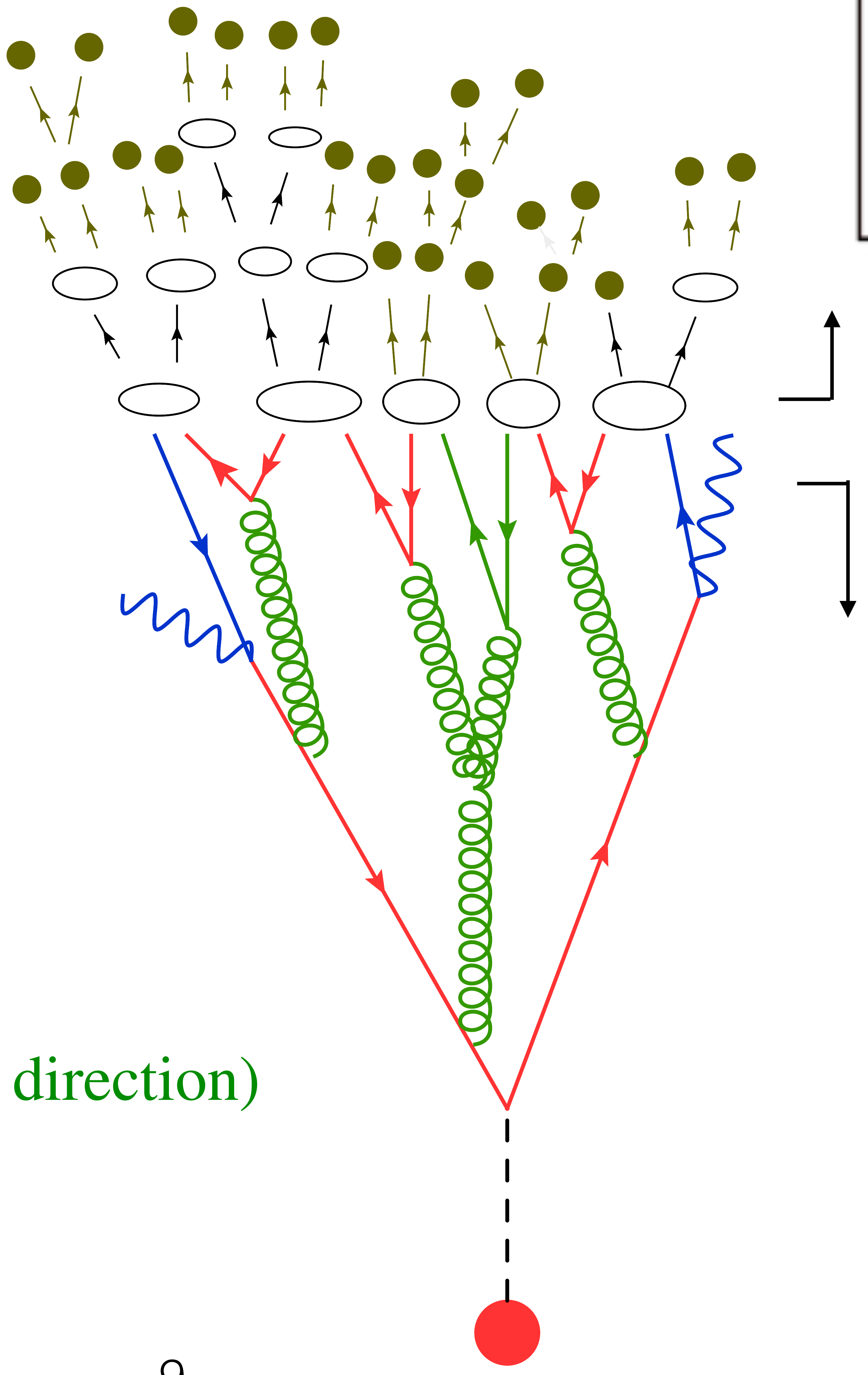
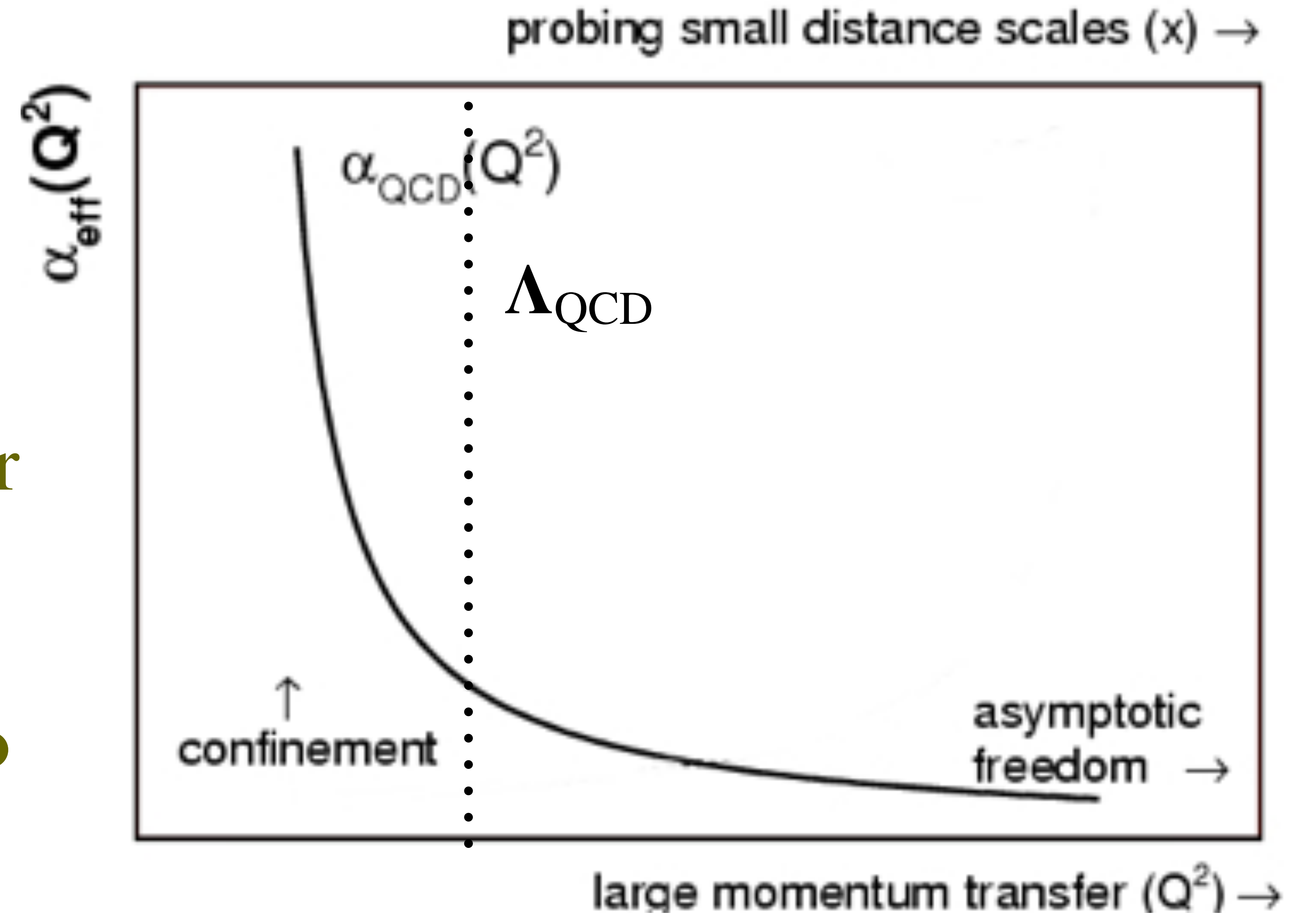


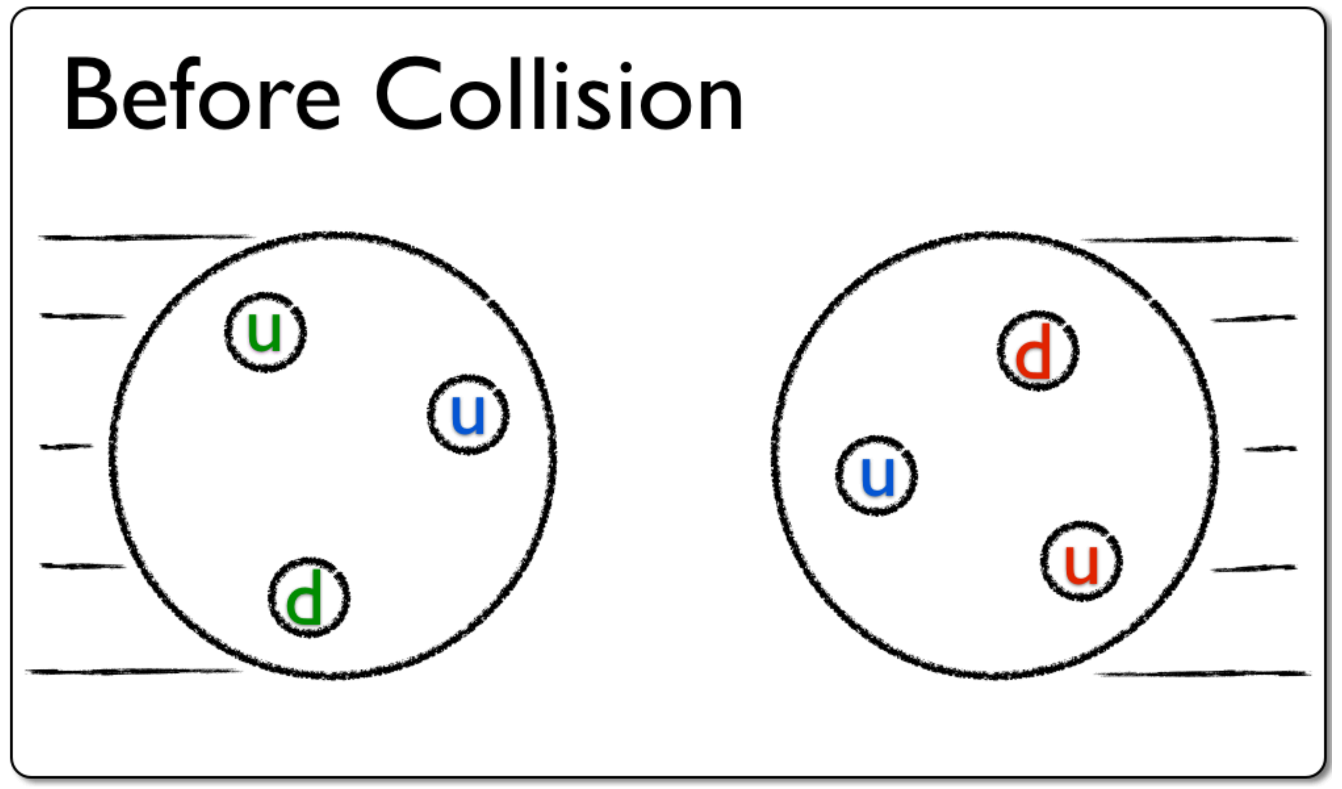
Hadronization
(non pQCD)

parton shower/
branching (pQCD)

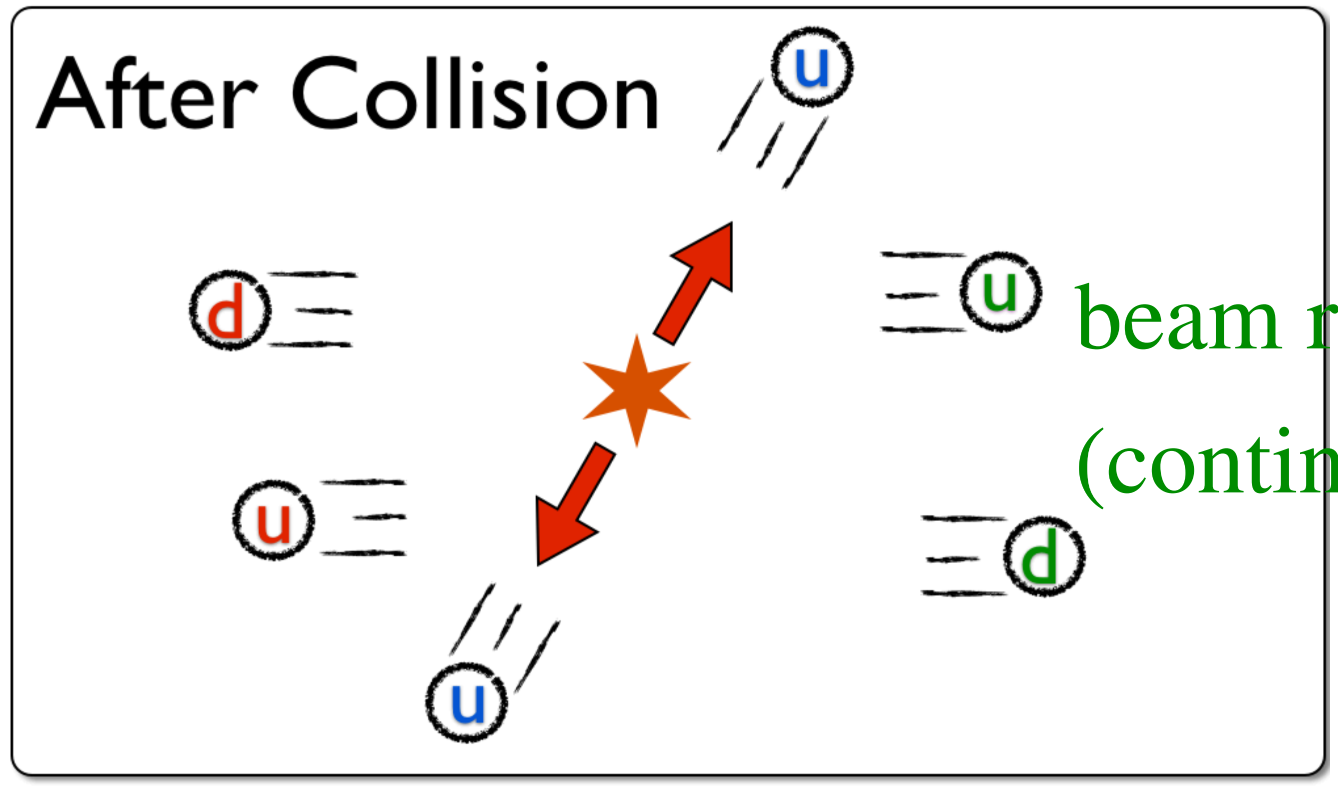


QCD Parton Shower

- Process with a large momentum transfer:



High momentum quarks
(in the transverse direction)



beam remnant
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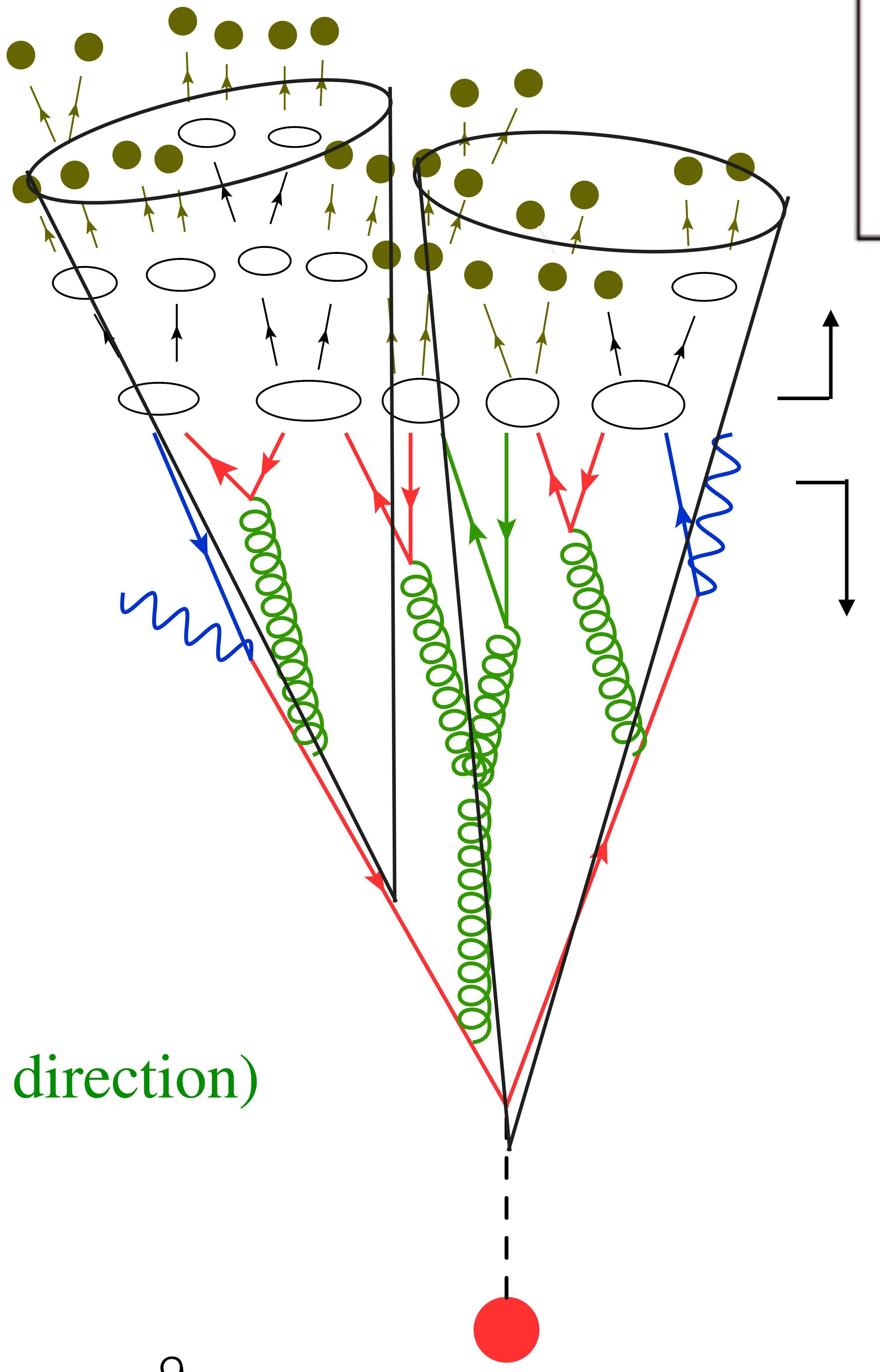
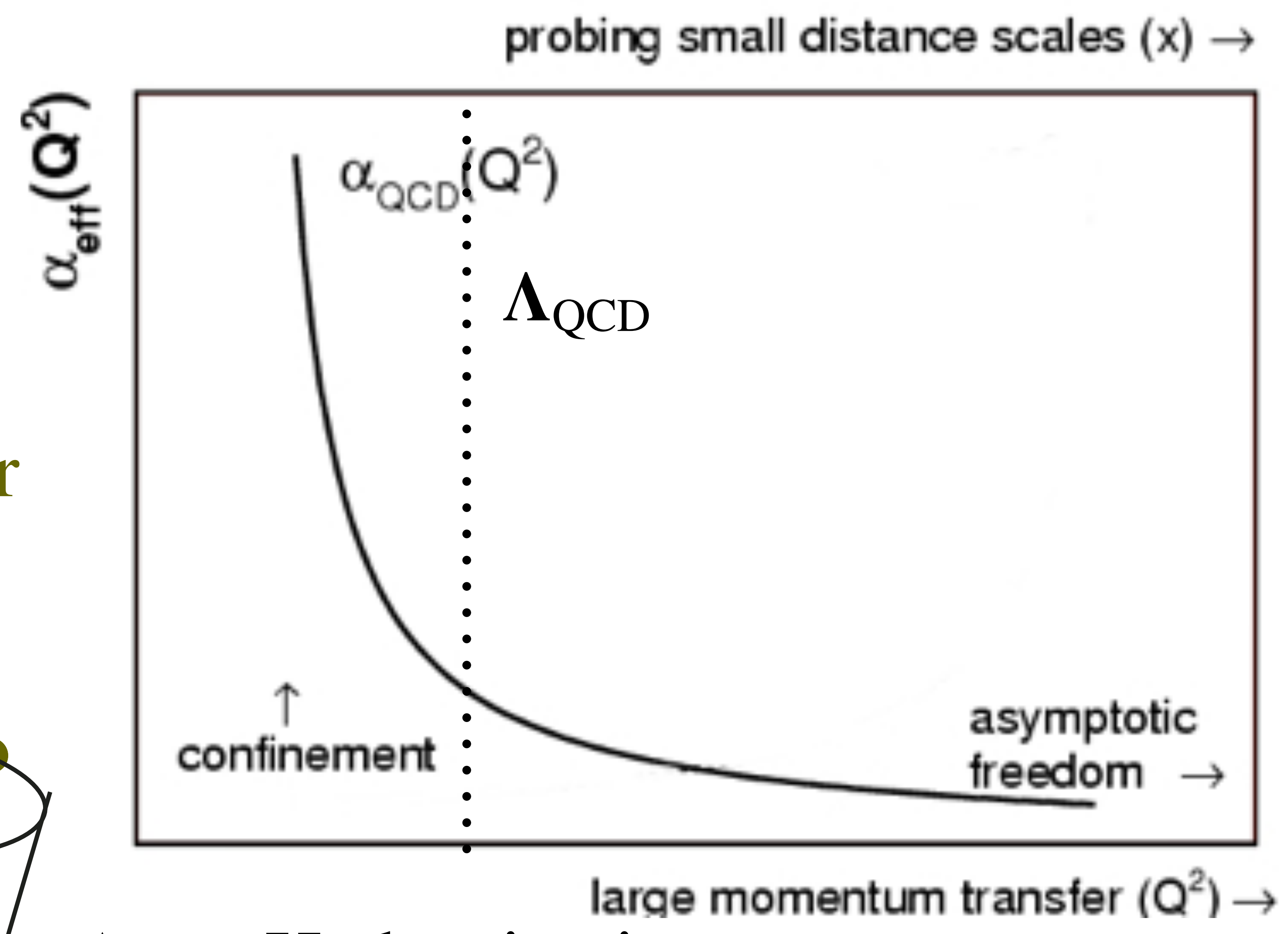


Hadronization
(non pQCD)

parton shower/
branching (pQCD)

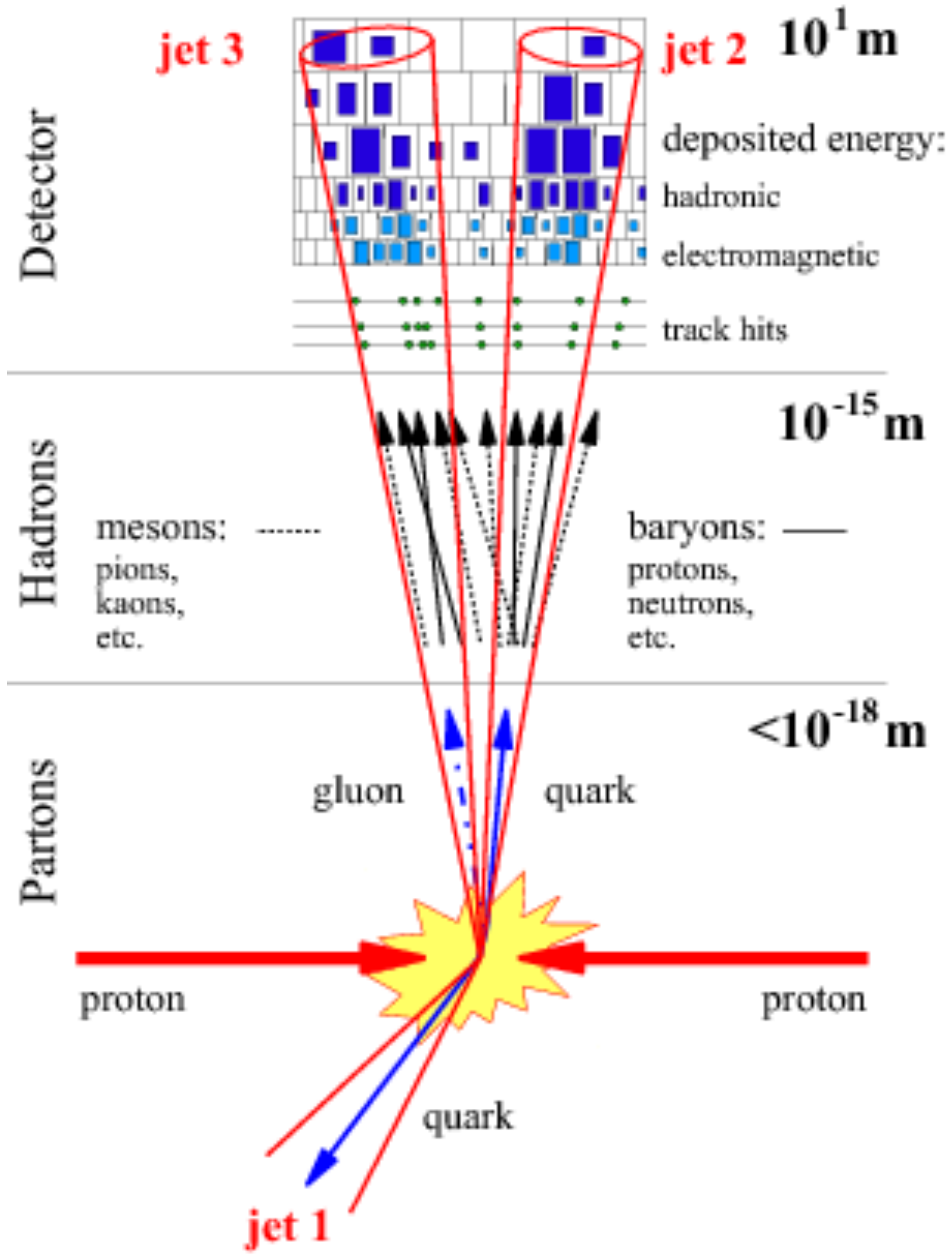
Jets

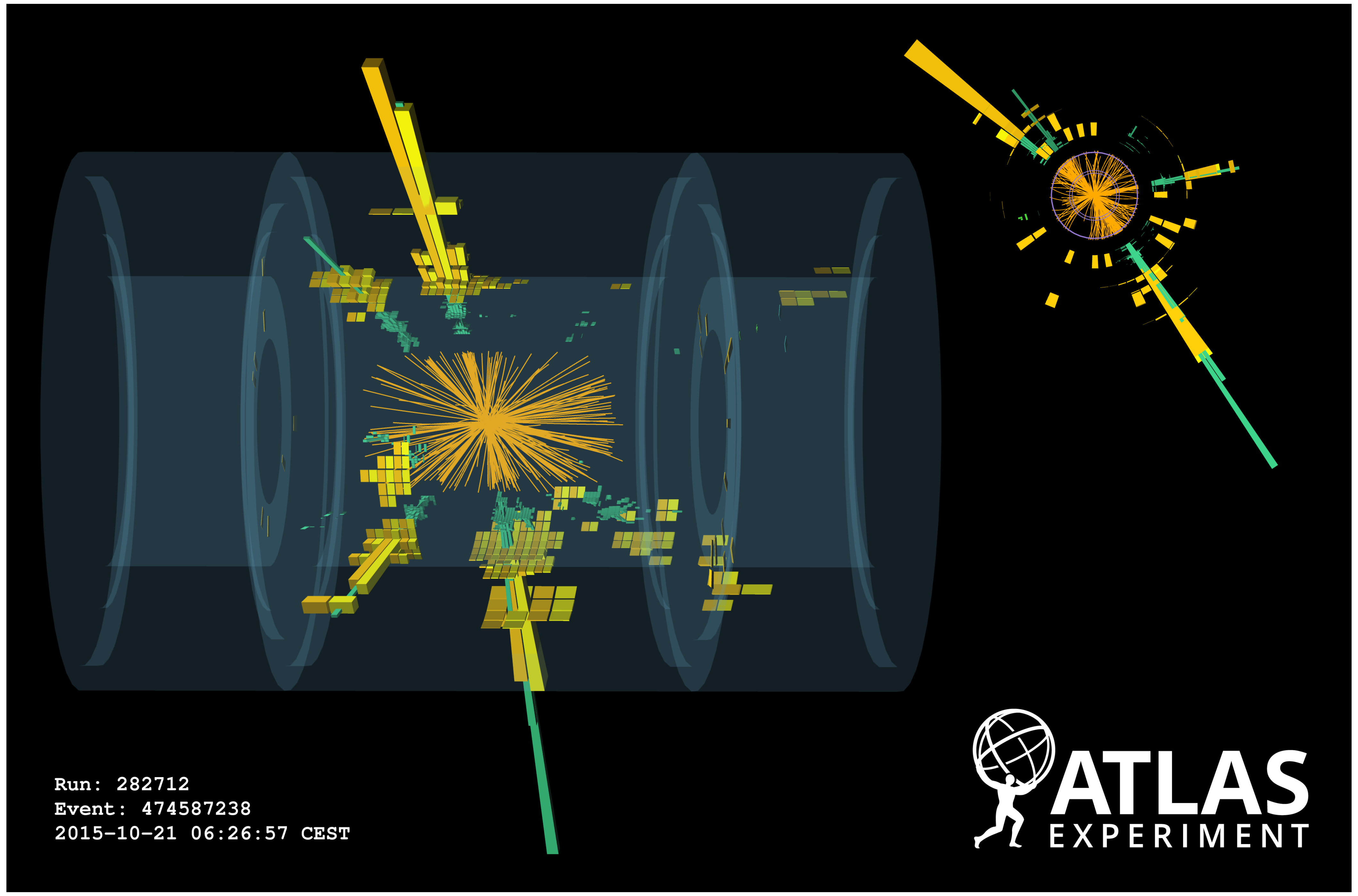


QCD Parton Shower to Jets

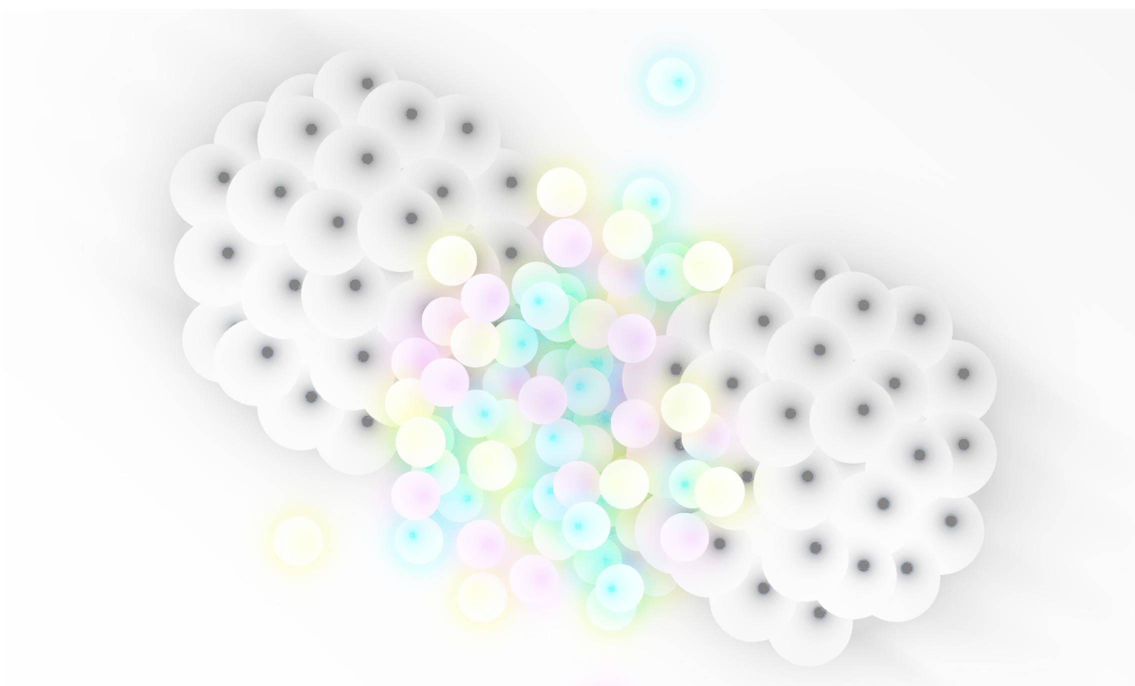
- What is a jet?
  - Spray of collimated particles that were originated by a high momentum parton (quark or gluon)

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





Jet algorithms



- Need a recipe to define it:
  - Jet clustering algorithm: define criteria to decide which particles are going to be clustered in the same jet

$$d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p})\frac{\Delta R_{ij}^2}{R^2} \begin{cases} p = 1 & k_T\ algorithm \\ p = 0 & Cambridge/Aachenalgorithm \\ p = -1 & anti - k_T\ algorithm \end{cases}$$

  - Jet size (radius): maximum "distance" that two particles can be to be considered as part of the same jet $R_{ij}^2 = (y_i \ \ y_j)^2 + (\phi_i - \phi_j)^2$

Jet algorithms

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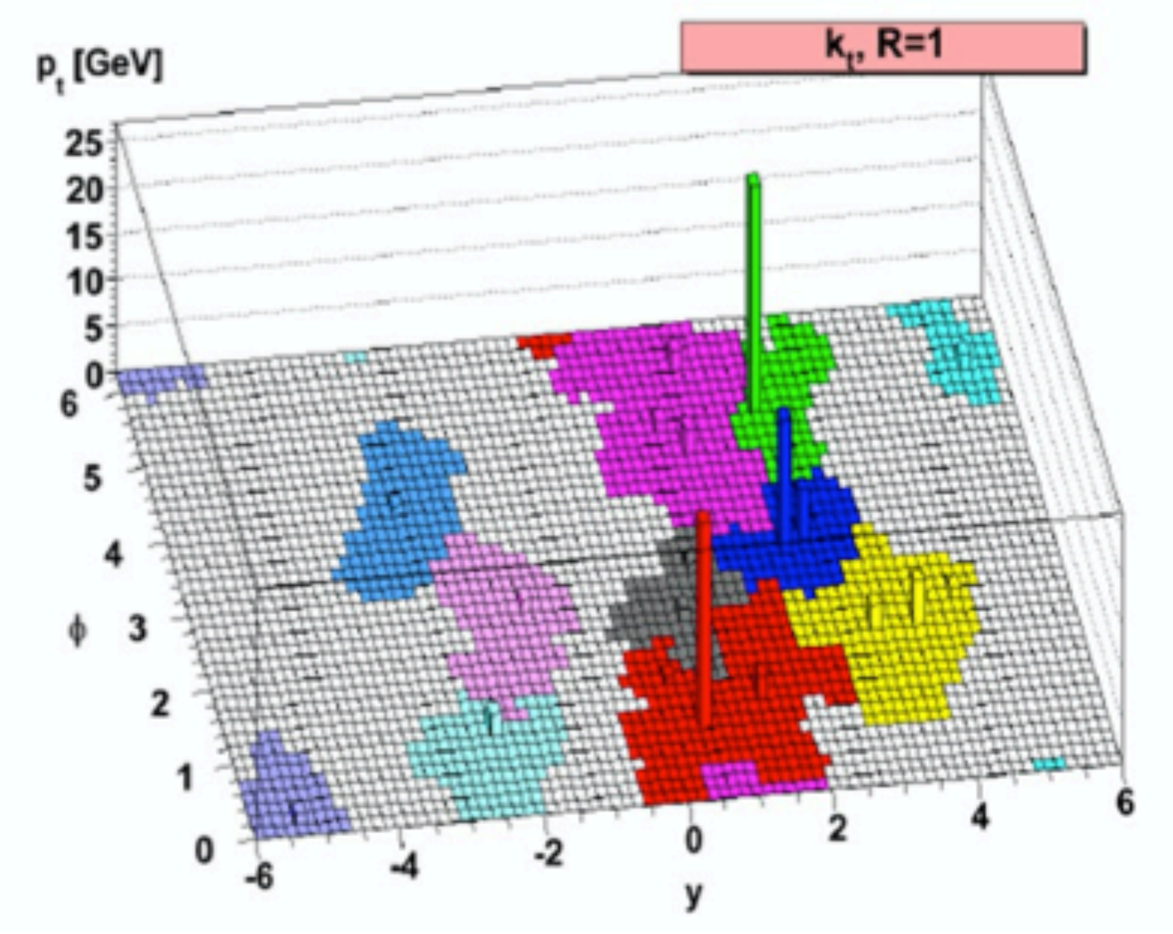
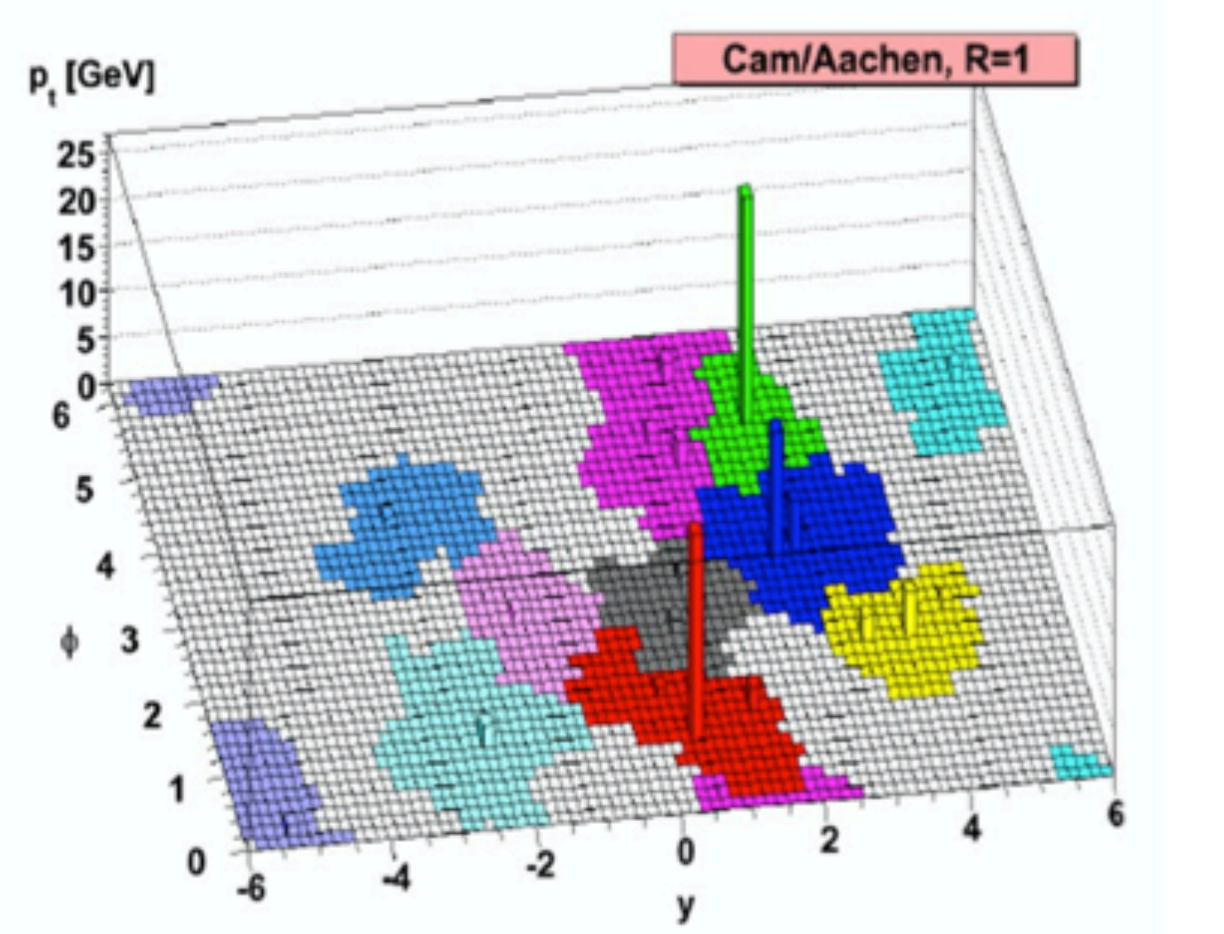
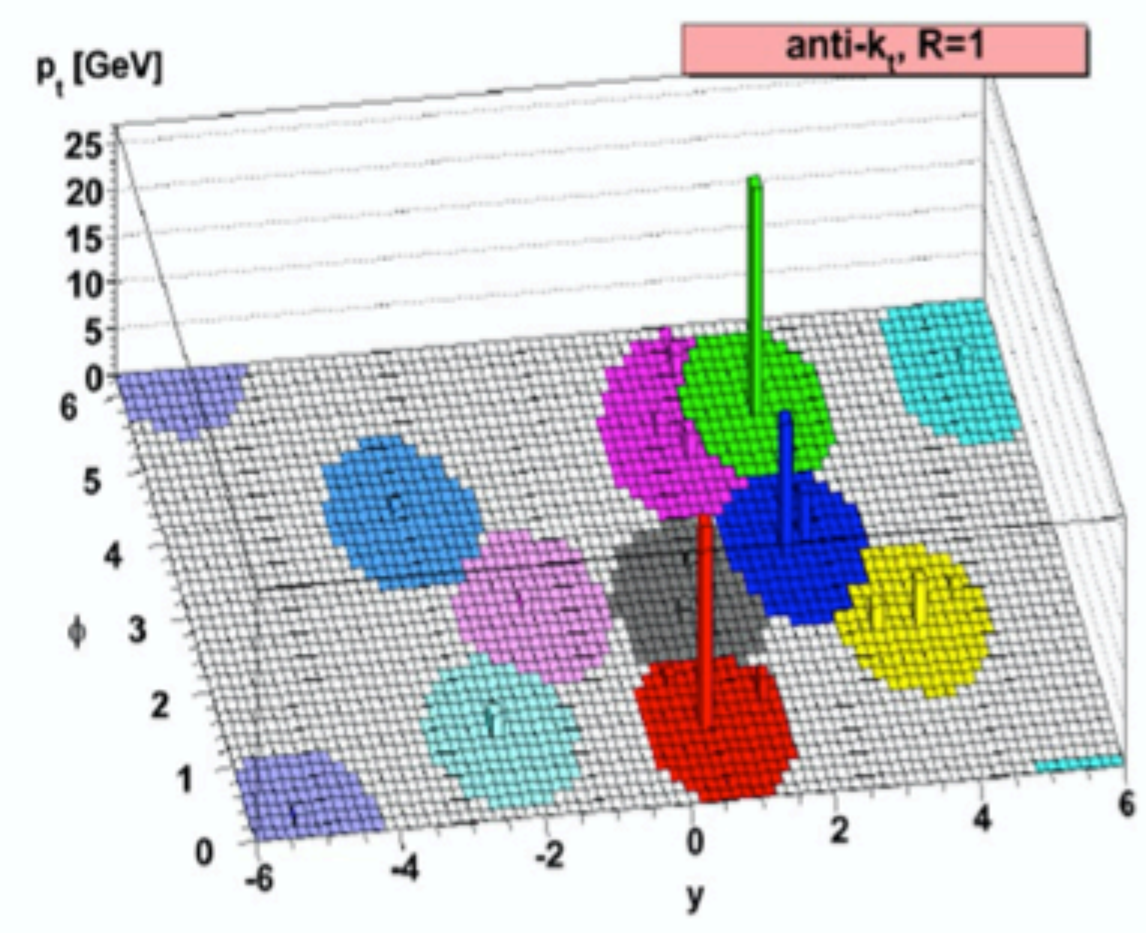


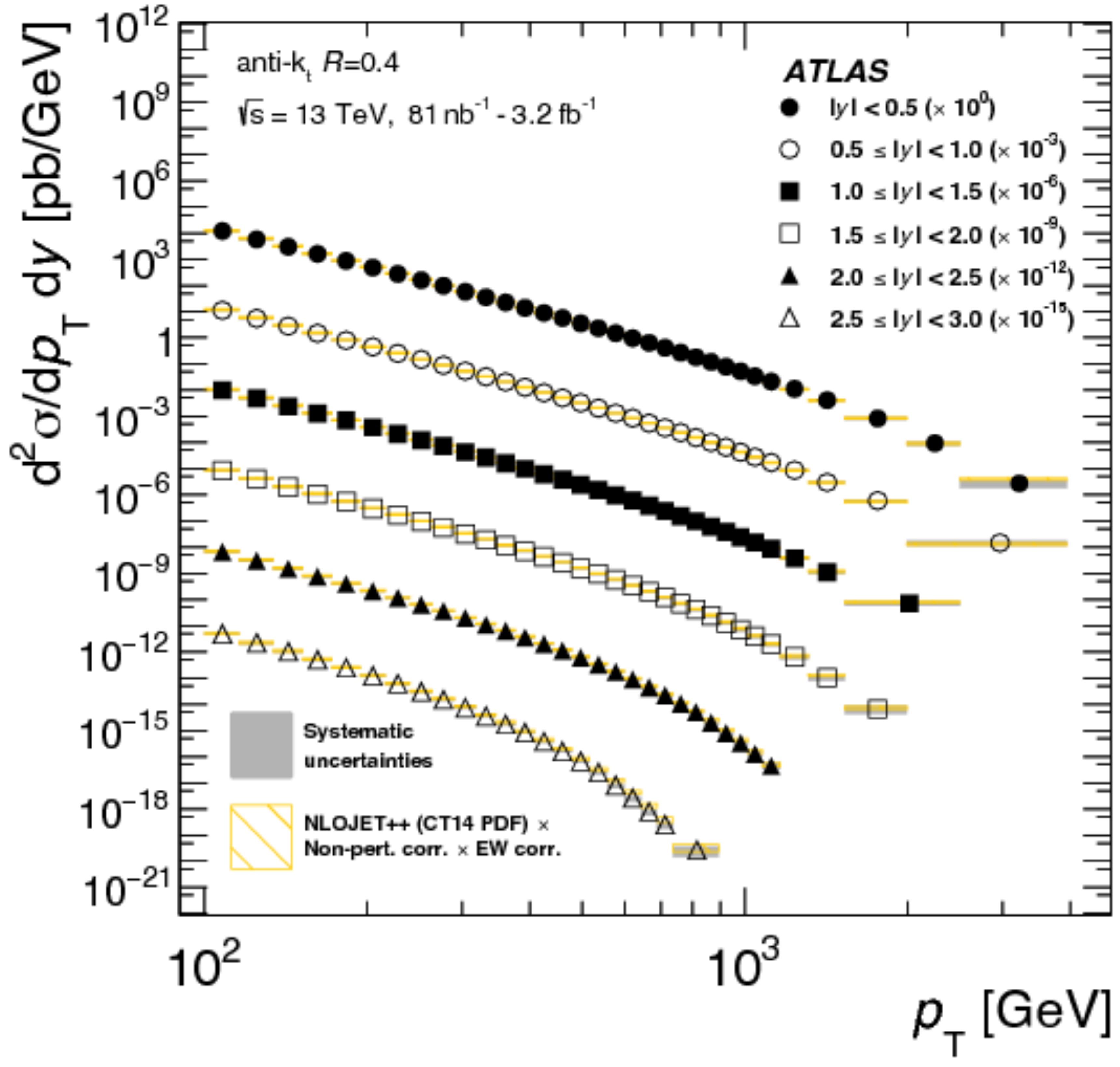




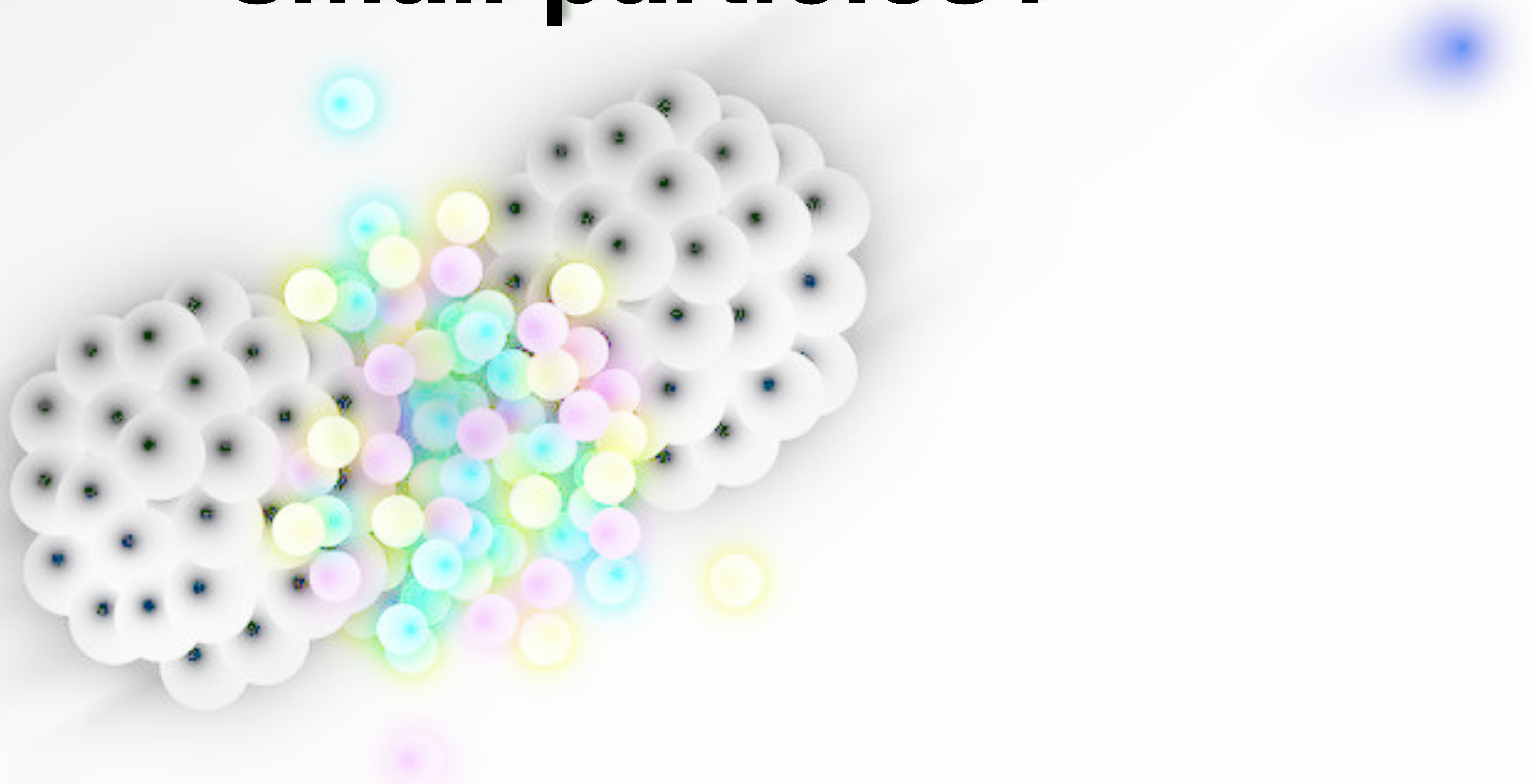
  - Jet size (radius): maximum "distance" that two particles can be to be considered as part of the same jet $R_{ij}^2 = (y_i\ y_j)^2 + (\phi_i - \phi_j)^2$

An example of QCD success

- Jets in pp collisions: excellent phenomenological tool!
    - Theoretical understanding from first principles
        - Accurate theoretical description of jet production in 10 orders of magnitude in cross-section!
    - Well controlled experimentally
        - Used in a multitude of phenomenological studies (top quark physics, Higgs, Electroweak, BSM searches, …)

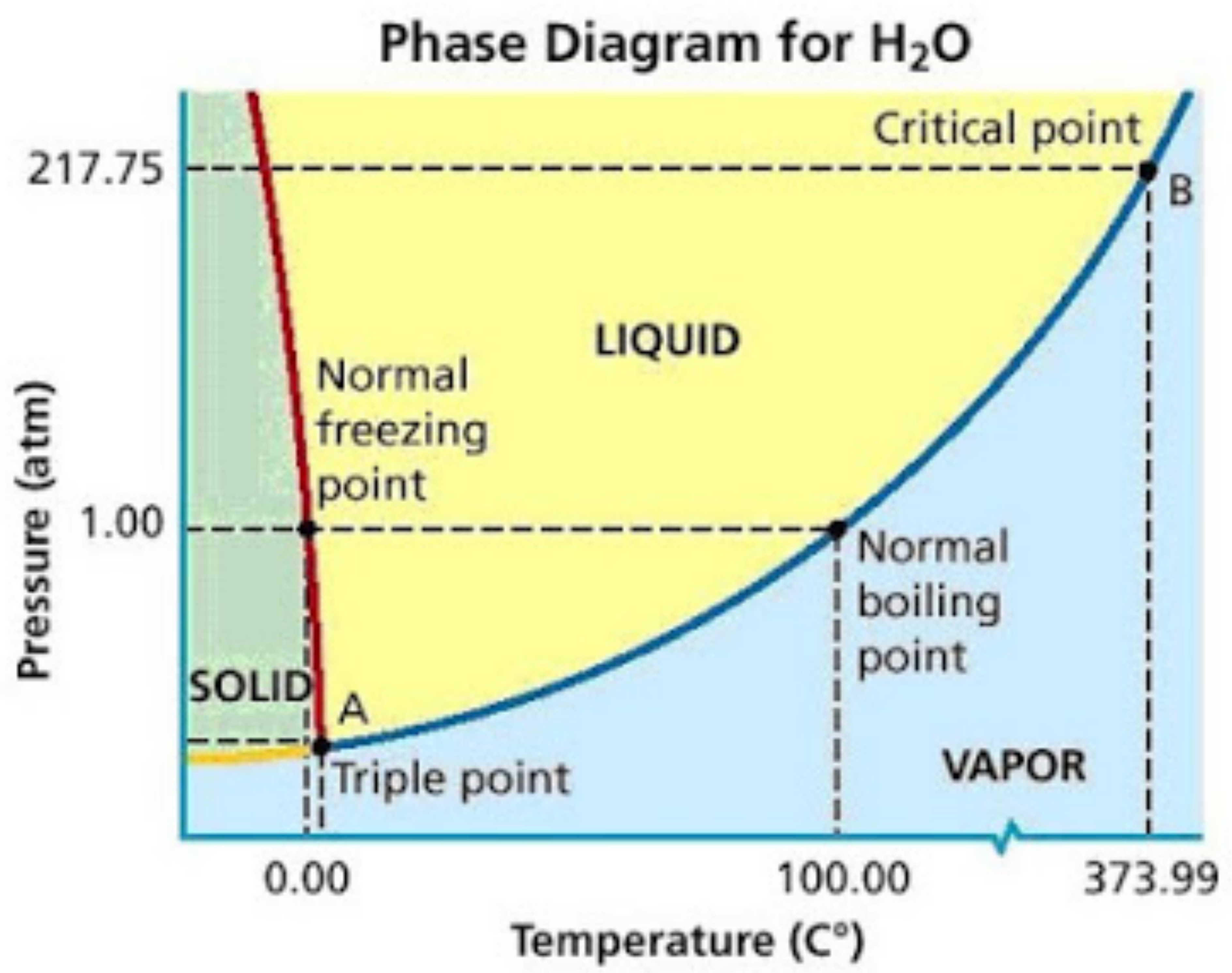


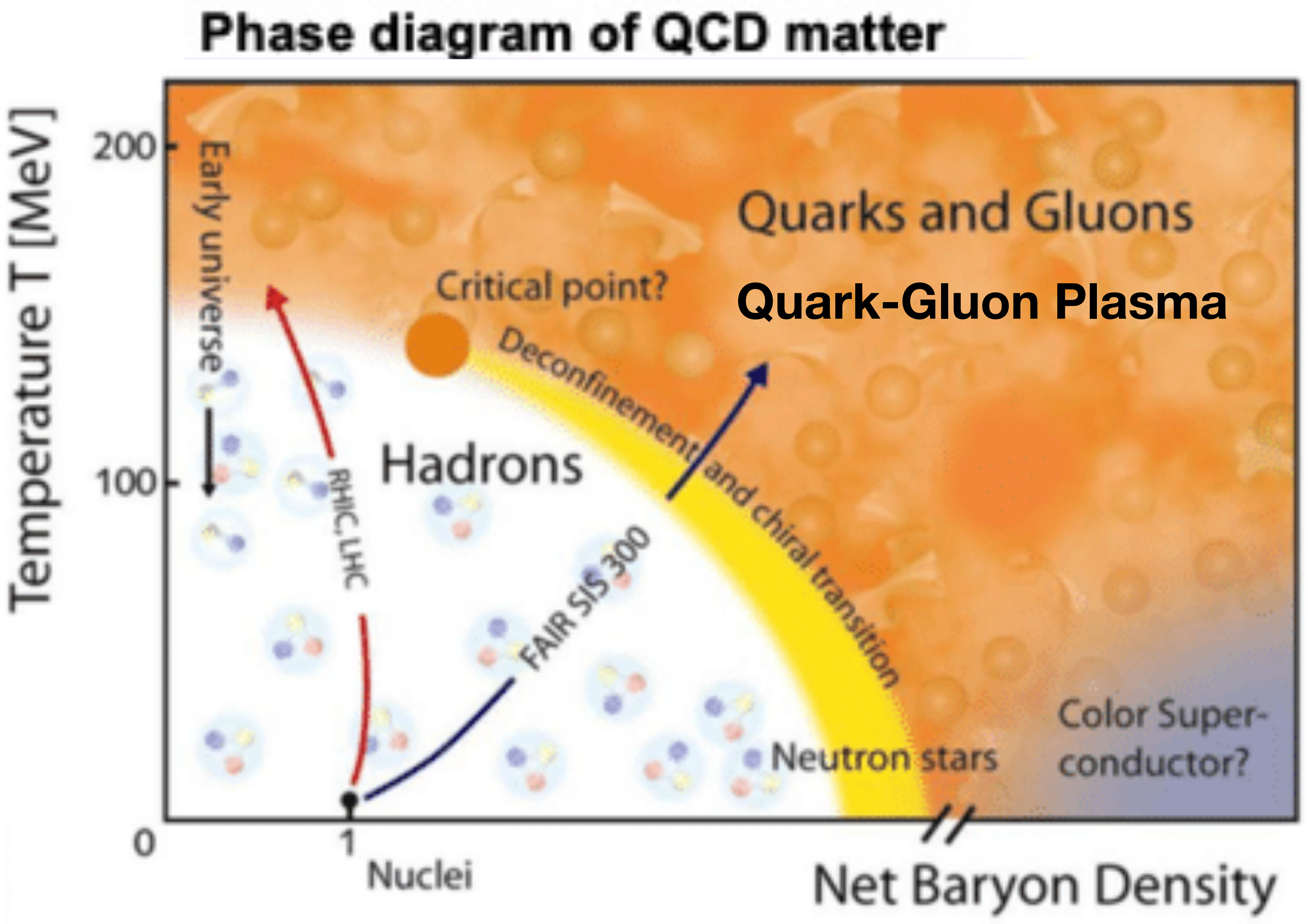
Is QCD limited to a collection of small particles?



From dilute QCD to dense QCD

- QCD matter has a rich and vast phase diagram:





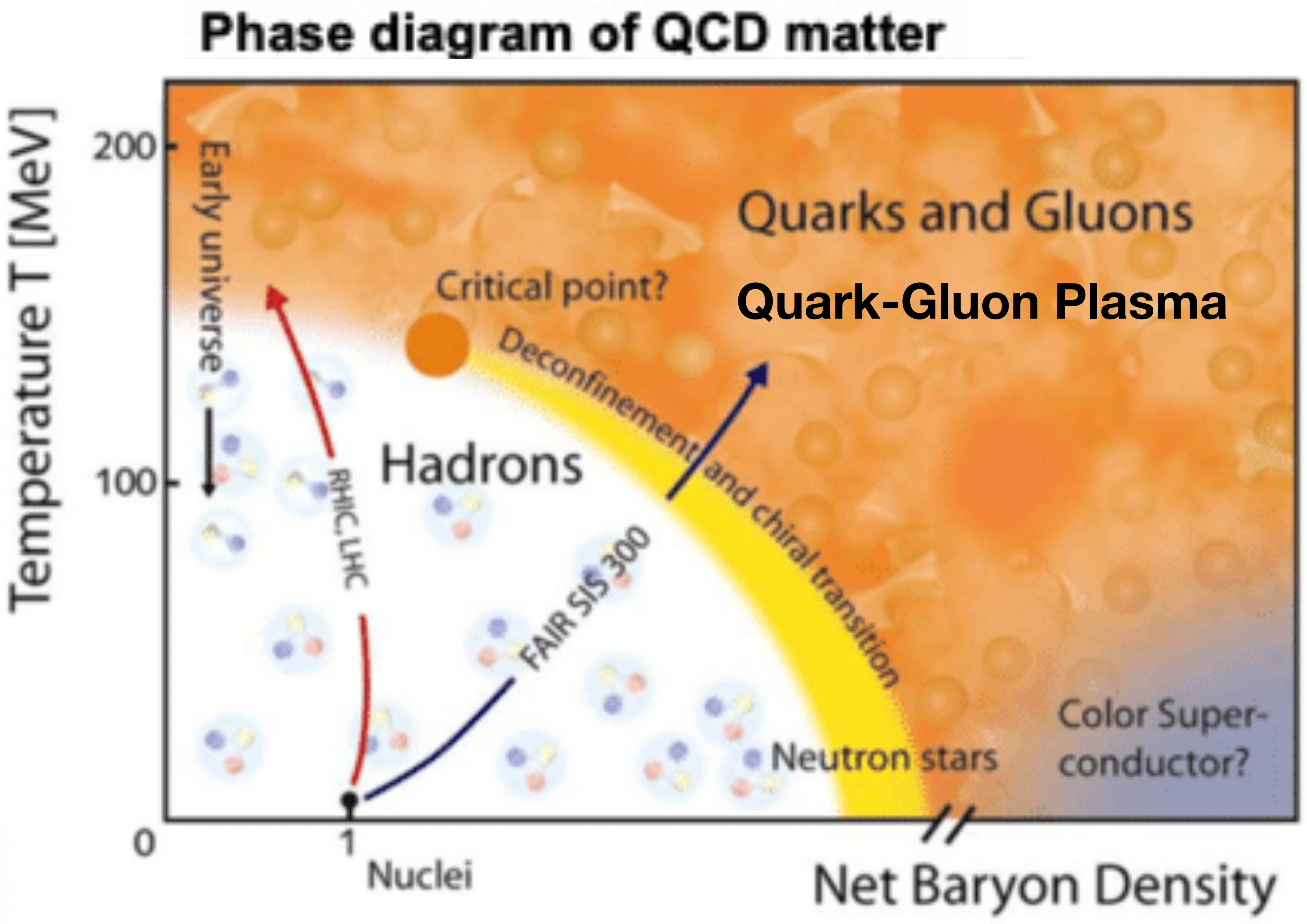
From dilute QCD to dense QCD

- QCD matter has a rich and vast phase diagram:

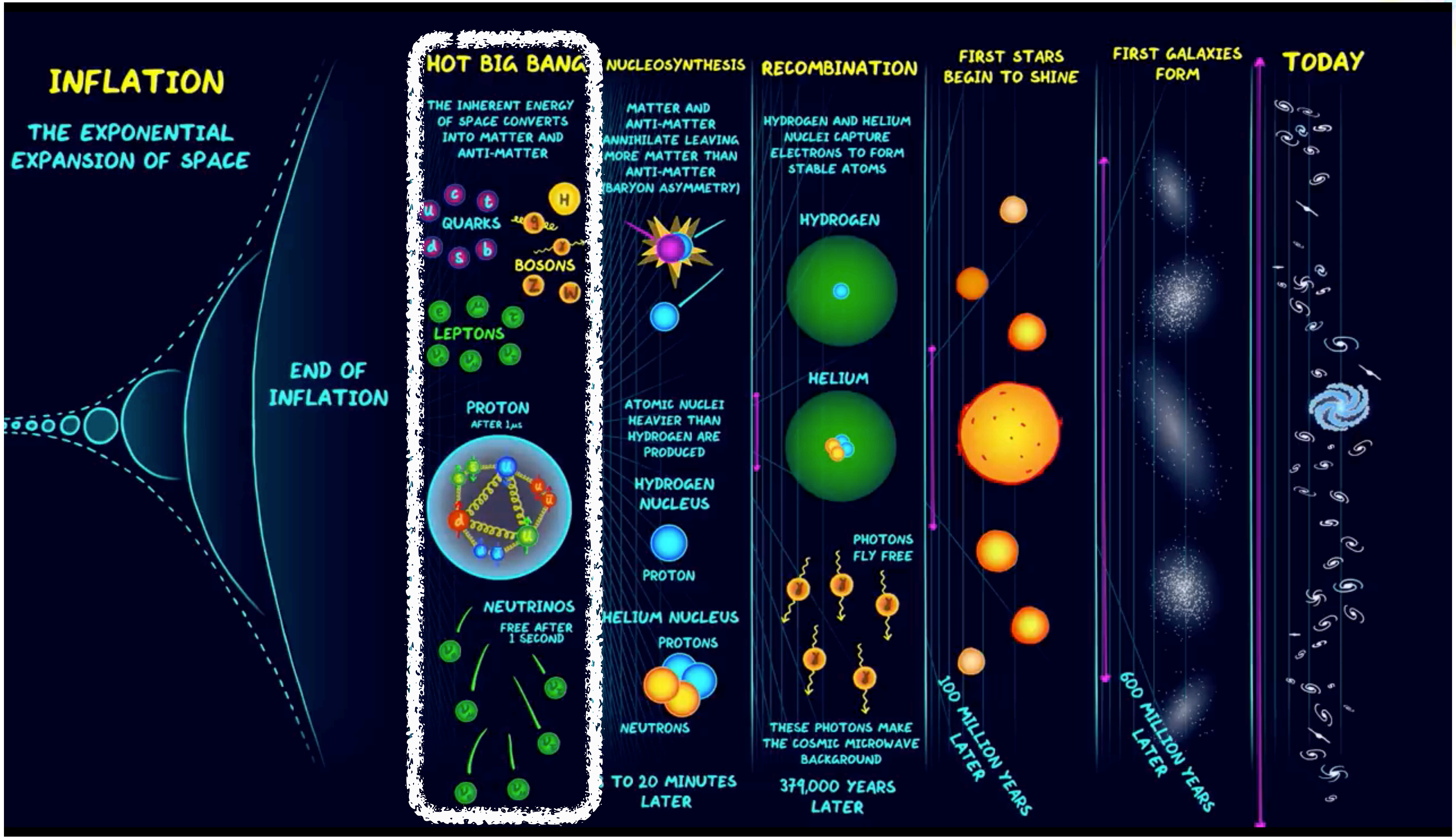
QCD theory (*1973*)
SU(3) Color symmetry; confinement; asymptotic freedom, …

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

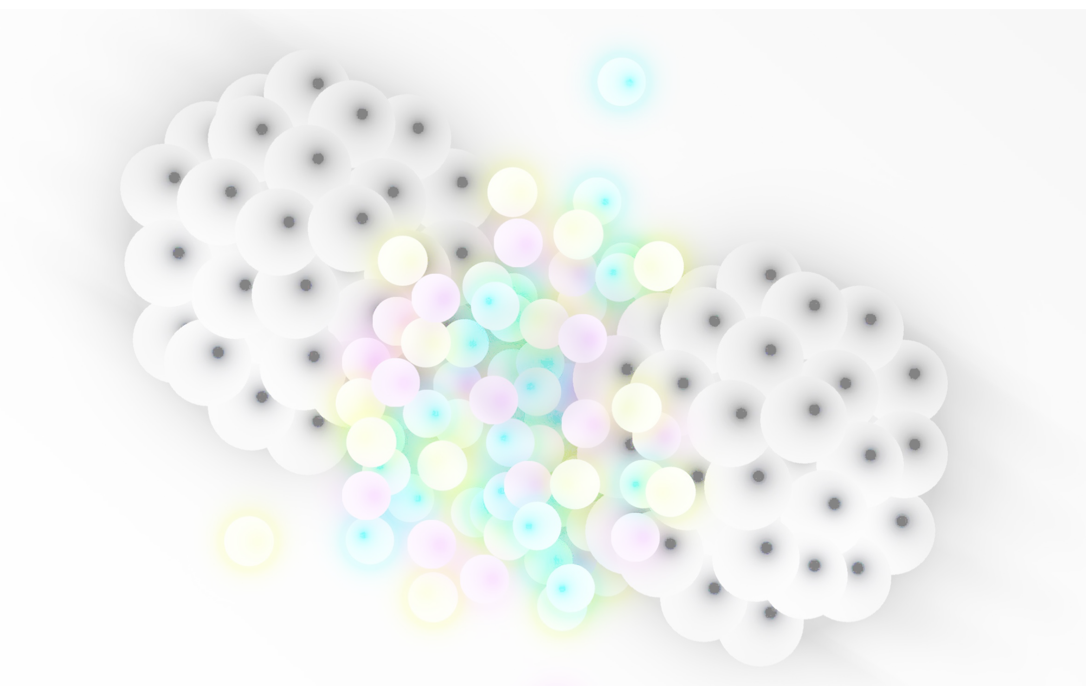
State of matter where quarks and gluons are asymptotically free



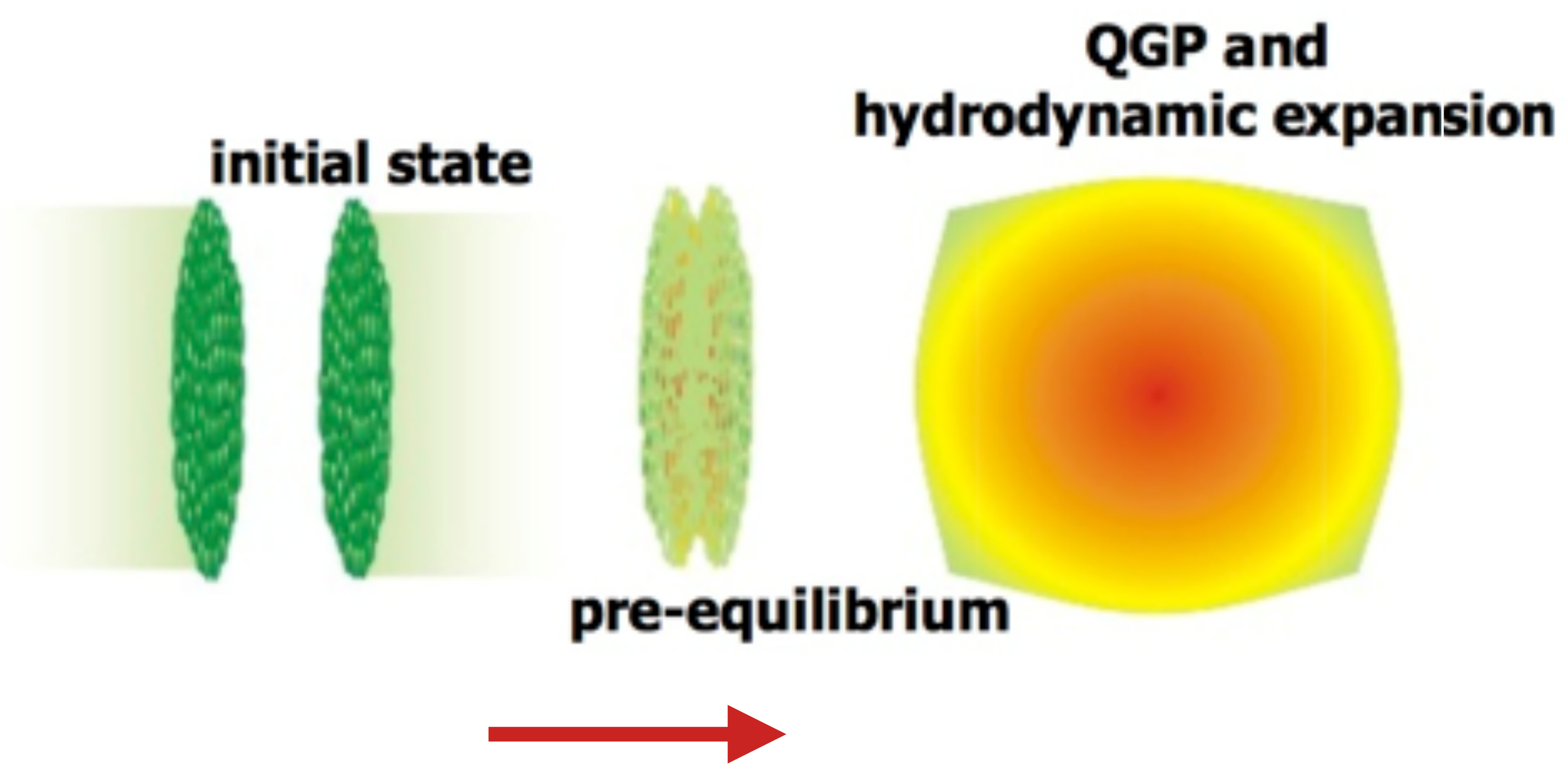
QGP @ Early Universe



QGP @ Heavy-Ion Collisions



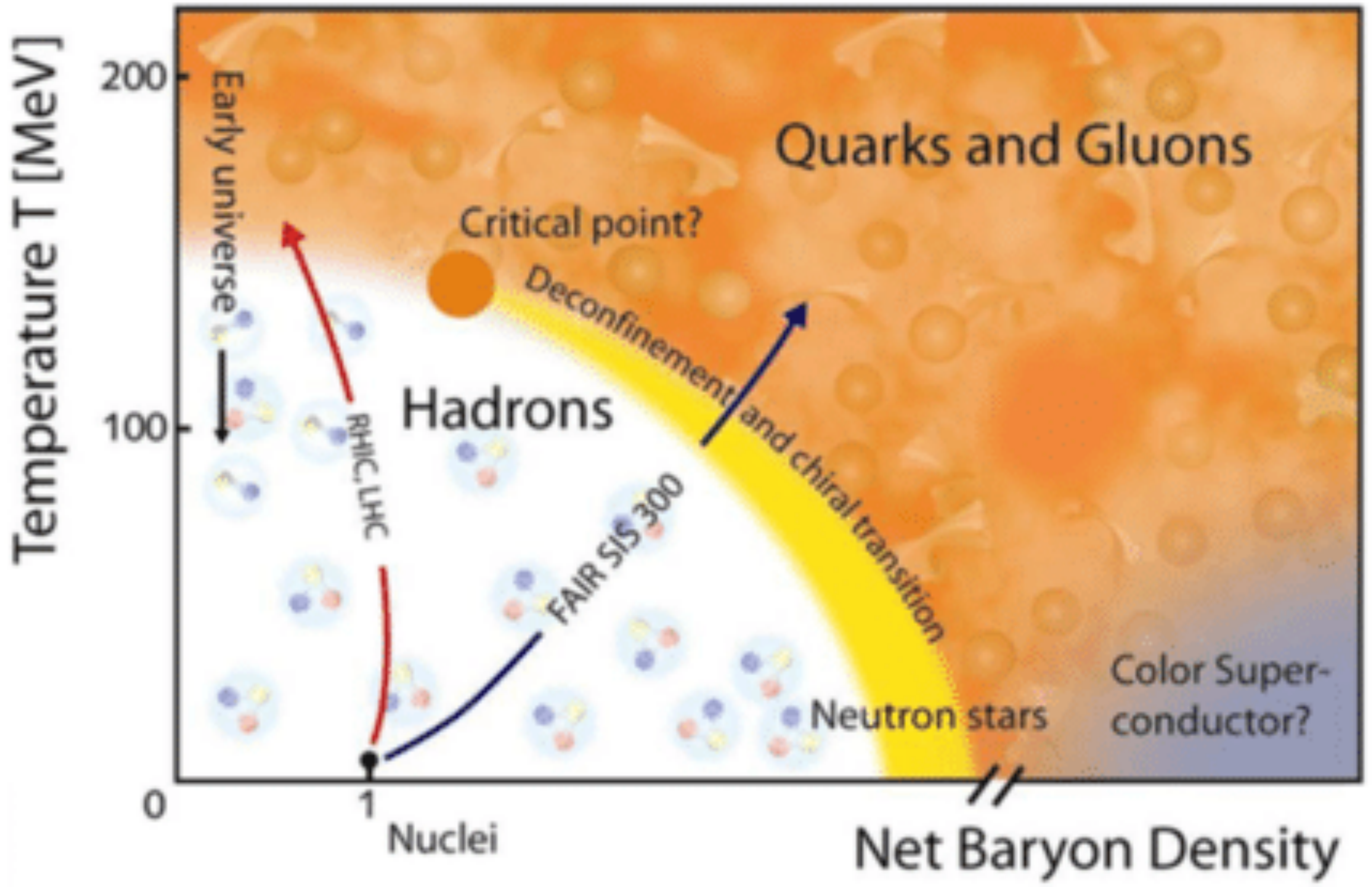
- Heavy-Ion Collisions:



RHIC (~2000):
AuAu @ 200 GeV

LHC (~2010):
PbPb @ 2.75/5.5 TeV

FCC?:
PbPb @ 39 TeV



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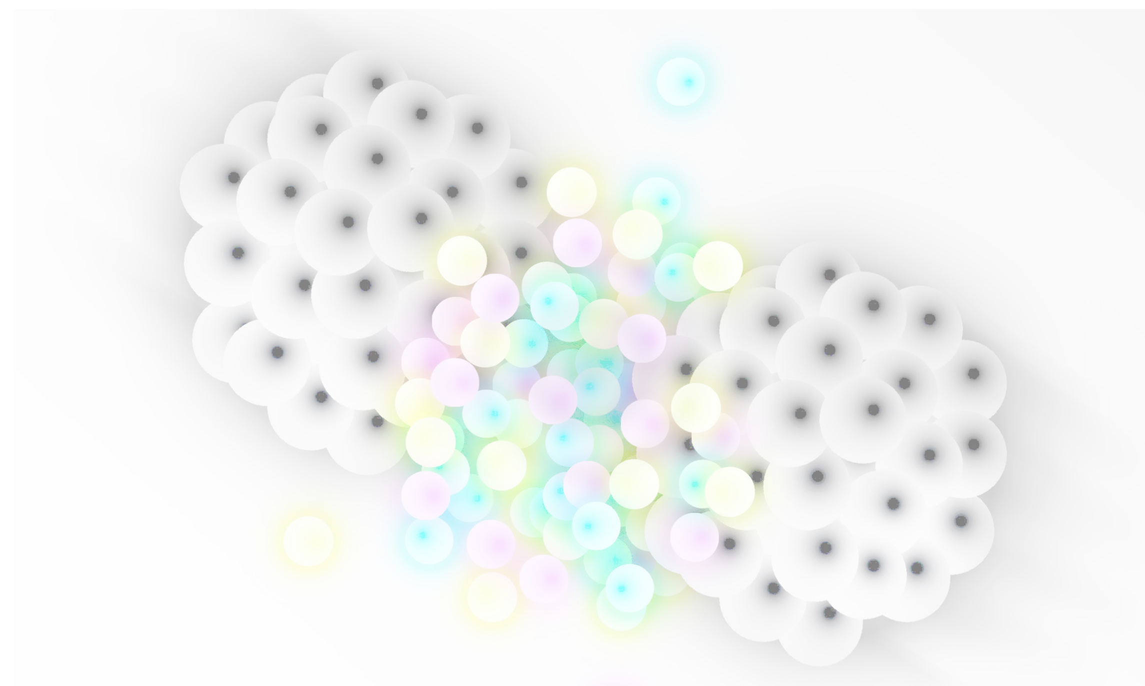
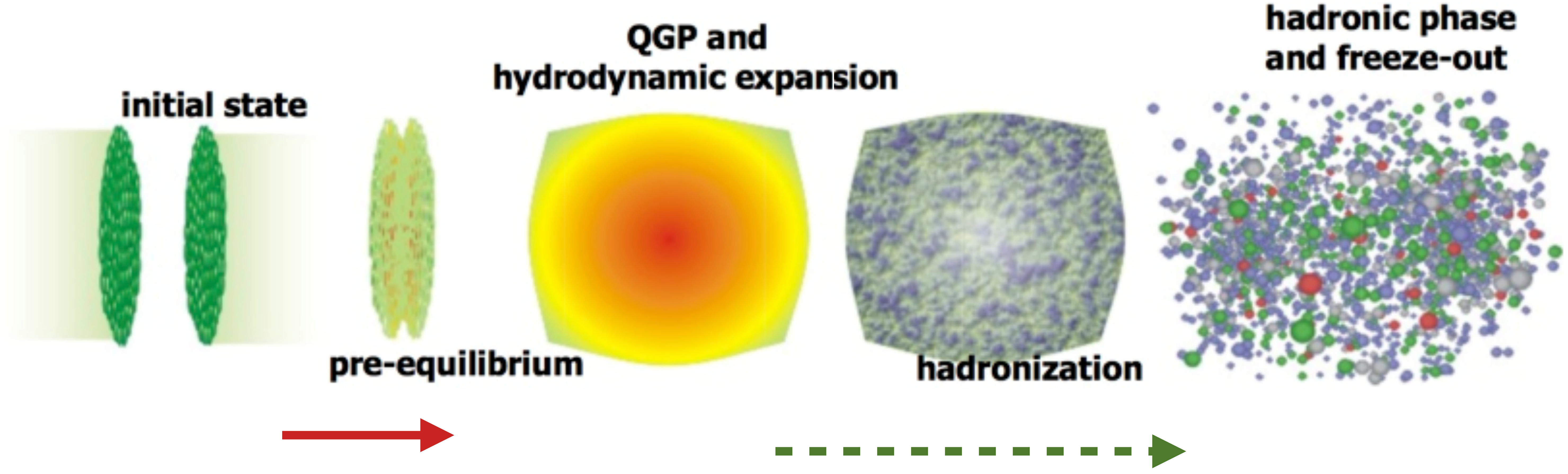


- Heavy-Ion Collisions:



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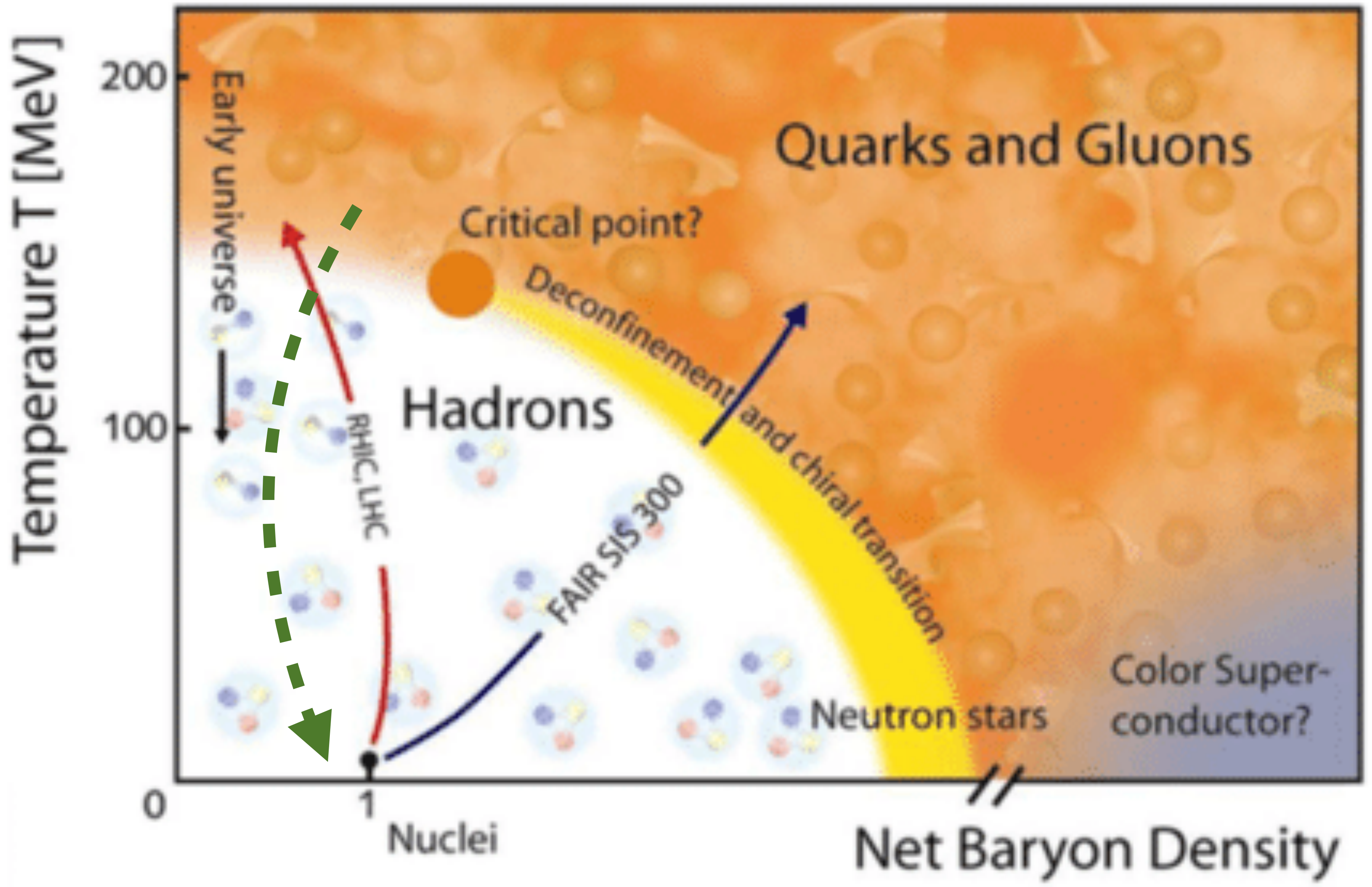
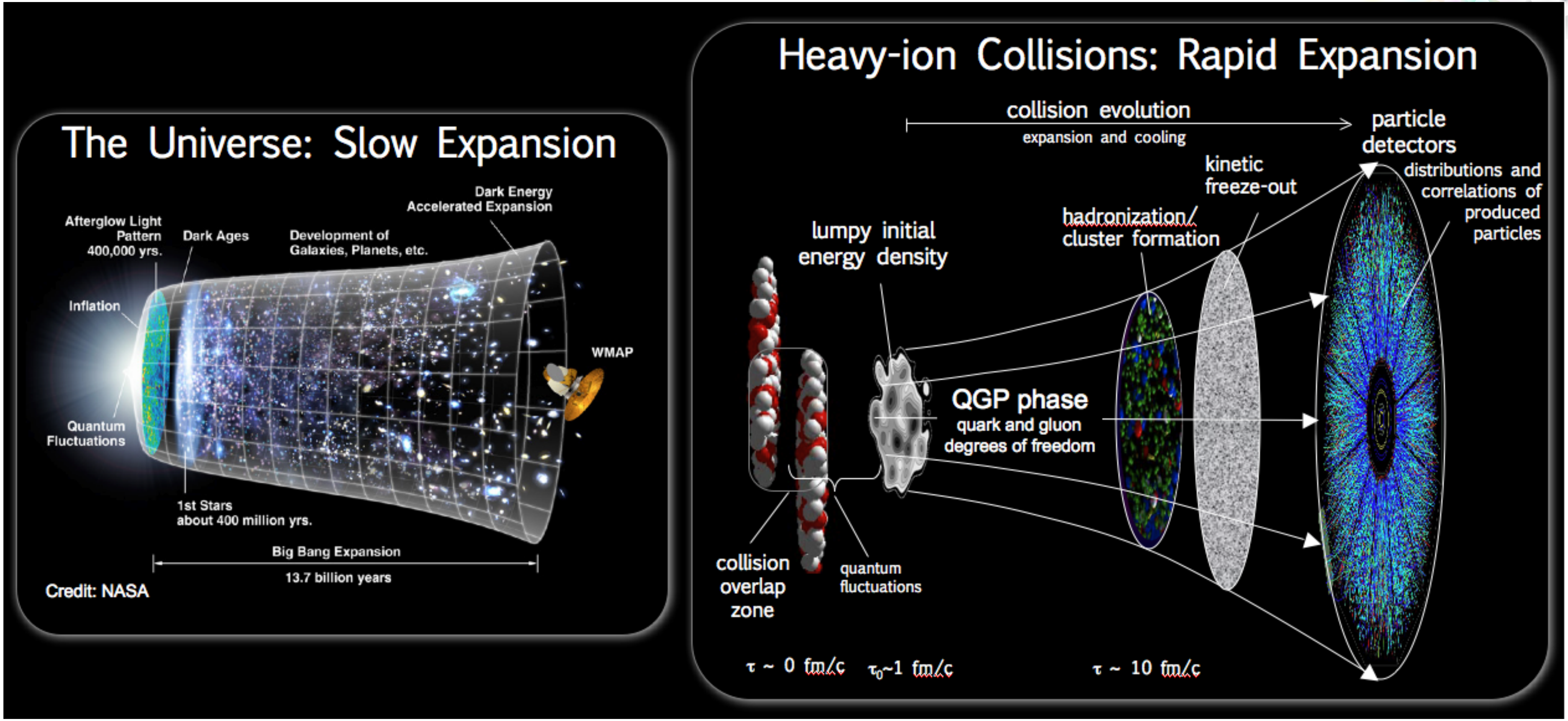


“Big-Bang” vs “Mini-Bang”



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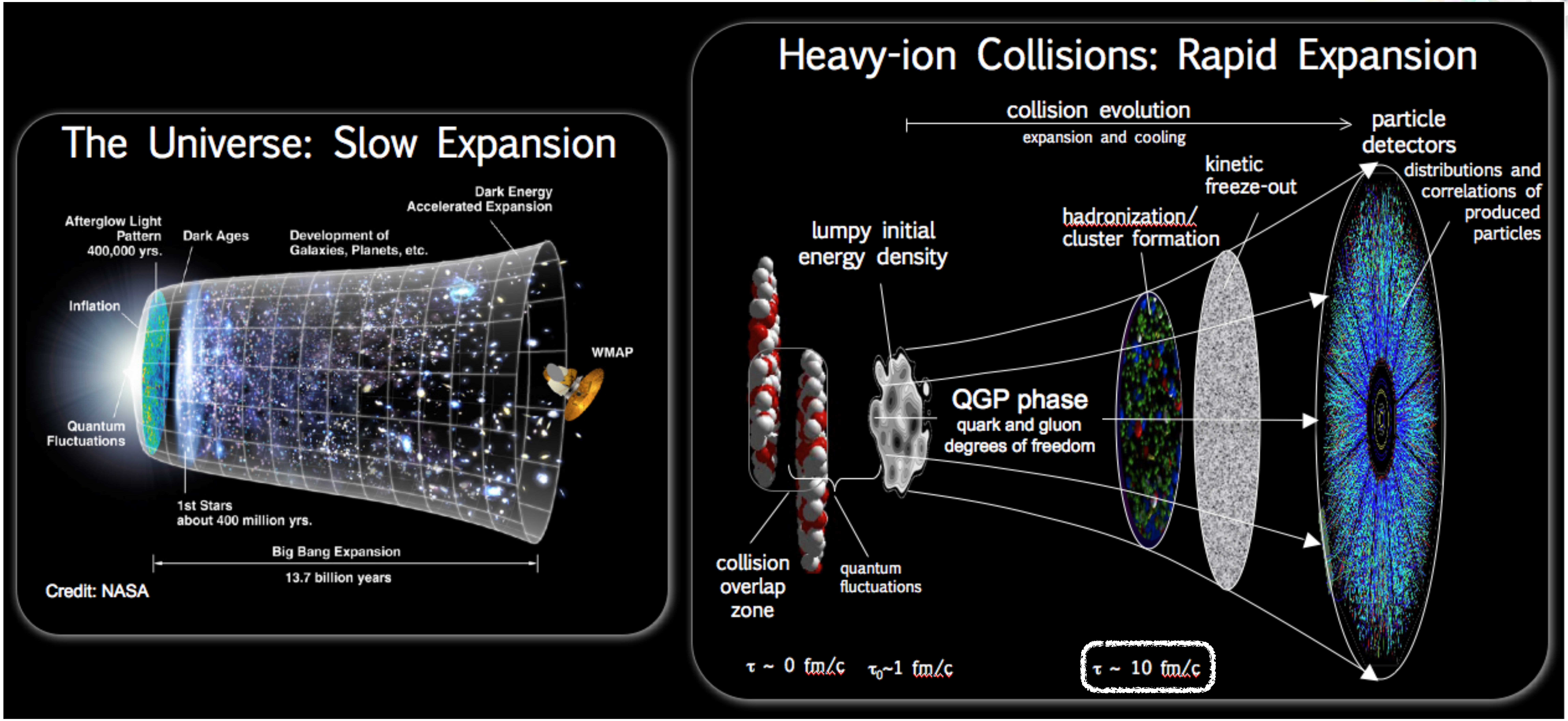
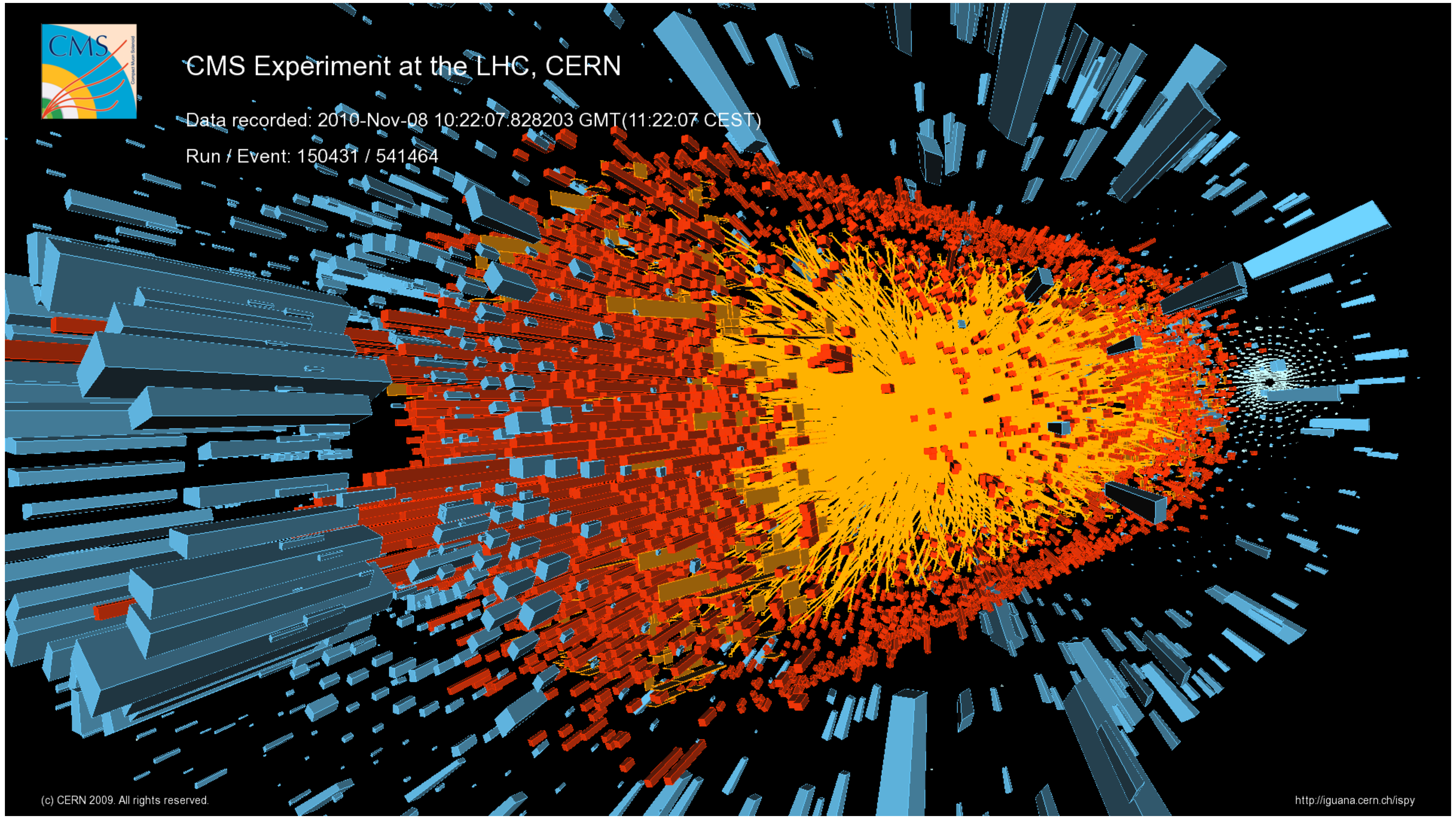


??? (fm/c = 10^{-24} s)

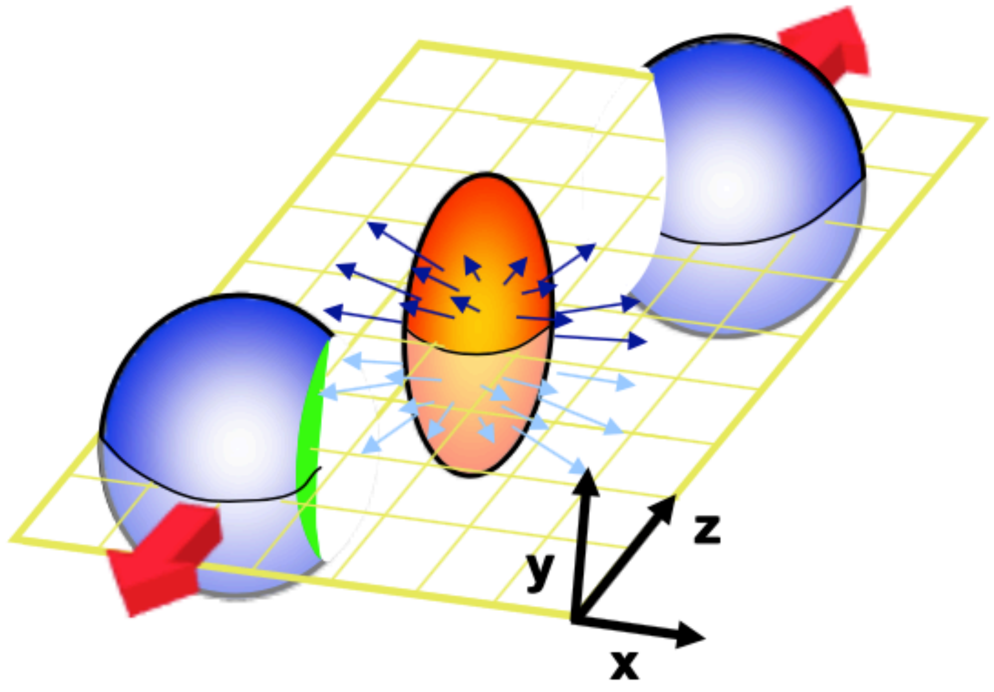
How to probe the QGP @ lab?

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

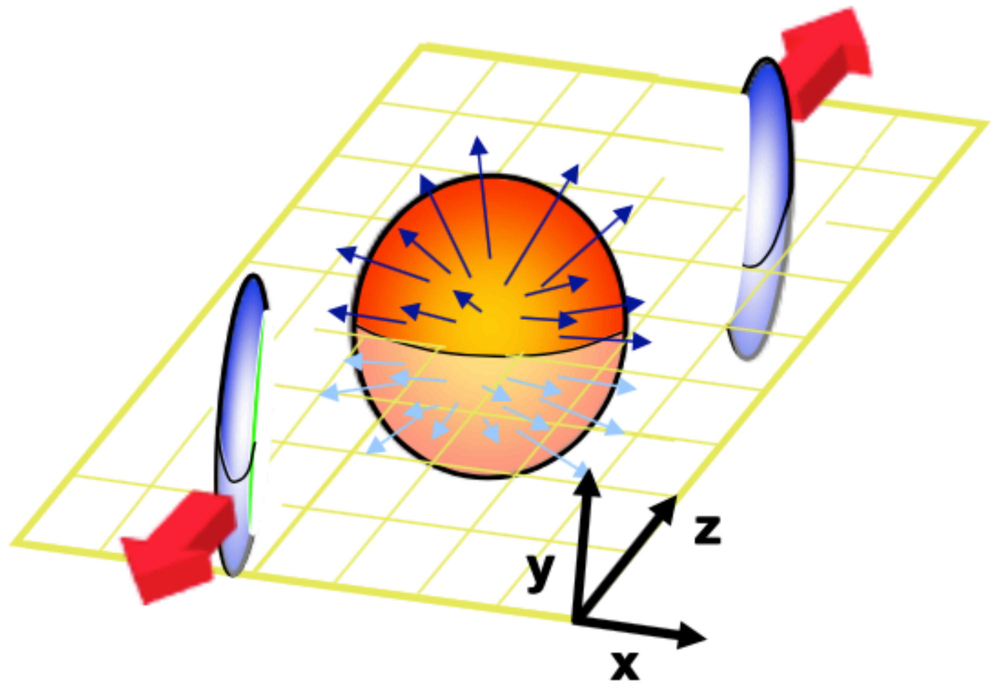


Try different centrality collisions

Peripheral Collision

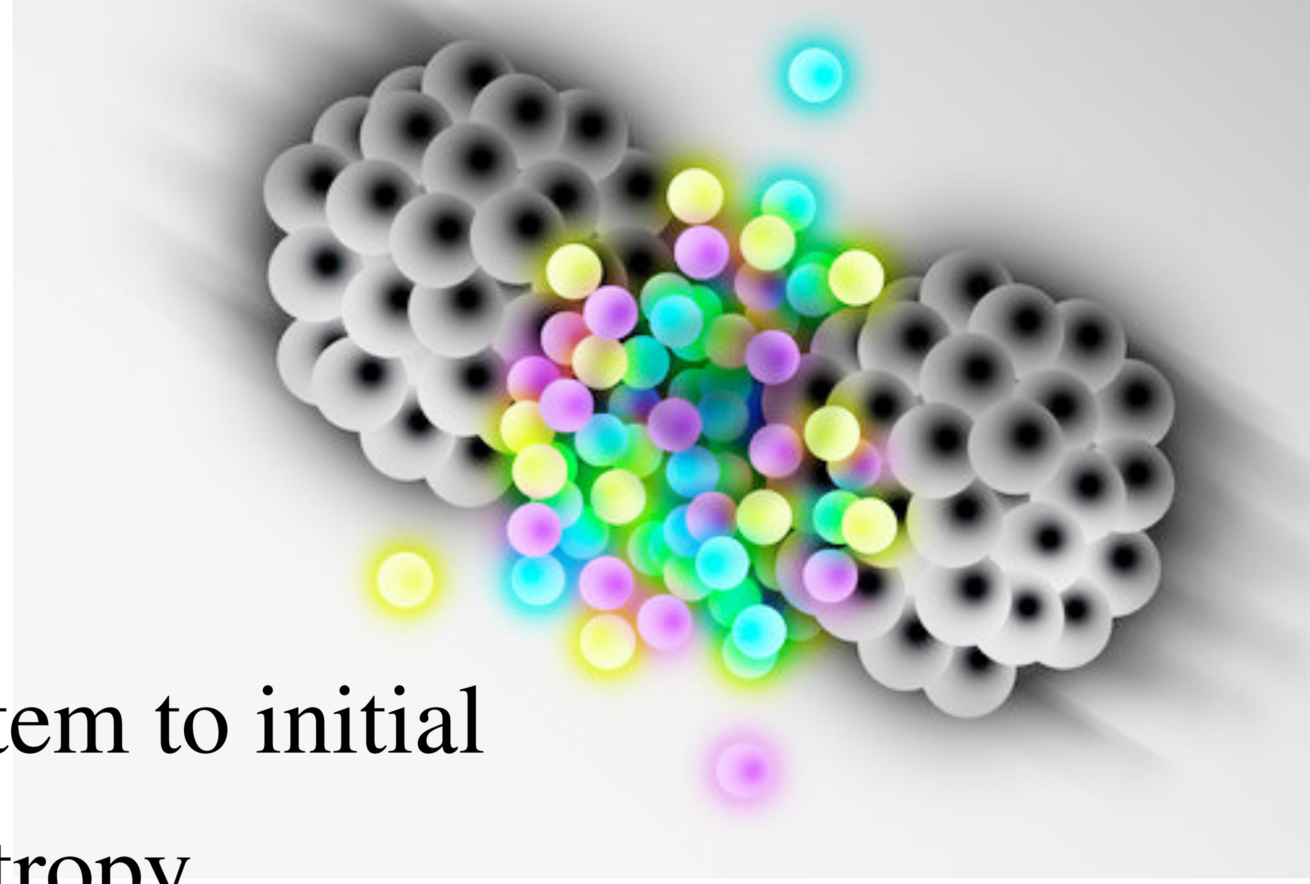


(near) Central Collision



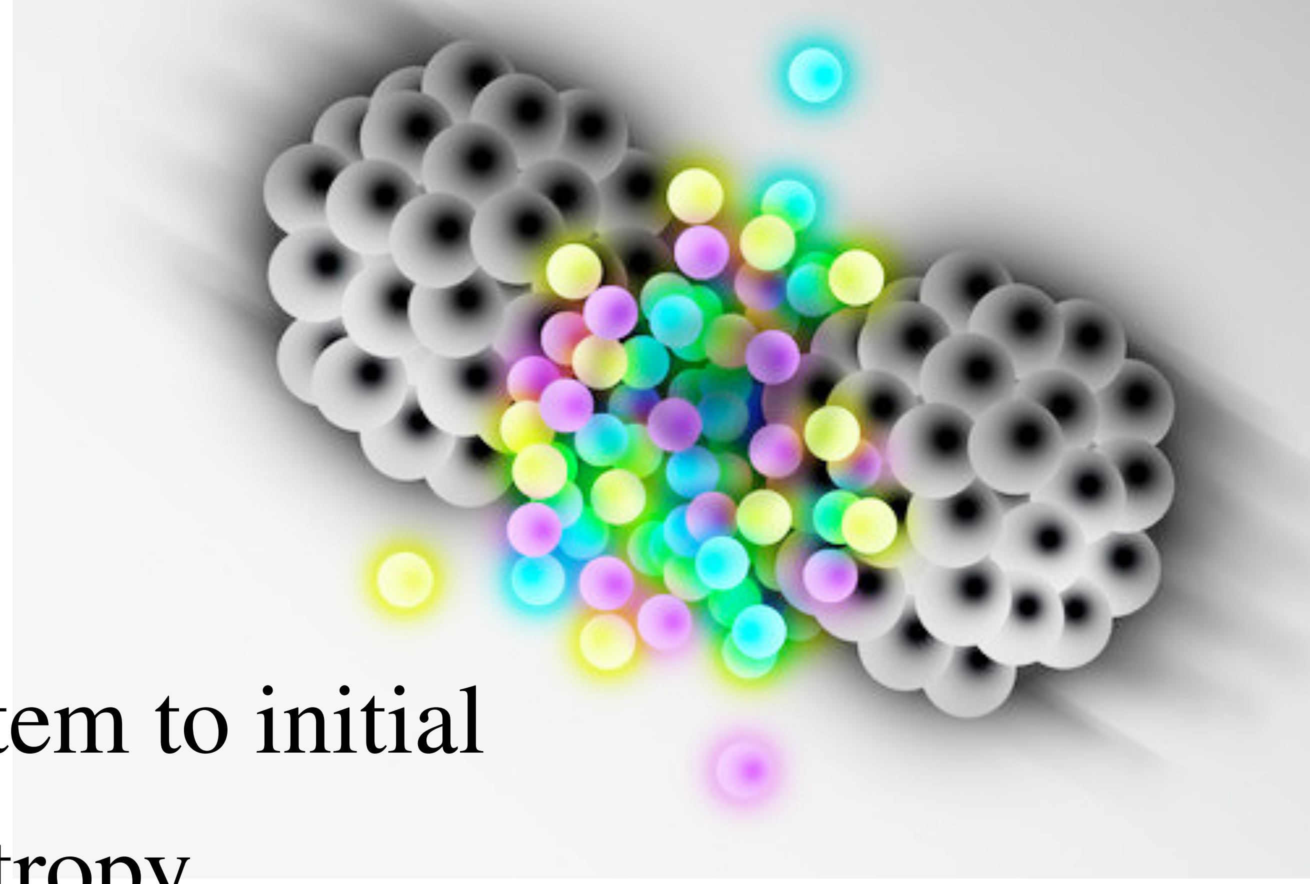
Soft probes

- Sensitive to macroscopic properties of the QGP:
  - Local or large scale collective behaviour?



Response of the system to initial spatial anisotropy

Soft probes



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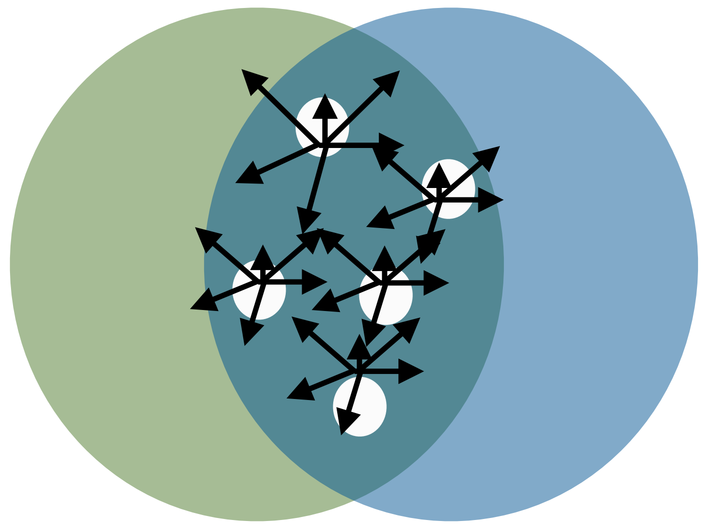
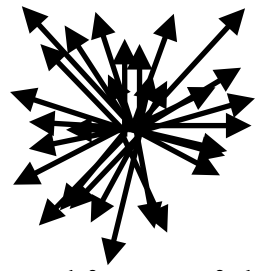
Response of the system to initial spatial anisotropy

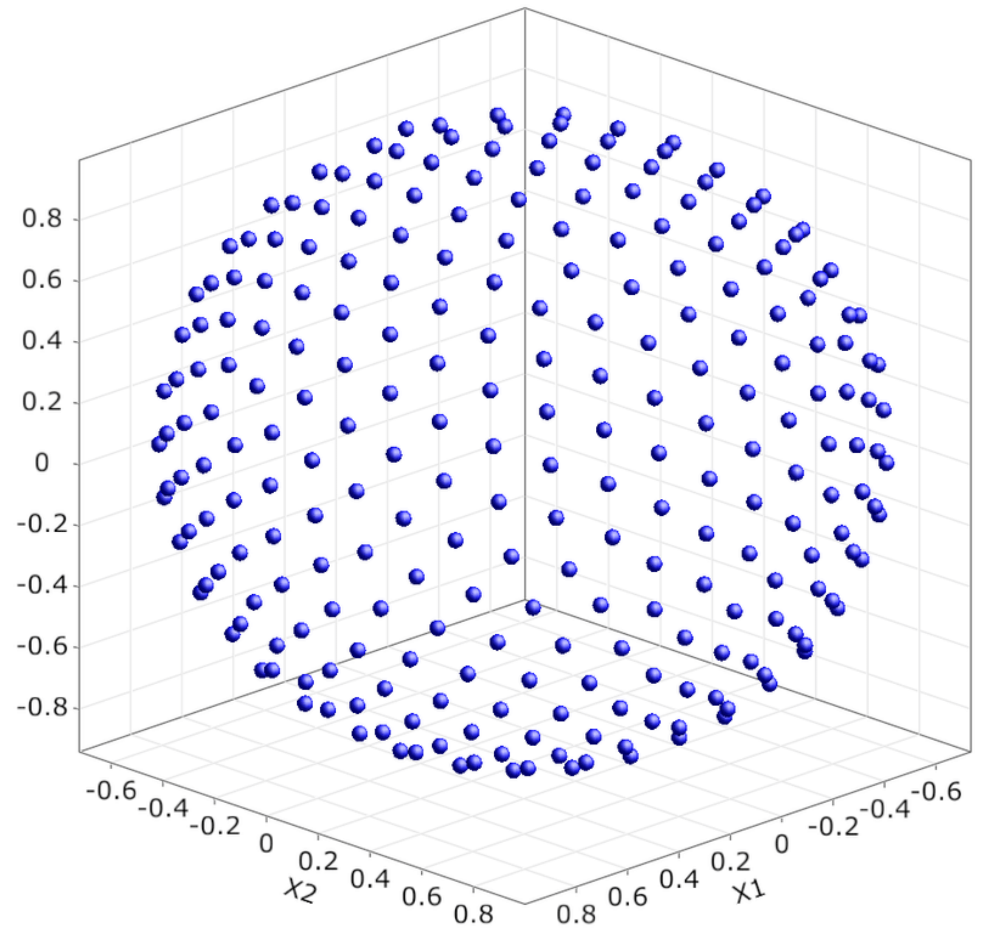
Superposition of multiple pp collisions



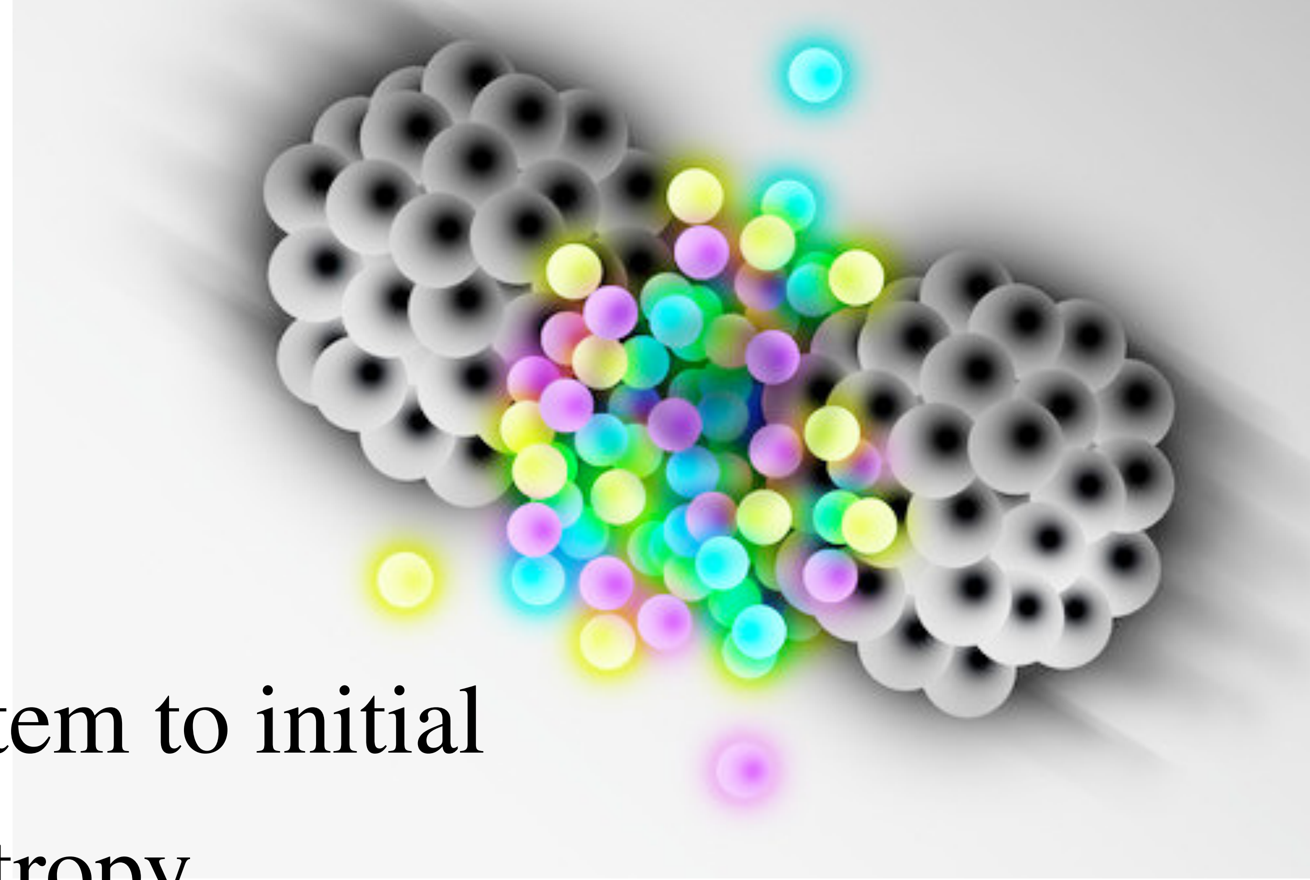
"Gas-like" behaviour?



Uniform distribution of final particles



Soft probes



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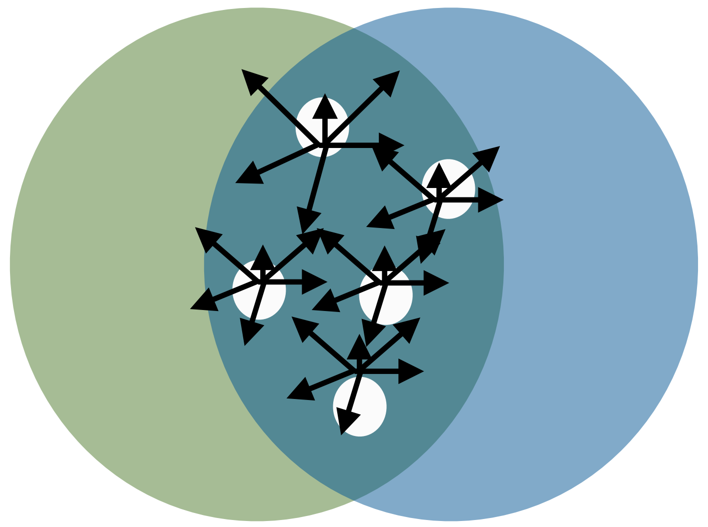

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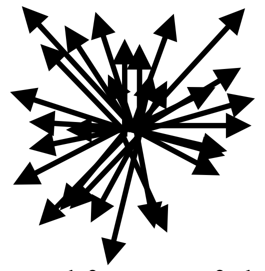

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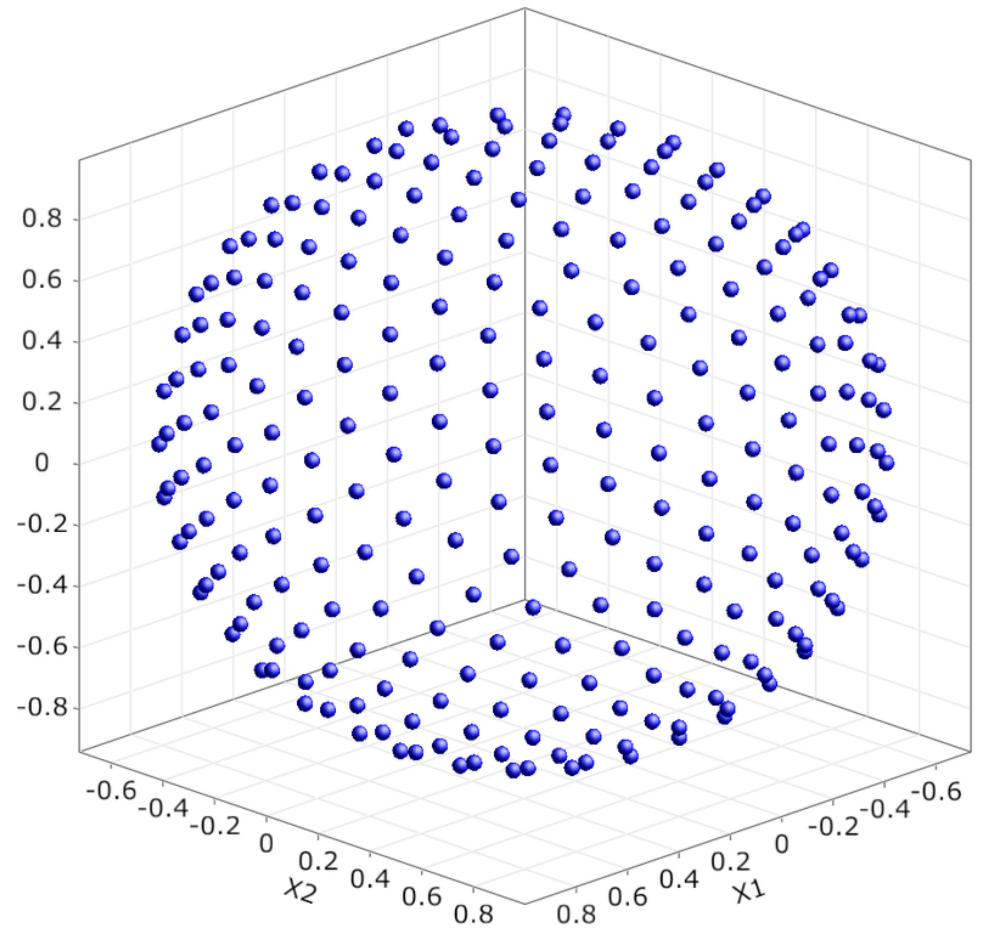
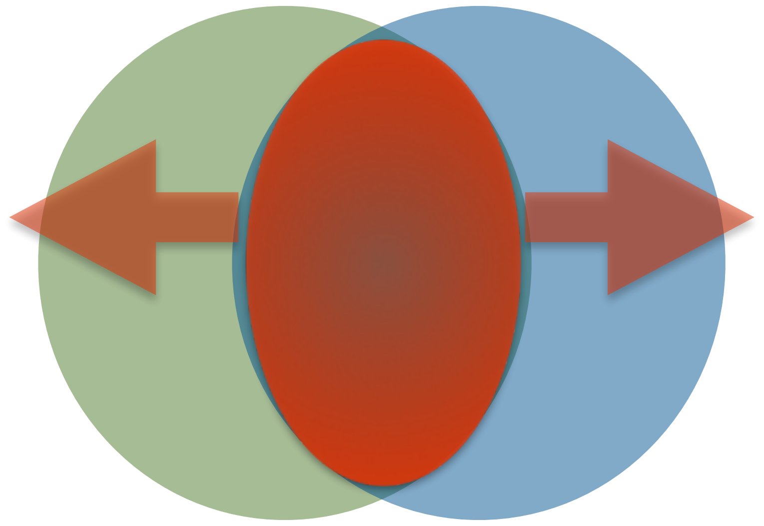
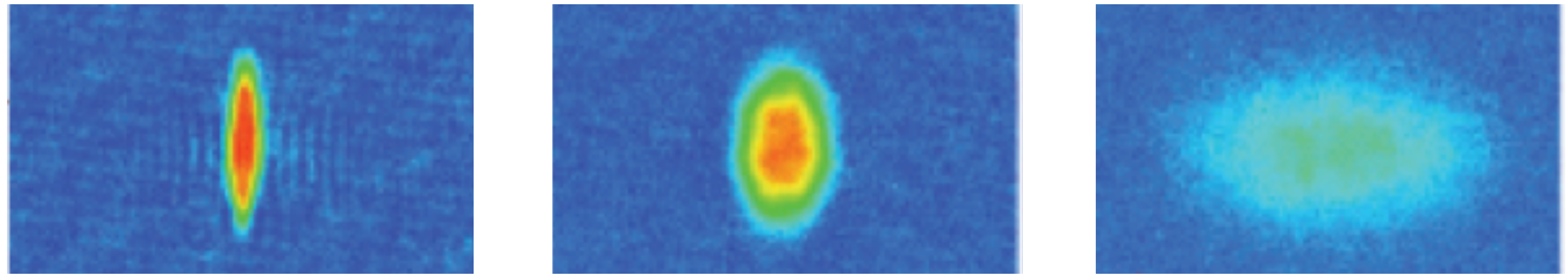


Collective bulk

“Liquid-like” behaviour?



Initial anisotropies also present in the distribution of final particles



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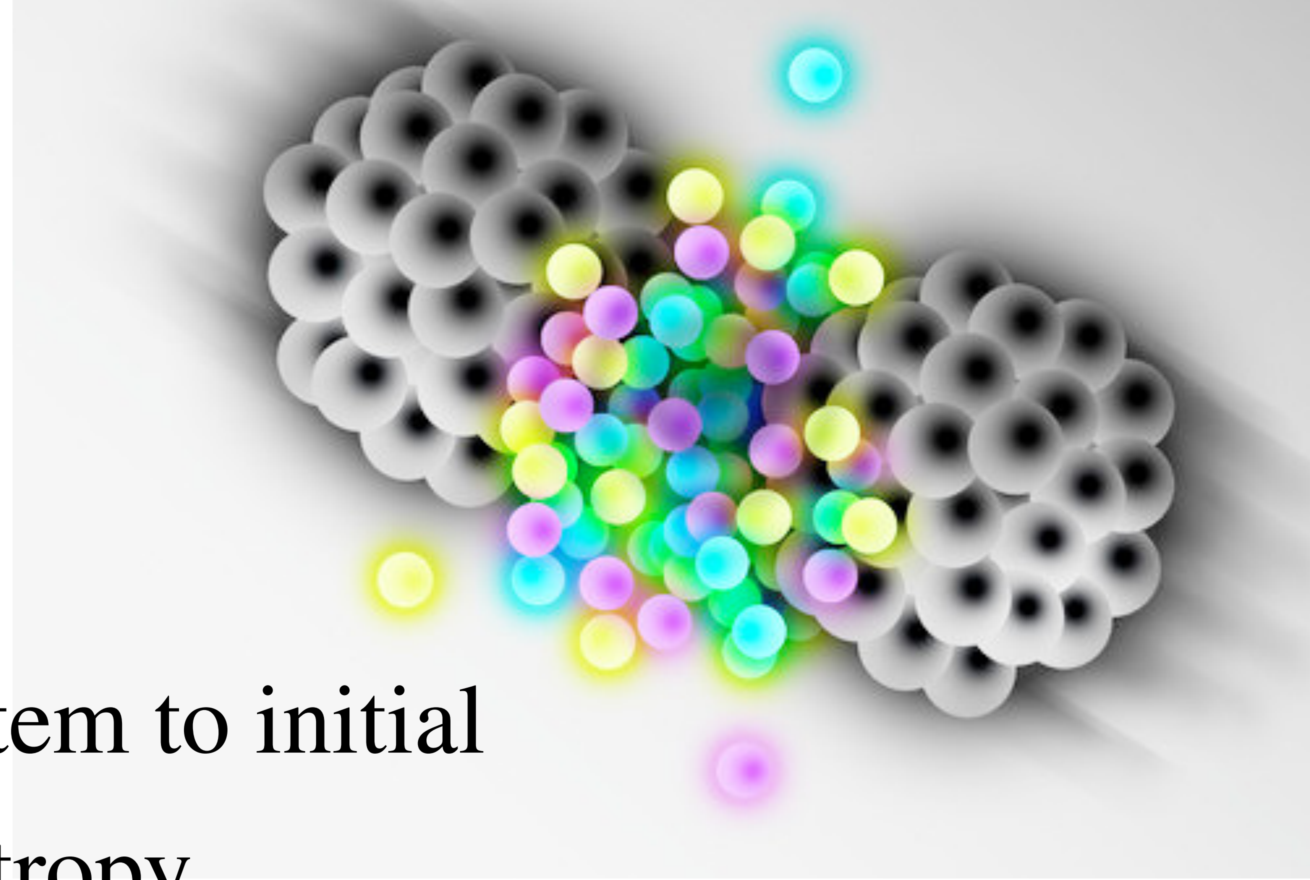

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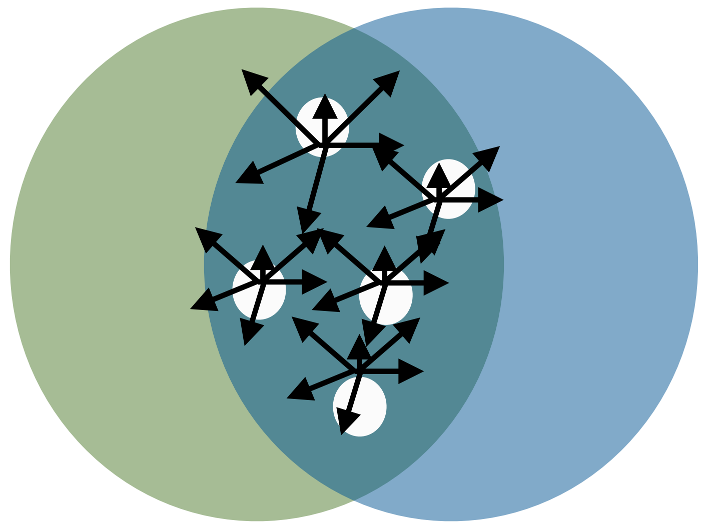
Superposition of multiple pp collisions



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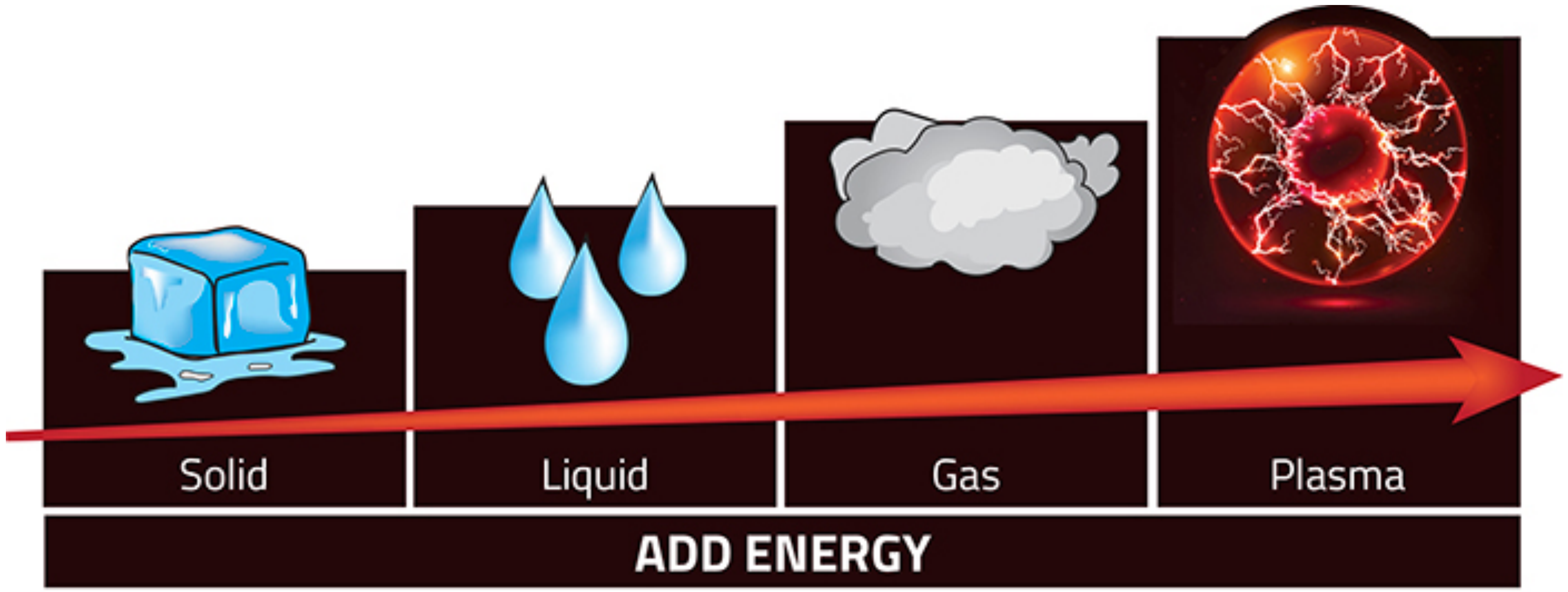
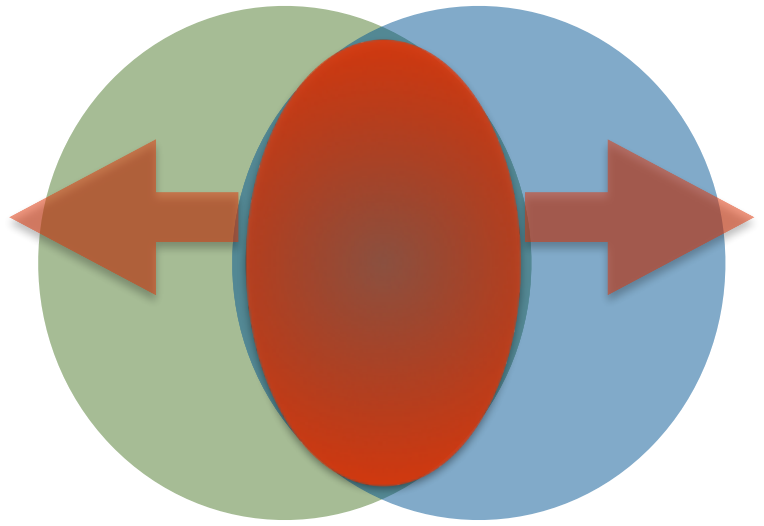


"Liquid-like" behaviour

Collective bulk



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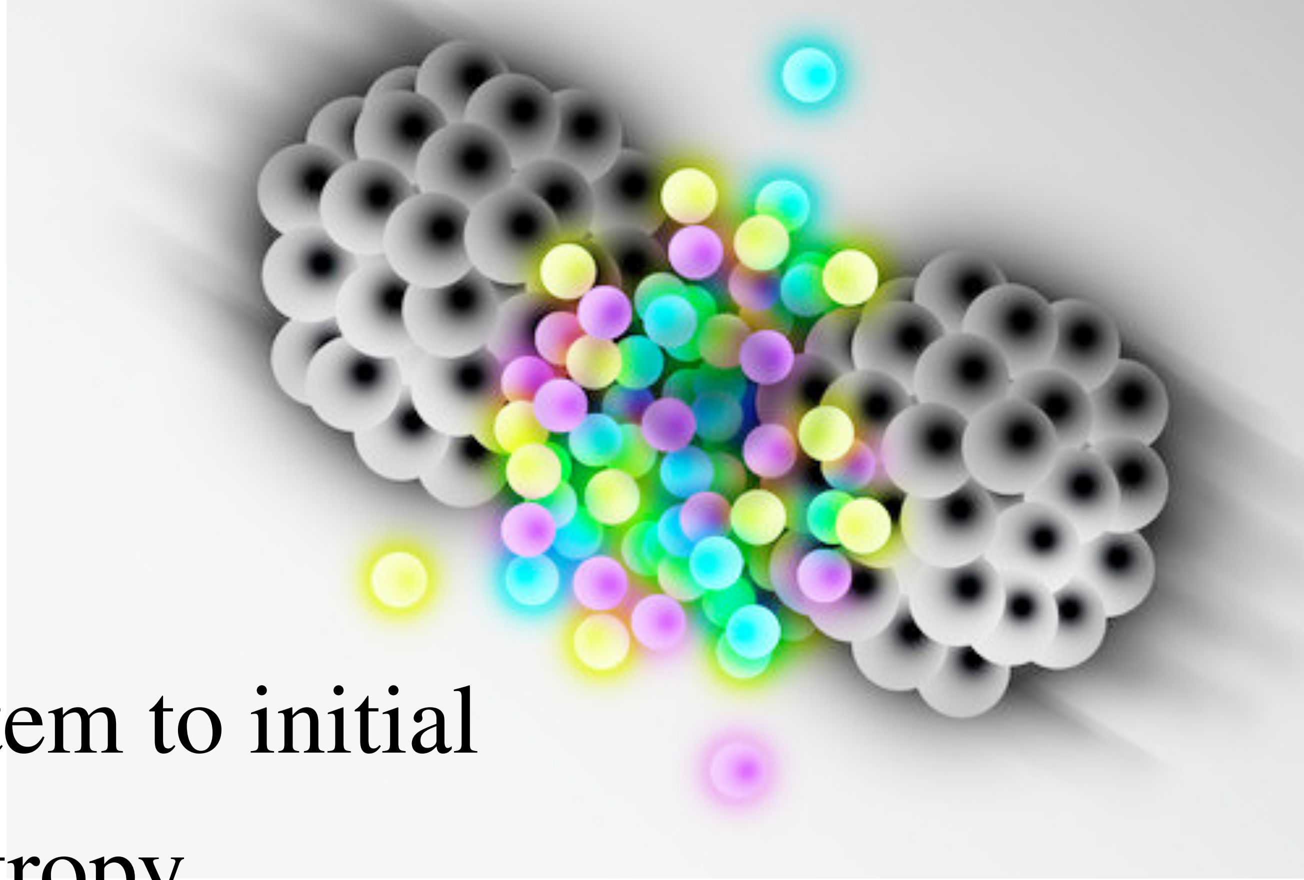

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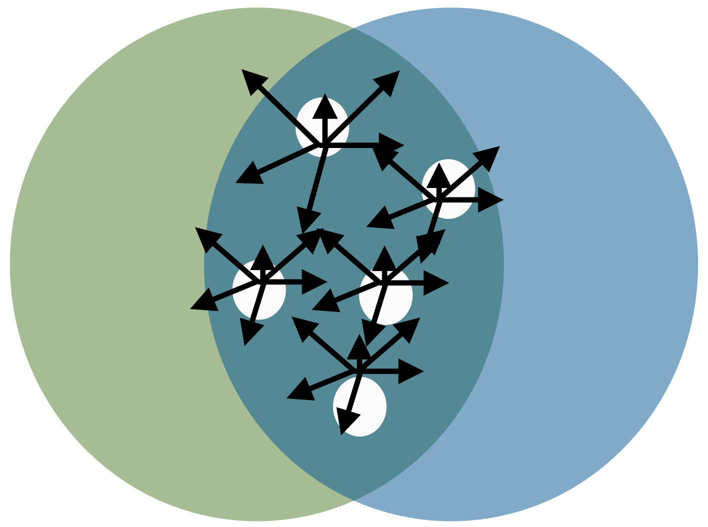
Superposition of multiple pp collisions



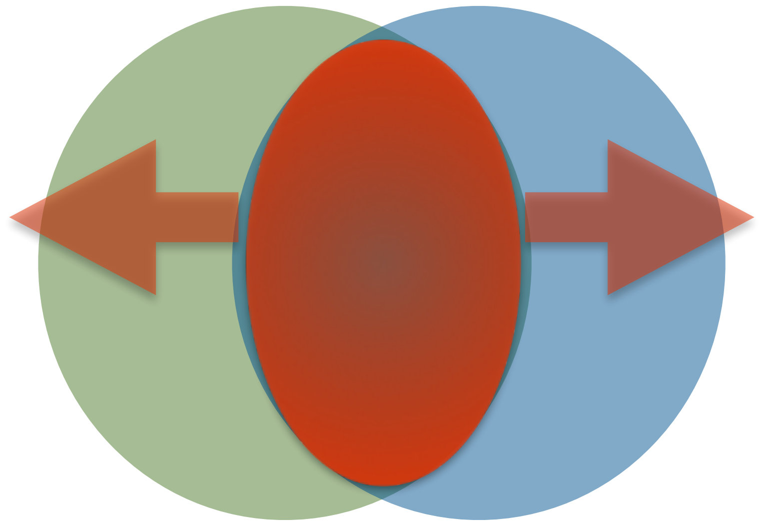
"Gas-like" behaviour

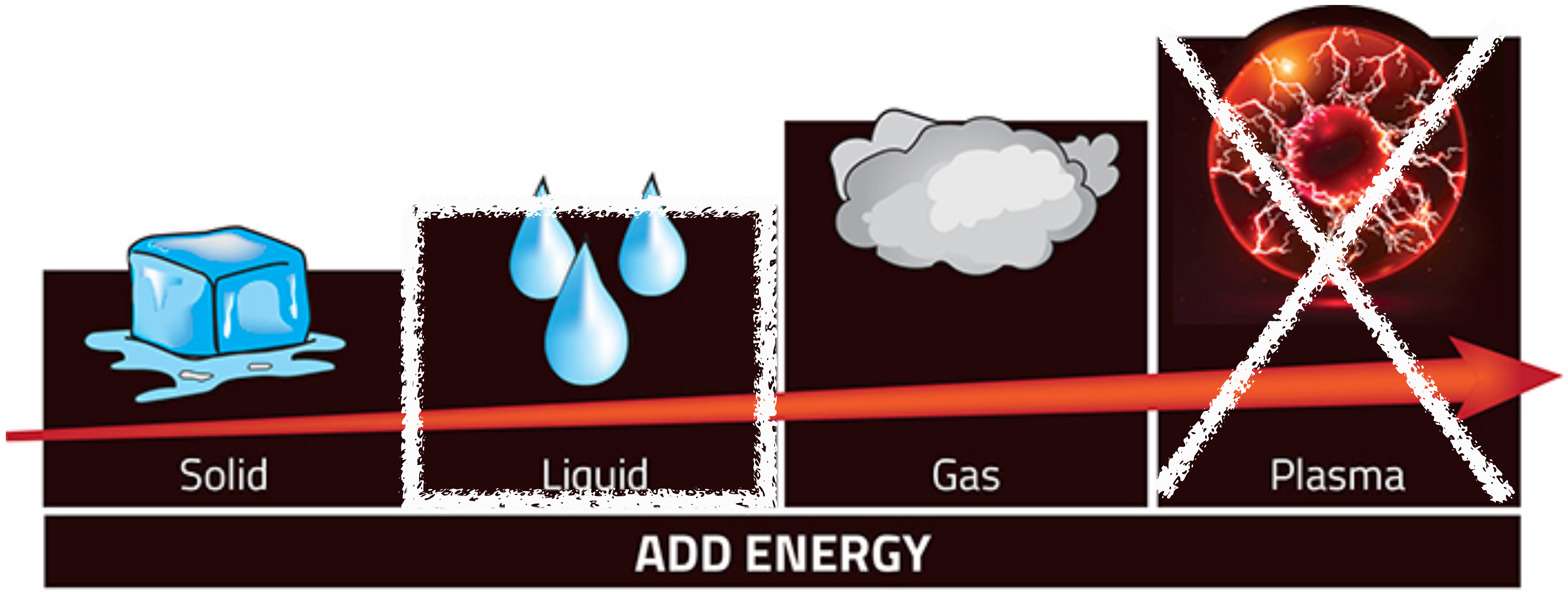
❌

✅

"Liquid-like" behaviour

Collective bulk



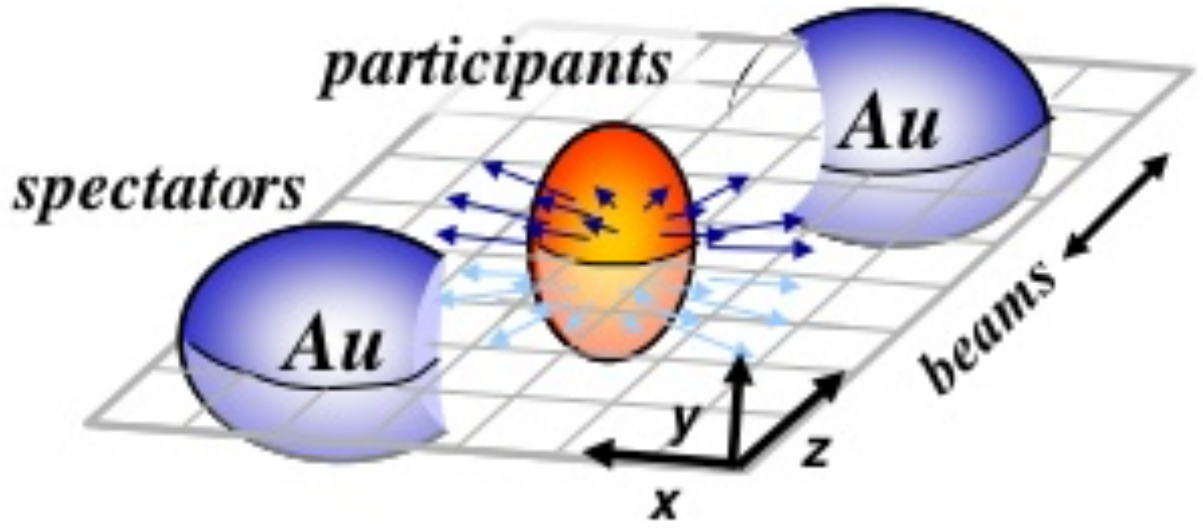


QGP: an almost perfect liquid

- Fourier decomposition in ϕ w.r.t. reaction plane Ψ_R:

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

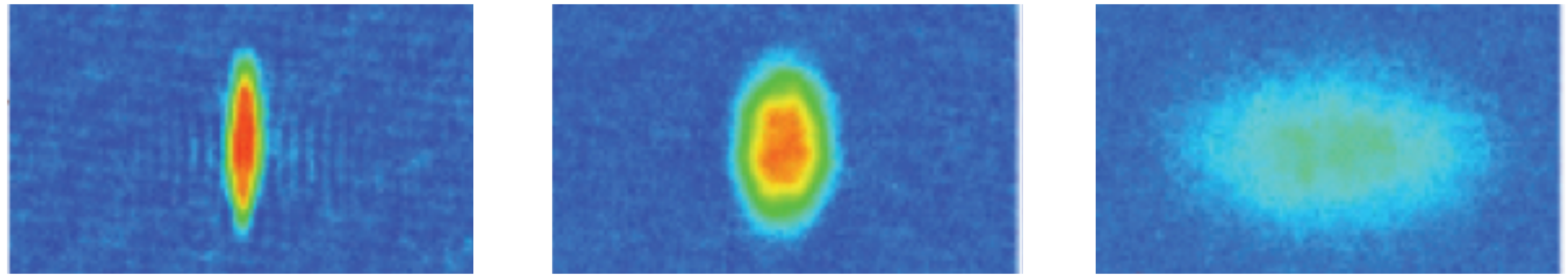
  - Elliptic flow: Second Fourier coefficient (v_2) of the observed particle distribution $v_2 = \langle \cos\left[2(\phi - \Psi_R)\right] \rangle$



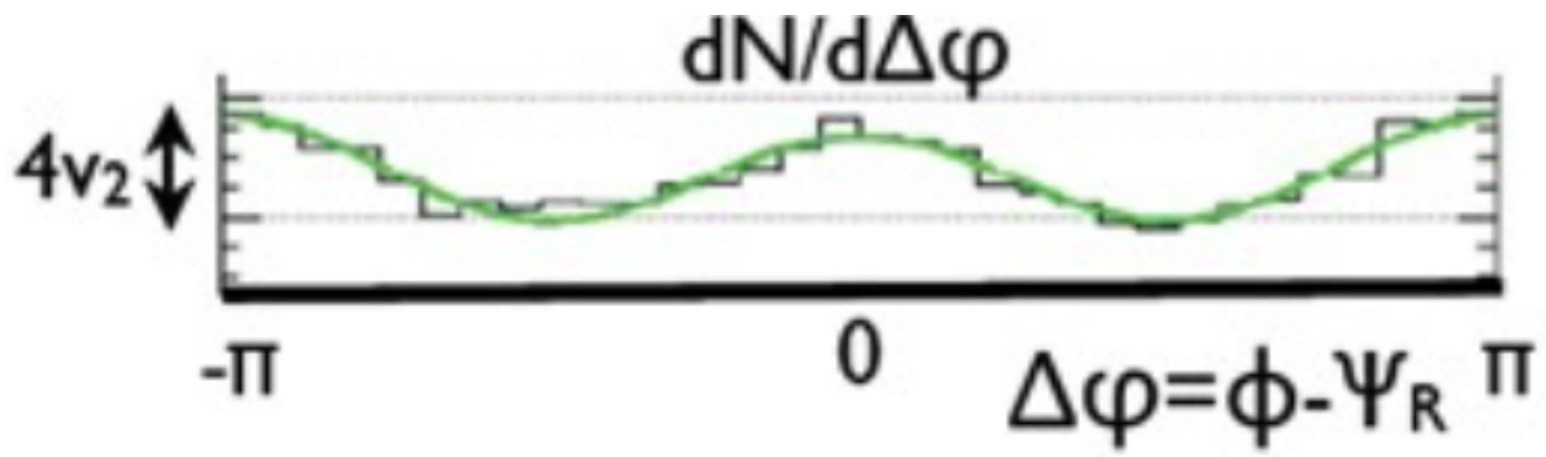
Reaction plane: z-x plane

(defines azimuthal angle Ψ_R)

Pressure driven expansion:



Final anisotropy:



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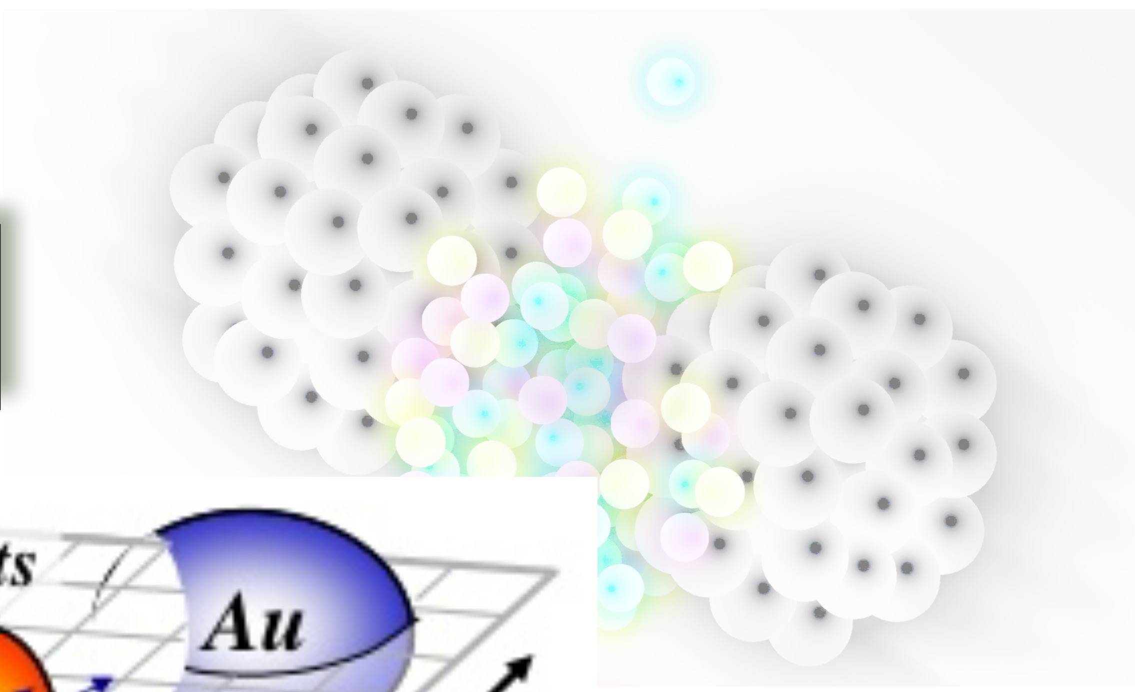

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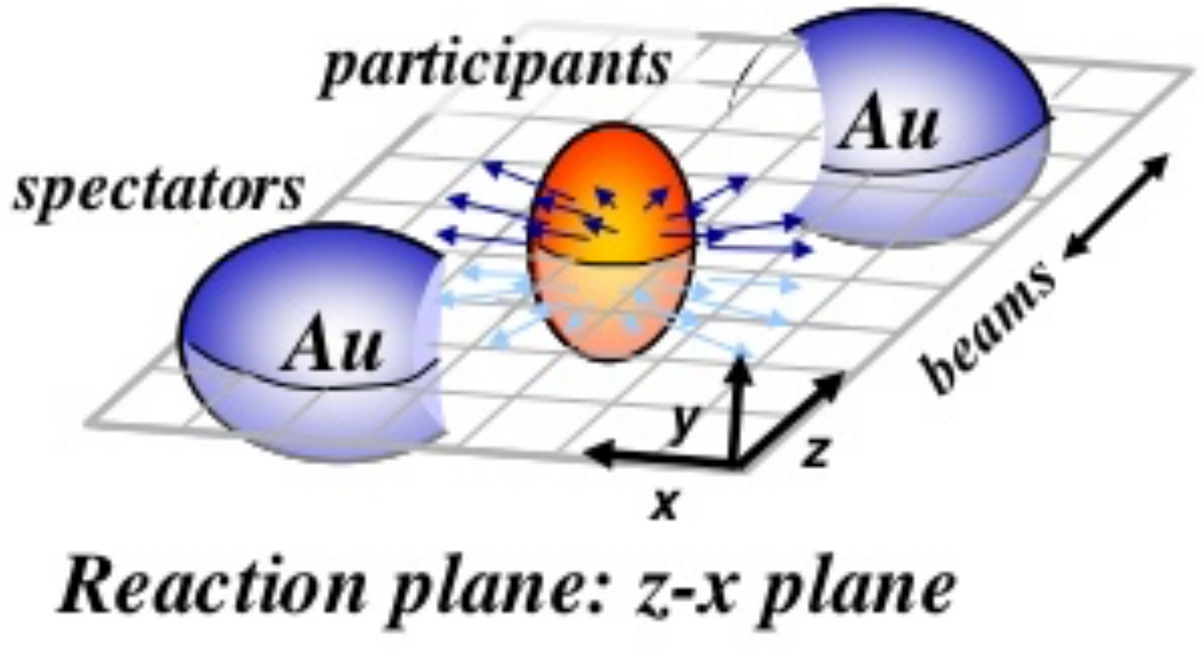

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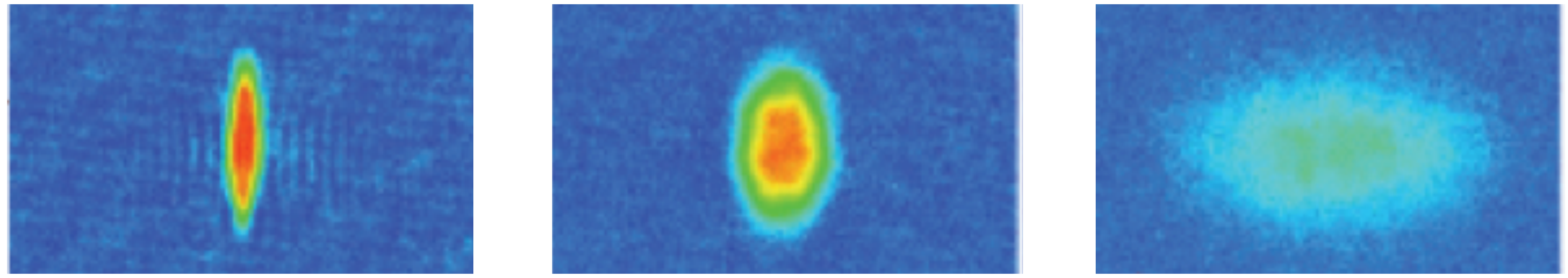

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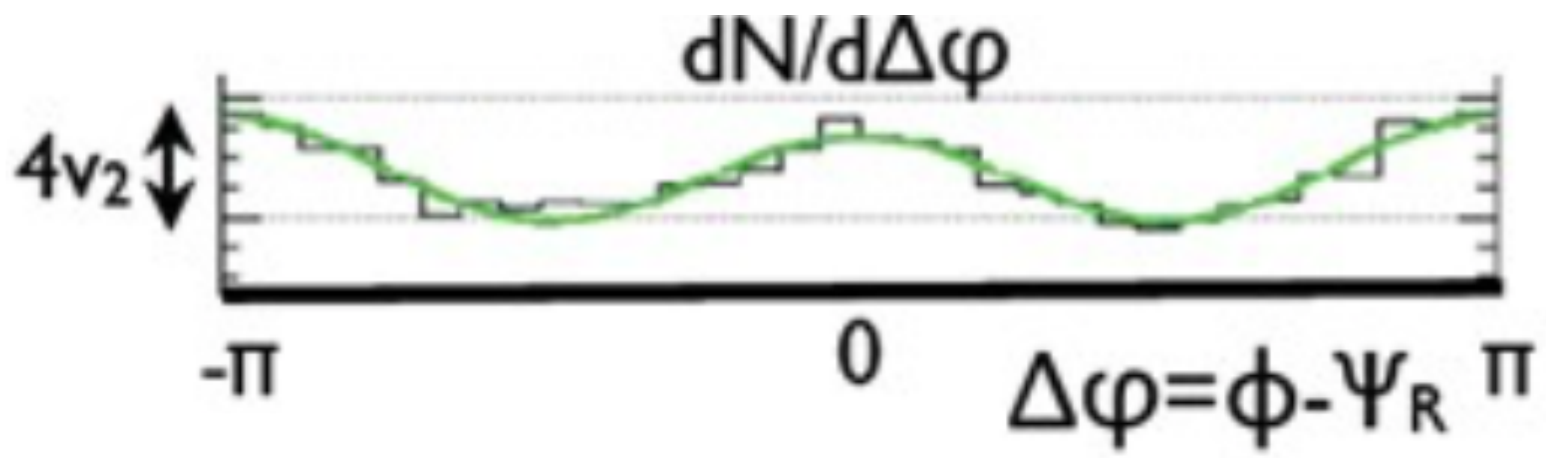
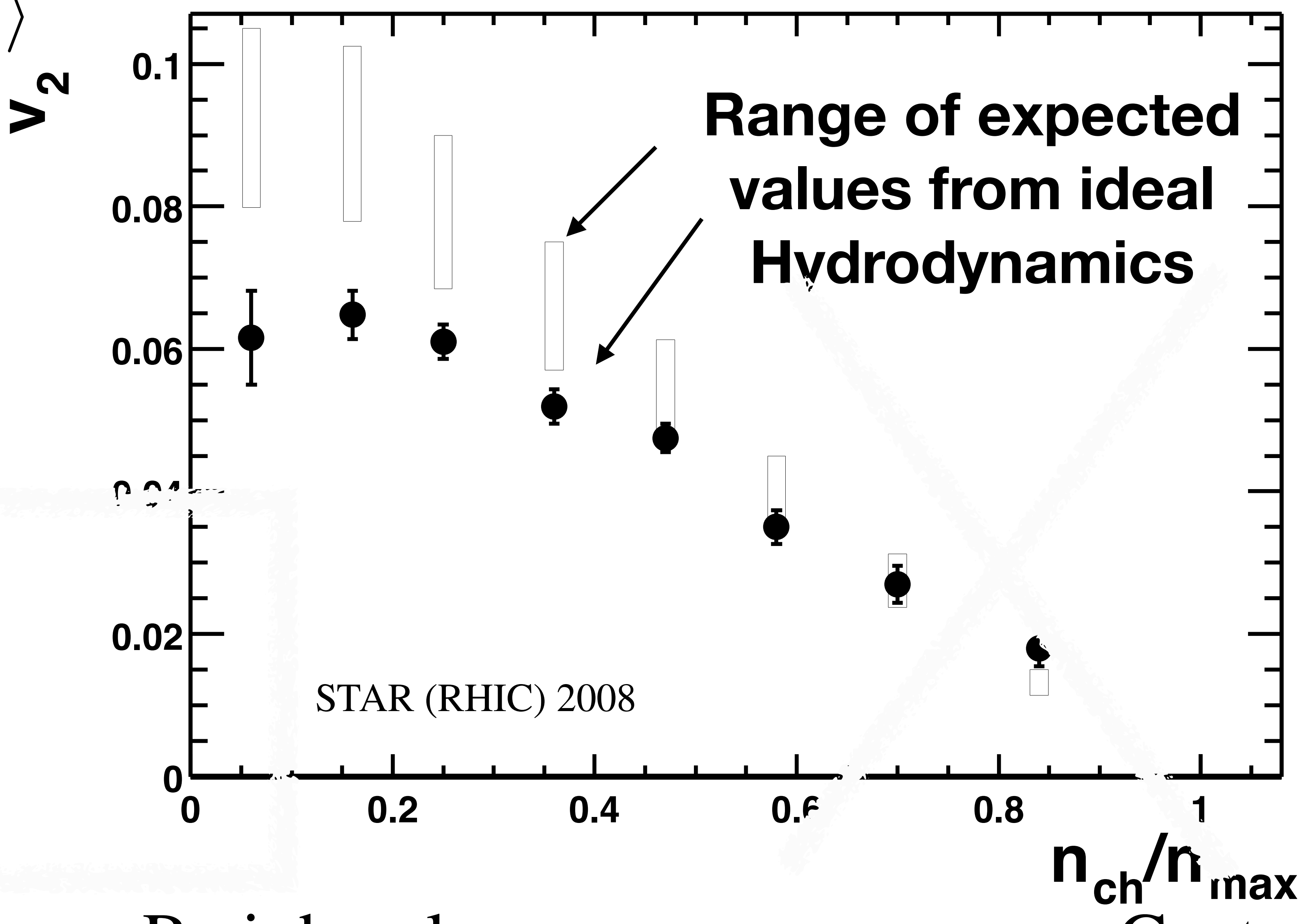
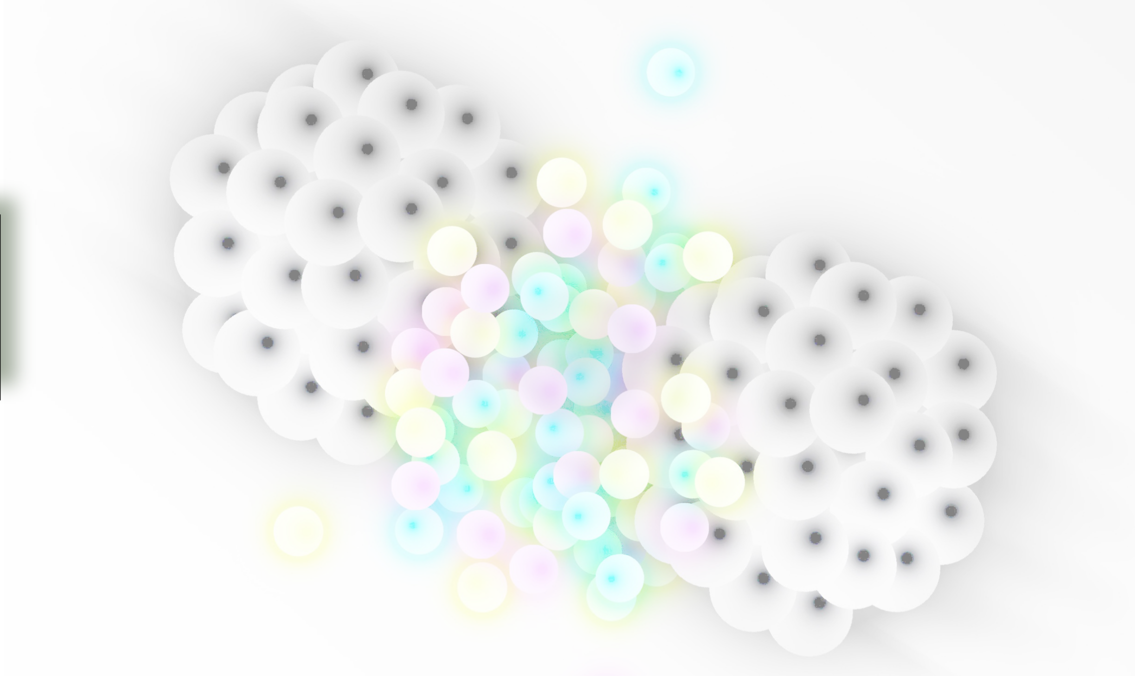


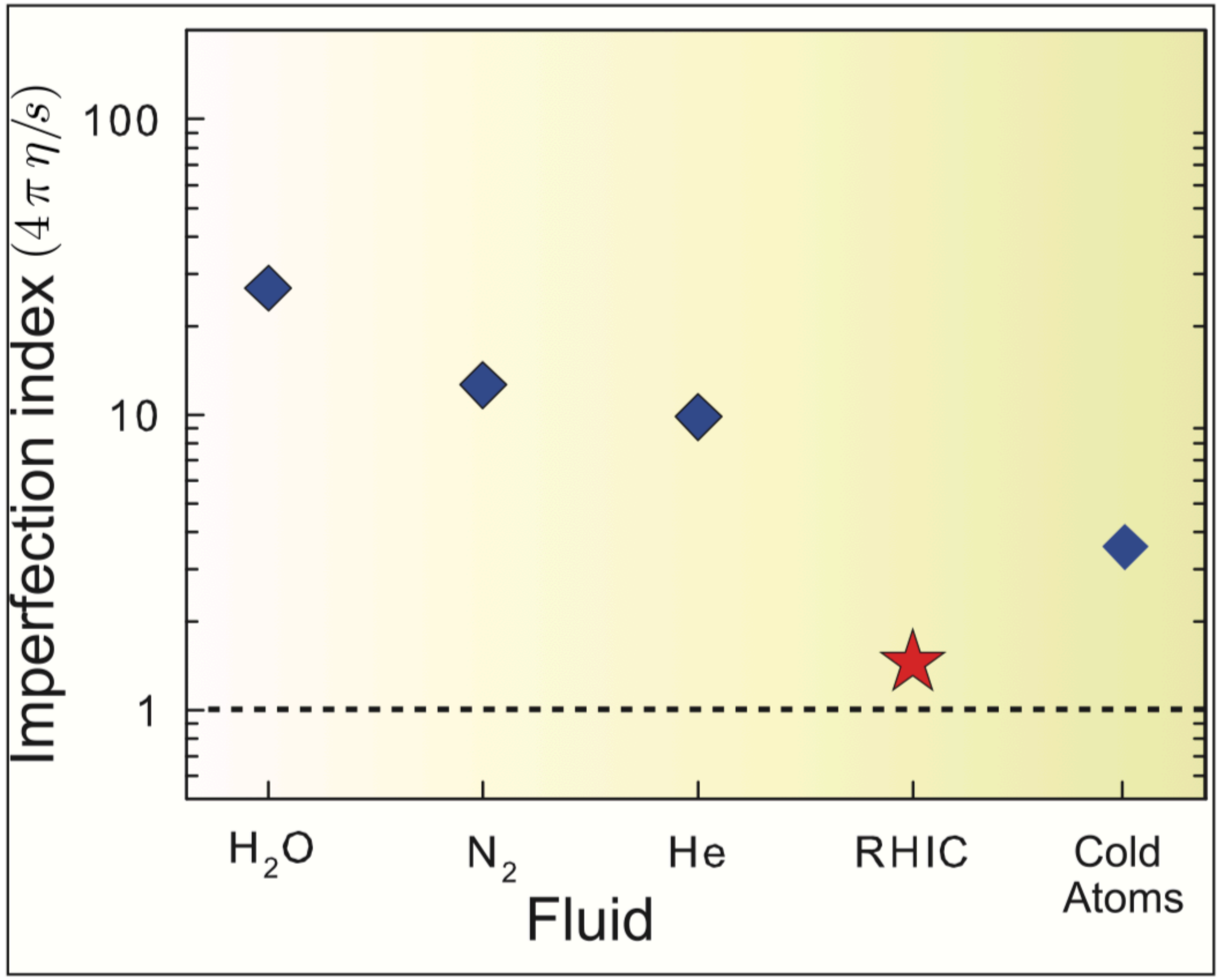


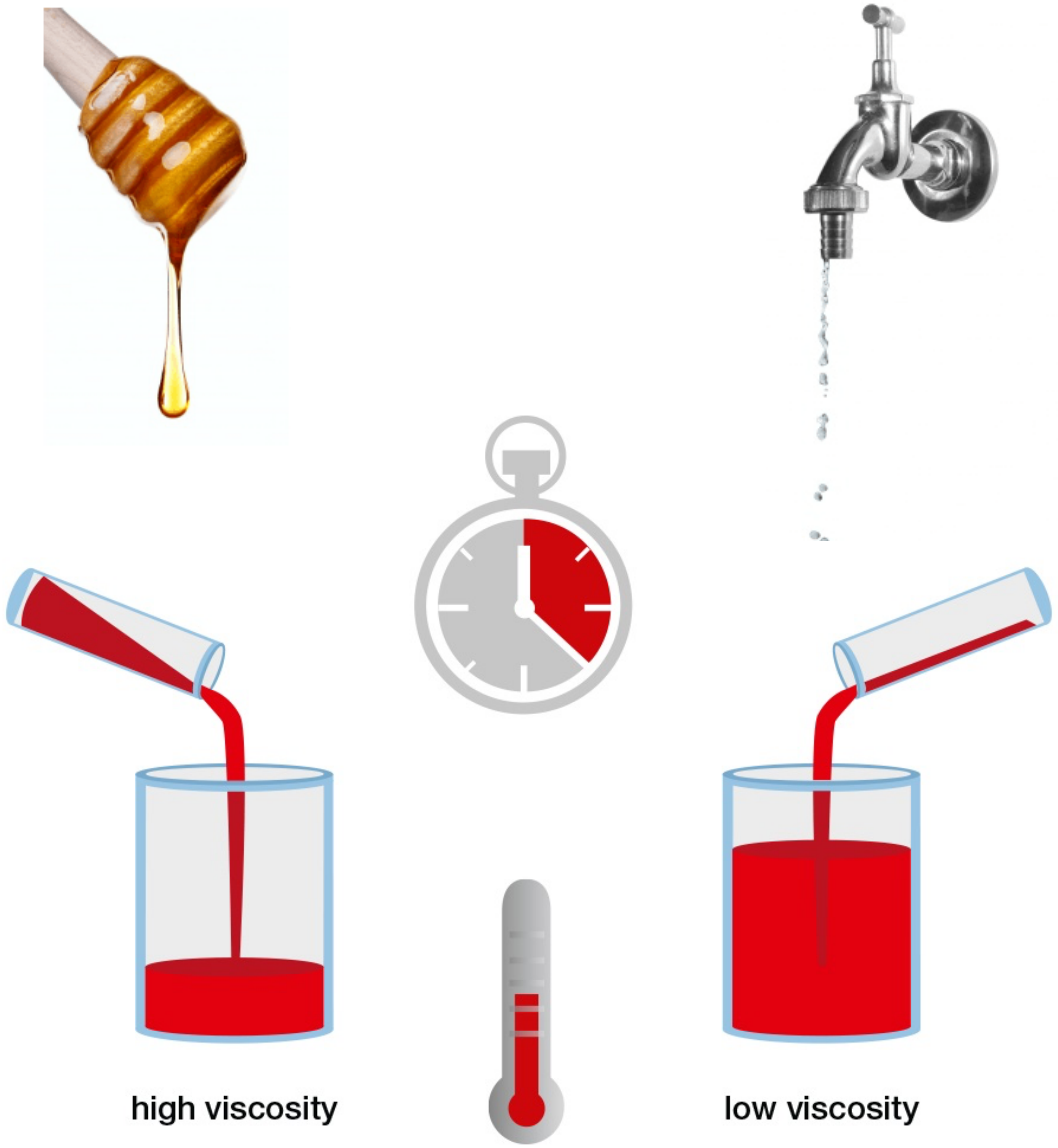
Peripheral ⟷ Central

QGP: an almost perfect liquid

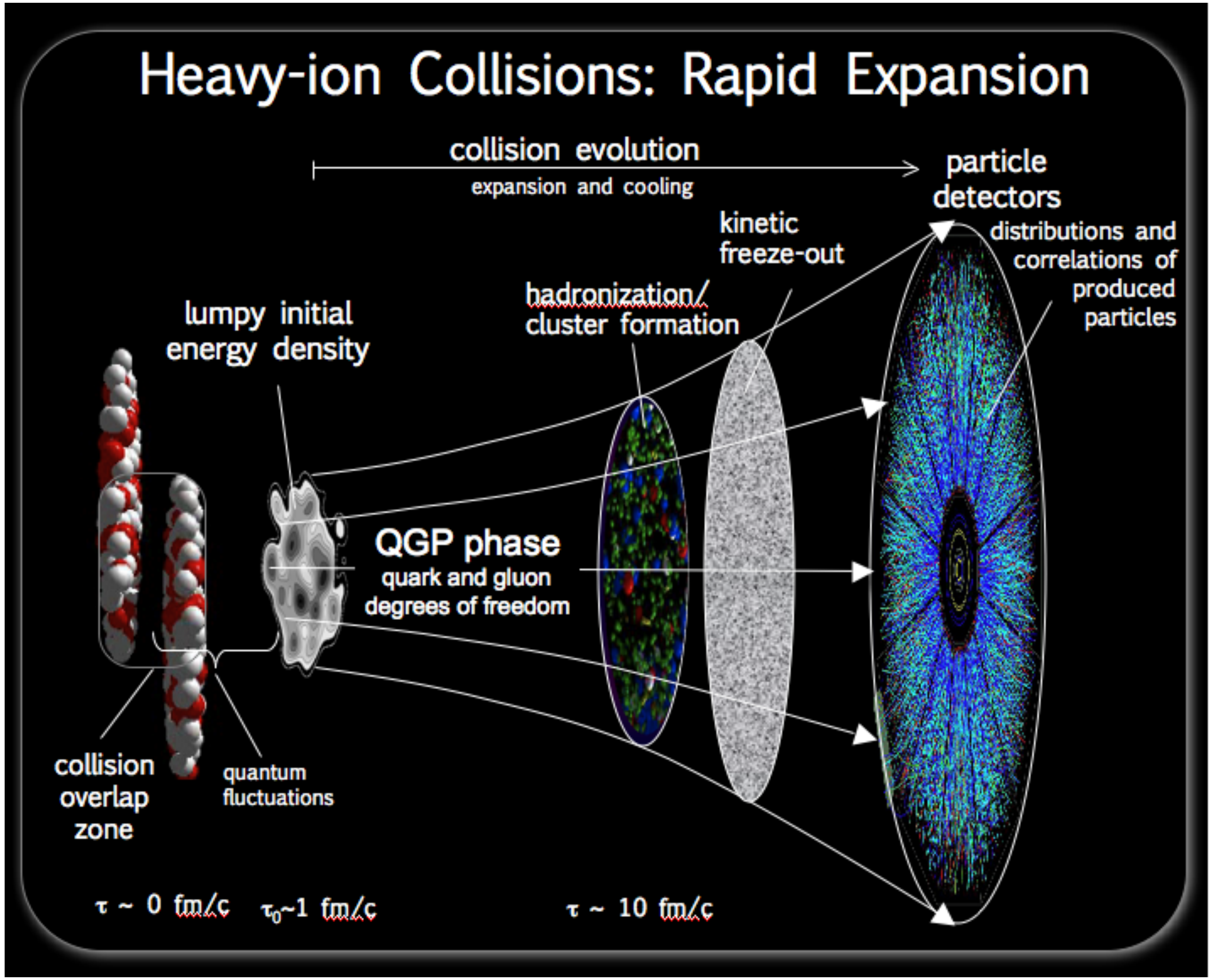


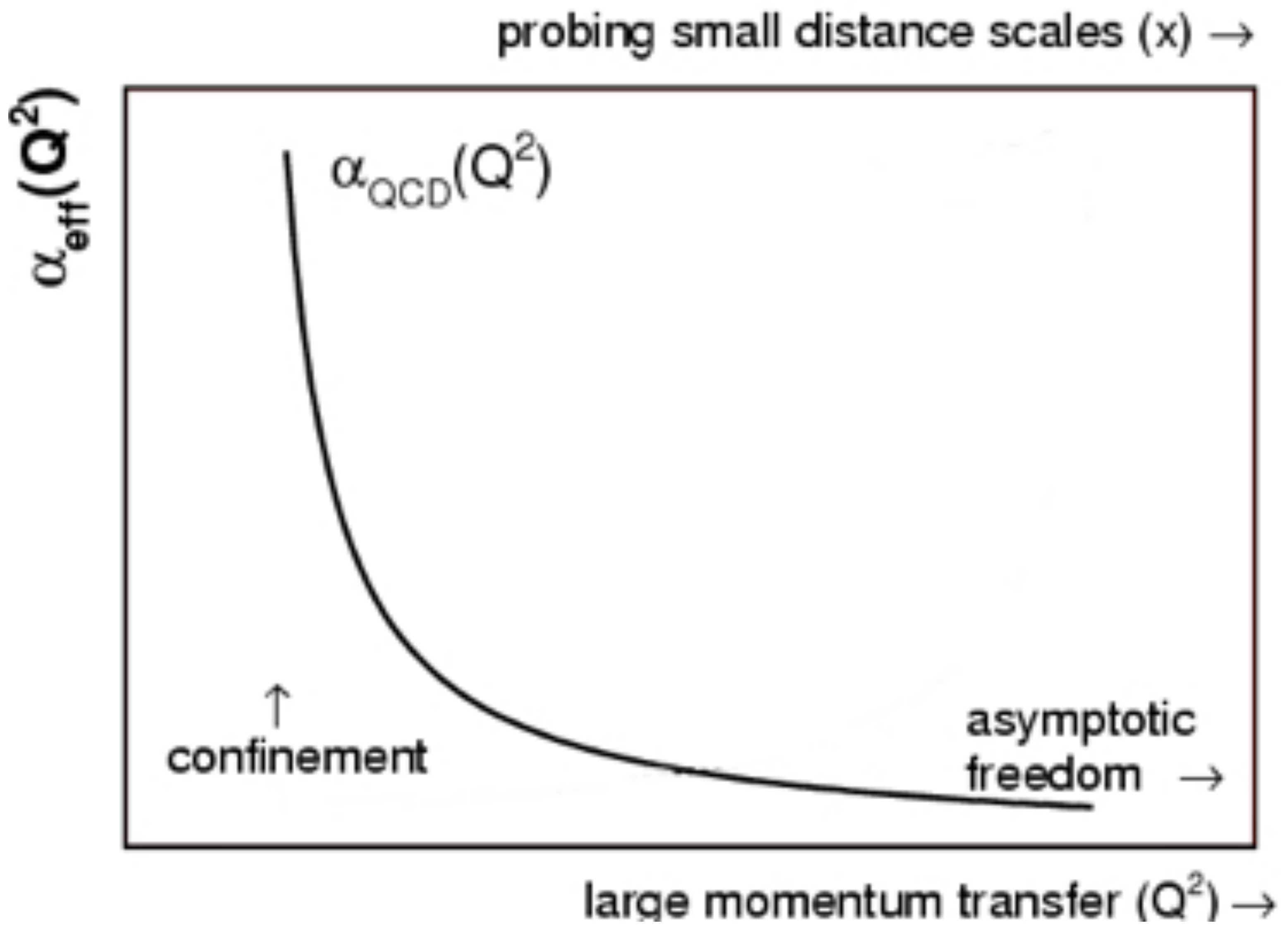
- Measuring the imperfection factor (viscosity)….





How to probe the QGP @ lab (v2)





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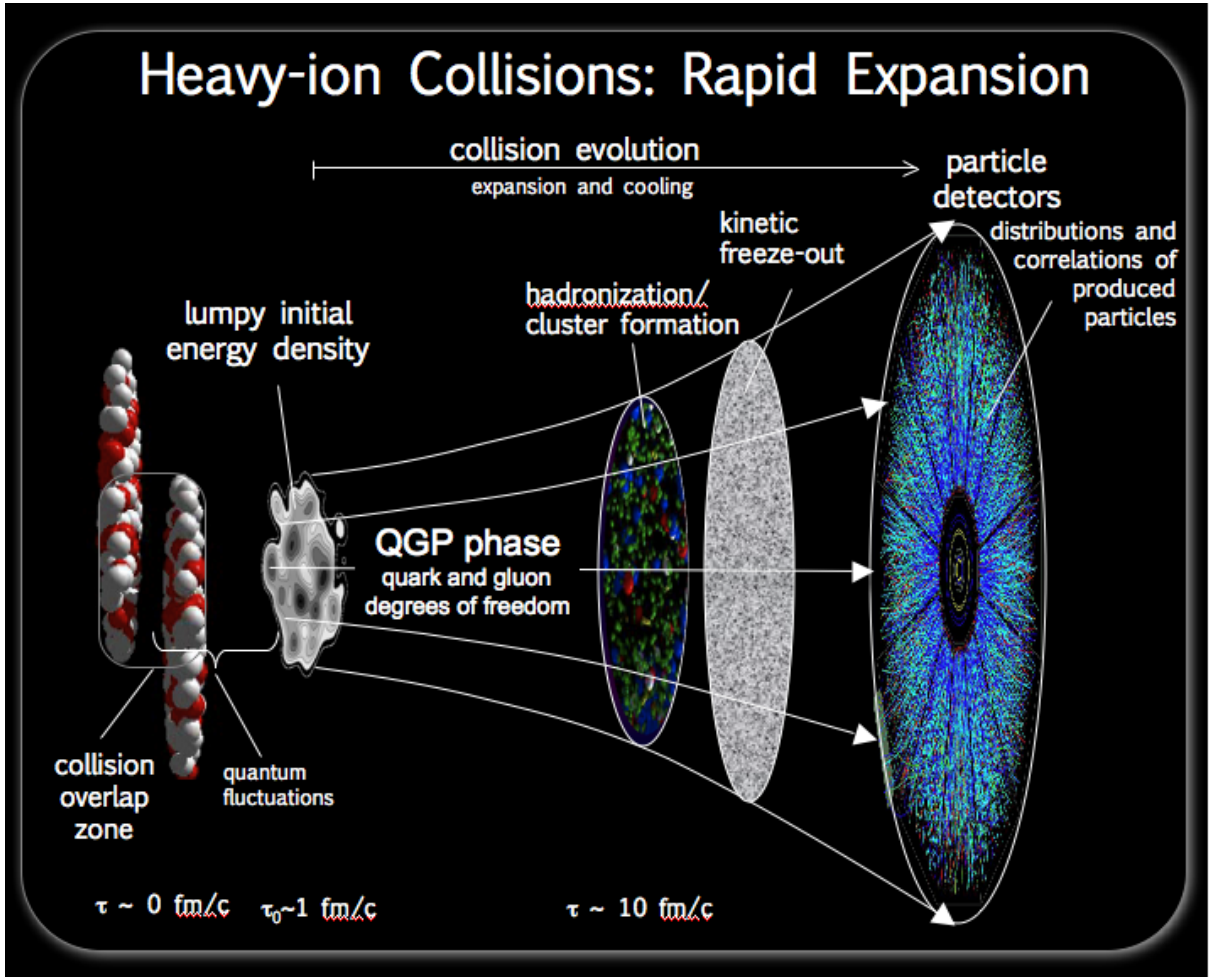
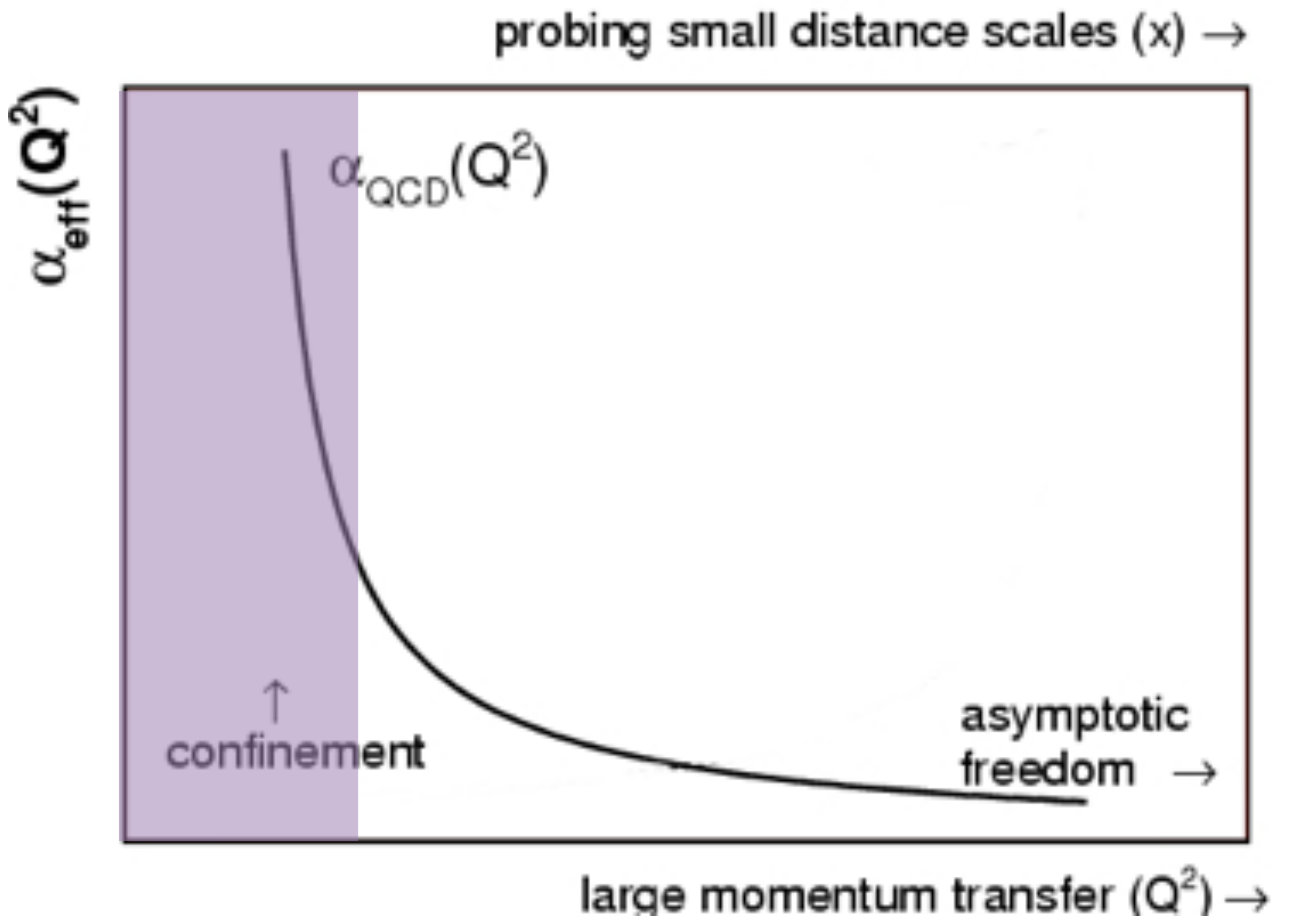
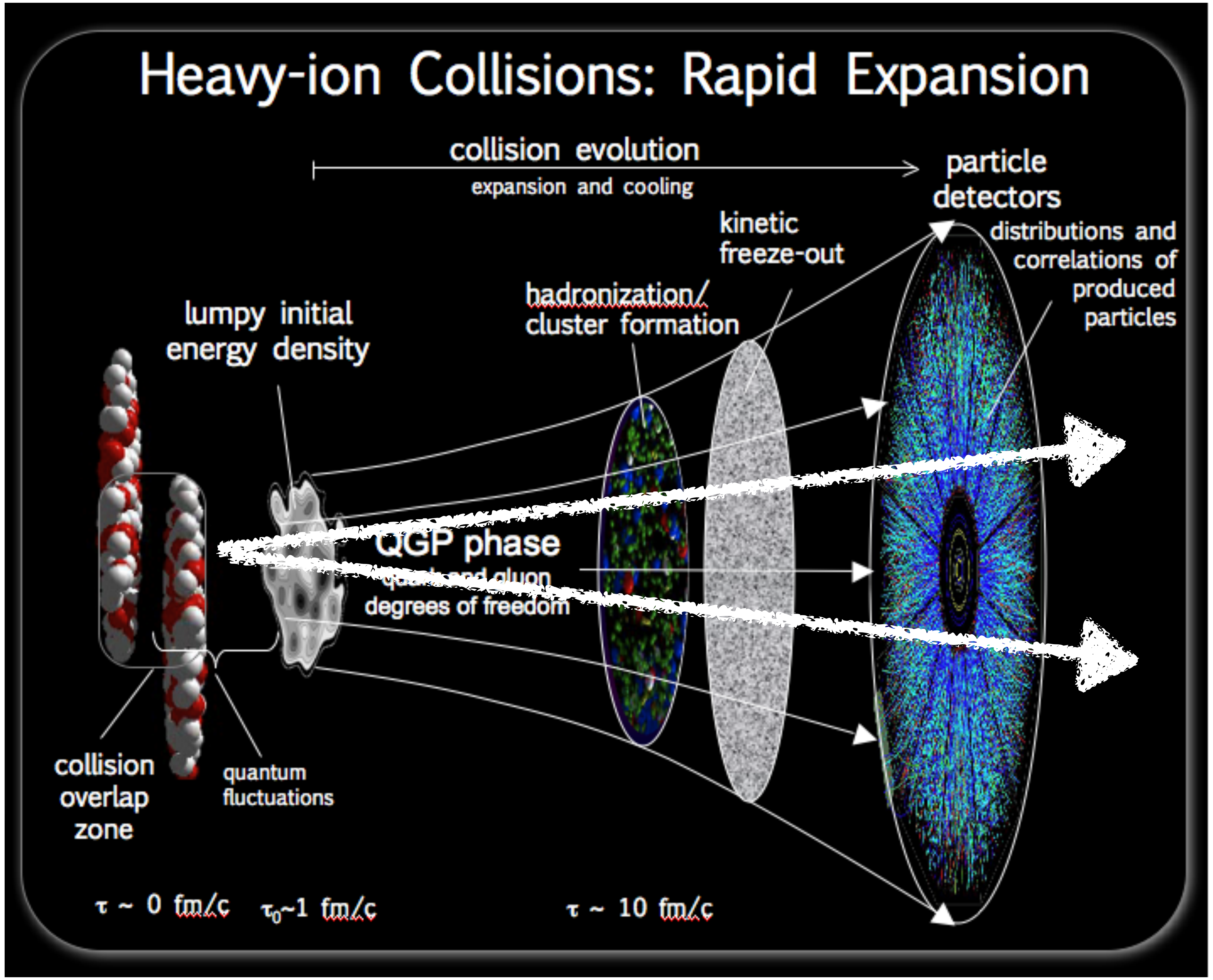


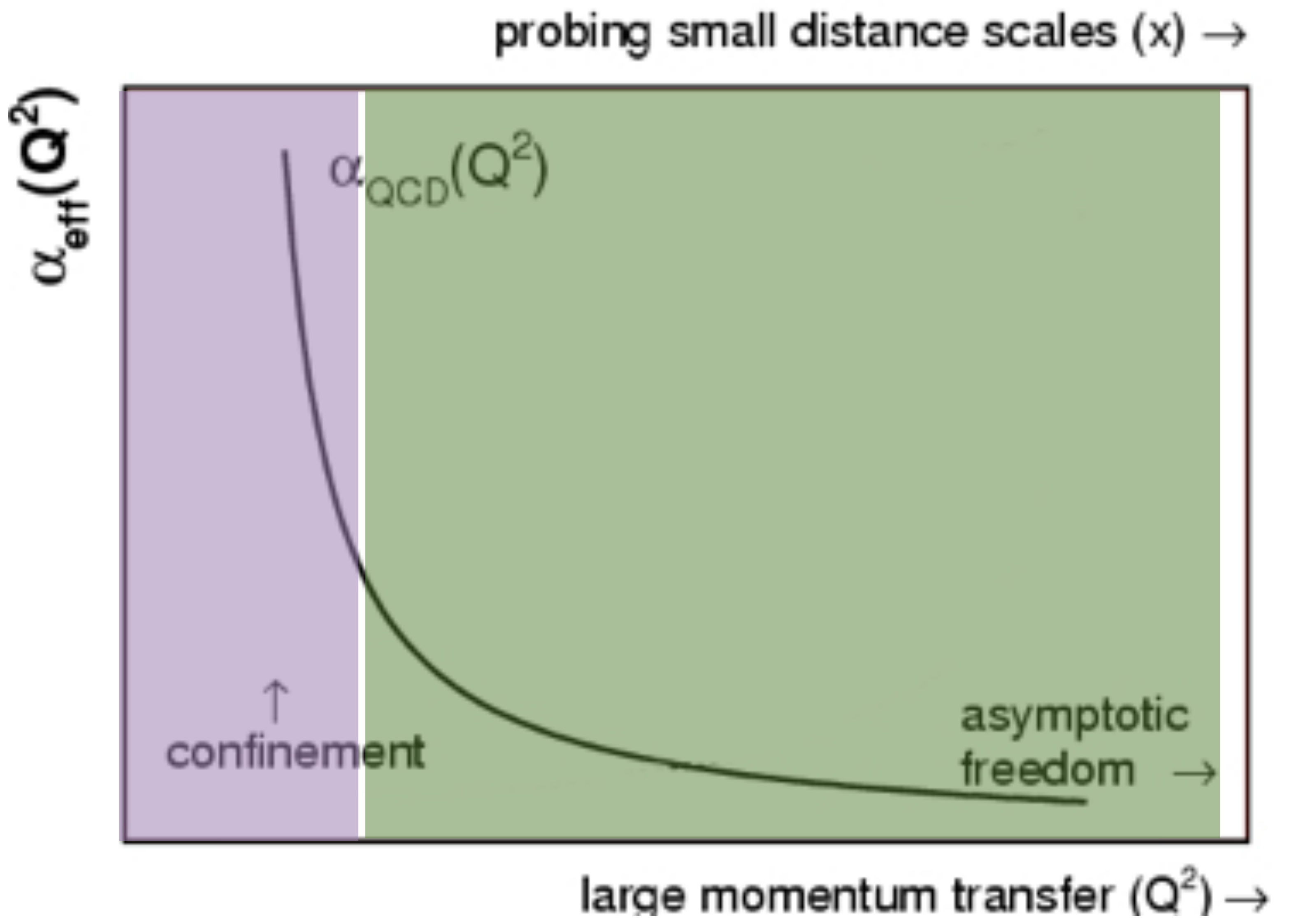


Soft probes

non-pQCD

How to probe the QGP @ lab (v2)





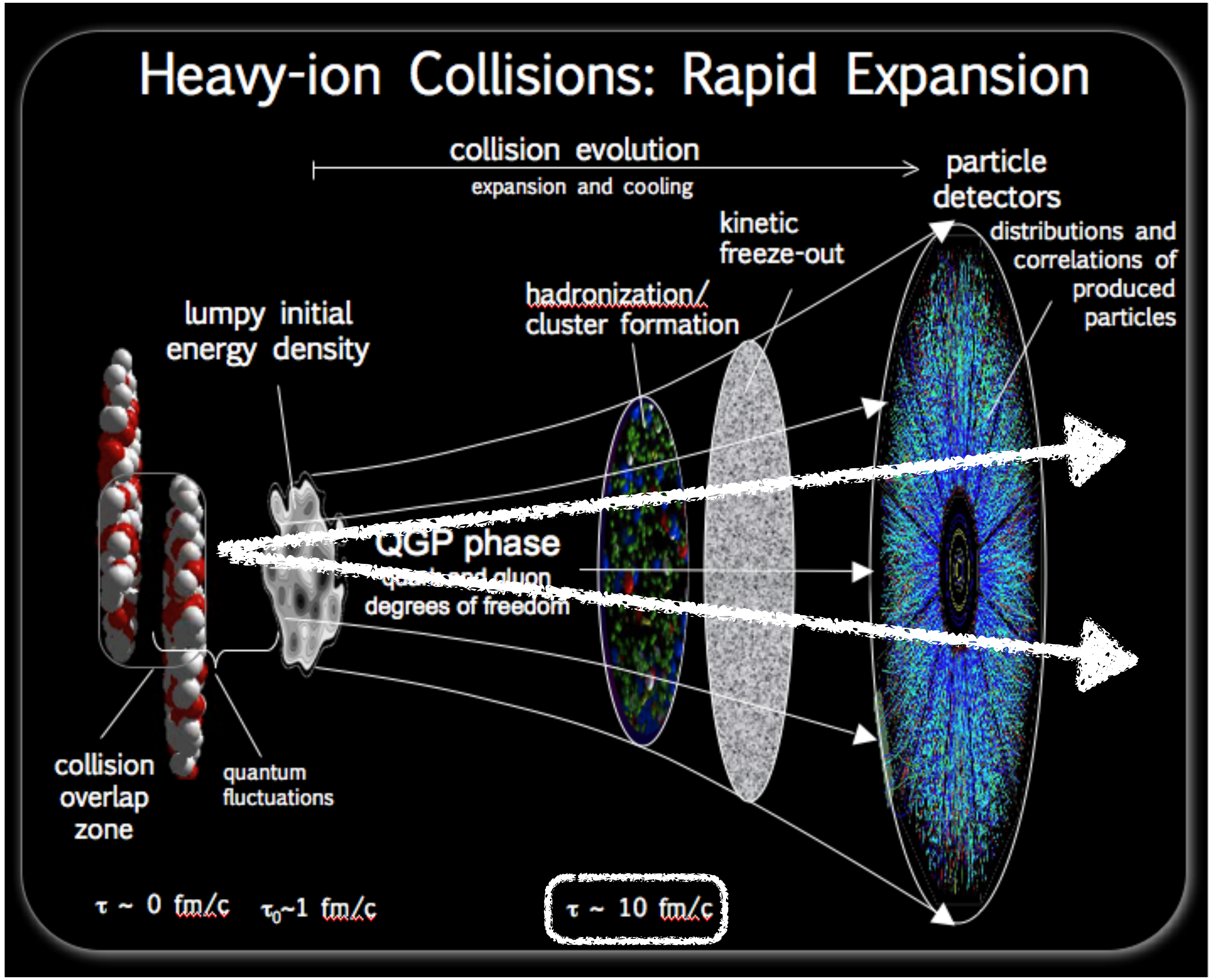
Soft probes

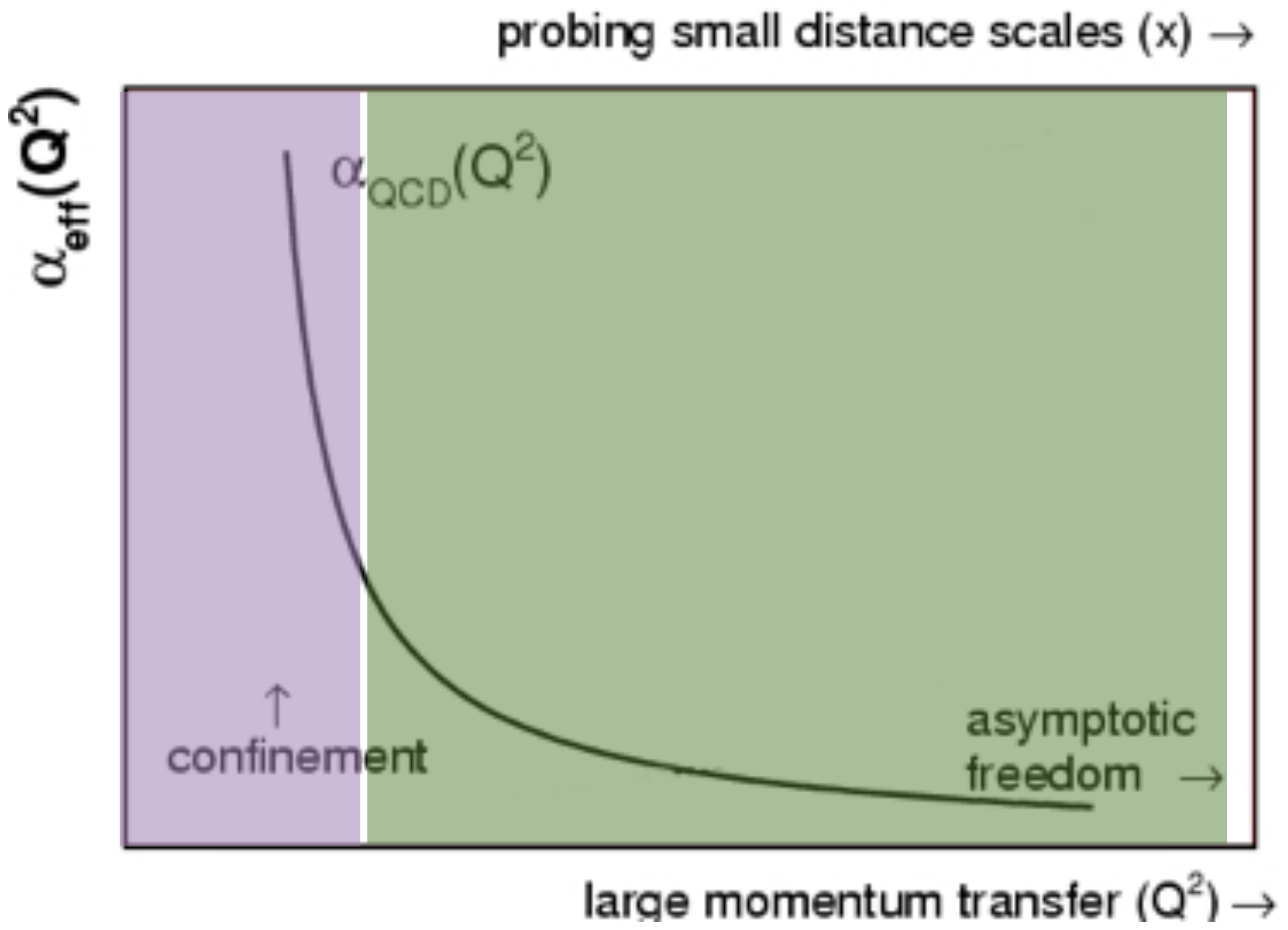
non-pQCD

Hard probes

pQCD

How to probe the QGP @ lab (v2)





Soft probes

non-pQCD

Hard probes

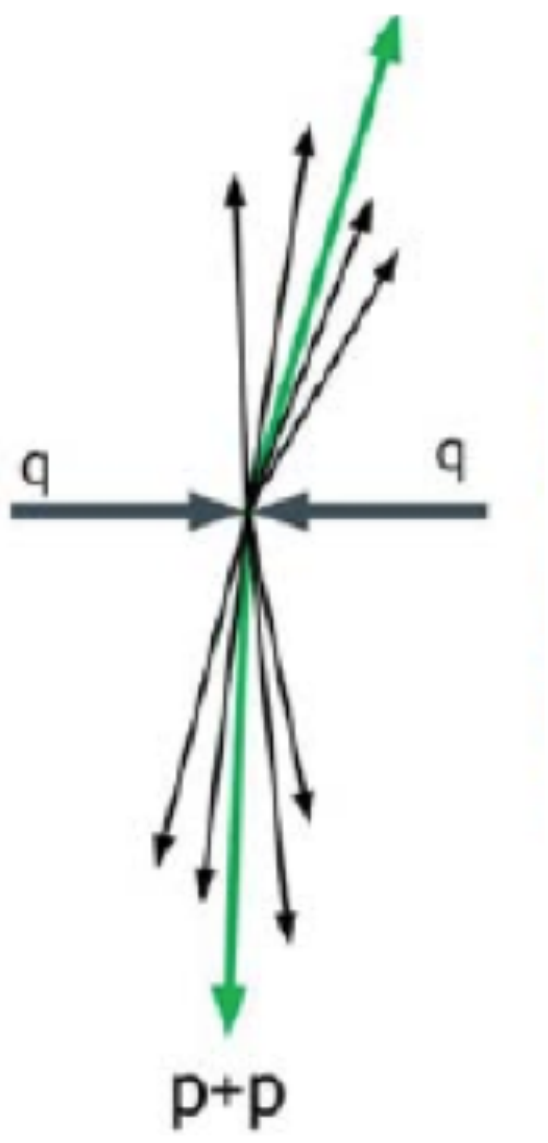
pQCD

Caveat: need to rely on self-generated probes

Hard Probes

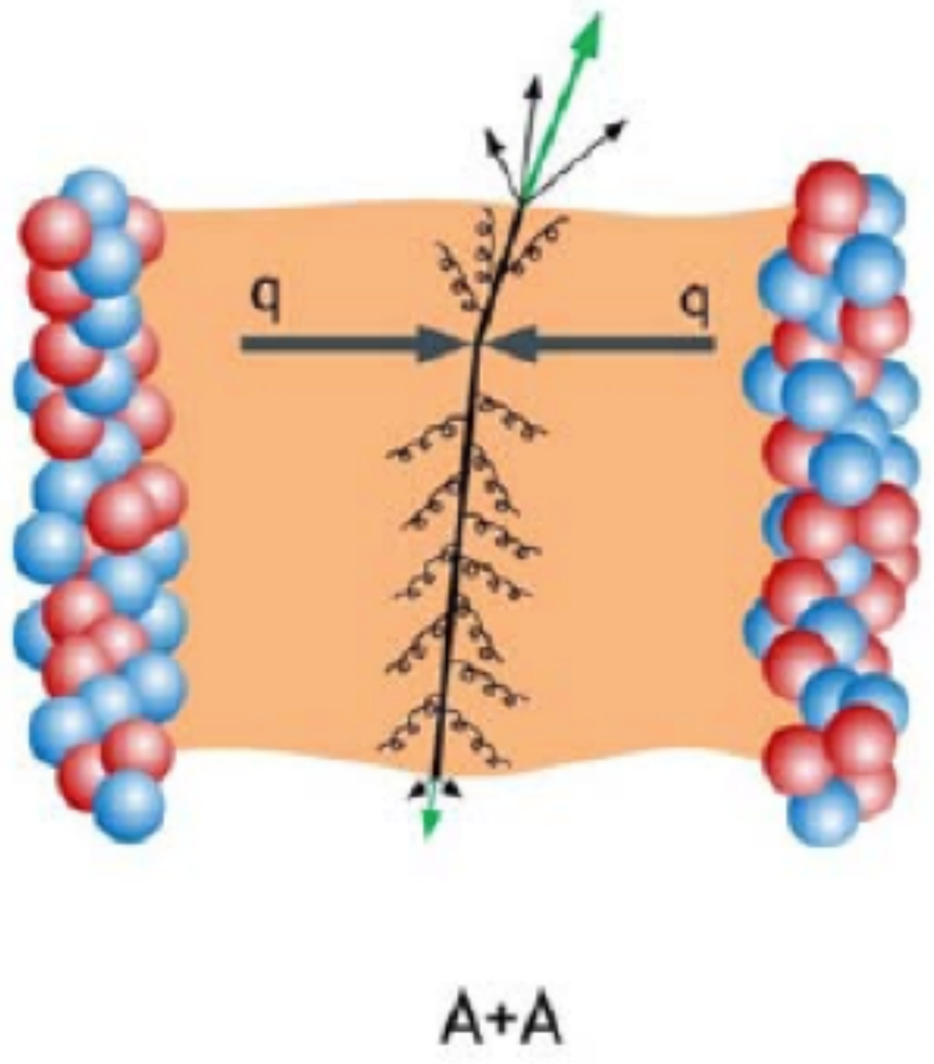
- “Shoot” a calibrated probe and see the final modifications with respect to a reference (usually pp)

Caveat: need to rely on self-generated probes



Example: jets in pp

(well known and theoretically understood)



Example: jets in PbPb

(modifications related to the QGP microscopic properties)

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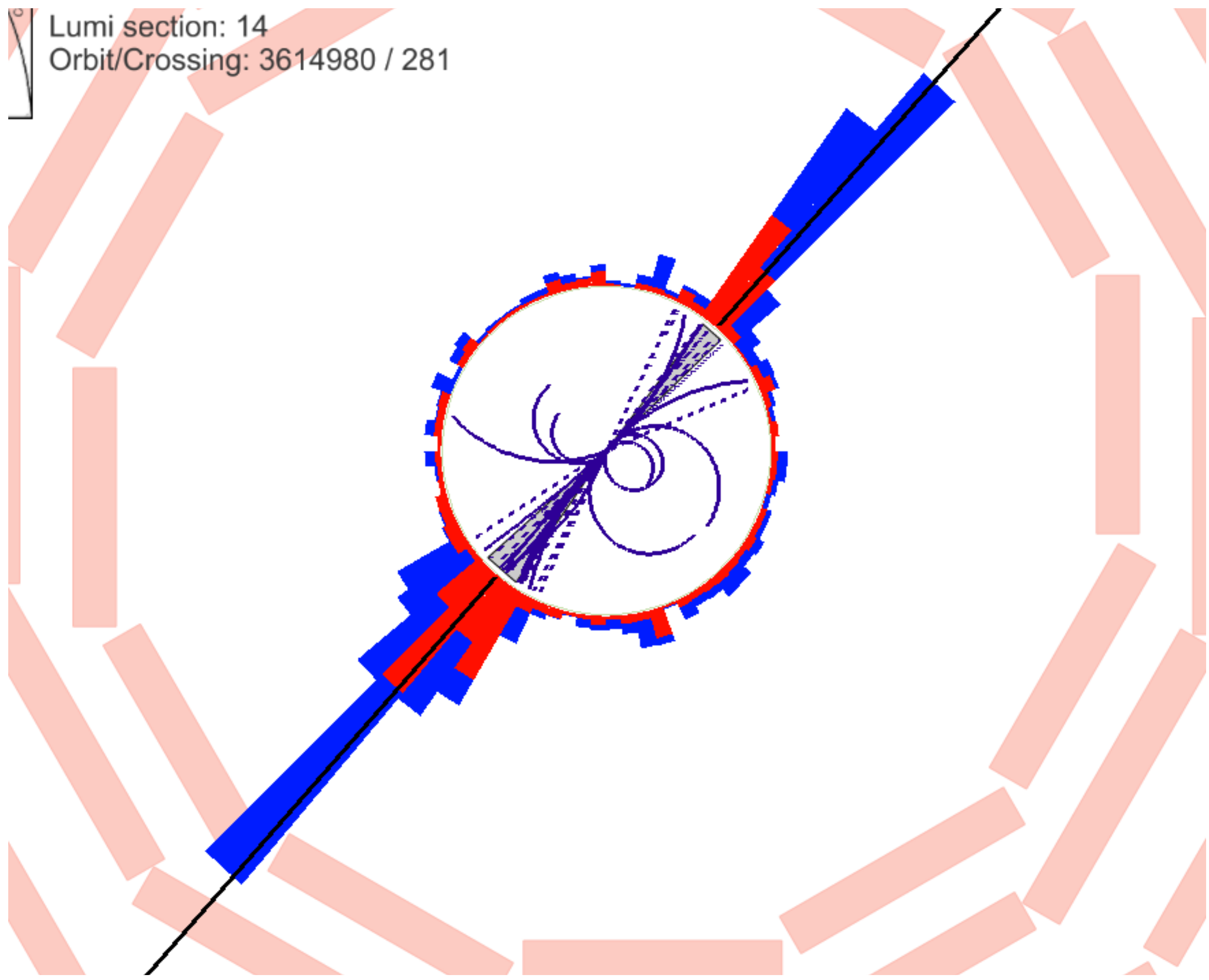
- “Shoot” a calibrated probe and see the final modifications with respect to a reference (usually pp)

Caveat: need to rely on self-generated probes



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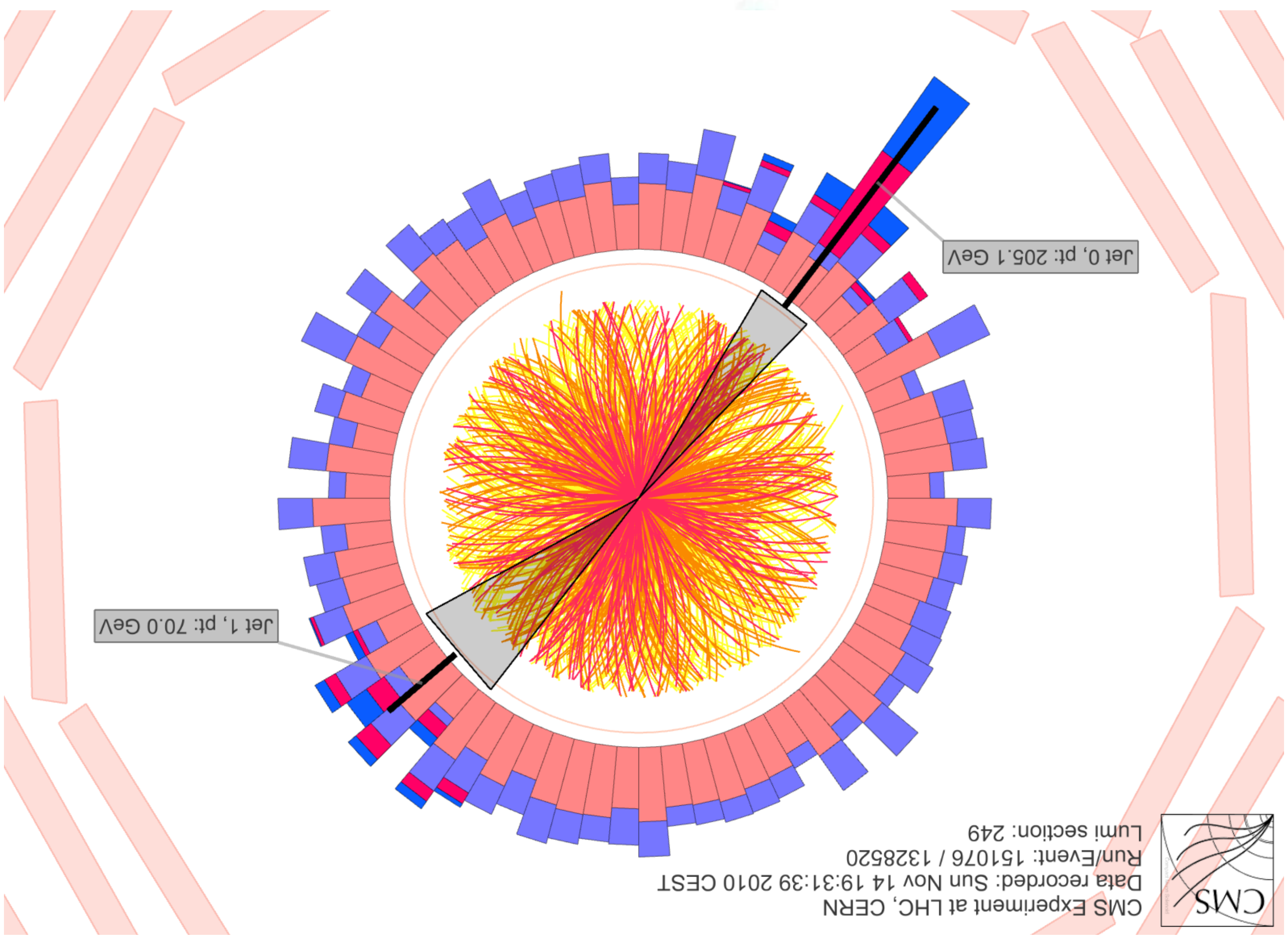

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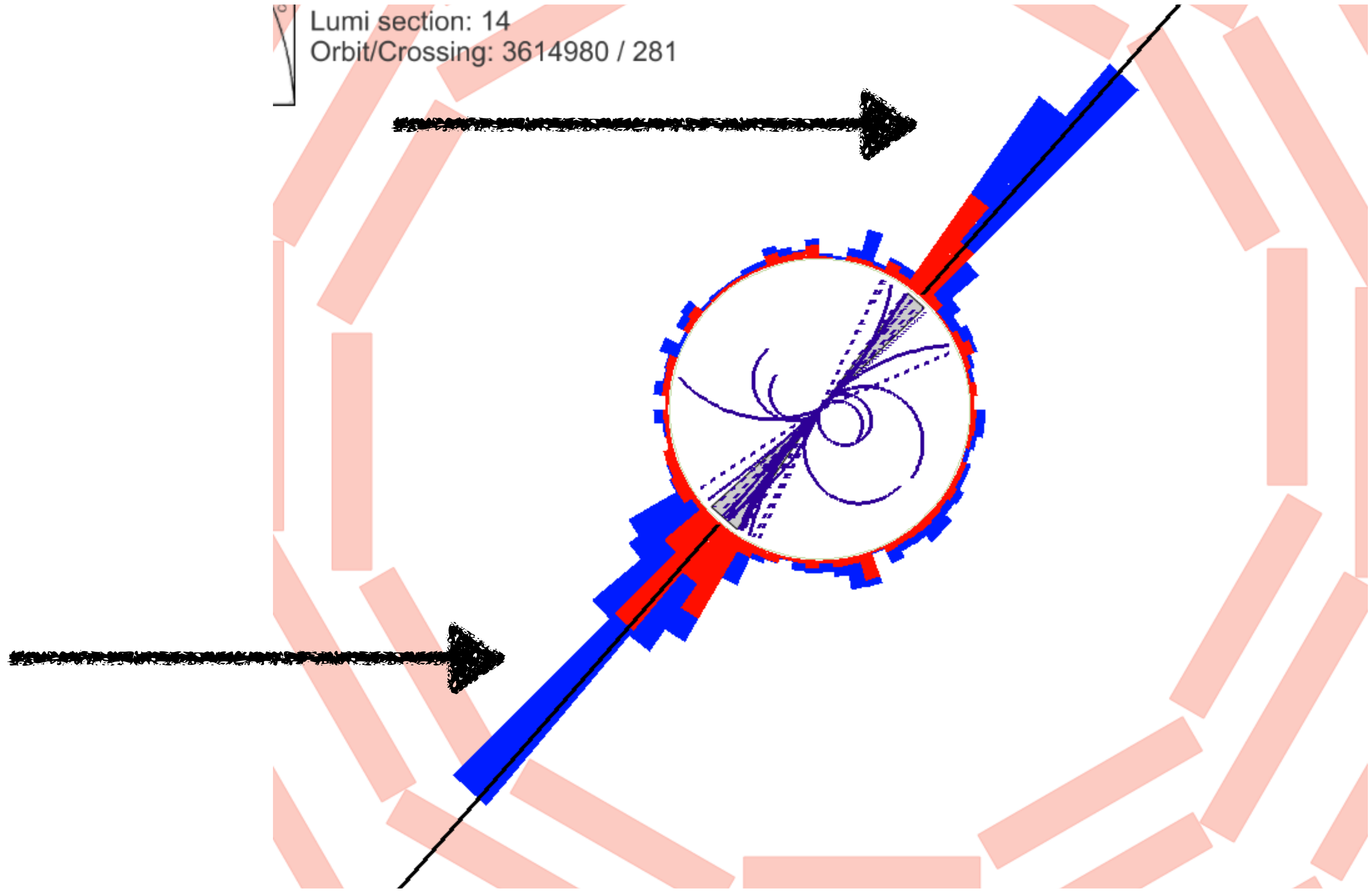

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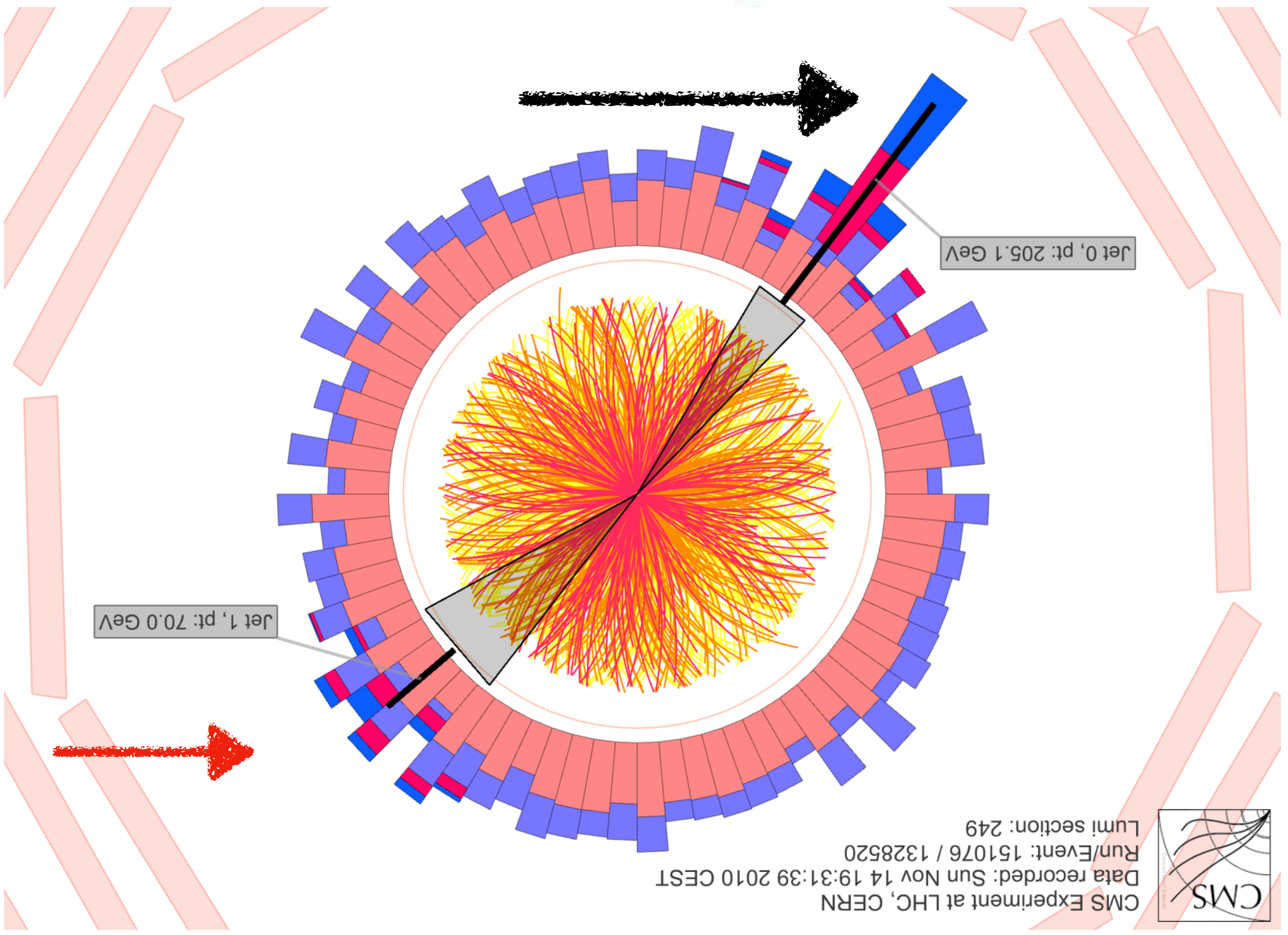

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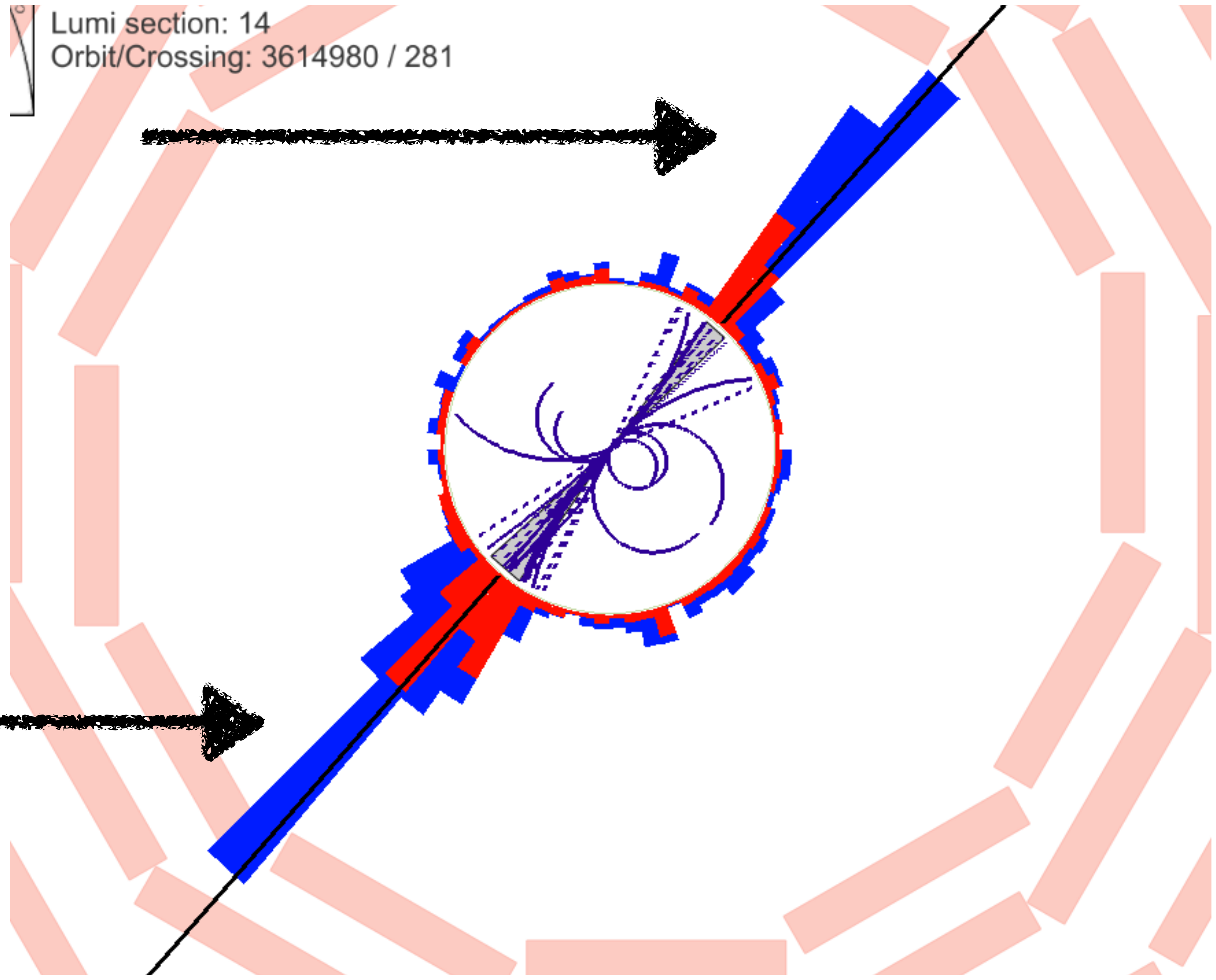

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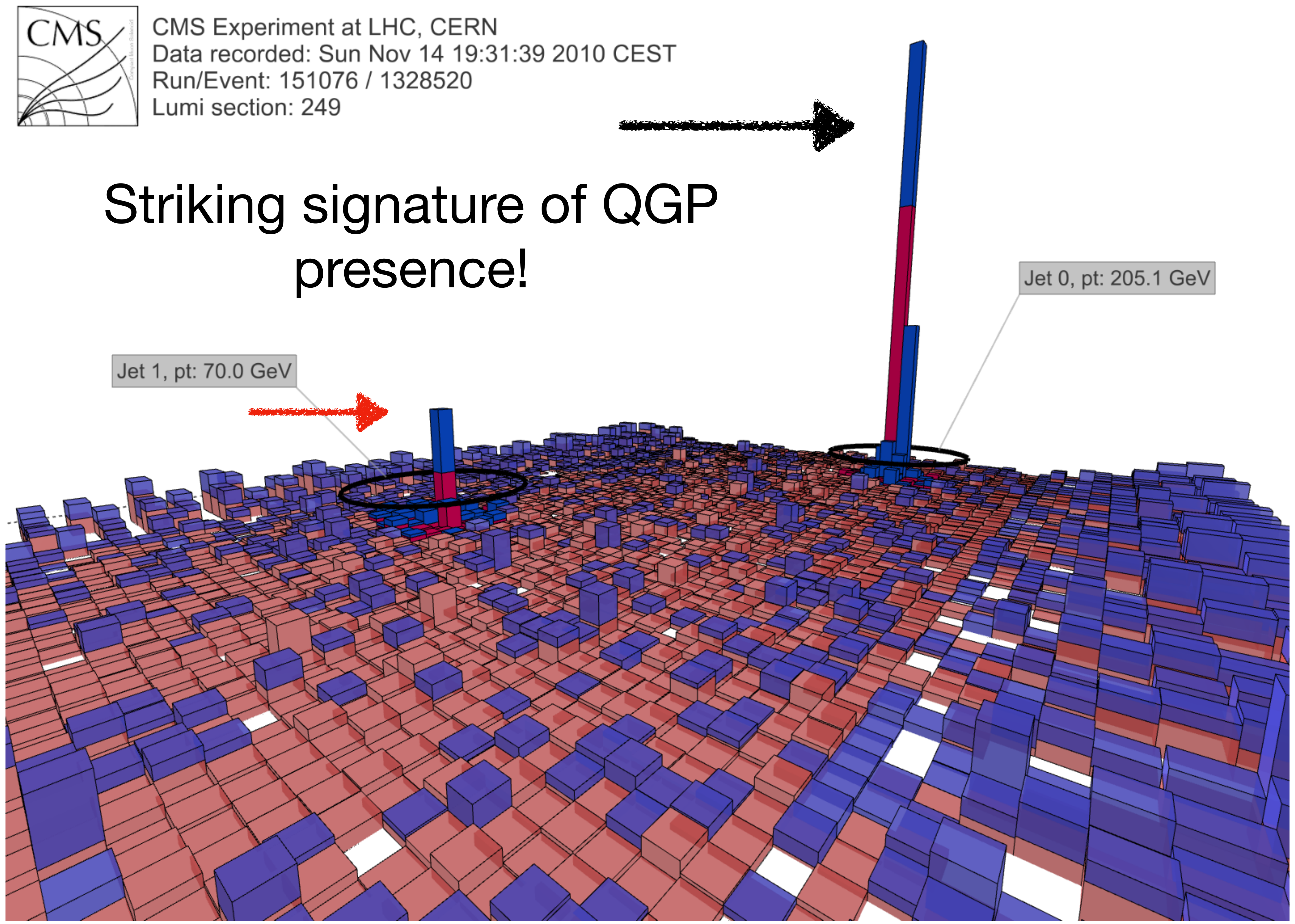
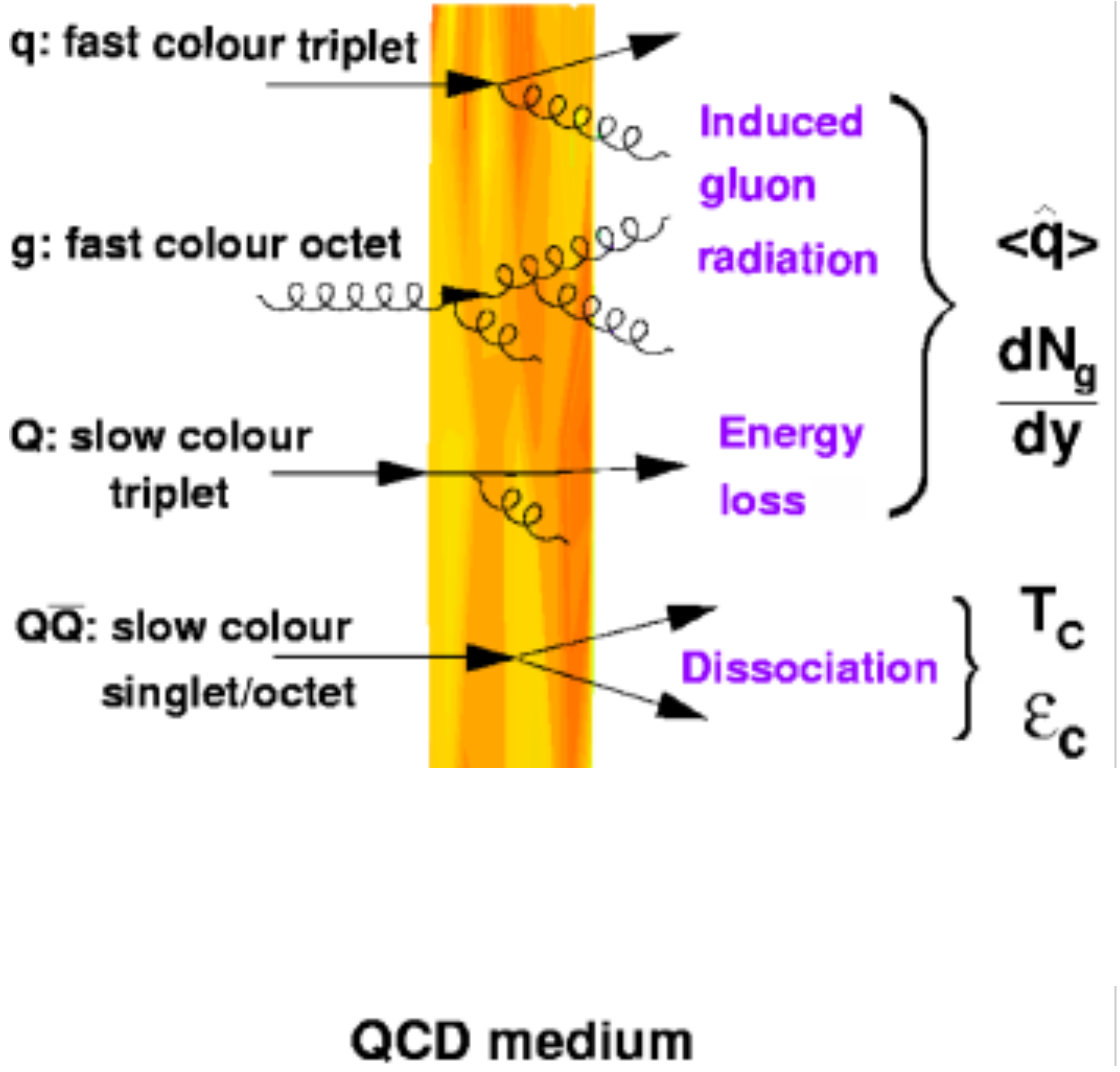
Striking signature of QGP presence!



Hard Probes

- Rare processes of high energy that are produced within the collision (hard scattering) and propagate through the QGP:
  - High momentum coloured objects:
    - Single particle measurements (B-meson, quarkonia,…)
    - Jets (Inclusive jets, b-initiated jets, …)



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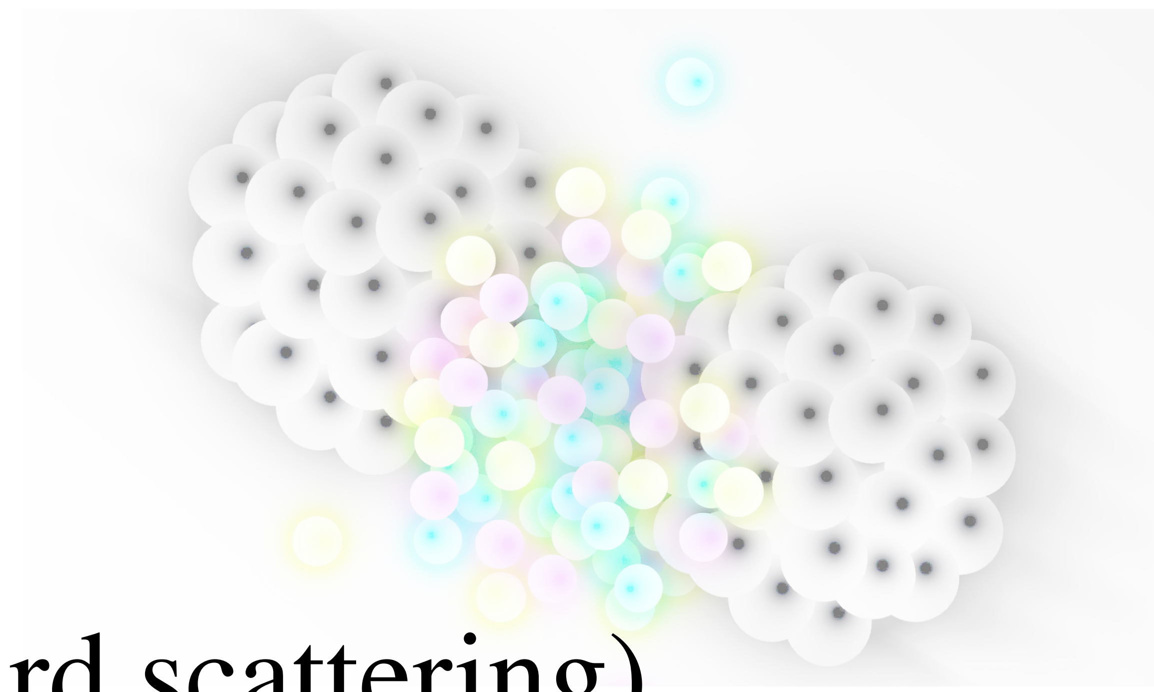

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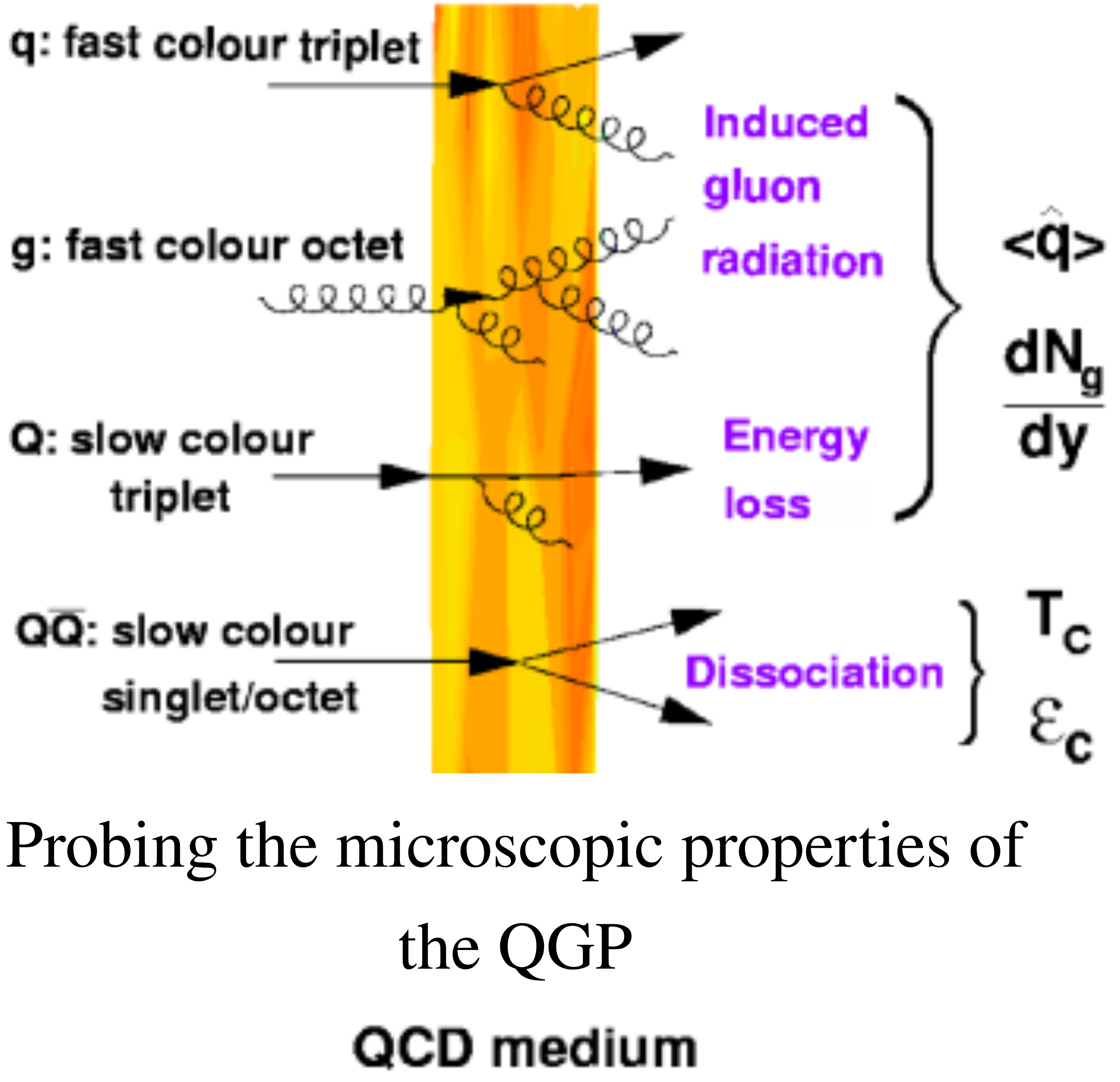
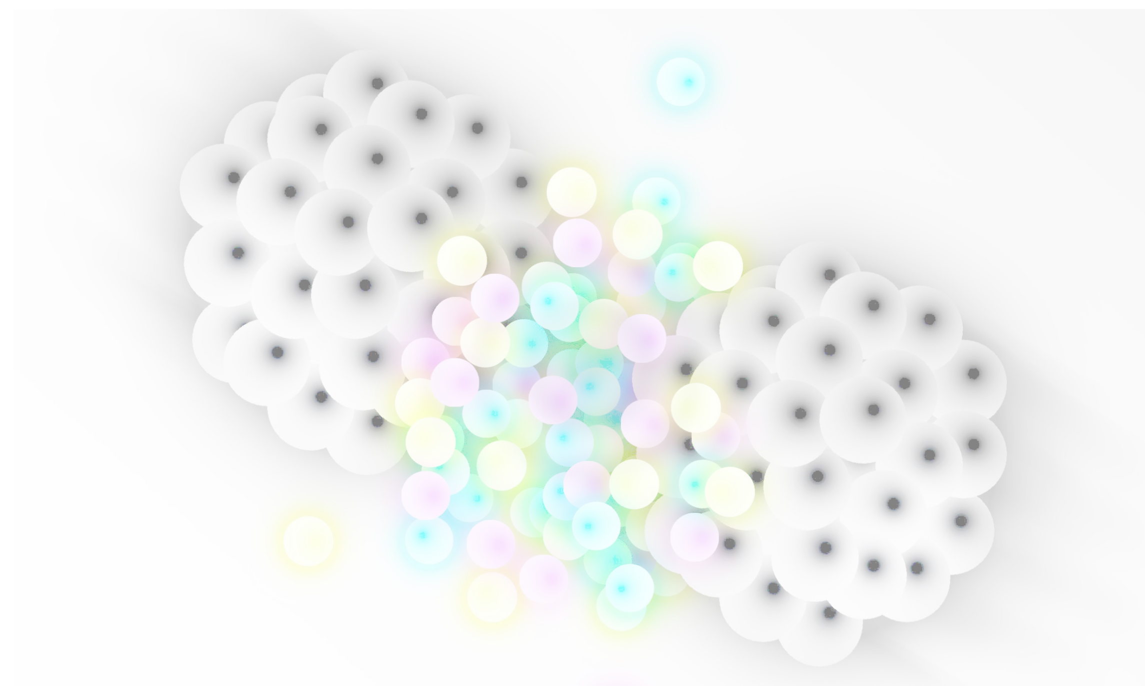


Theoretical description of interaction with QGP ⟷ Experimental Data

Probing the microscopic properties of the QGP

Hard Probes



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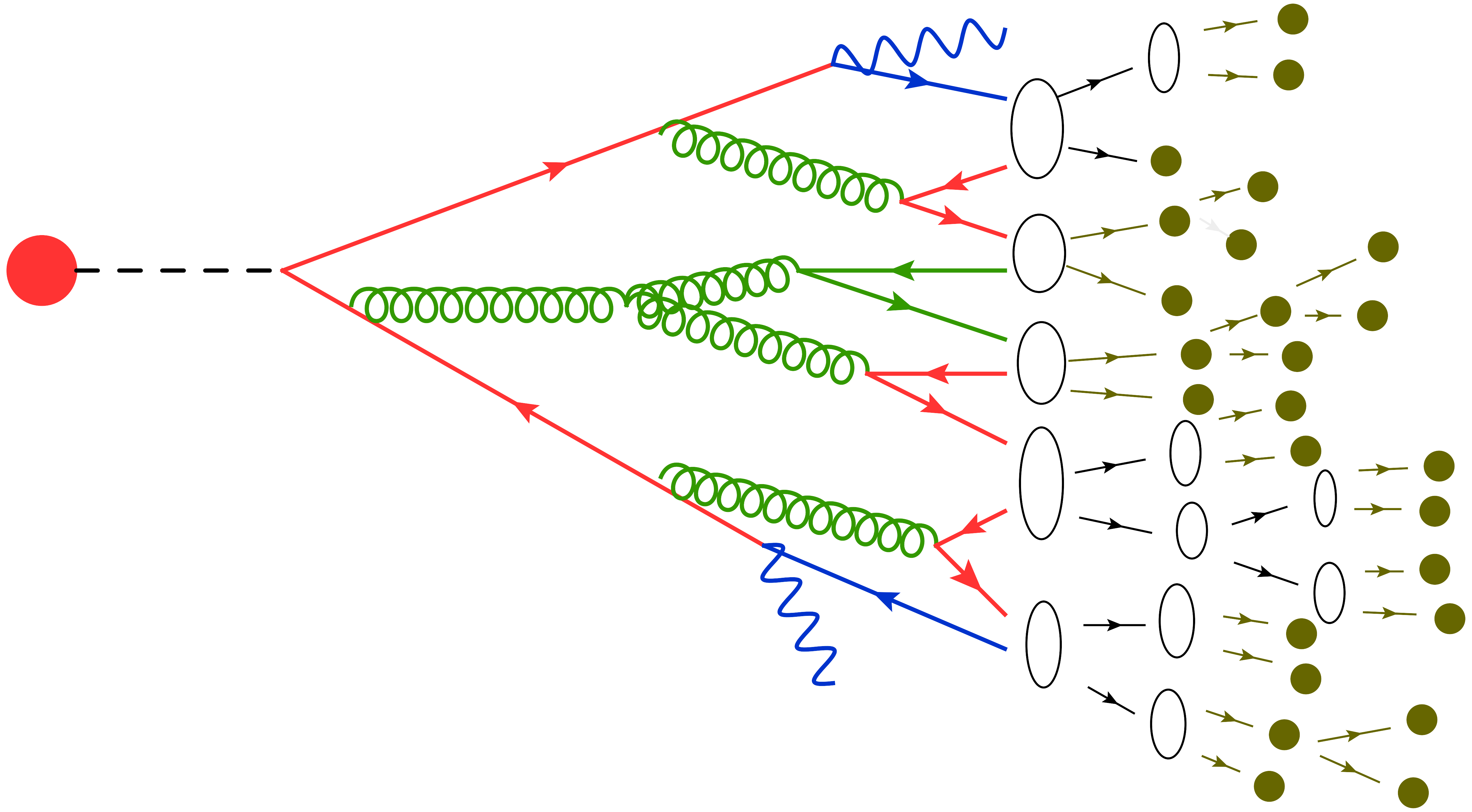

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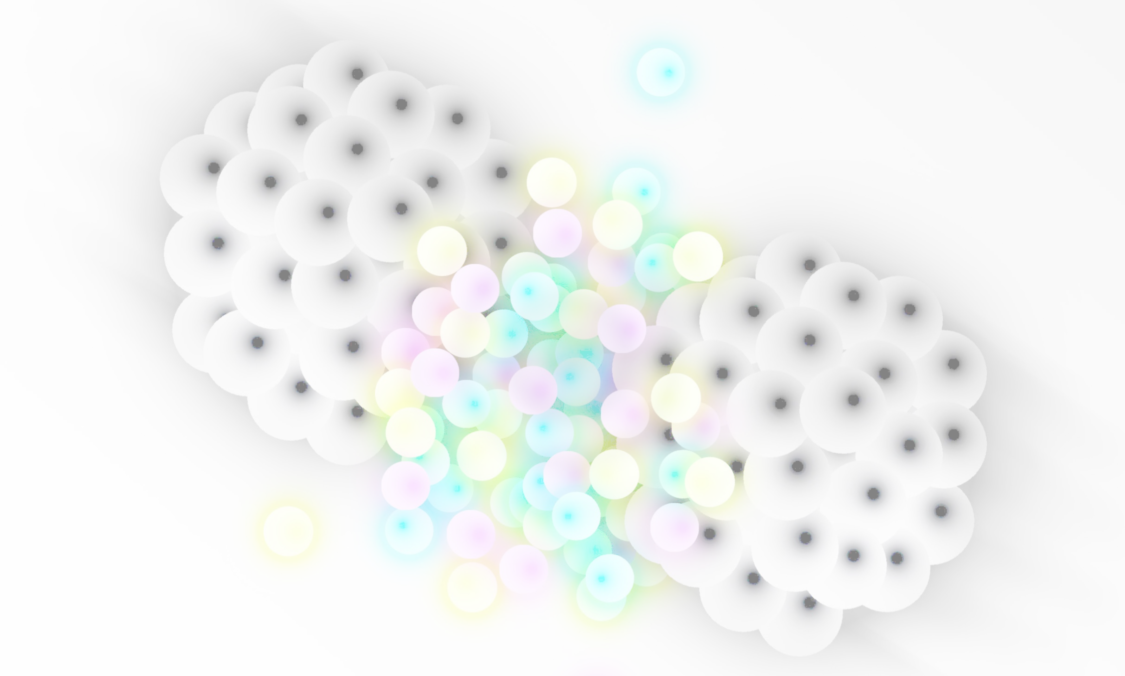

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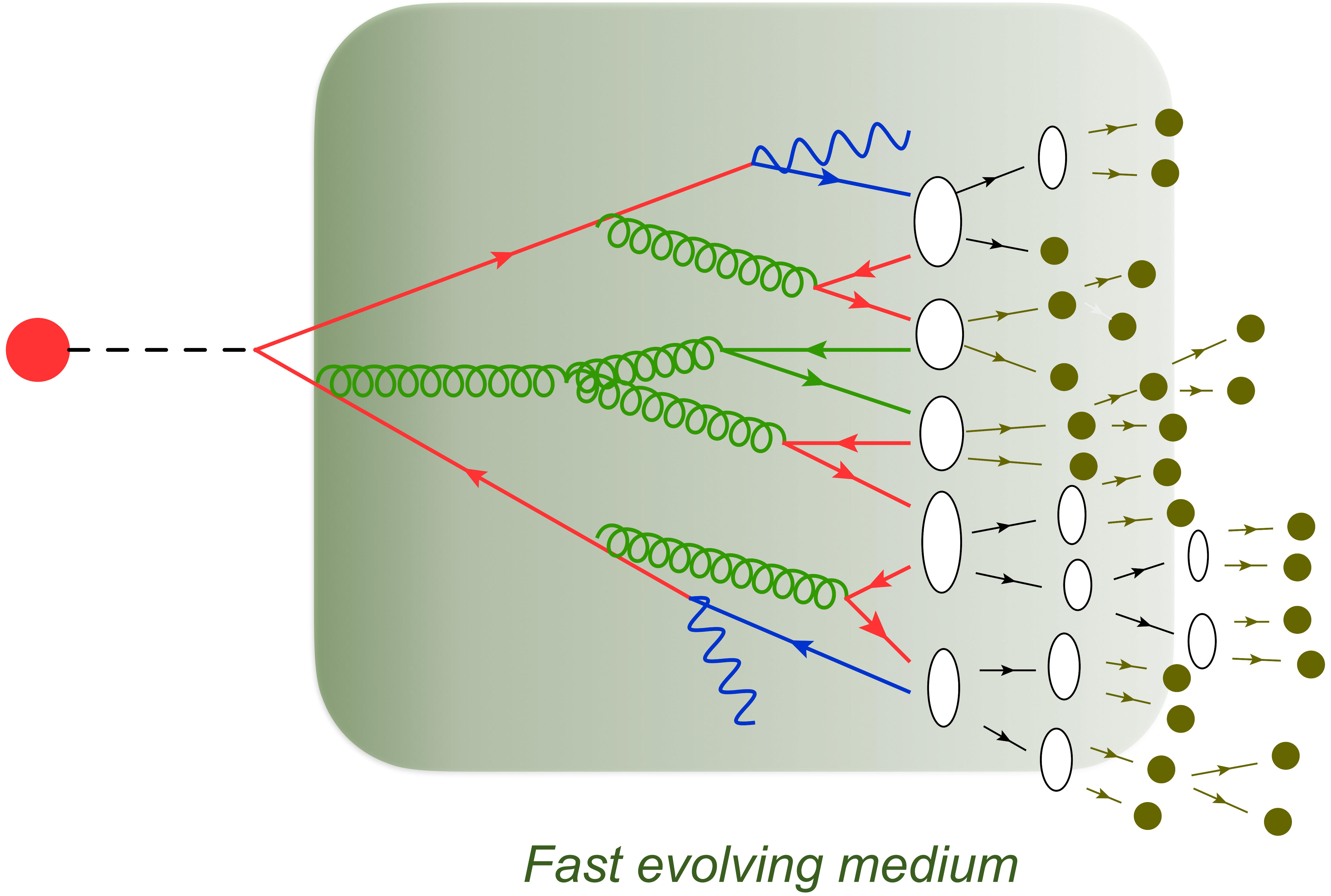

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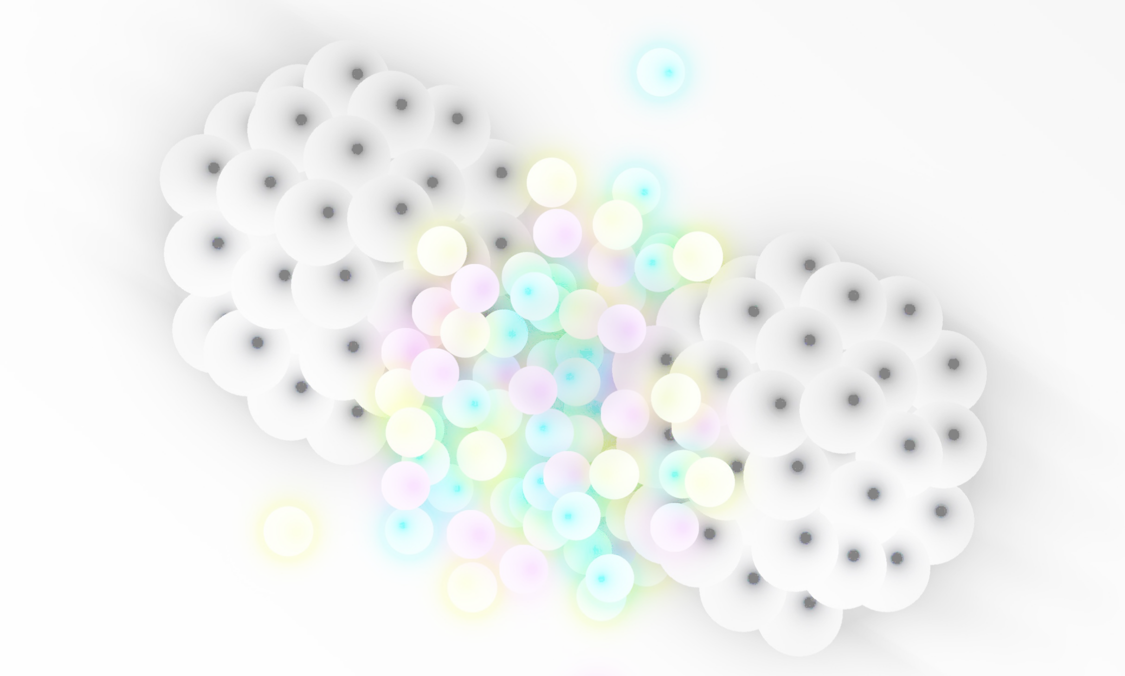

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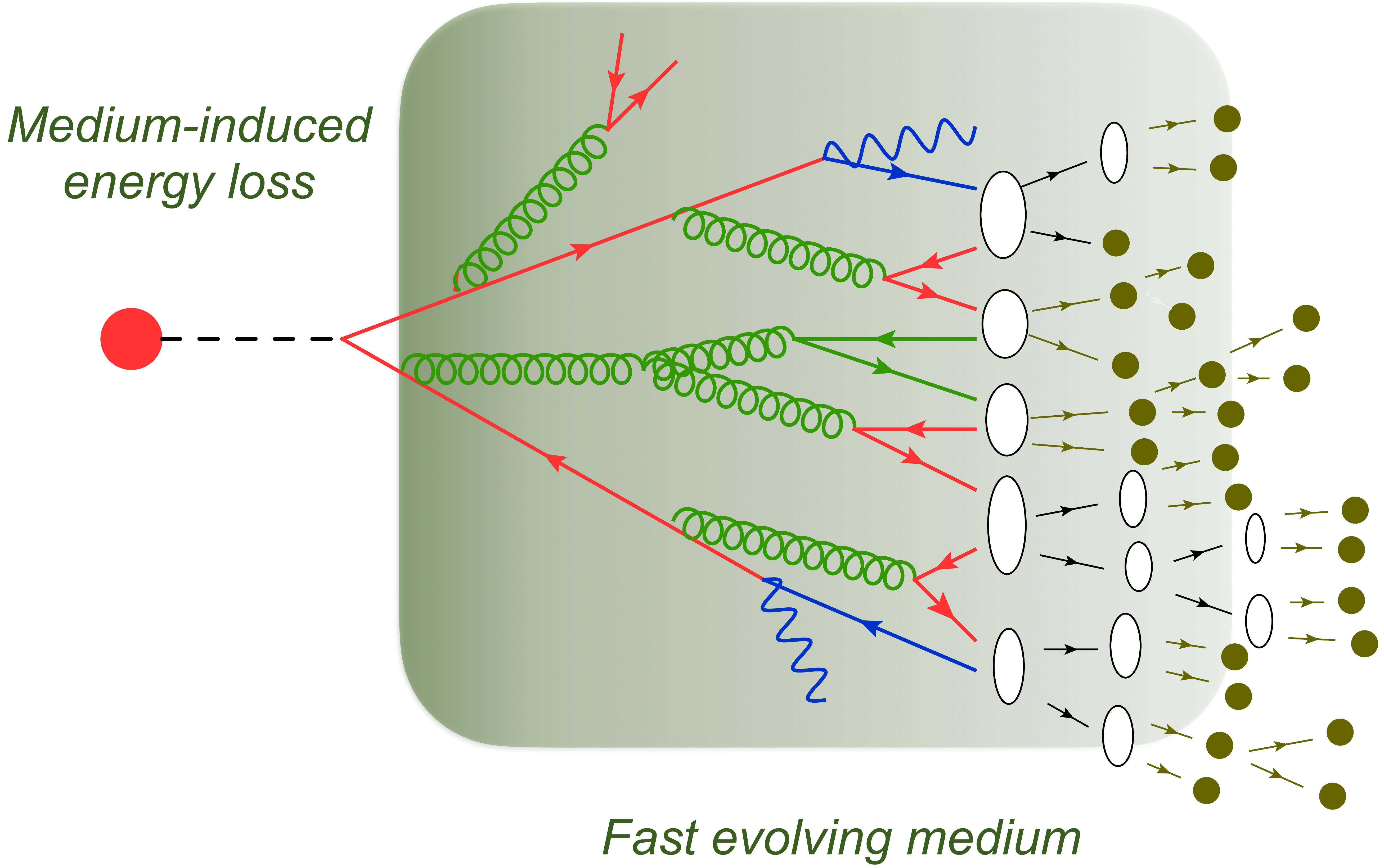

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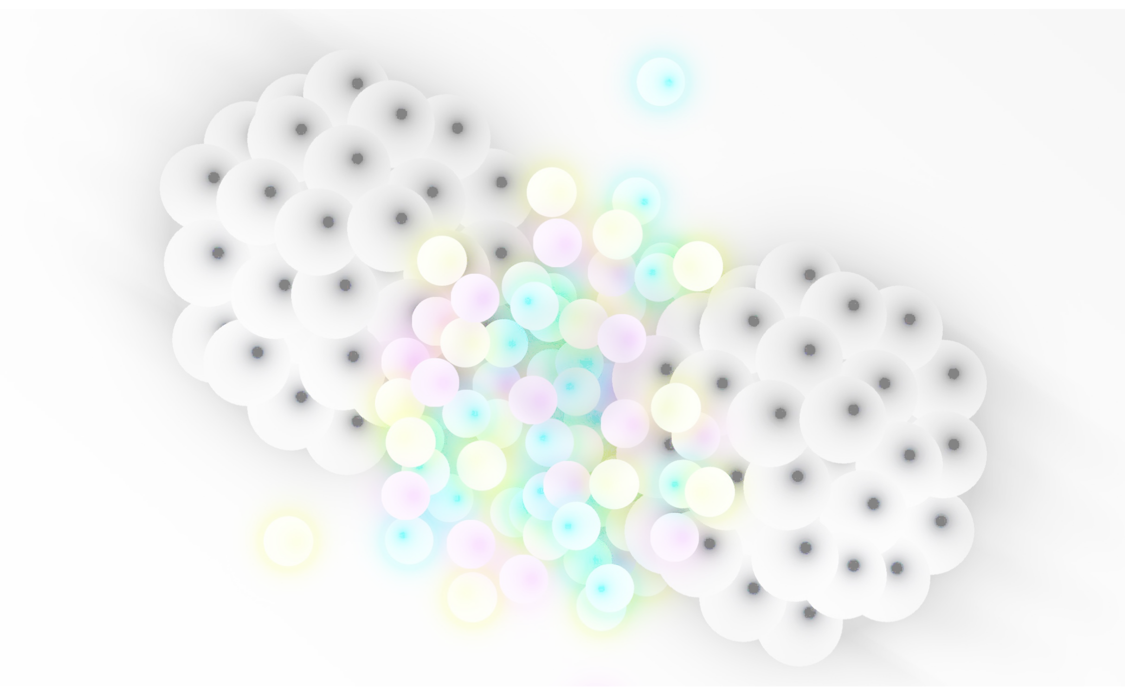

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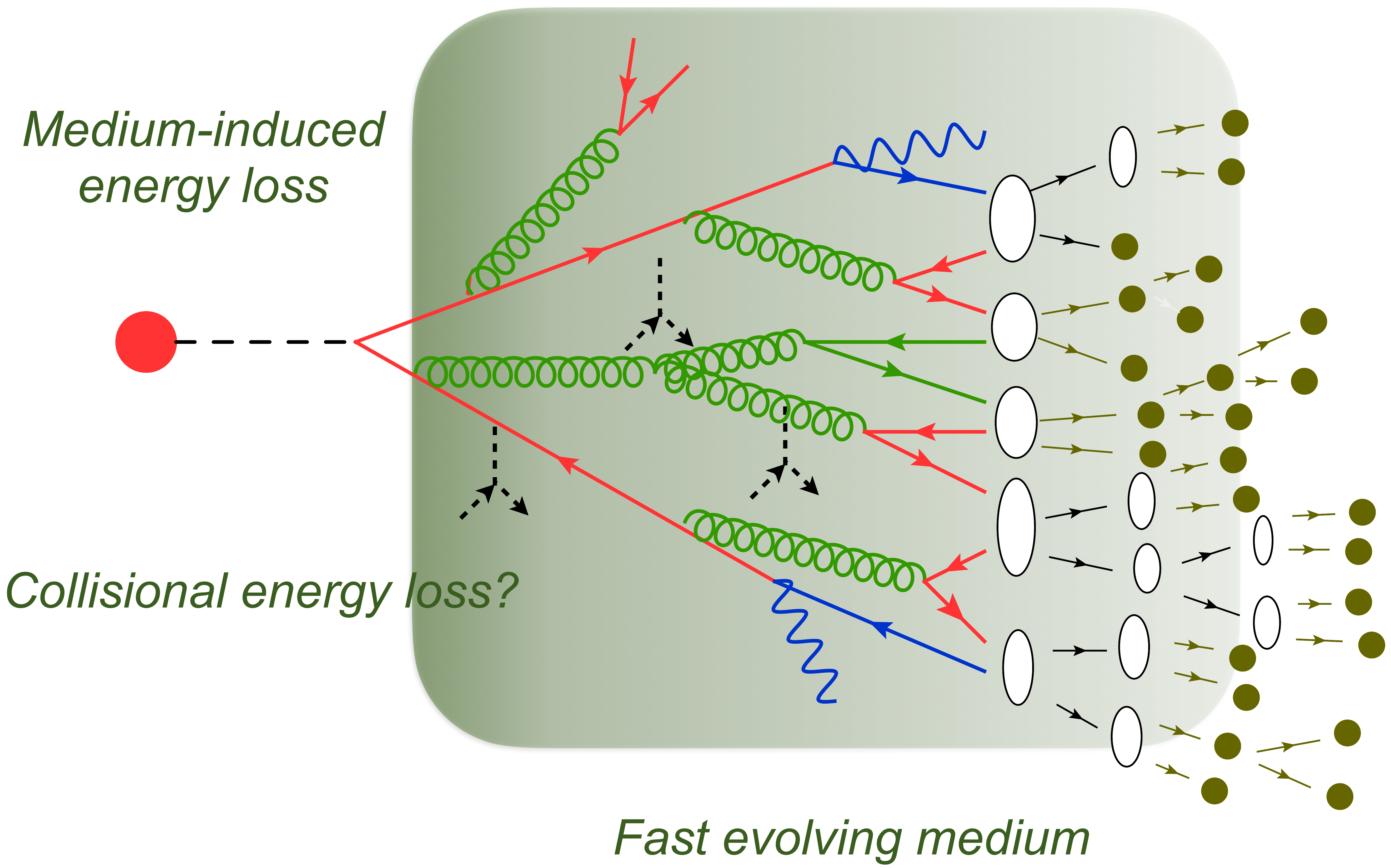

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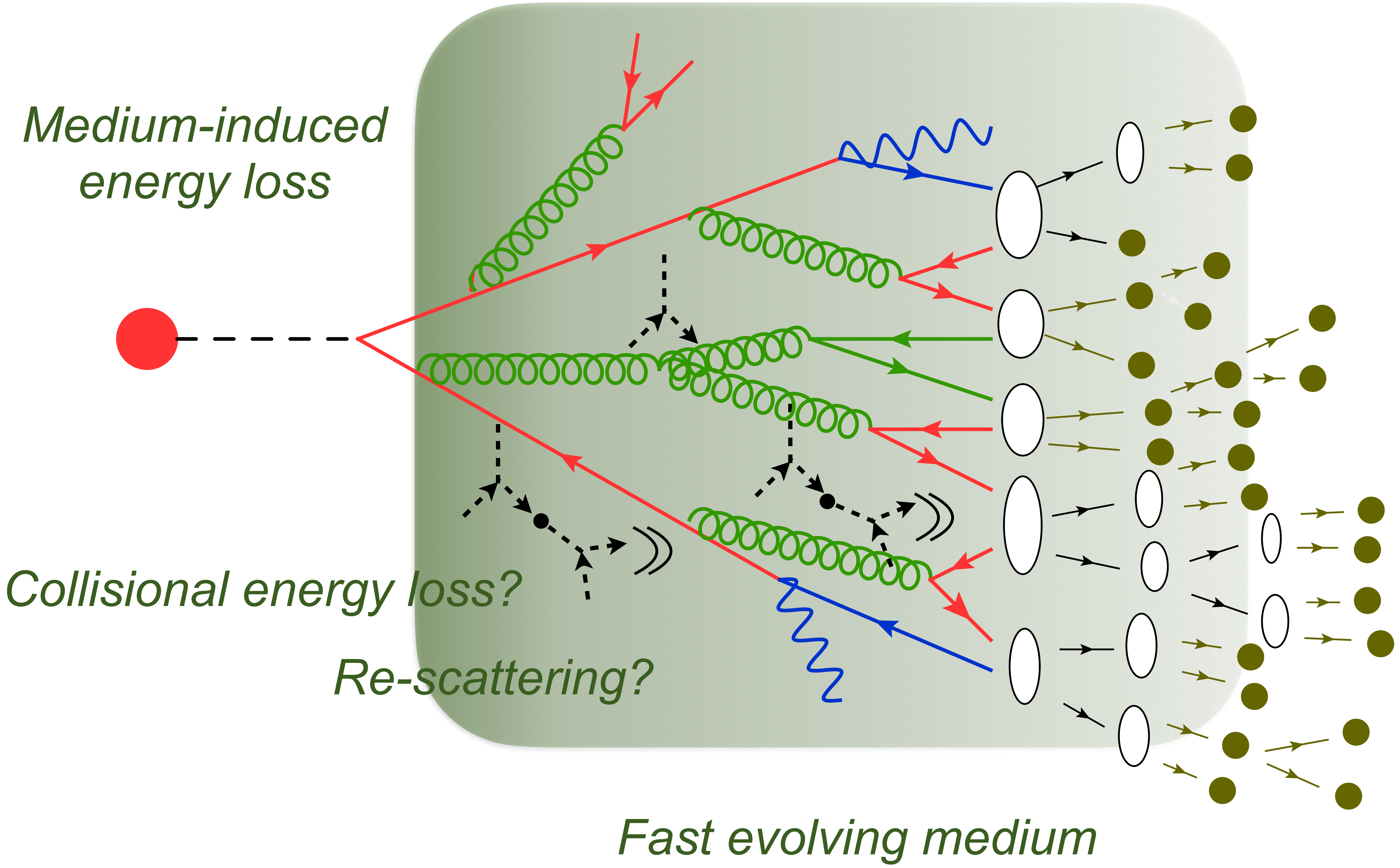

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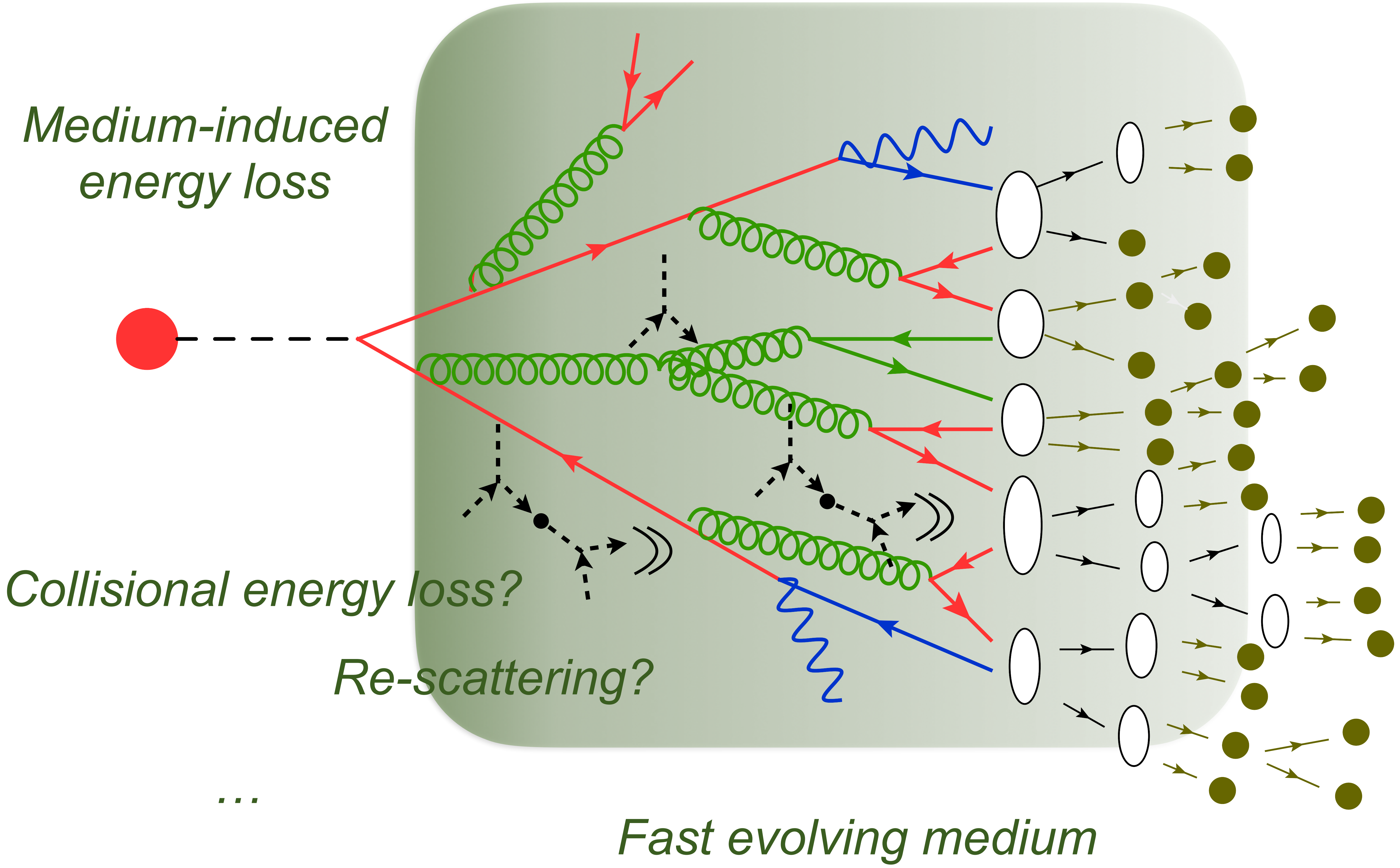

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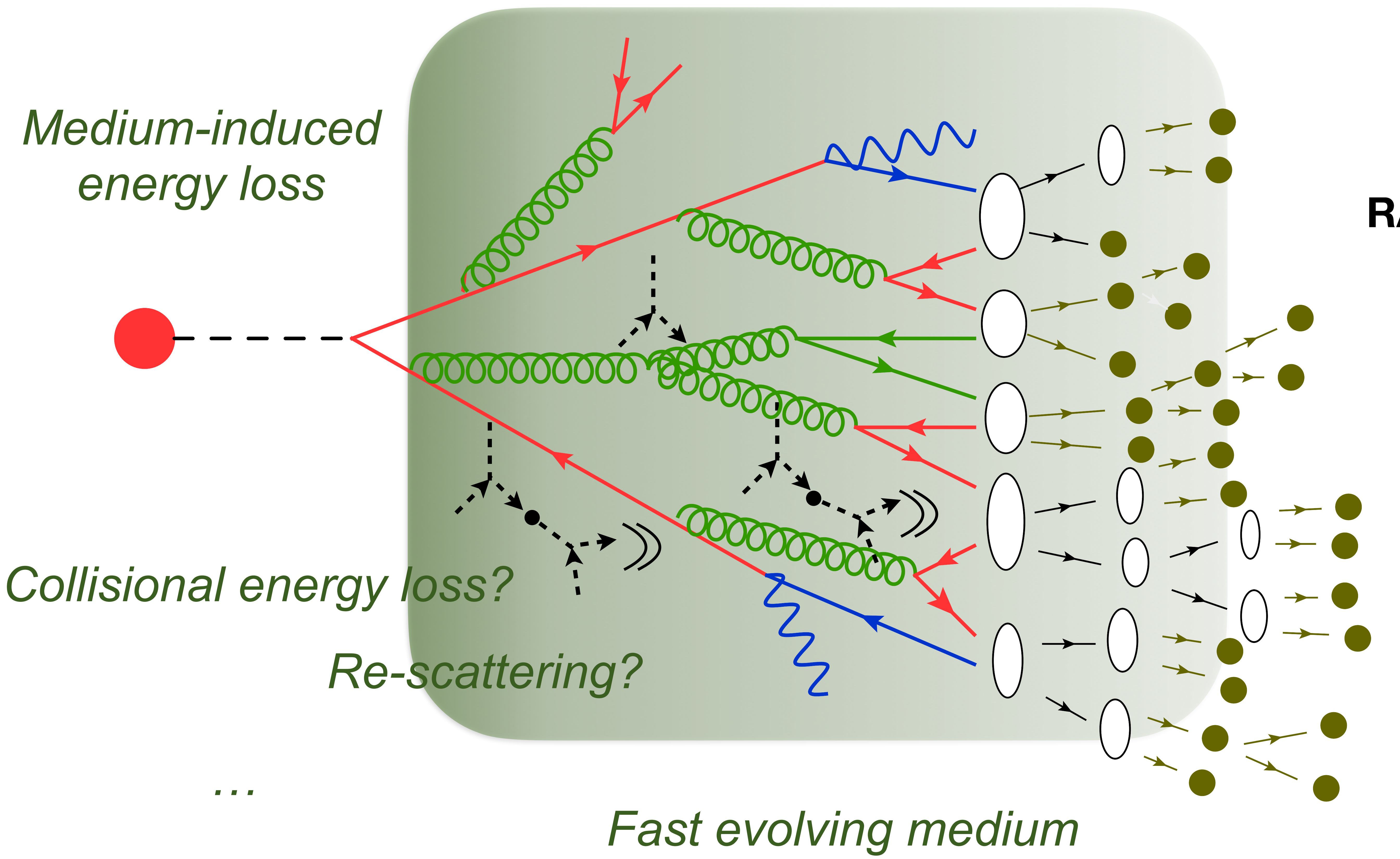
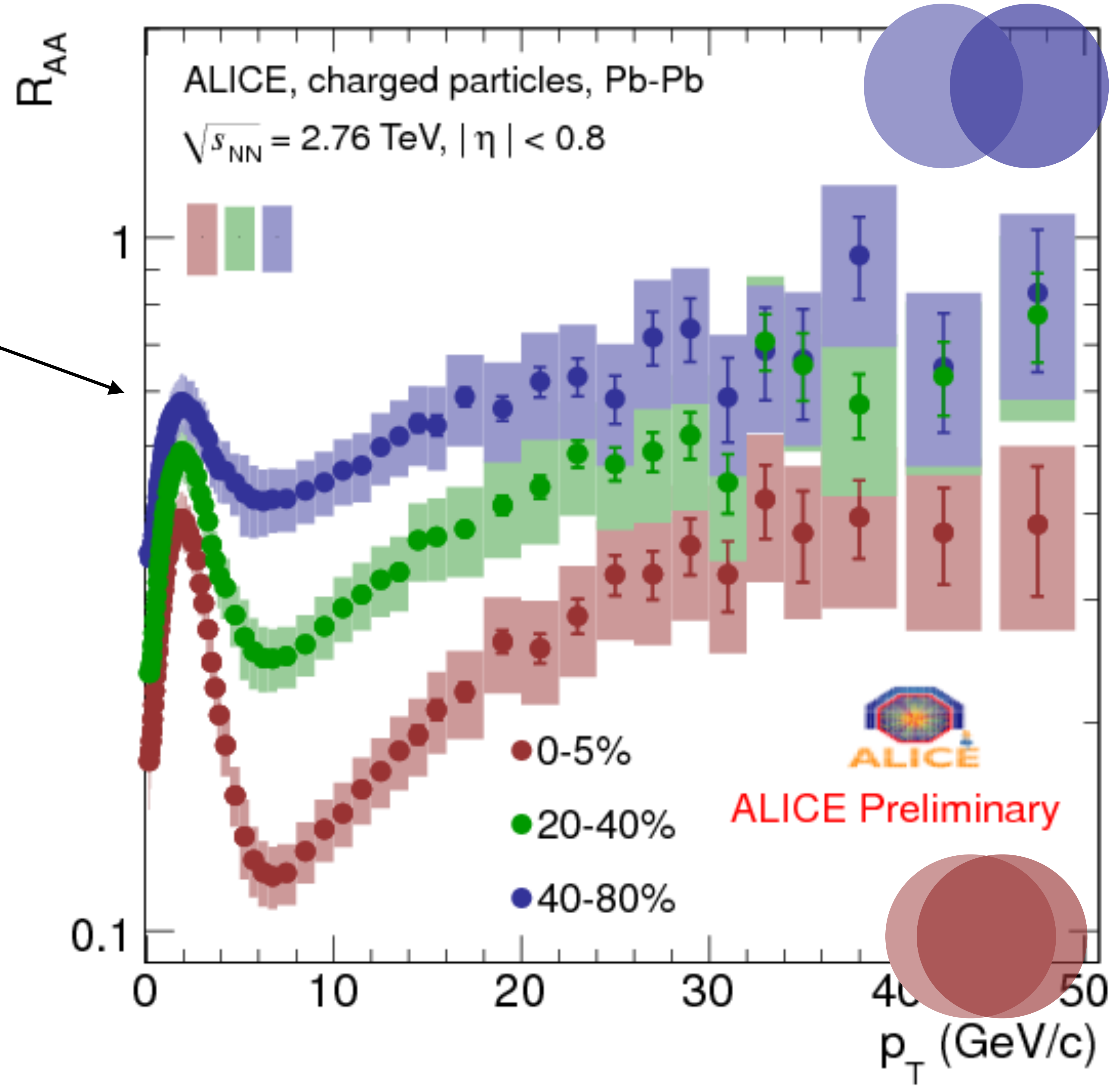


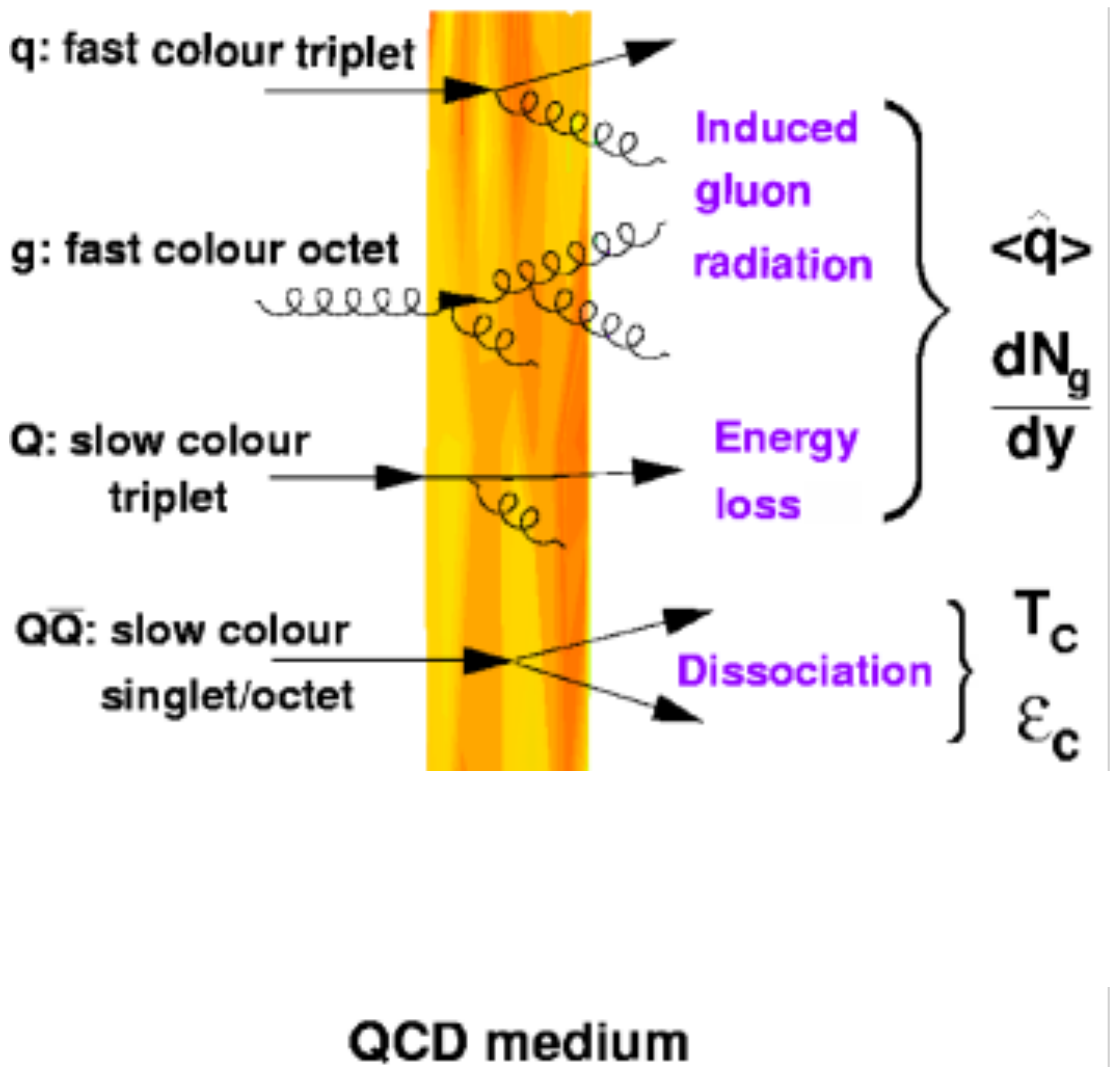
$$\text{RAA} = \frac{\text{\# Particles in PbPb}}{\text{(\#Particles in pp) x (\#pp collisions)}}$$

RAA < 1



Color Neutral Probes

- Colourless objects (Photon, W-boson,…) do not interact with the QGP
    - Reference (without the need to compare to pp collisions)



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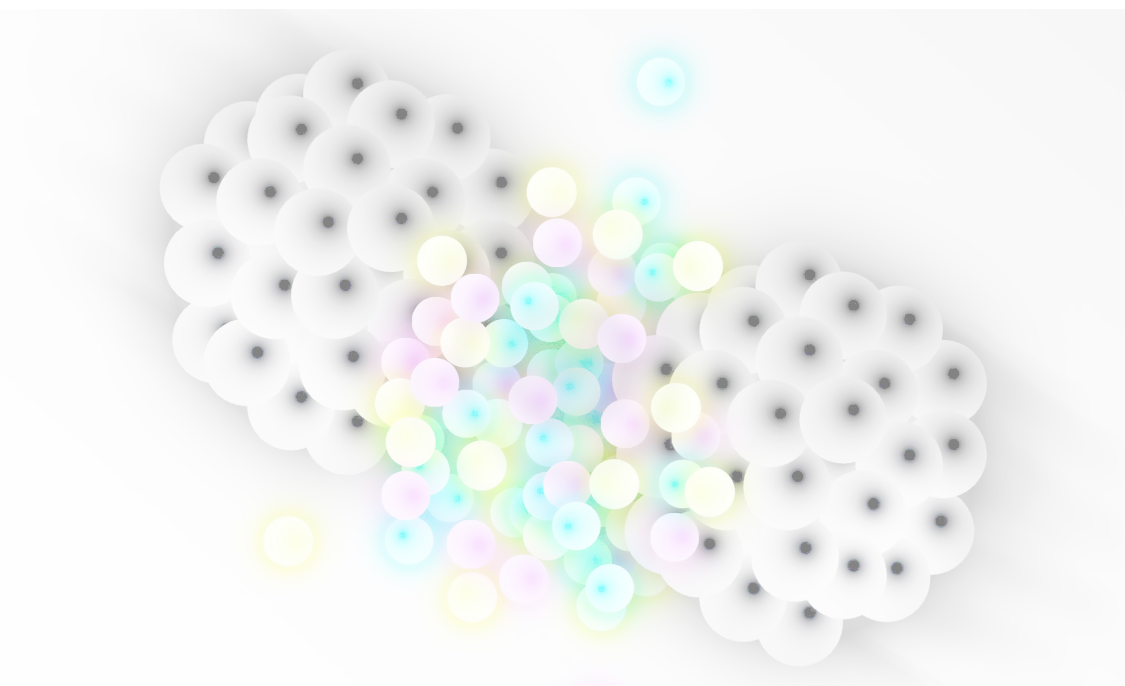

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Color neutral objects

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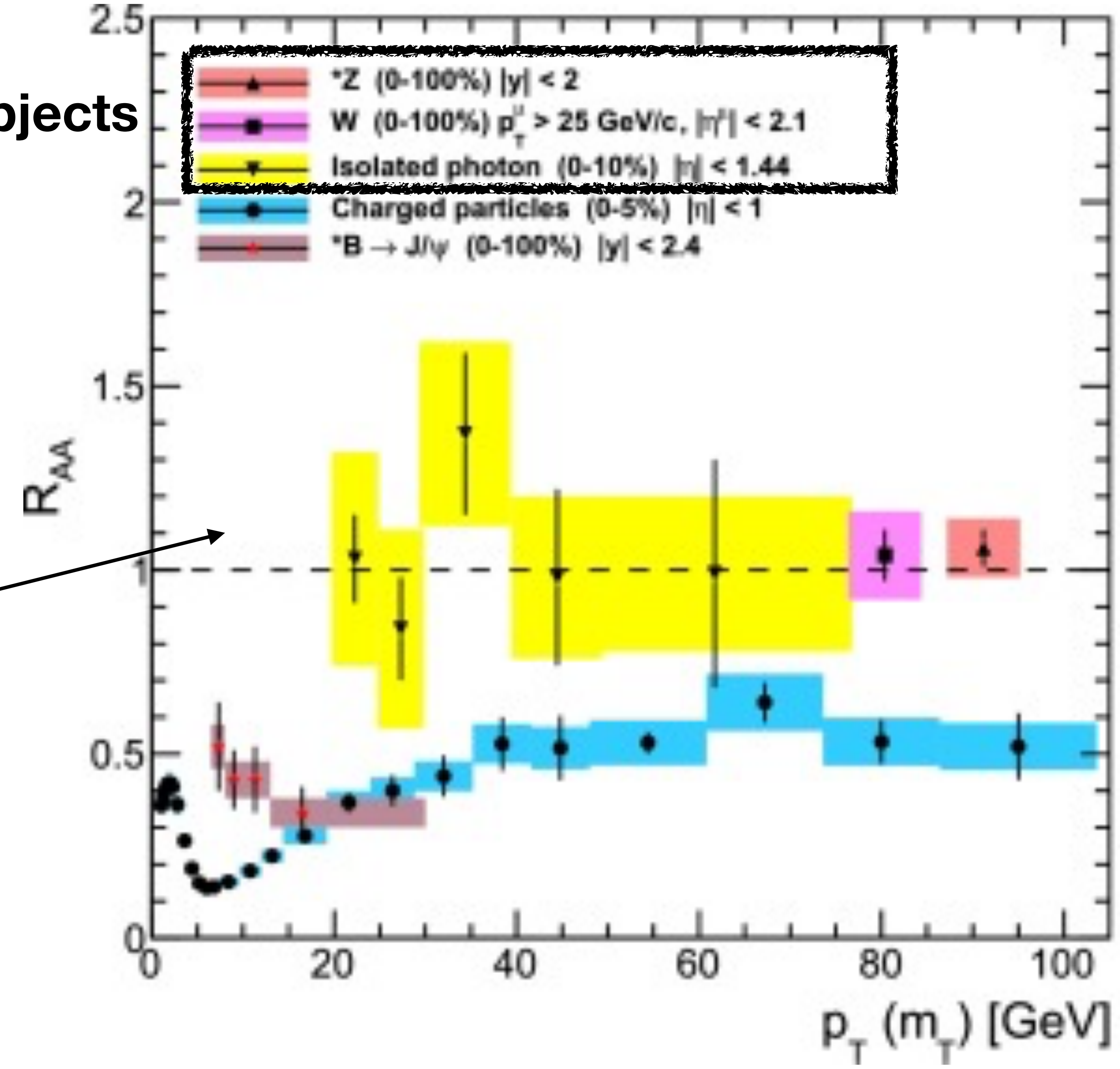

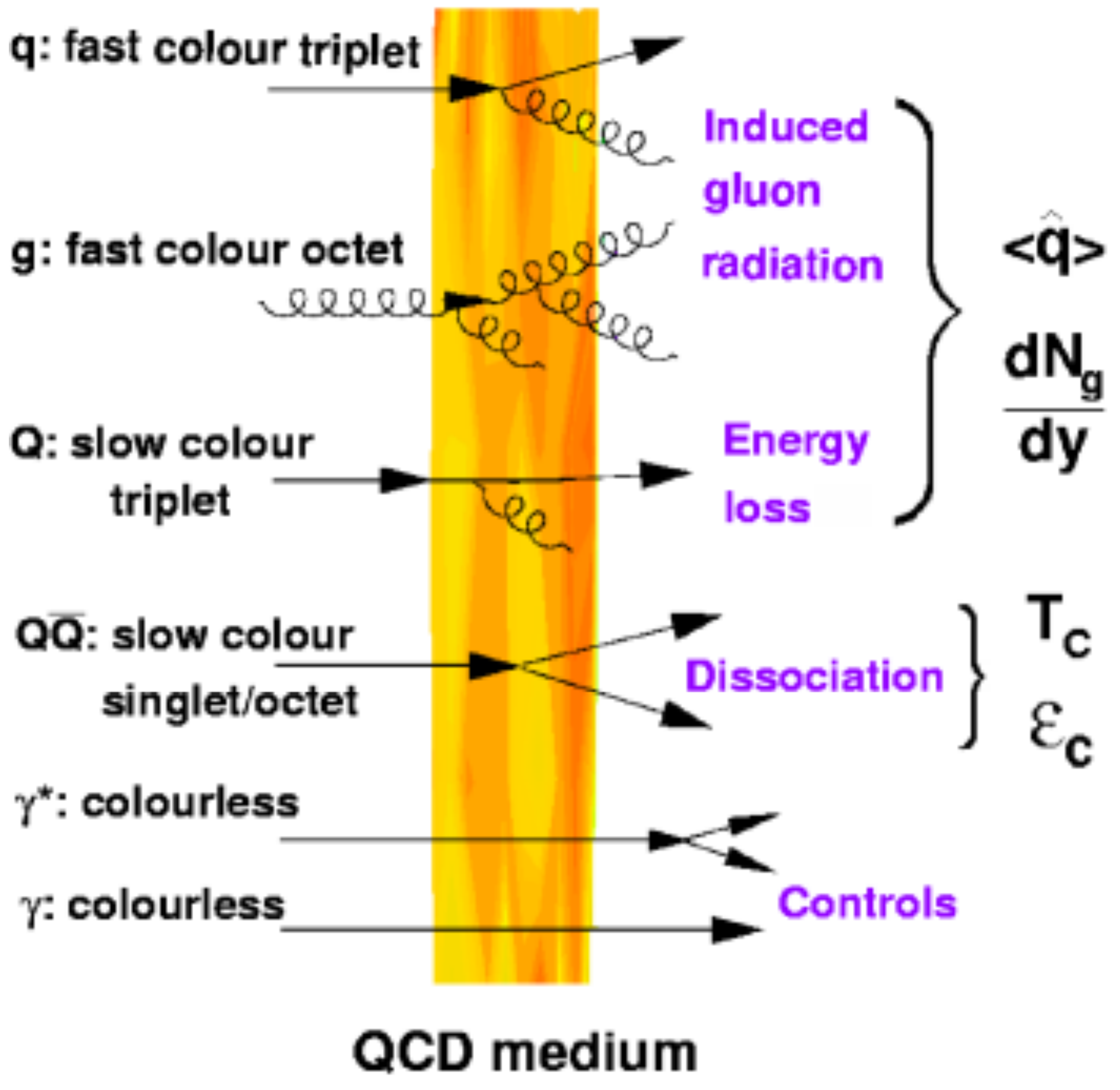

And more on Hard Probes

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    - Lots of new opportunities to test frontiers of QCD and unveil QGP characteristics

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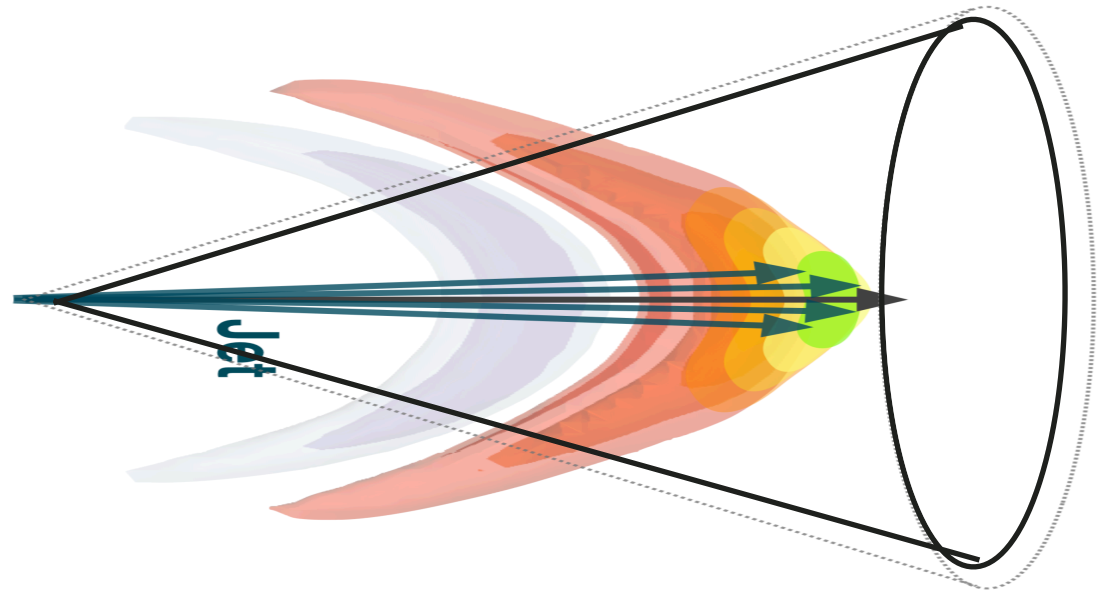
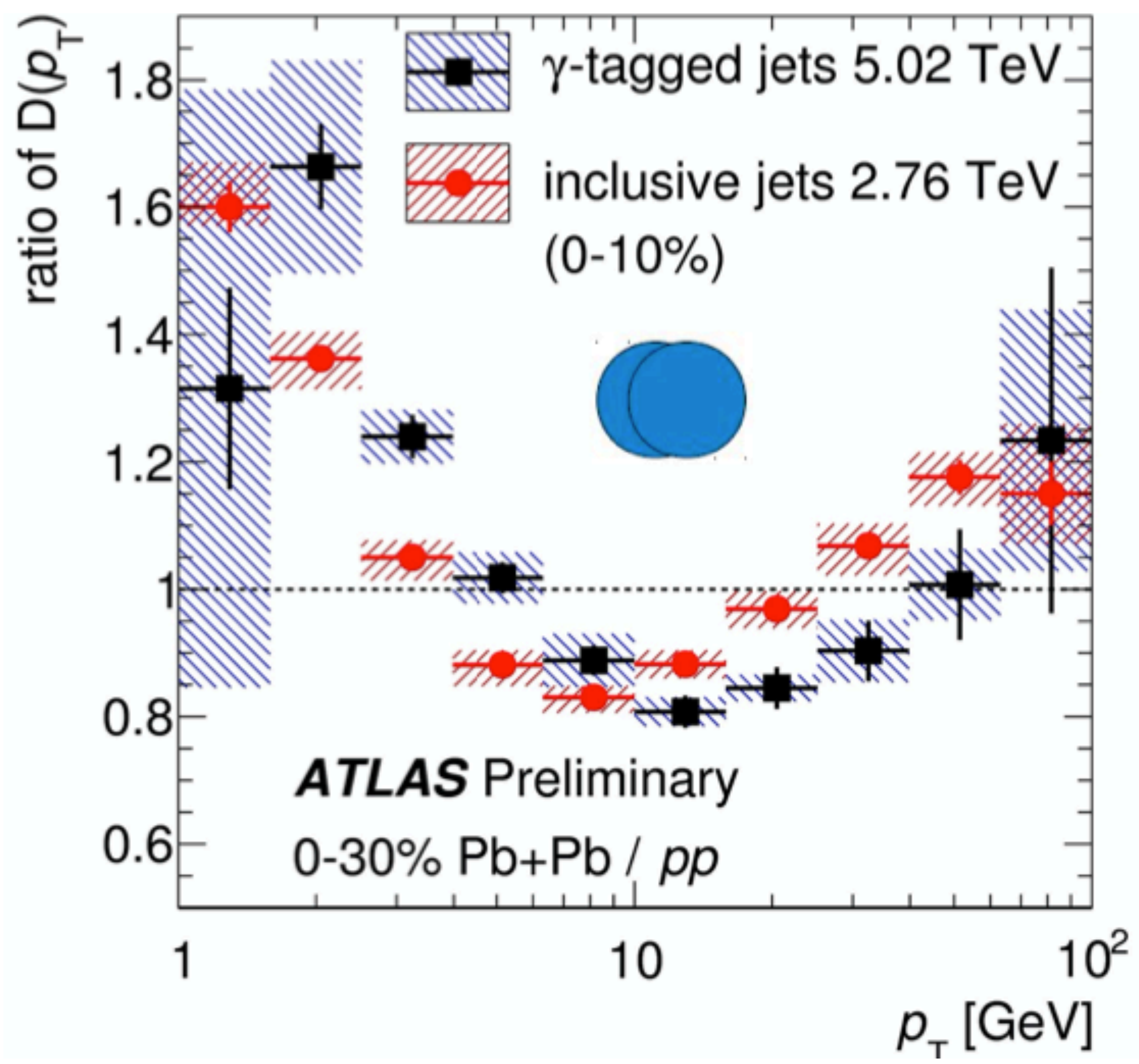


Looking inside of (large radius) jets to check energy/momentum deposition



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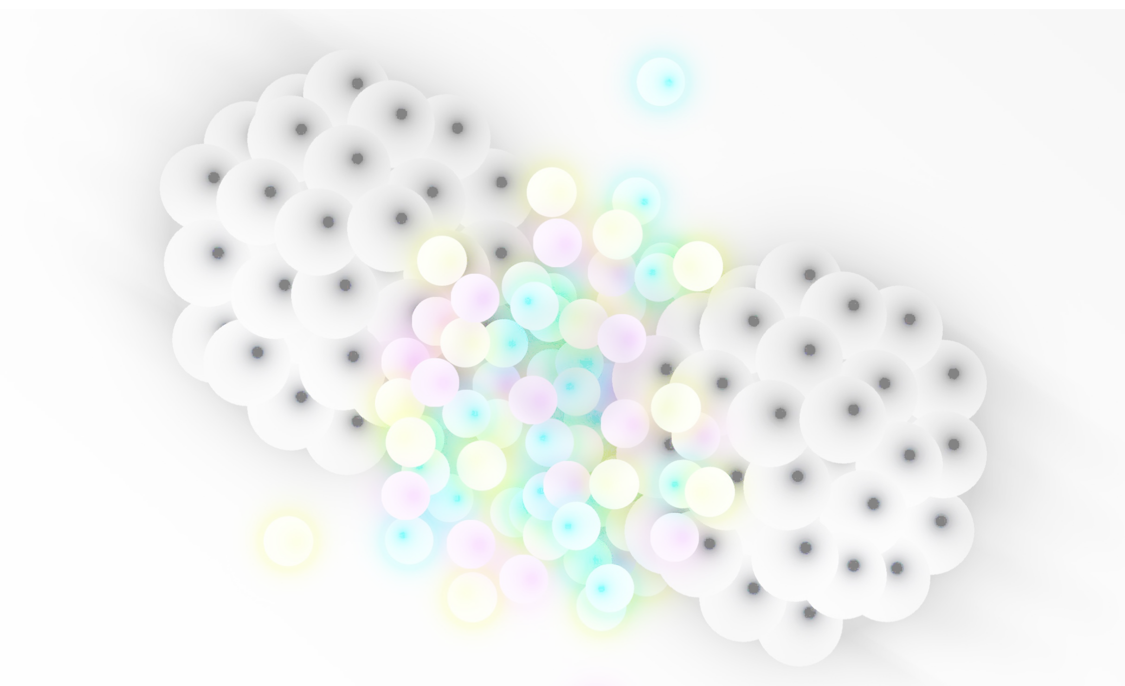

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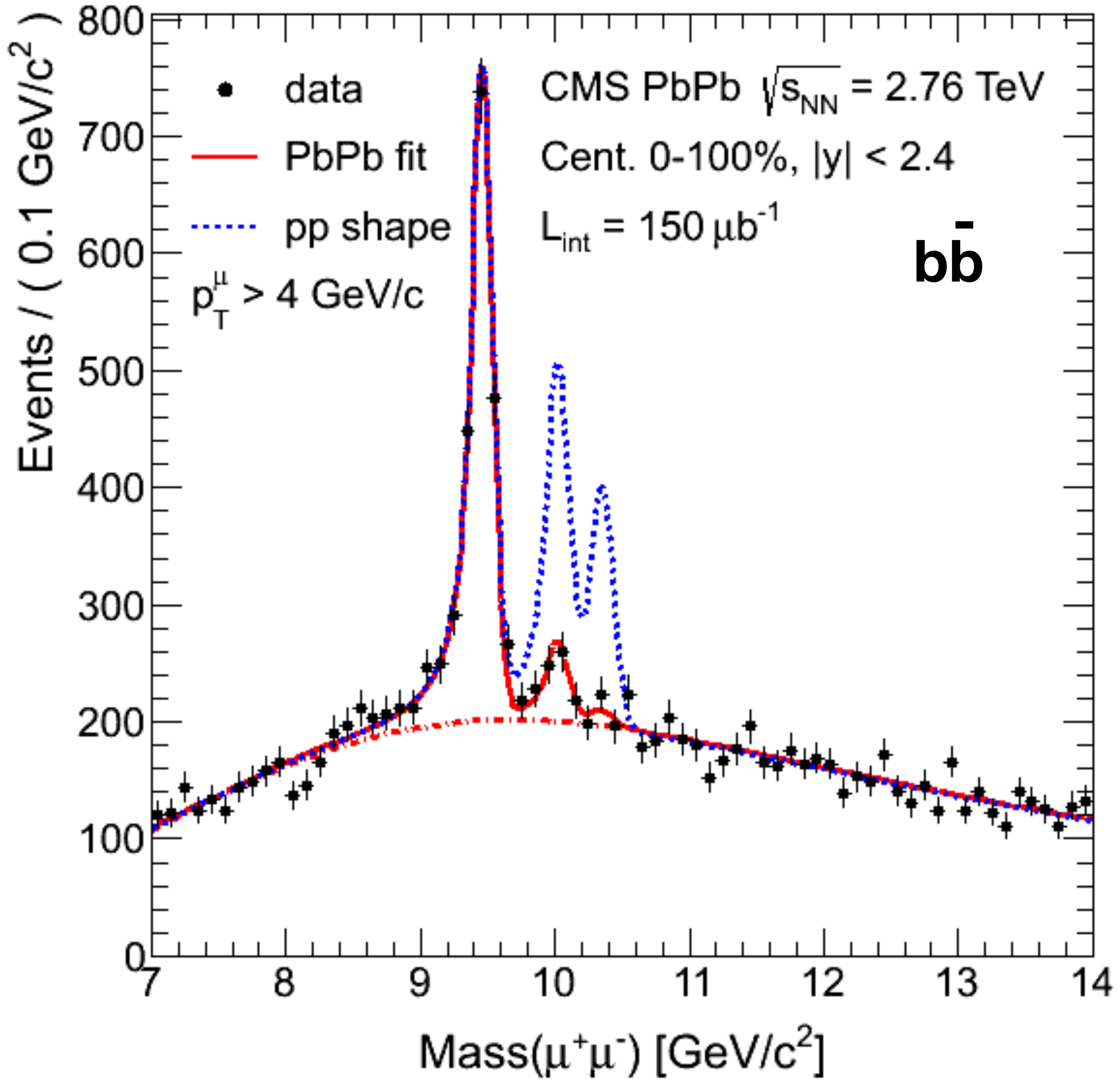
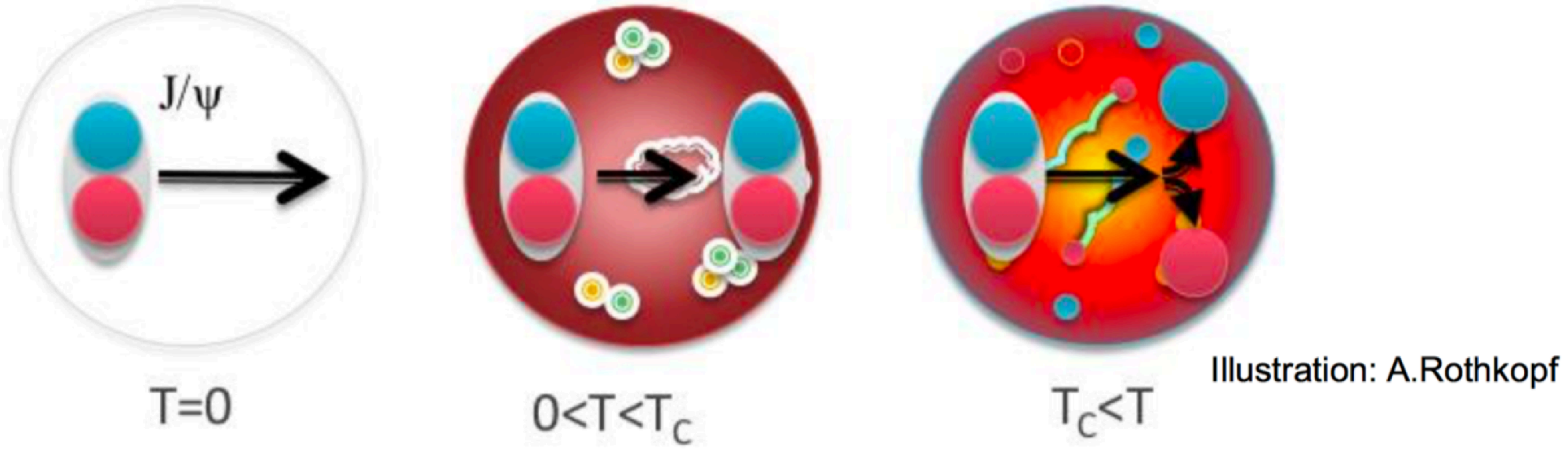
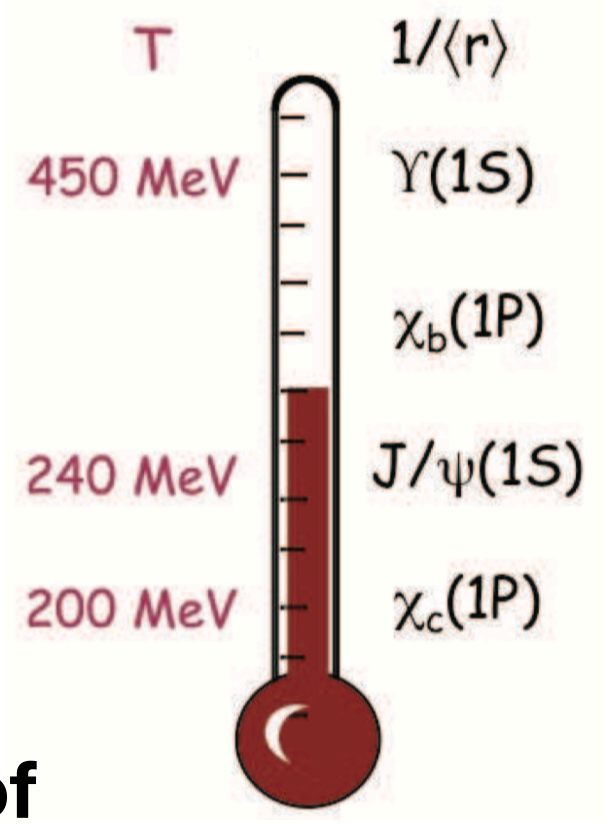


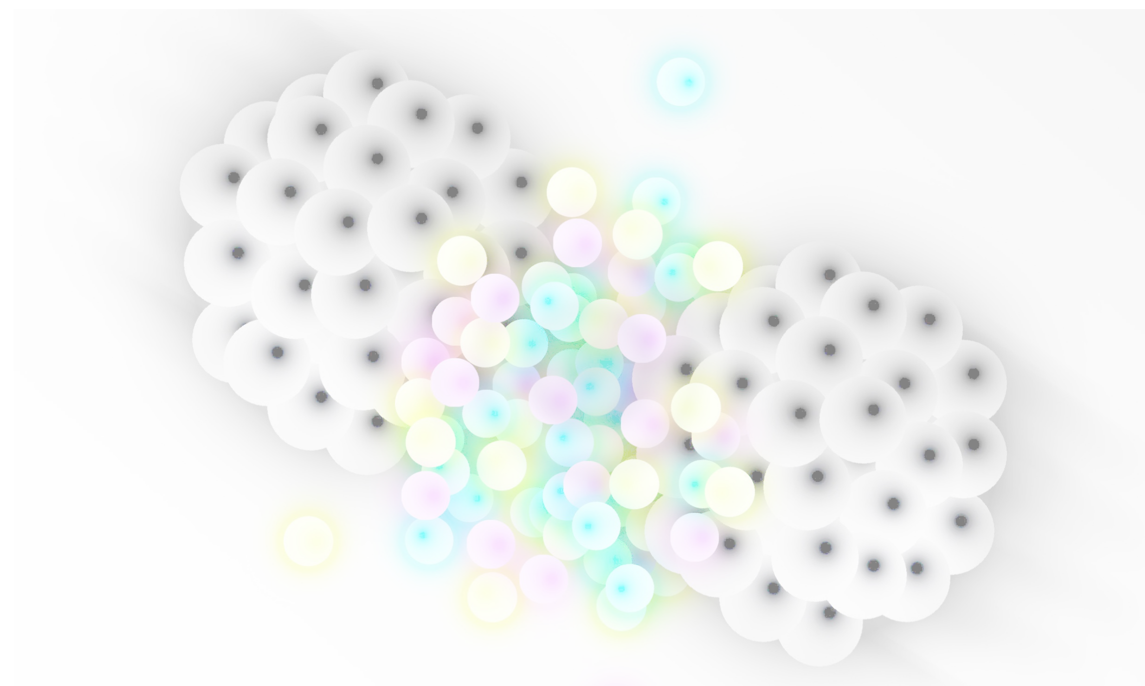
How fast is QGP evolution? How is the temperature/density evolving?





Measuring rate of quarkonia state can give map of the QGP temperature evolution

And more on Hard Probes



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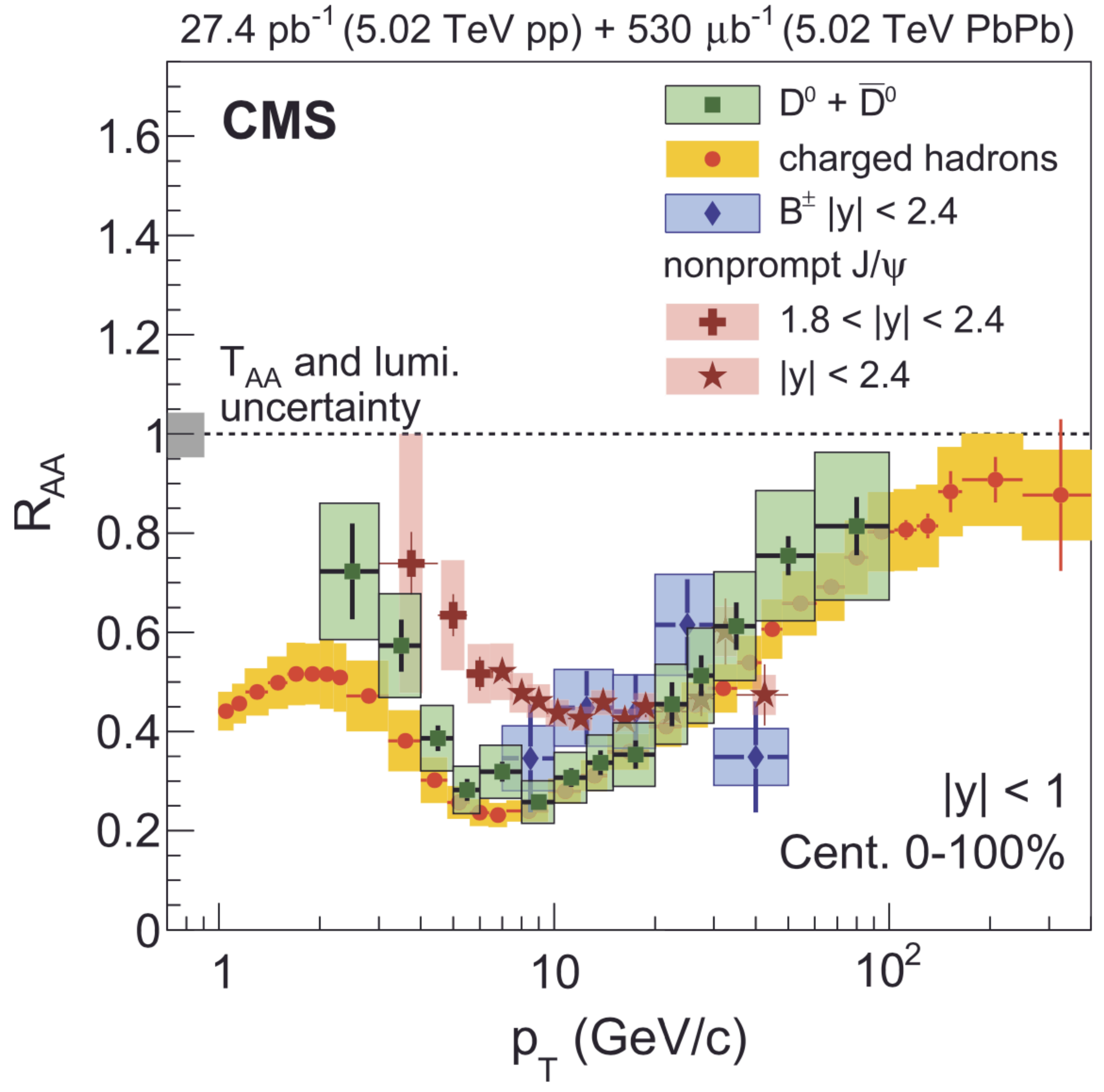
Are heavy-quarks modified by the QGP?

Flavour dependency (QGP does not alter flavour, but can affect phase space for medium-induced processes)



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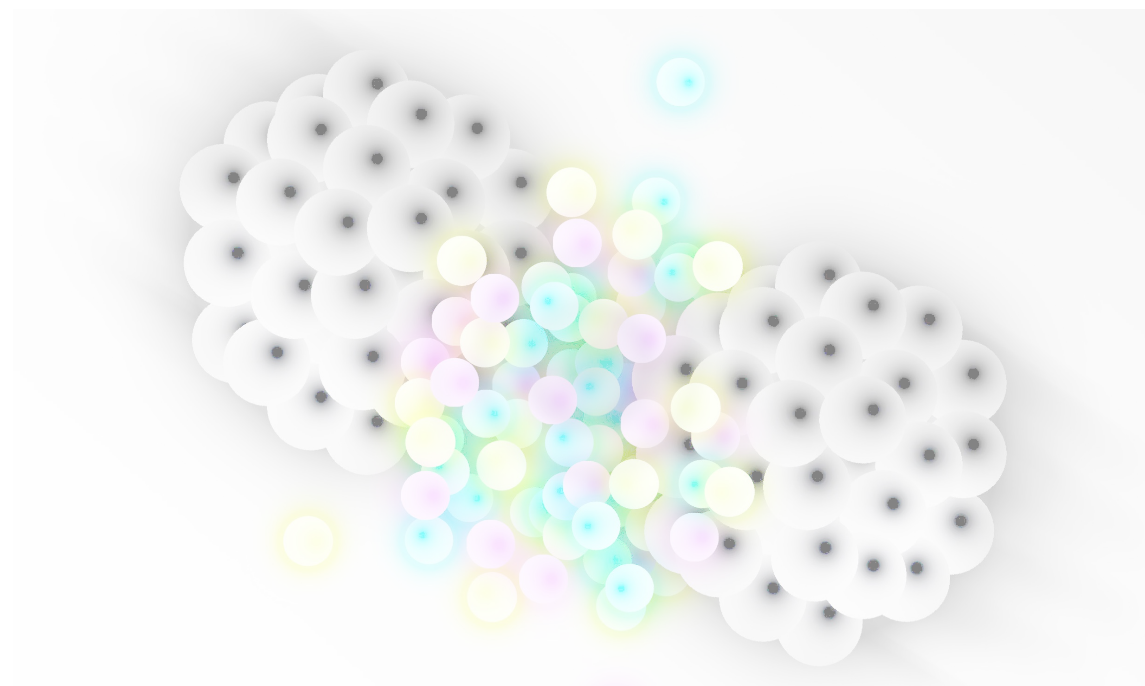

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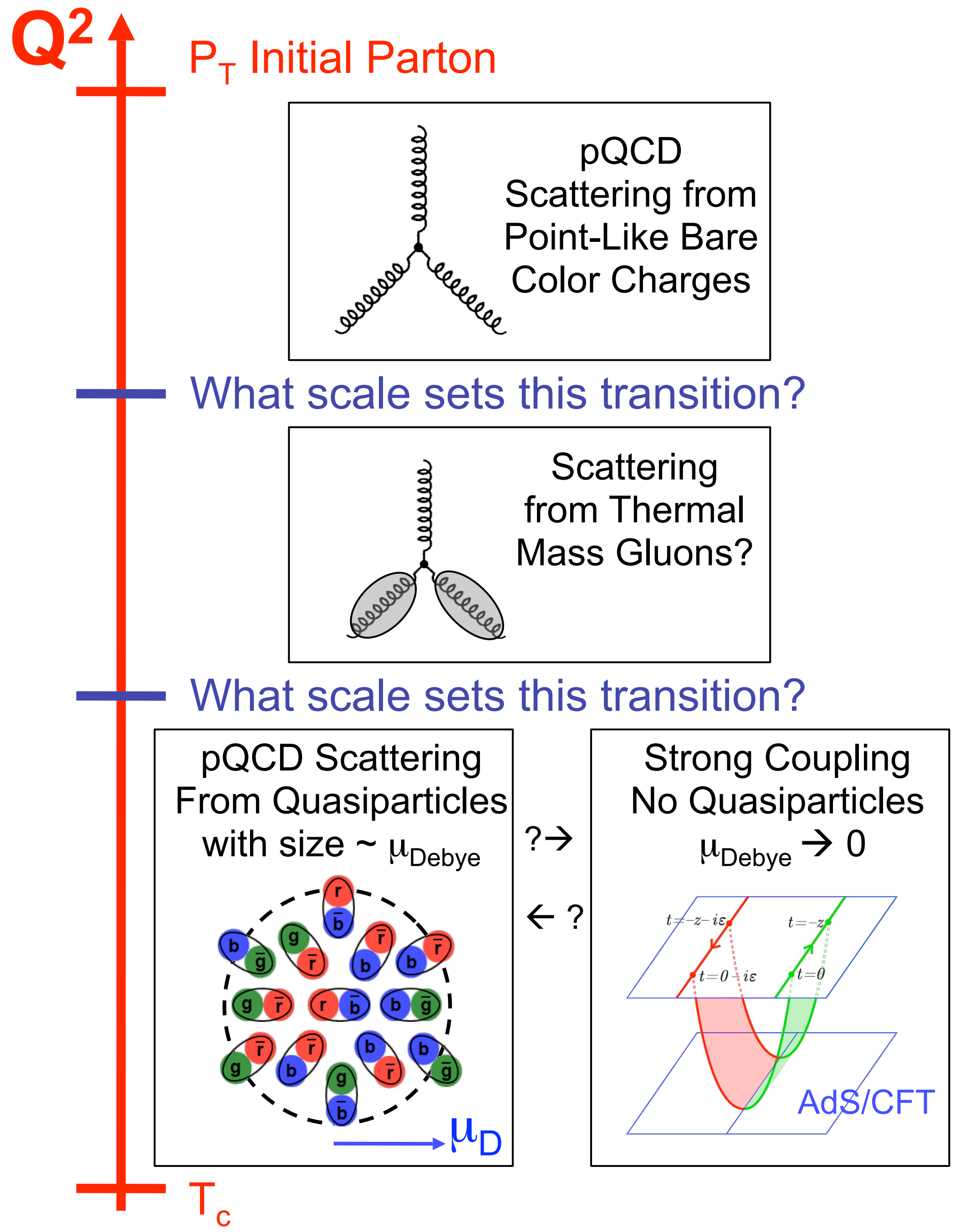
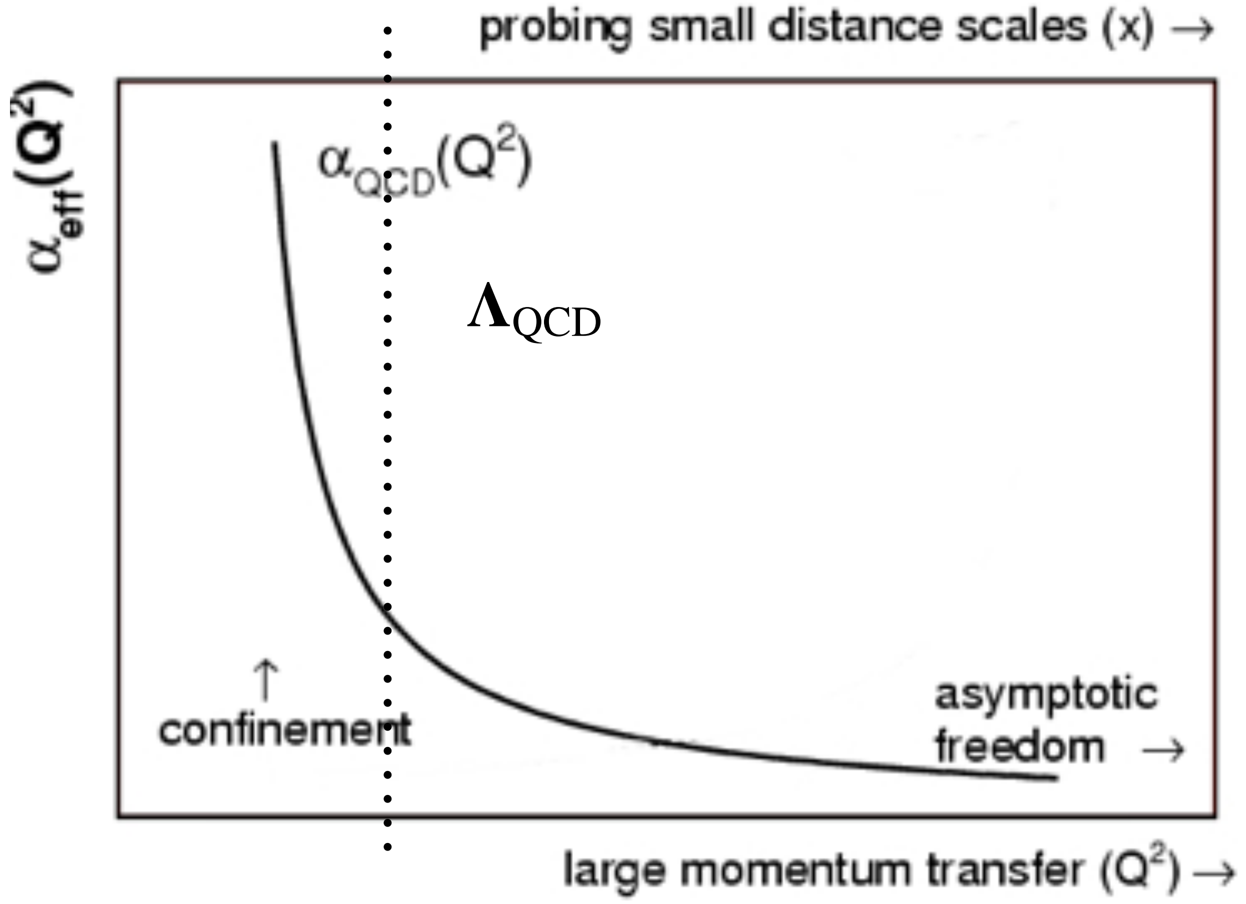
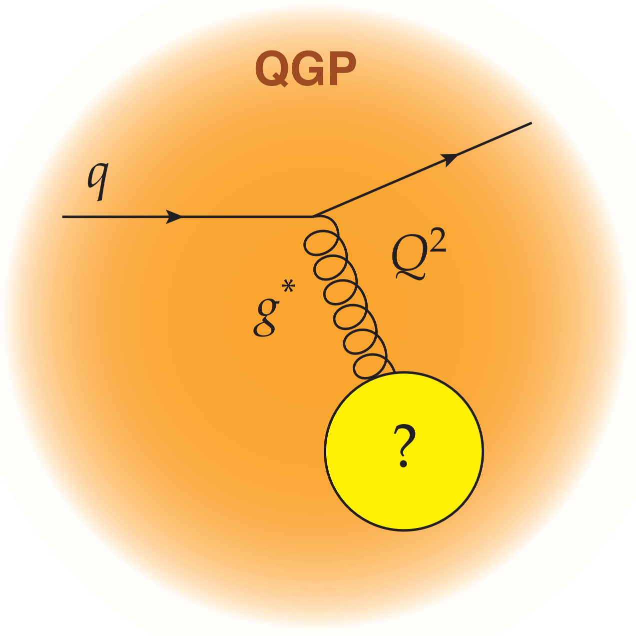
What is the intrinsic constitution of the QGP?







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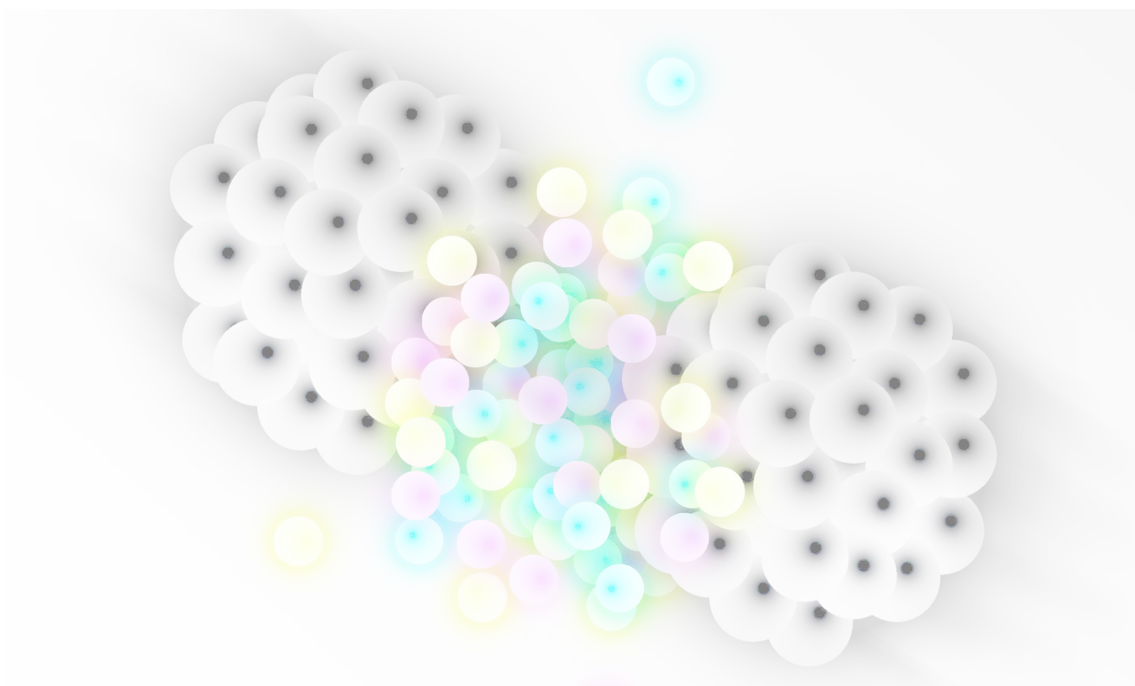

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Summary

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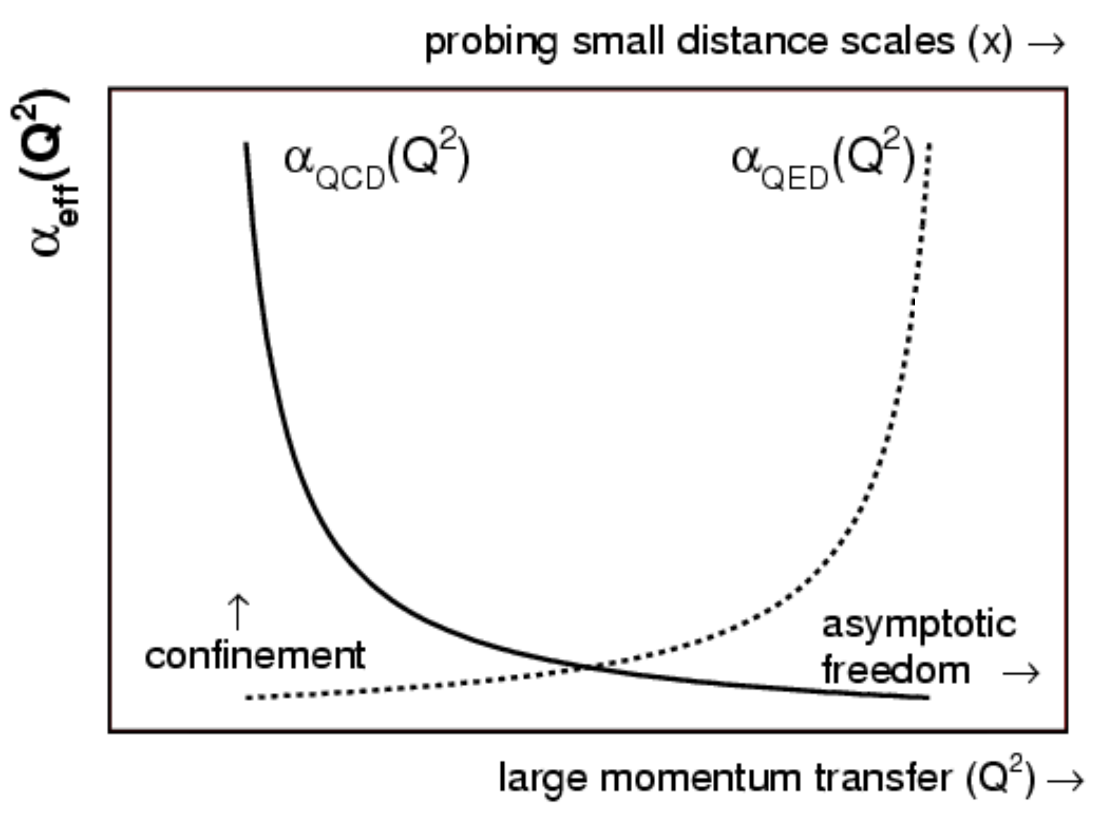
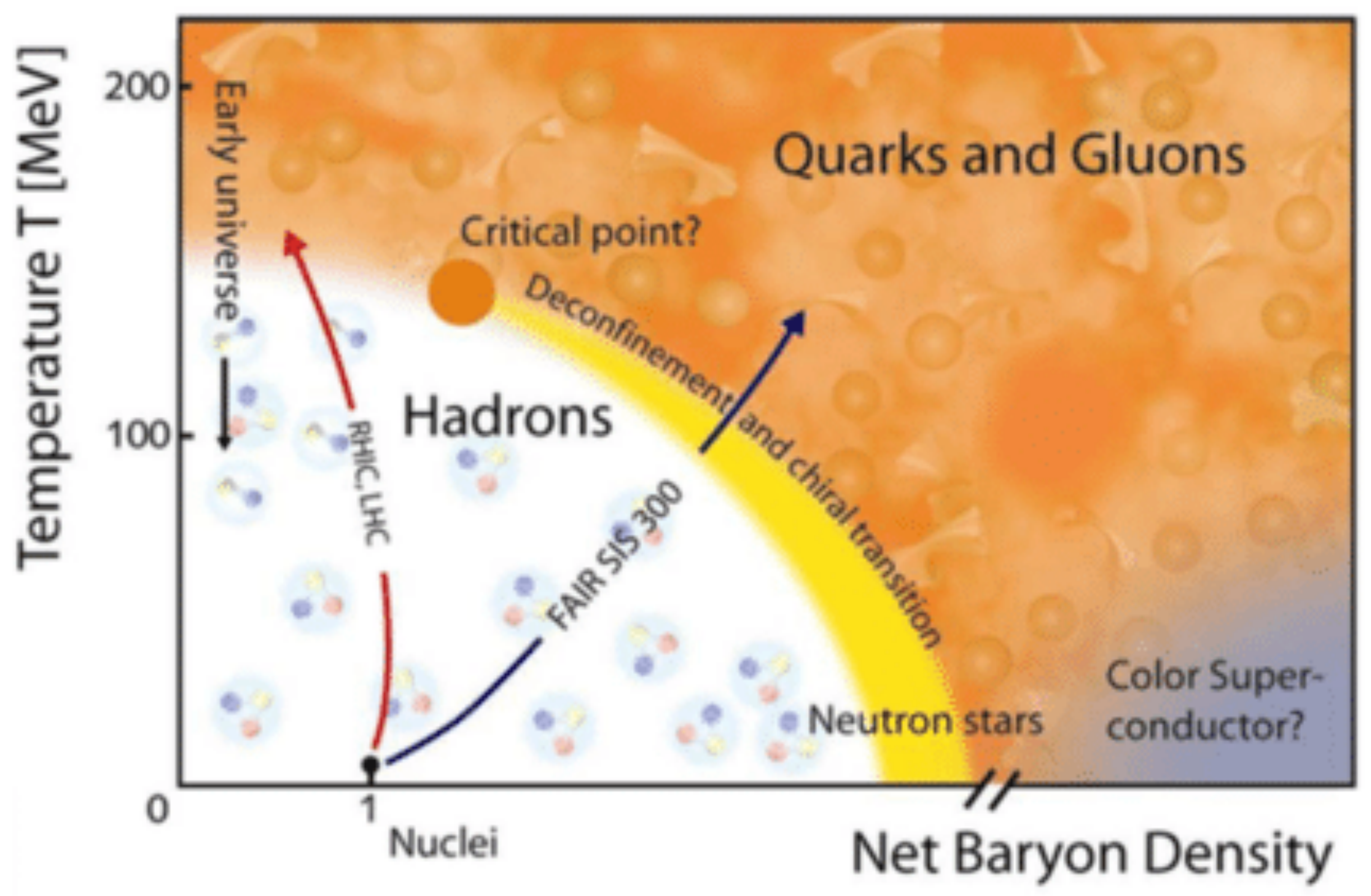
    - Wide, rich and active field!





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- Quantum Chromodynamics (QCD):
  - Wide, rich and active field!
- Heavy-Ions:
  - Unique opportunity to study the Quark-Gluon Plasma
    - Test theoretical description of the interaction from QCD first principles;
    - Development of simulation codes and analysis;
    - Identification of the 'right' observable…