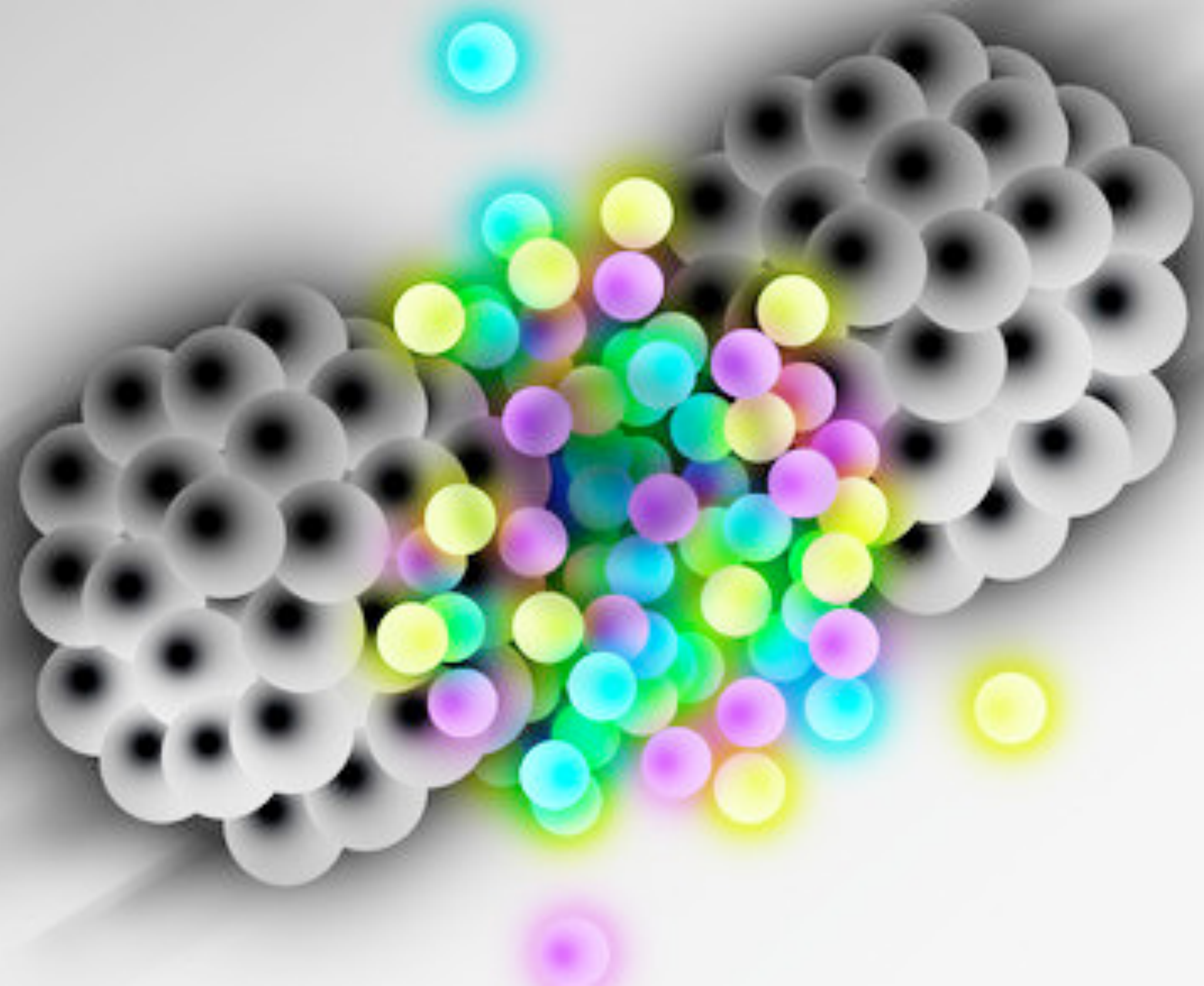
QCD & Heavy-Ion Physics



Liliana Apolinário

LIP

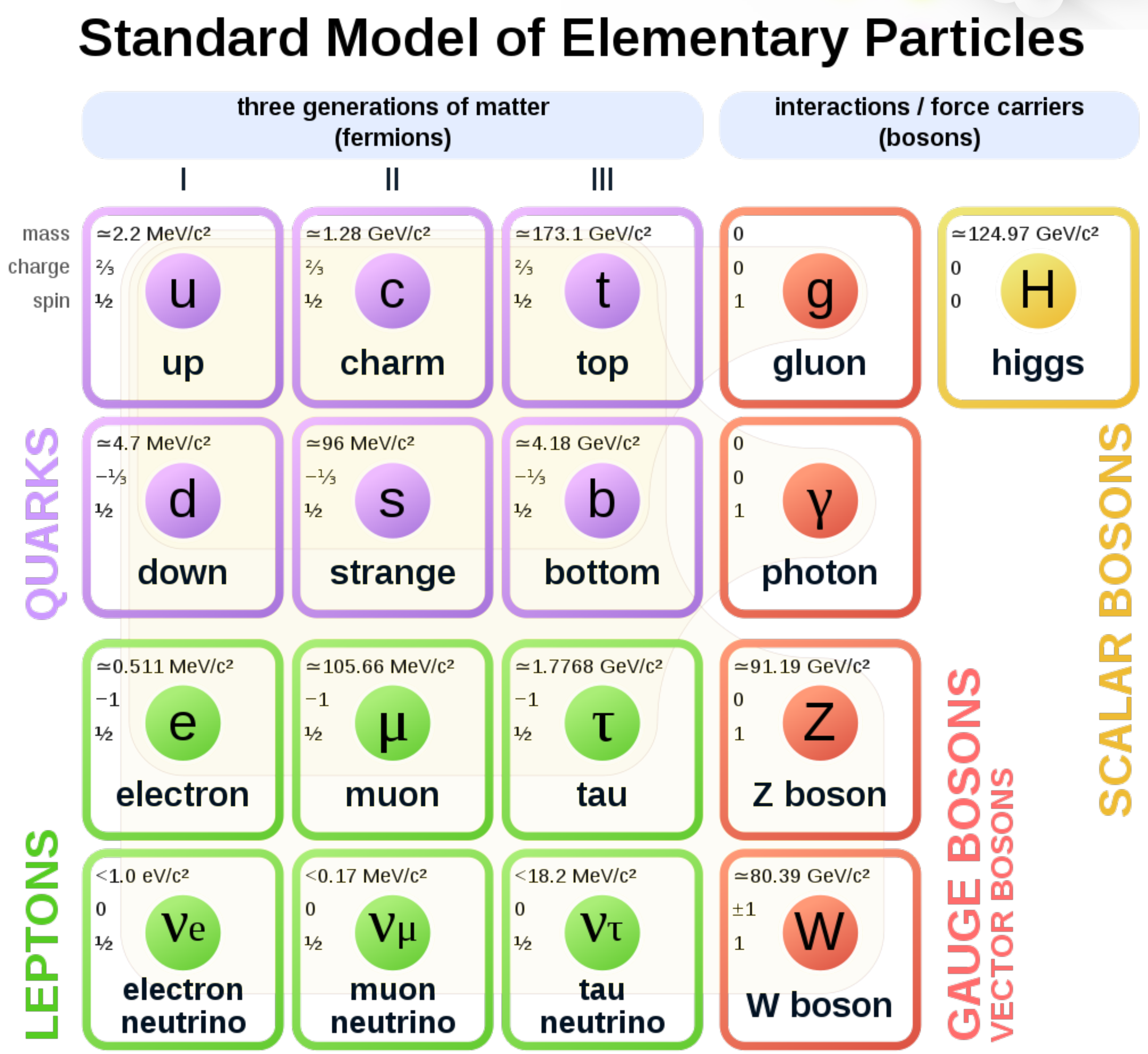
TÉCNICO LISBOA

LIP, July 2022

LIP Internship Program

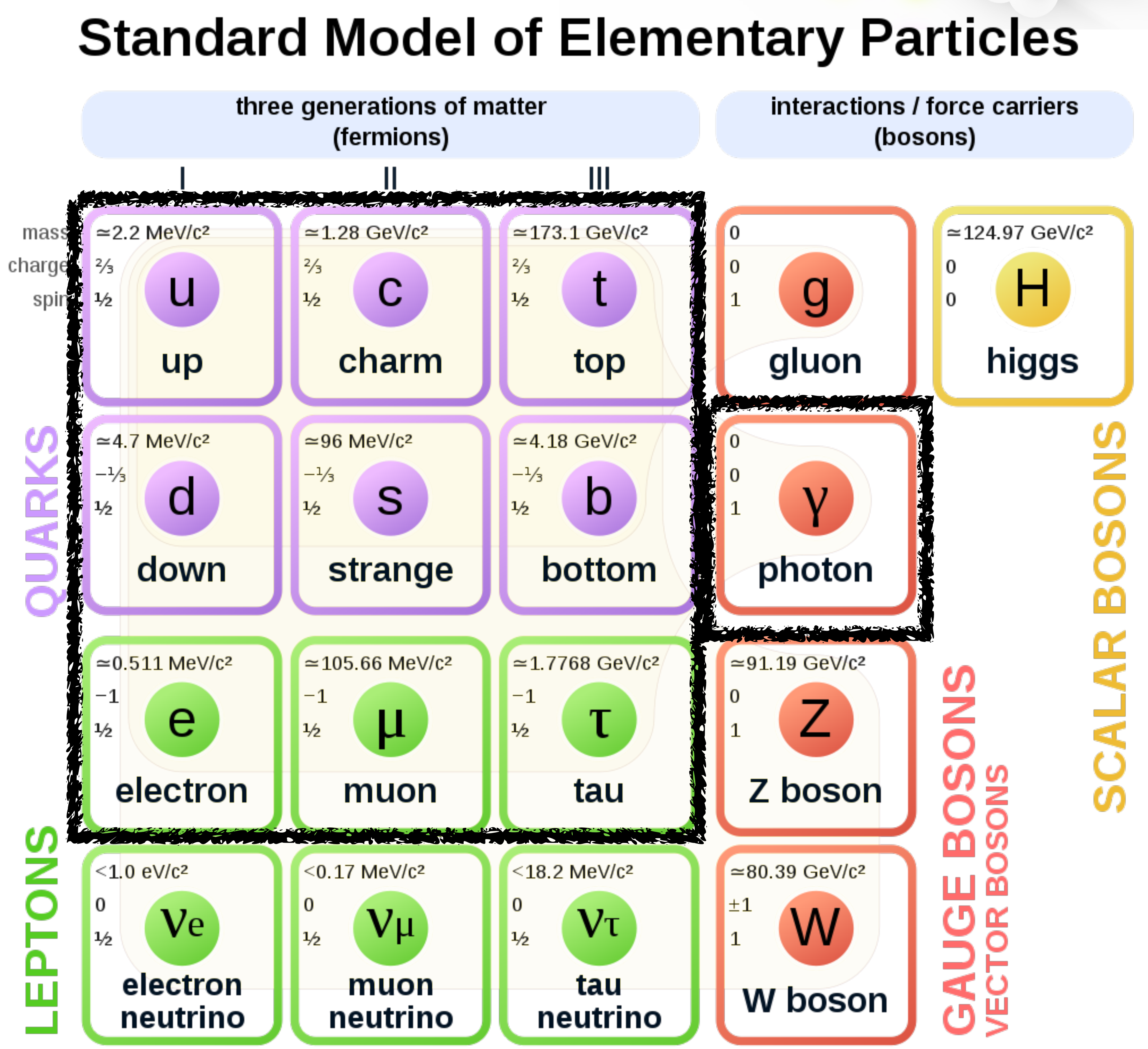
Standard Model: Recap

- Gauge Bosons (“Force carriers”)



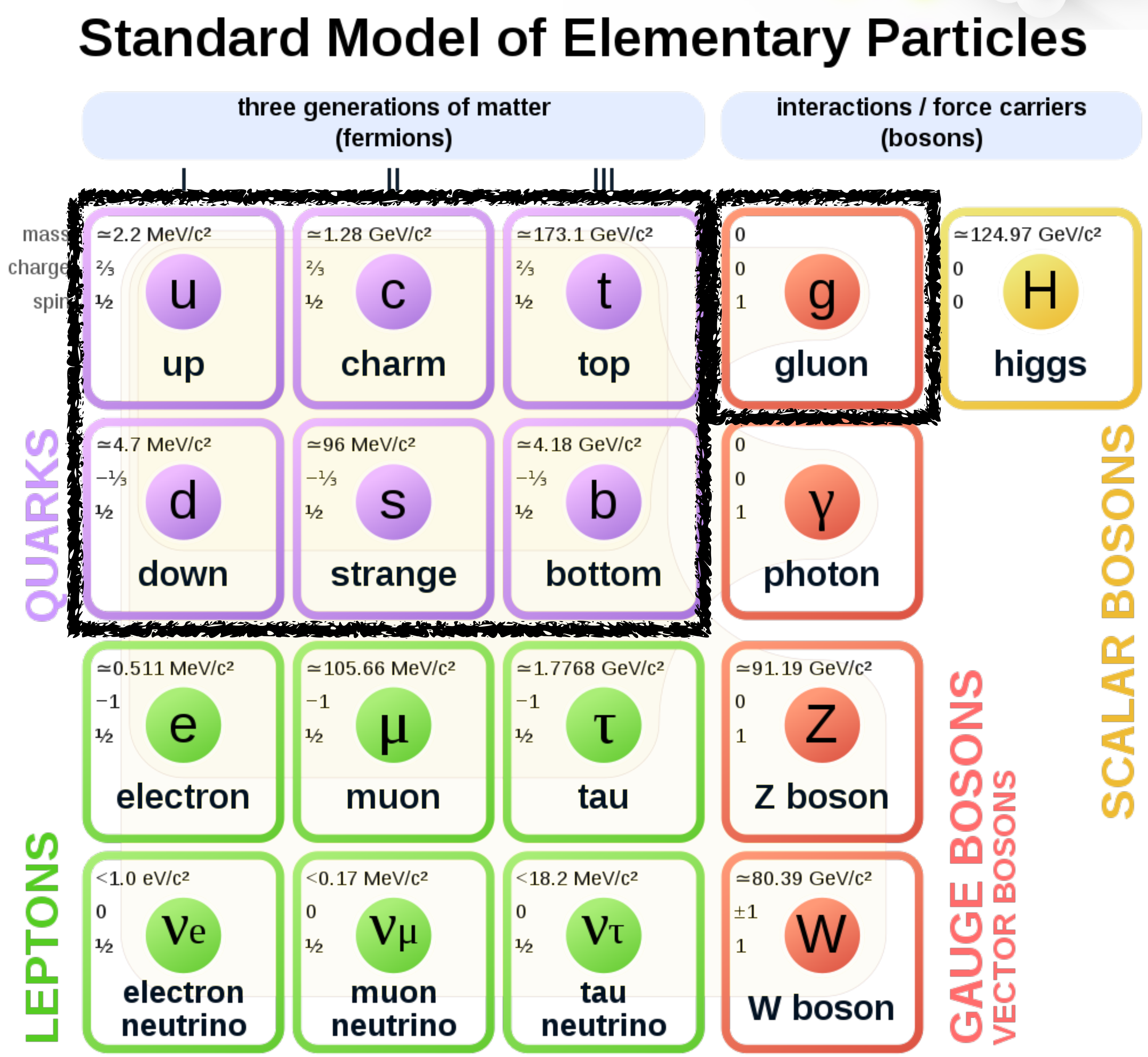
Standard Model: Recap

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



Standard Model: Recap

- 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 (RR, GG, BB)



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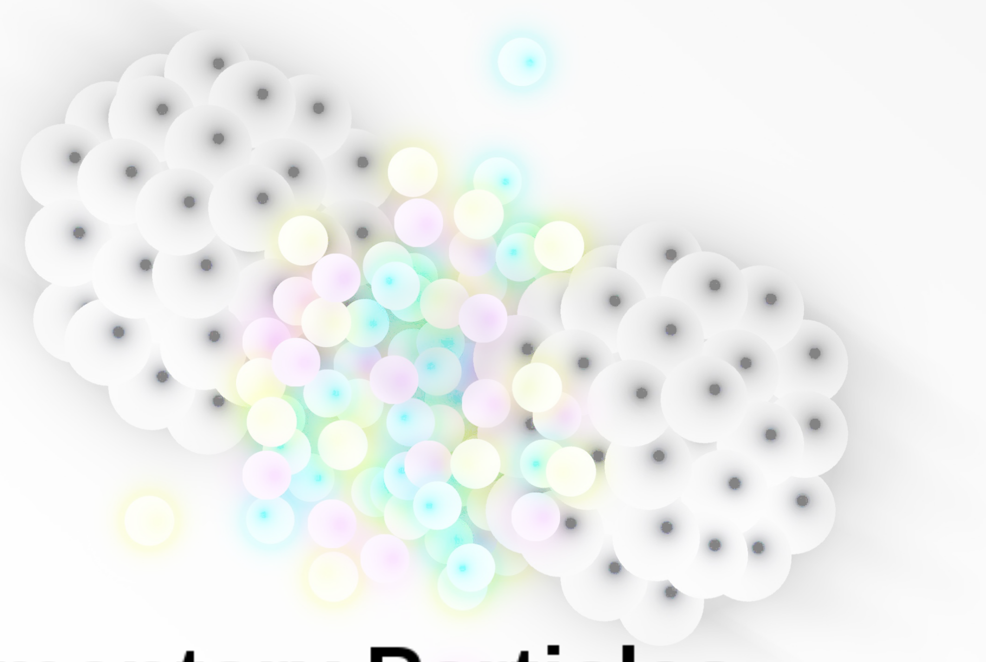
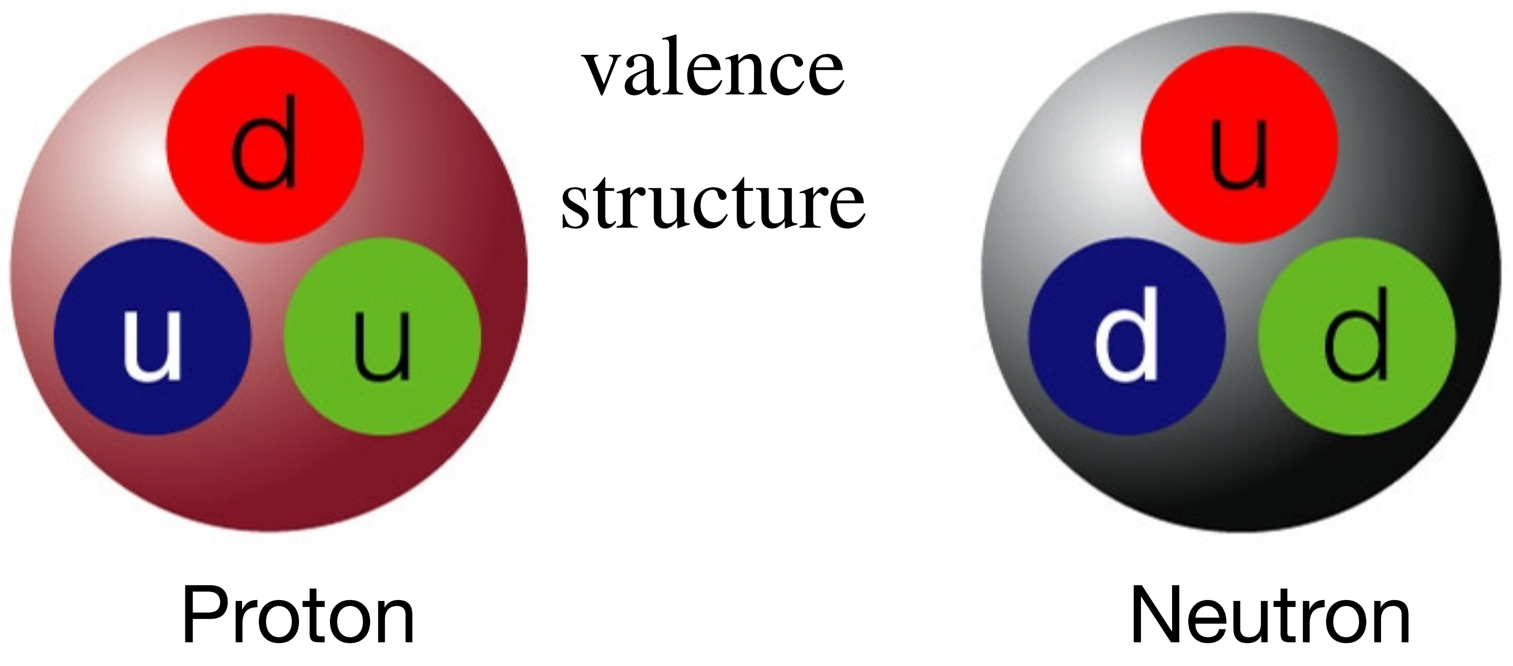
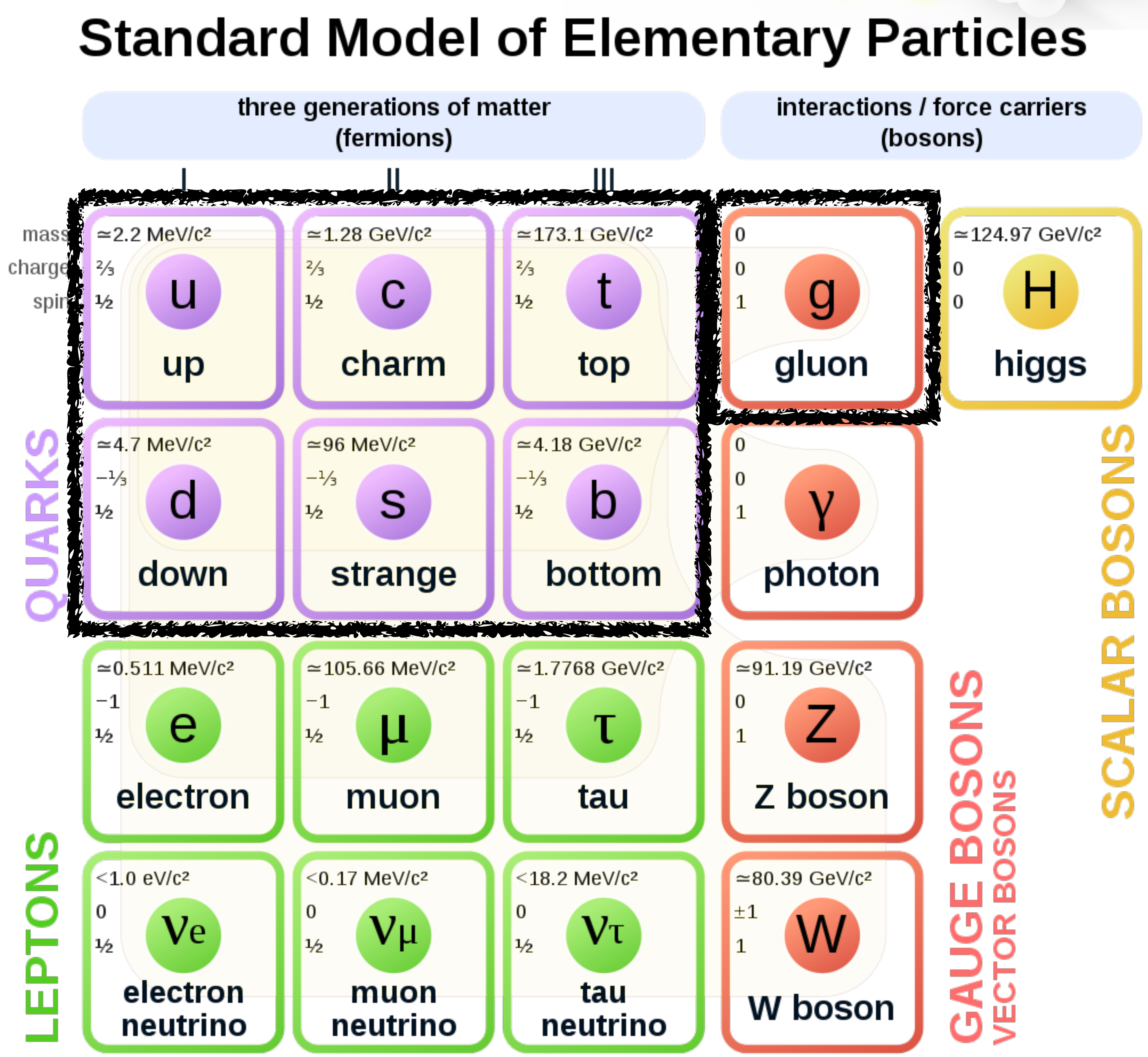


- Higgs: mass to elementary particles
- QCD: contributes largely to the mass of composite particles (mesons, baryons,…)





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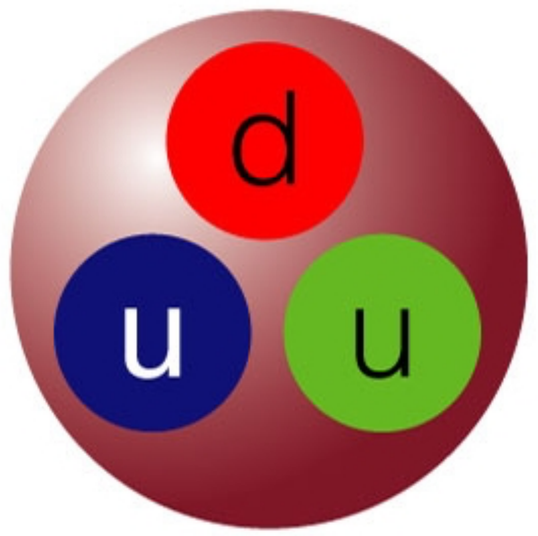
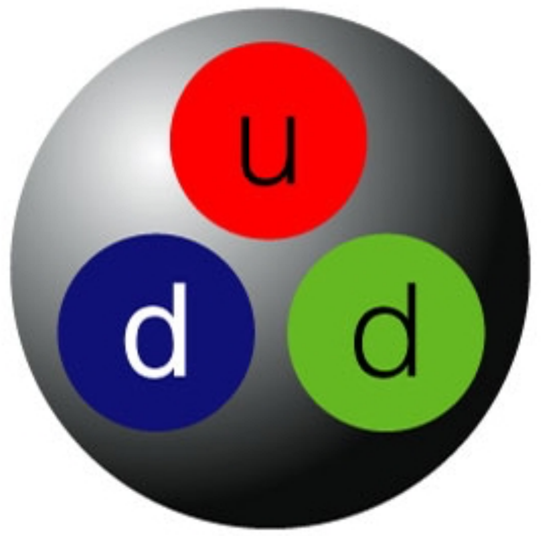


Proton

valence structure

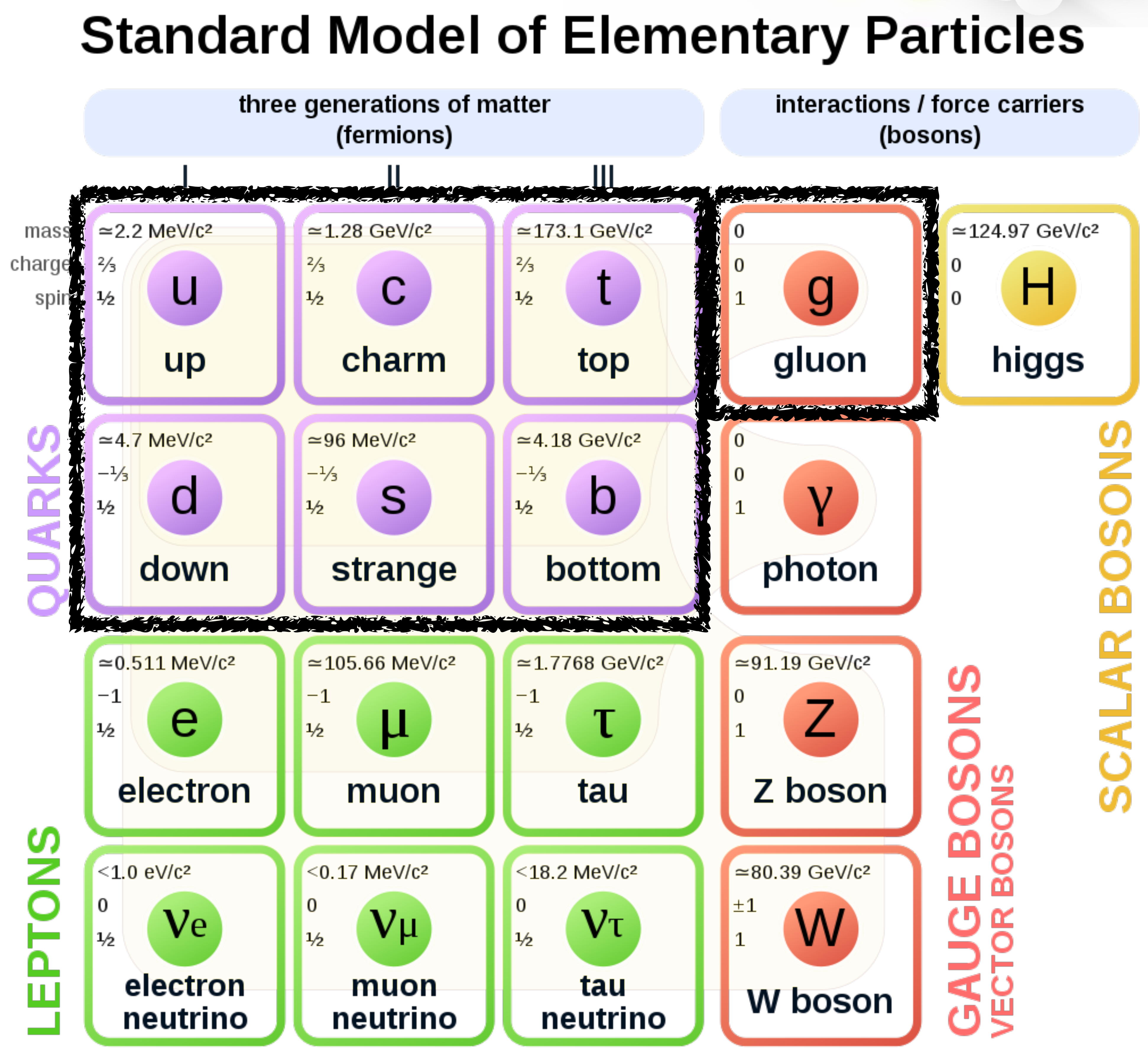


Neutron

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

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

~1% mass



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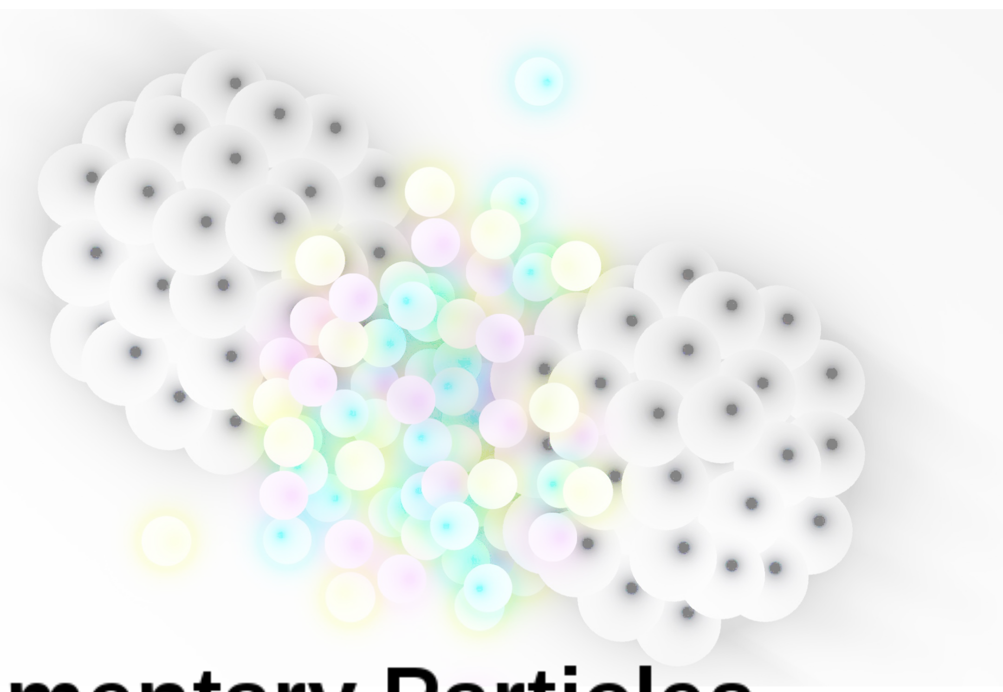

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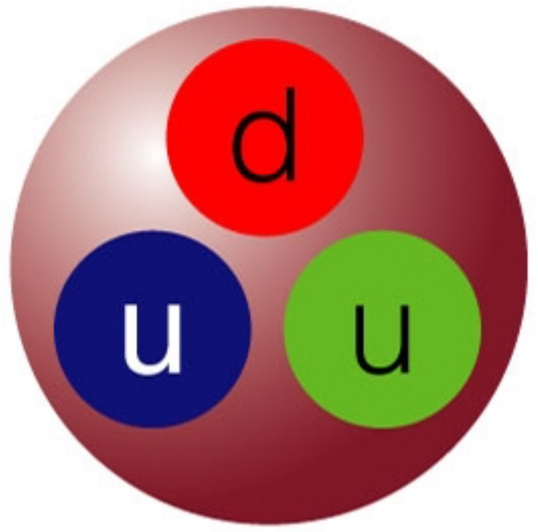

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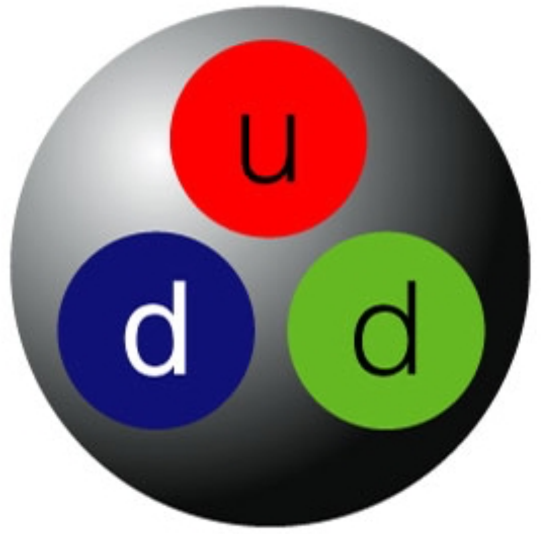


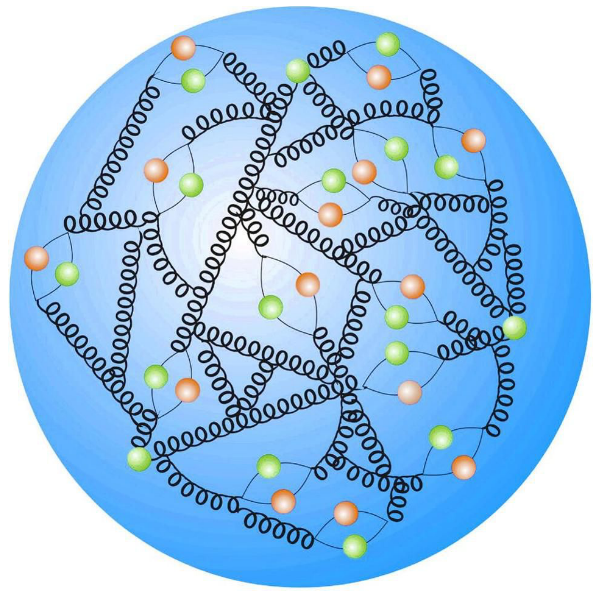
Neutron

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

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

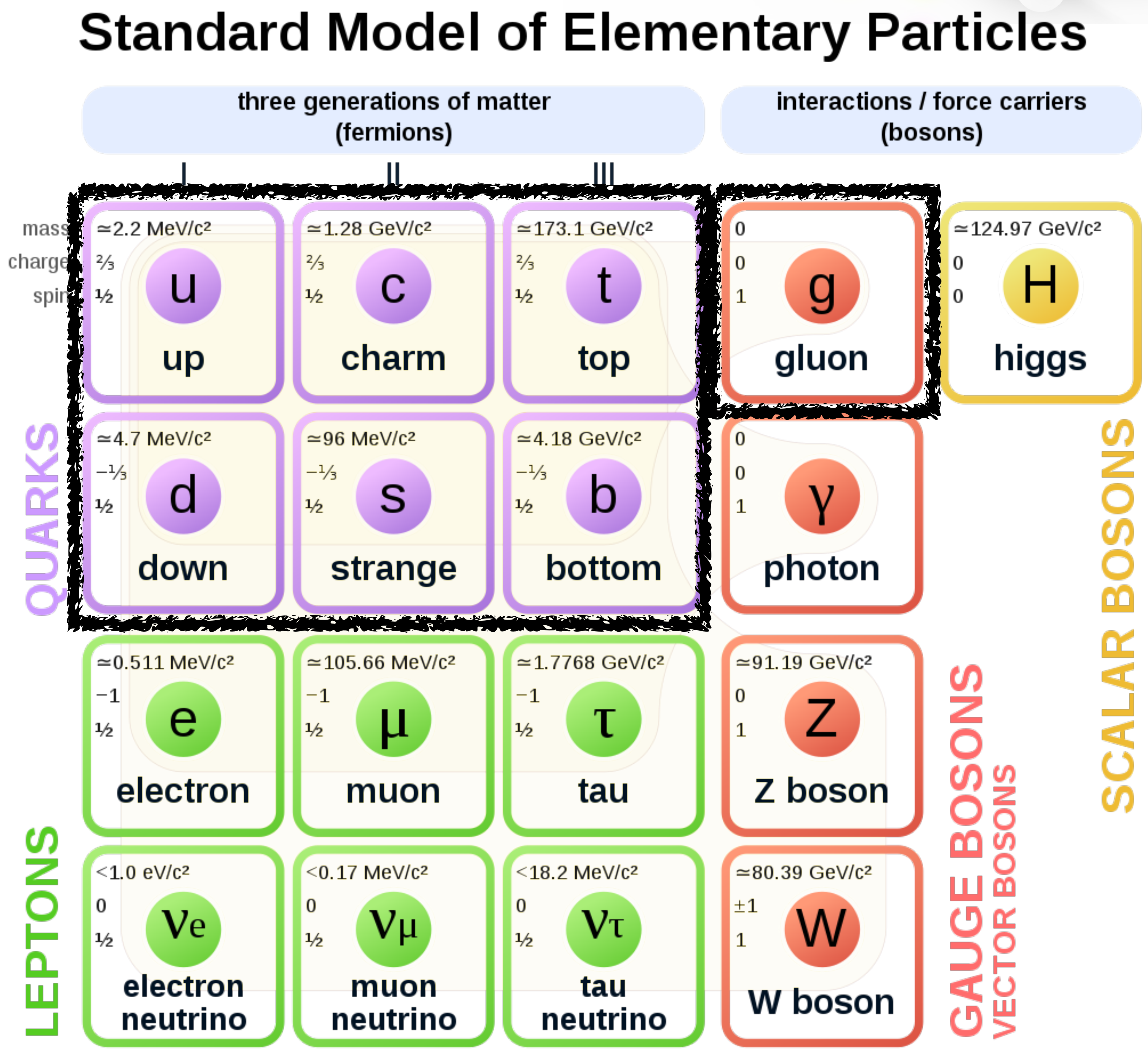
~1% mass

(more realistic) proton structure

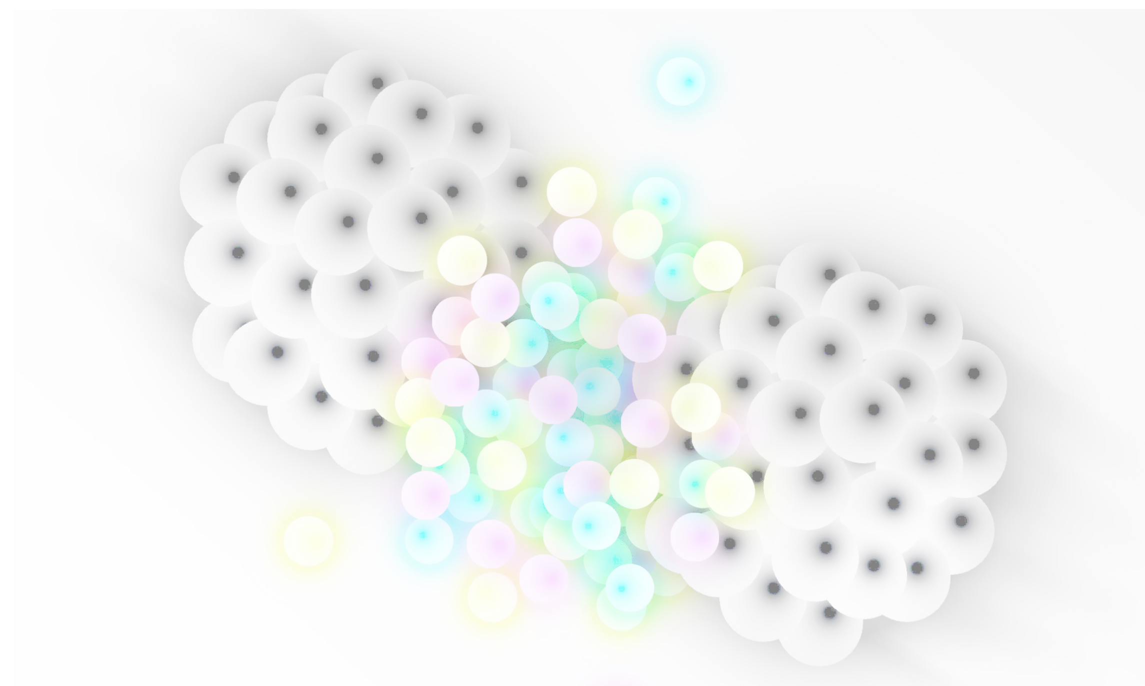


valence + sea (quarks and gluons)

100% mass



QED vs QCD

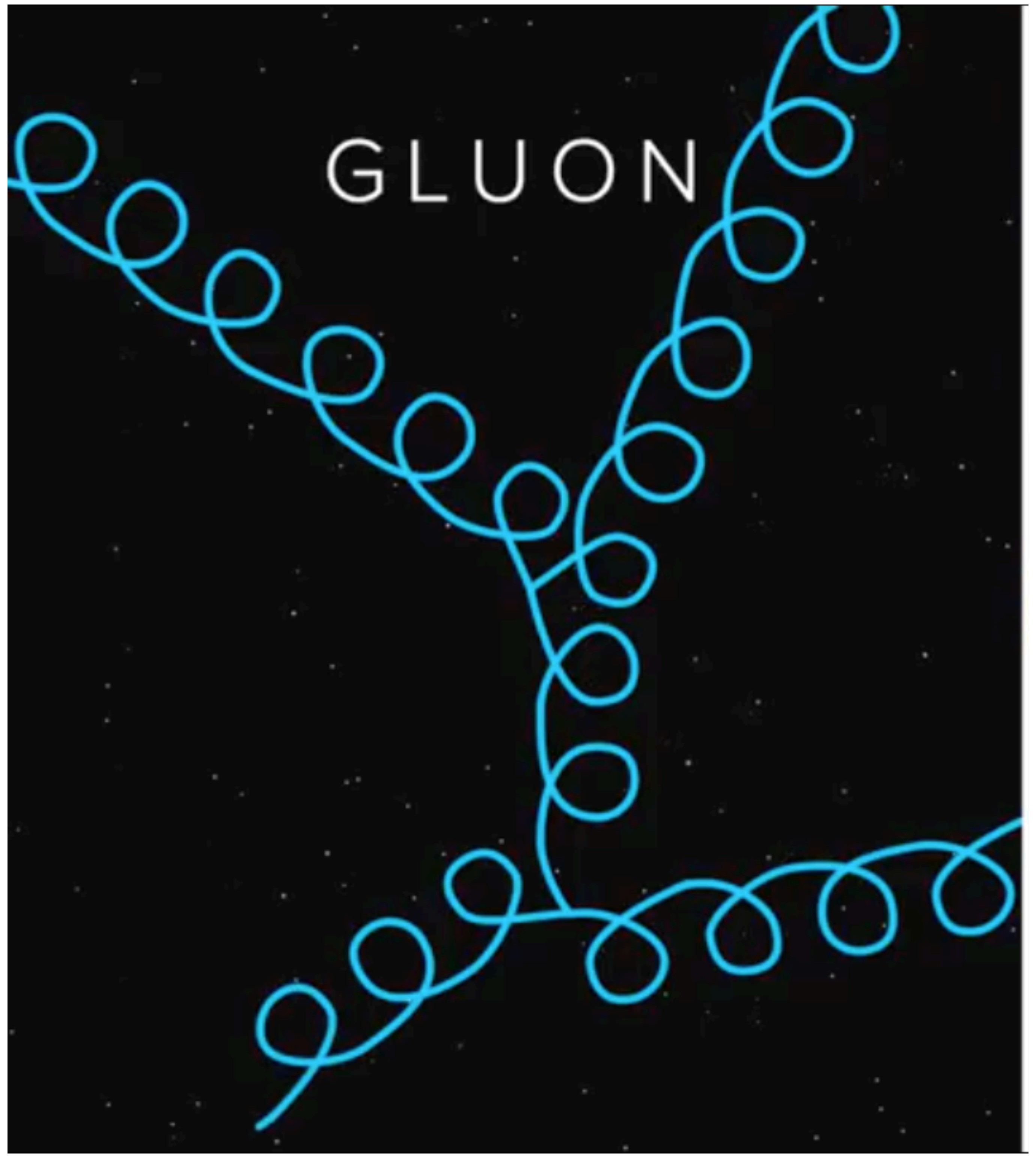


- Quantum Electrodynamics

Photons do not have electric charge

- Quantum Chromodynamics

Gluons are colourful



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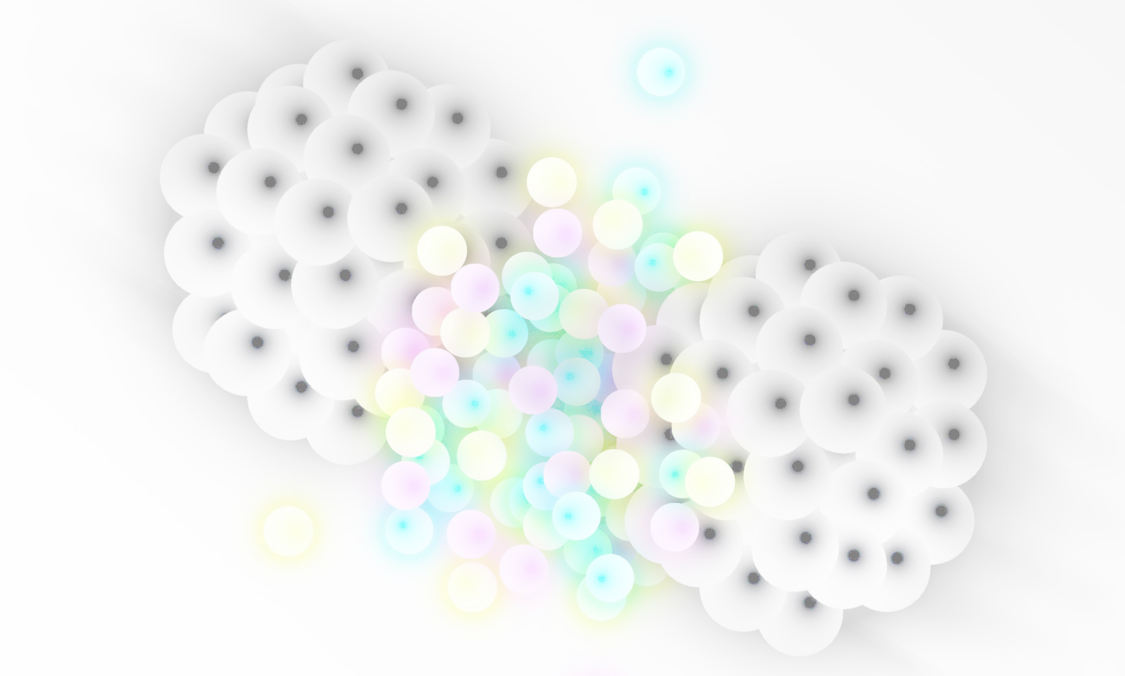
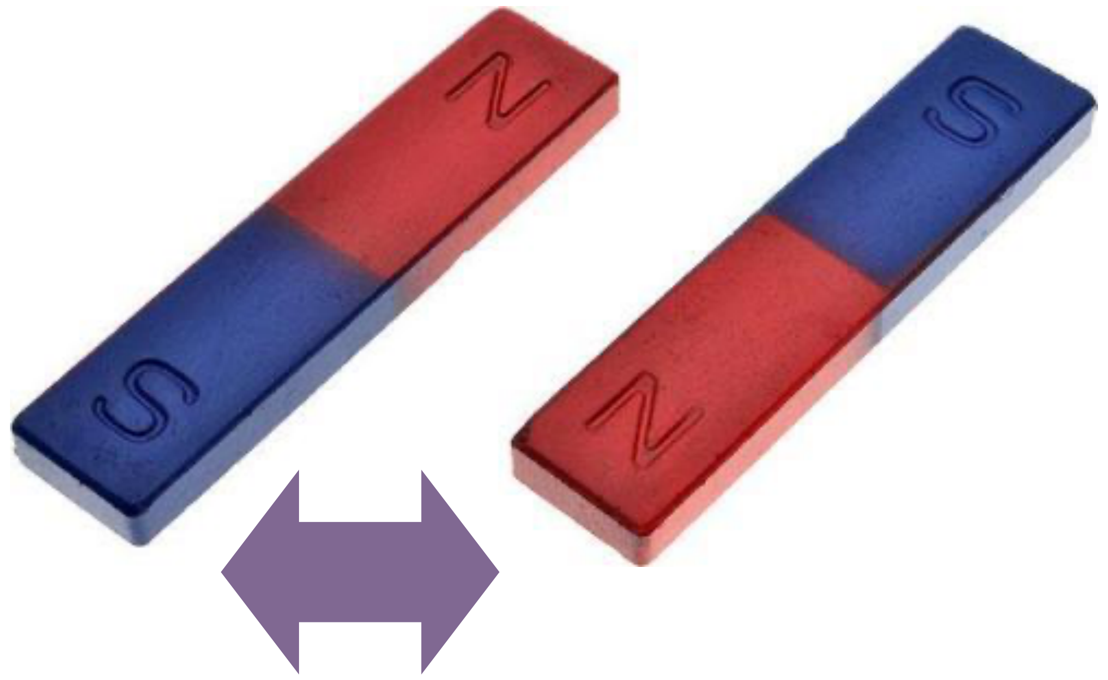


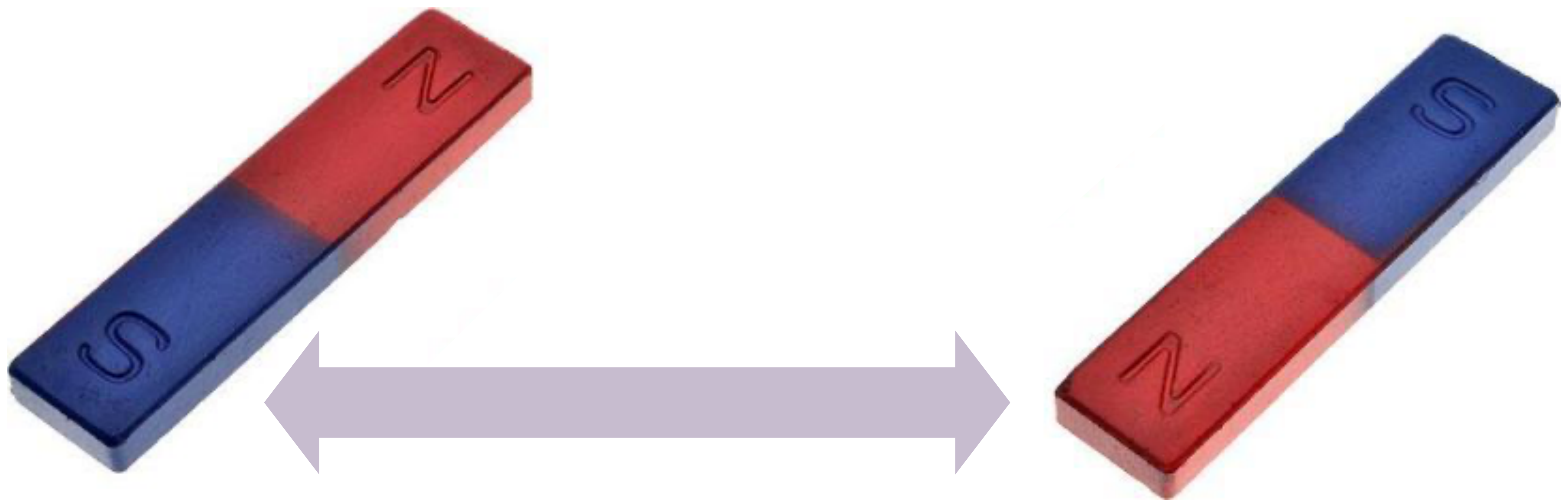
- Quantum Electrodynamics

Photons do not have electric charge

Larger attraction



Smaller attraction



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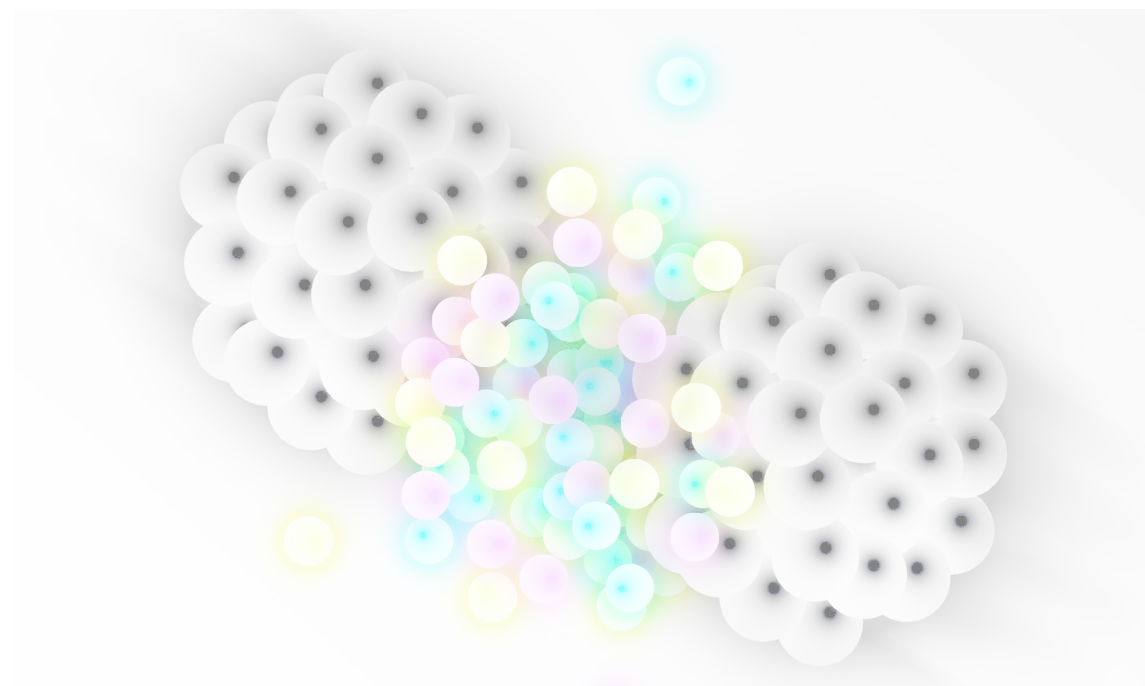

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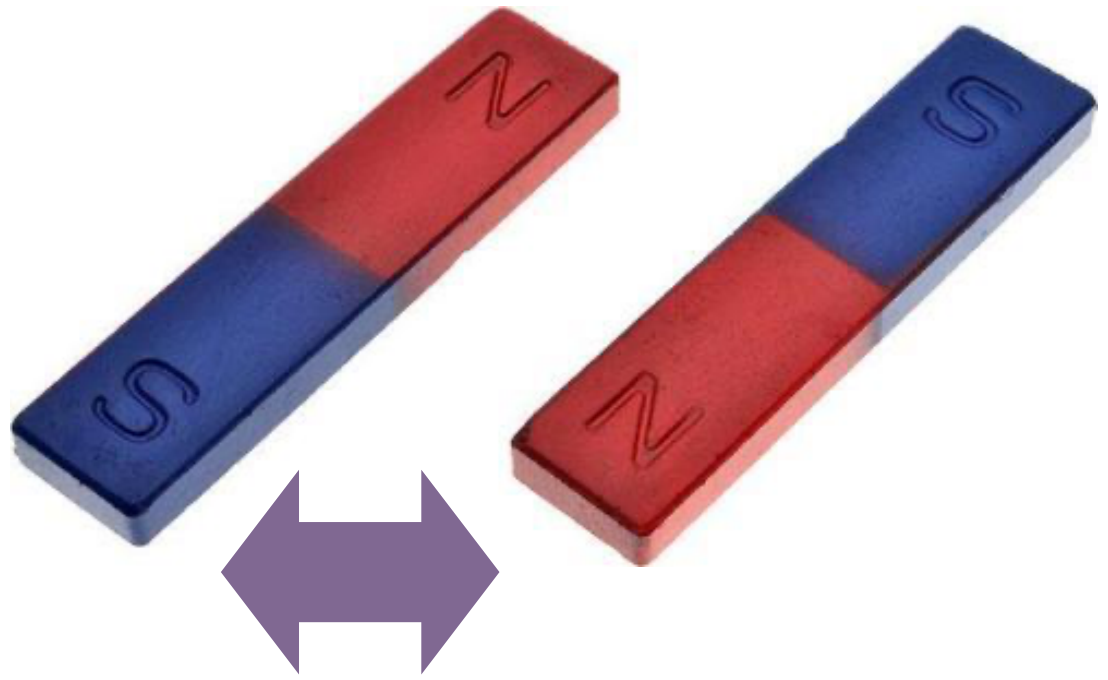

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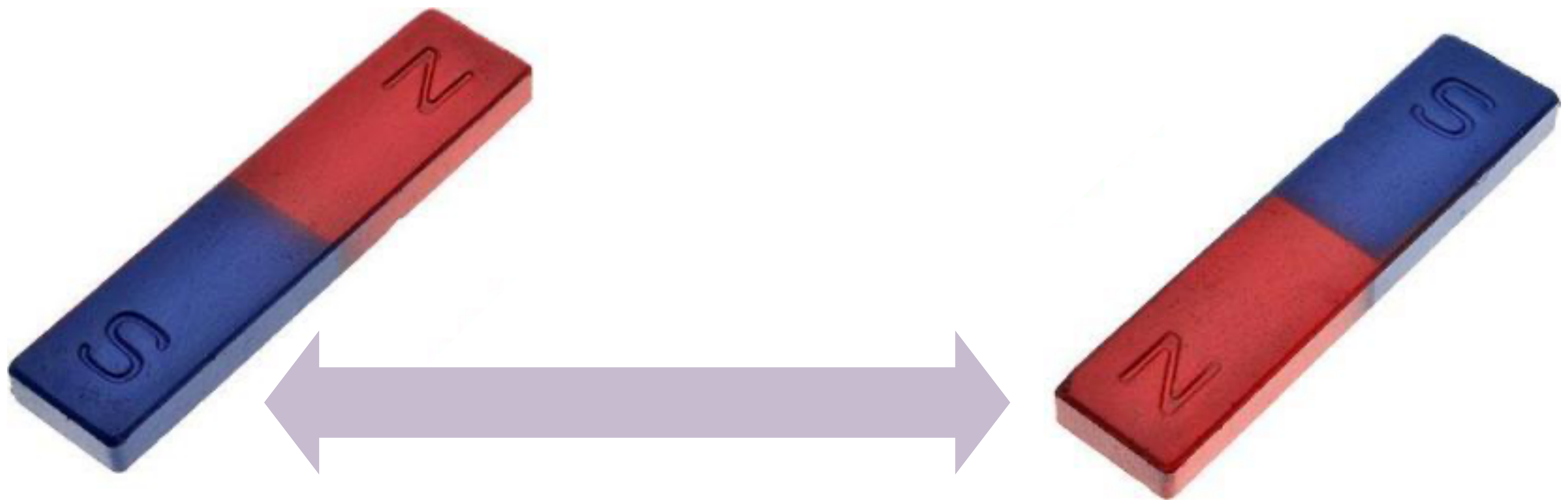

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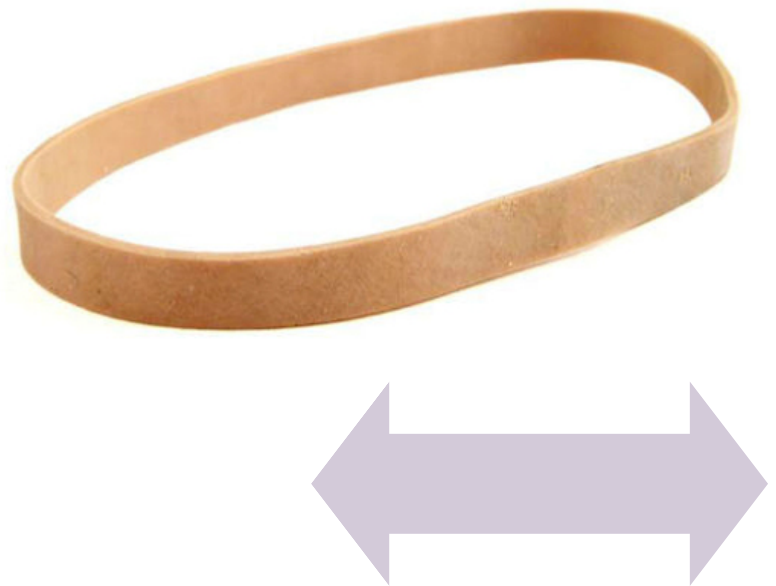

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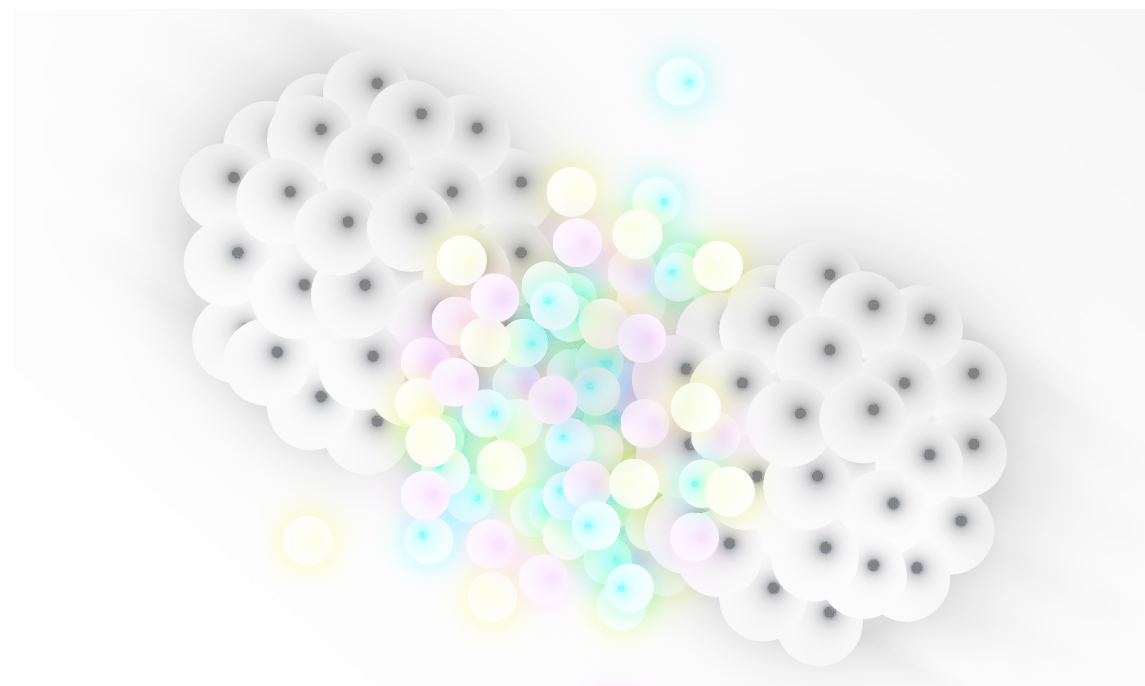

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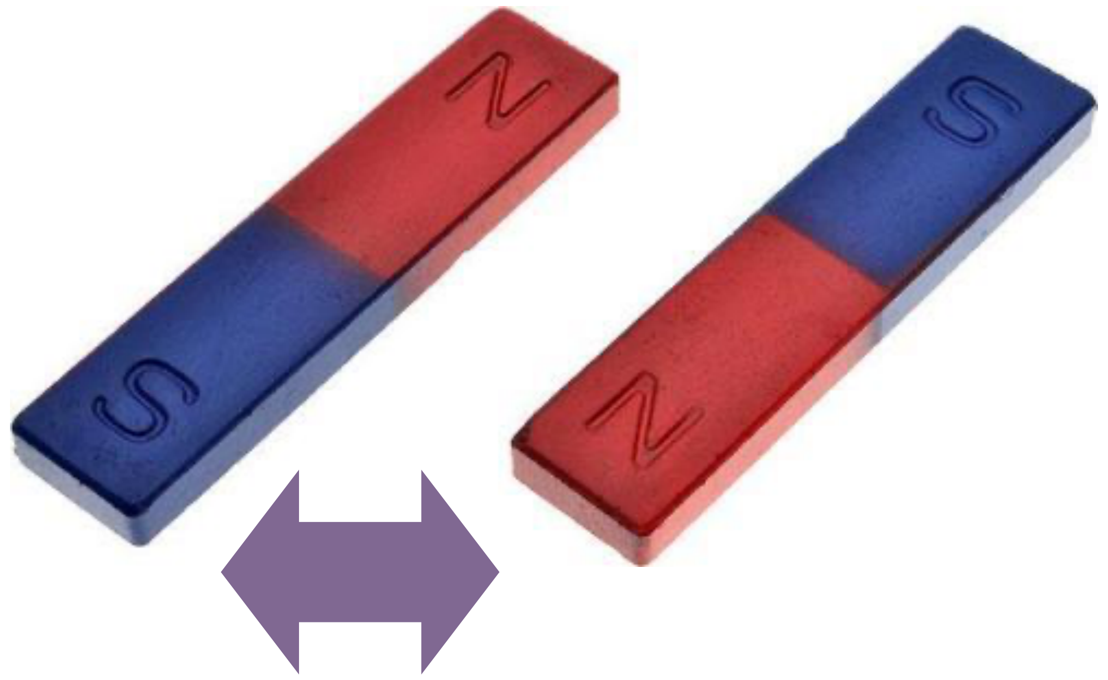

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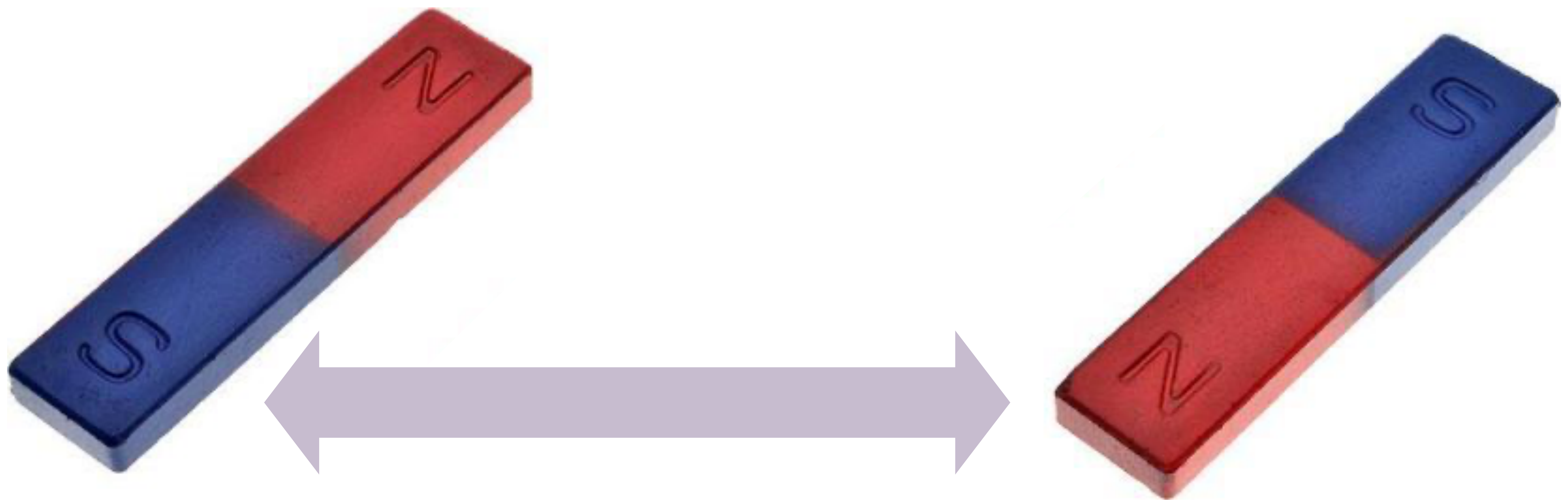
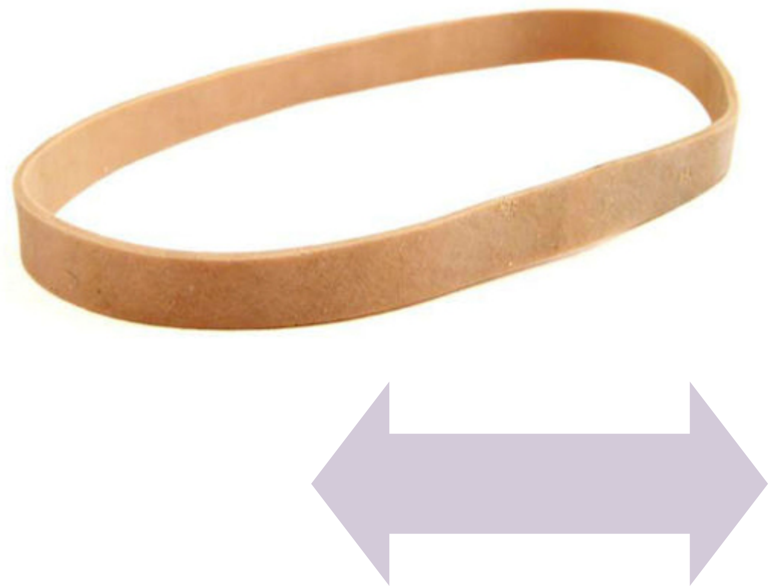


- Quantum Chromodynamics = Strong Force

Gluons are colourful

Smaller attraction



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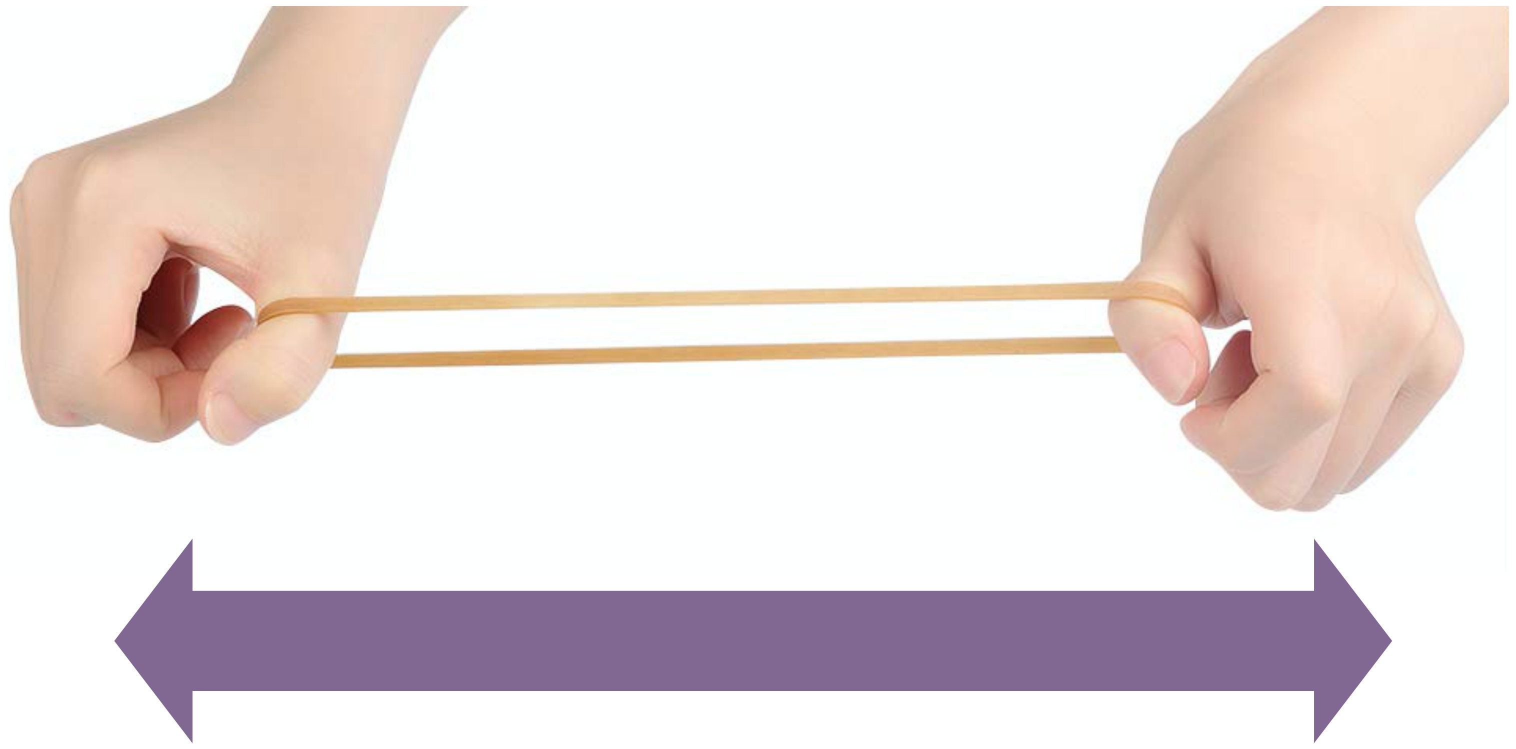
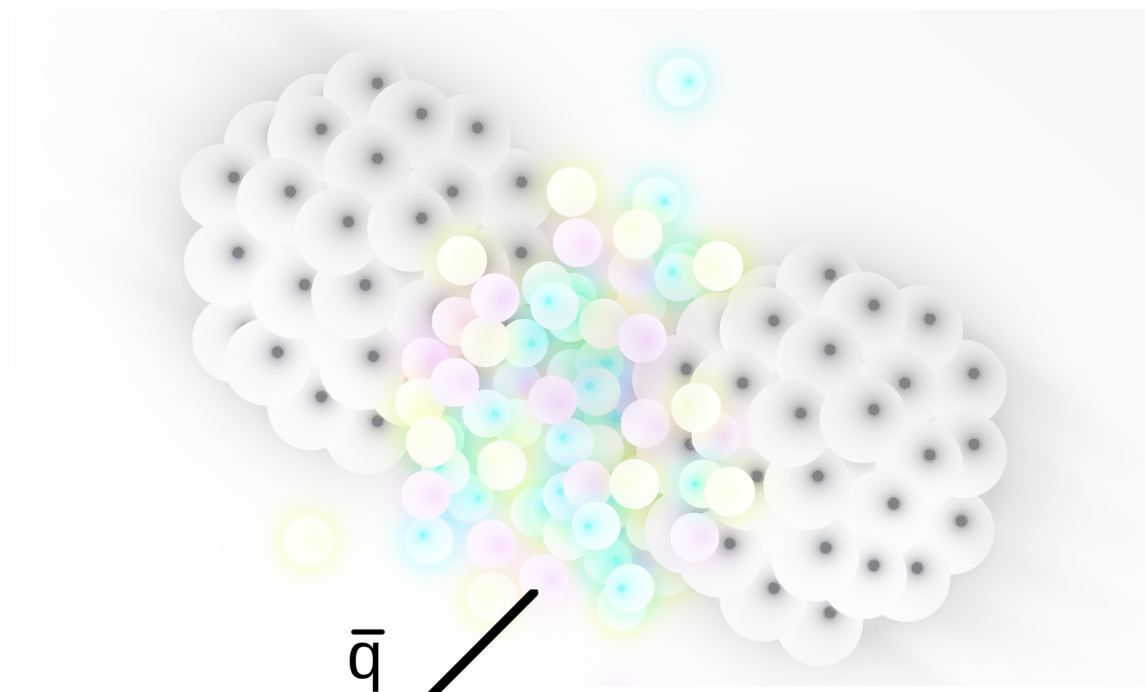
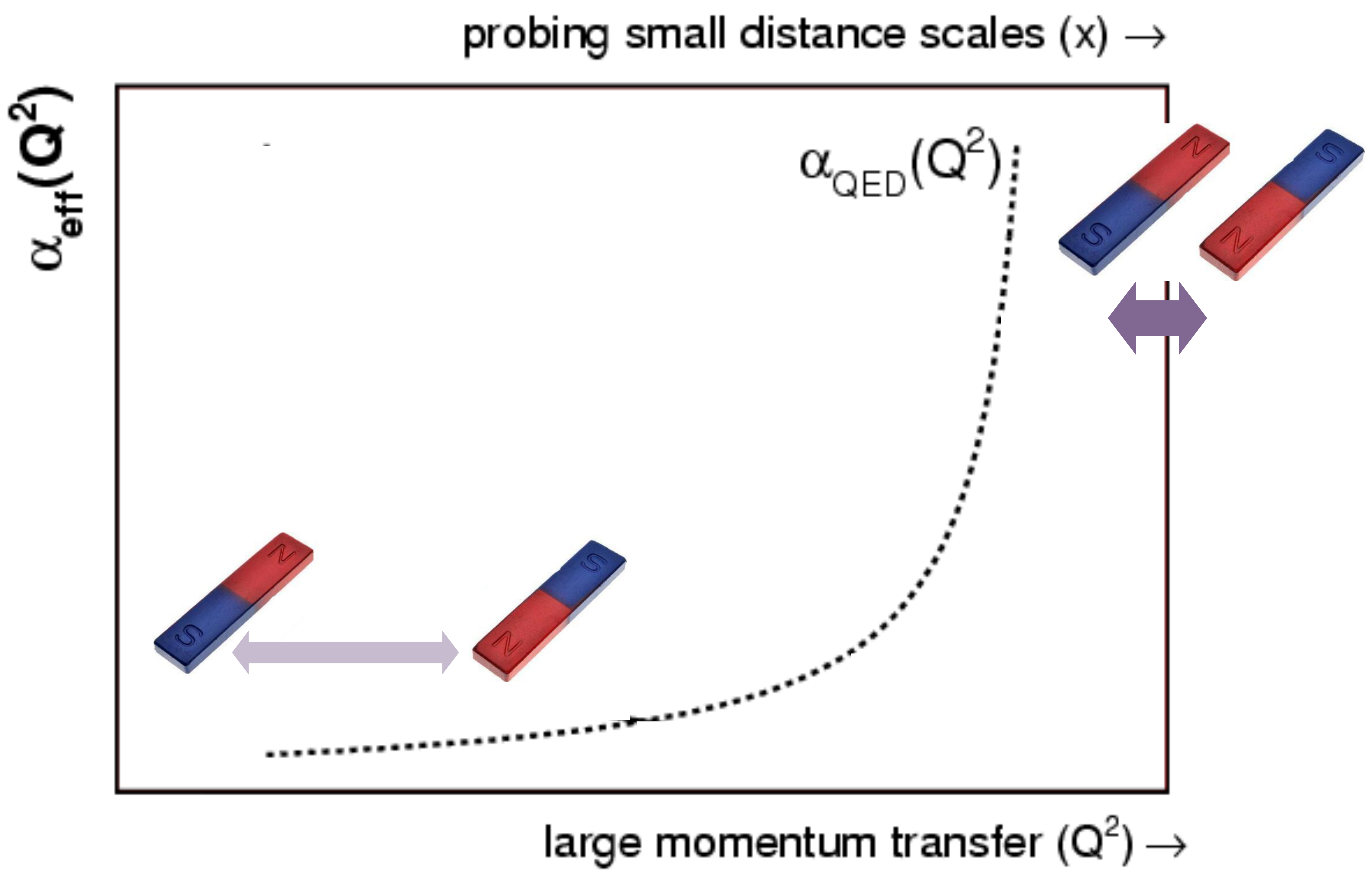


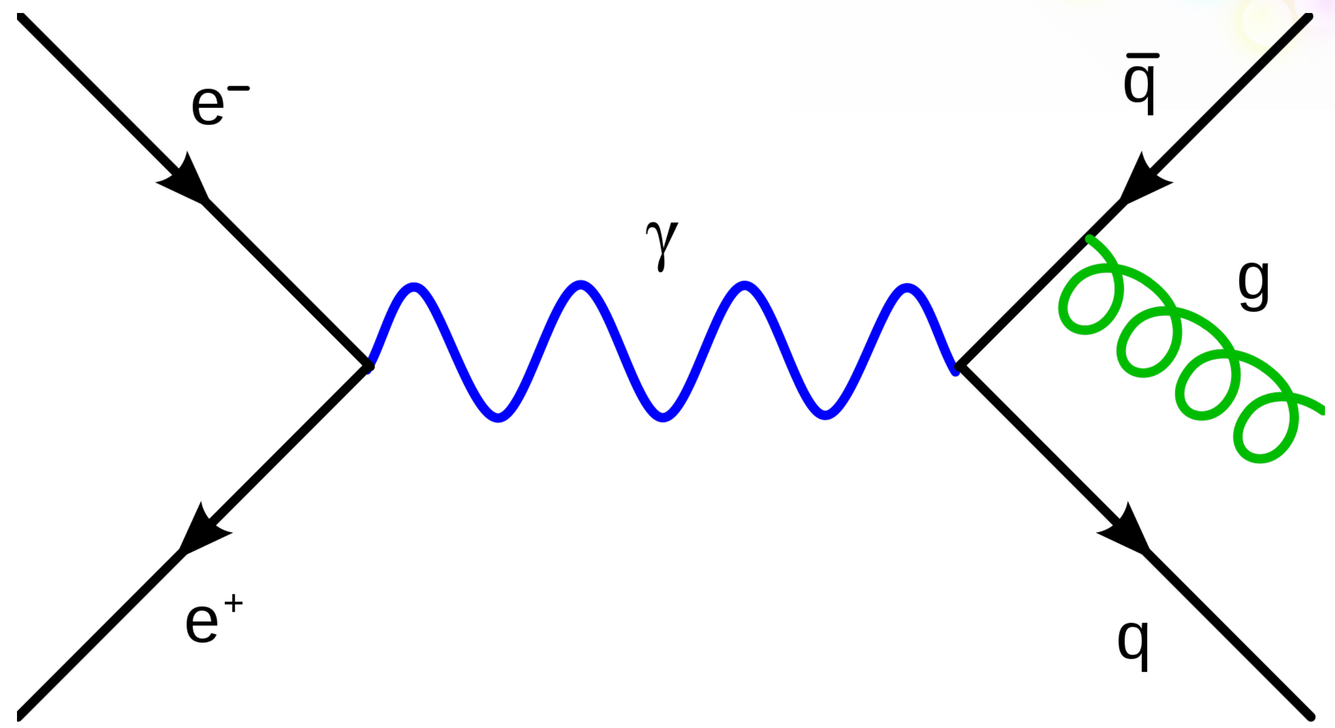
Coupling Constant

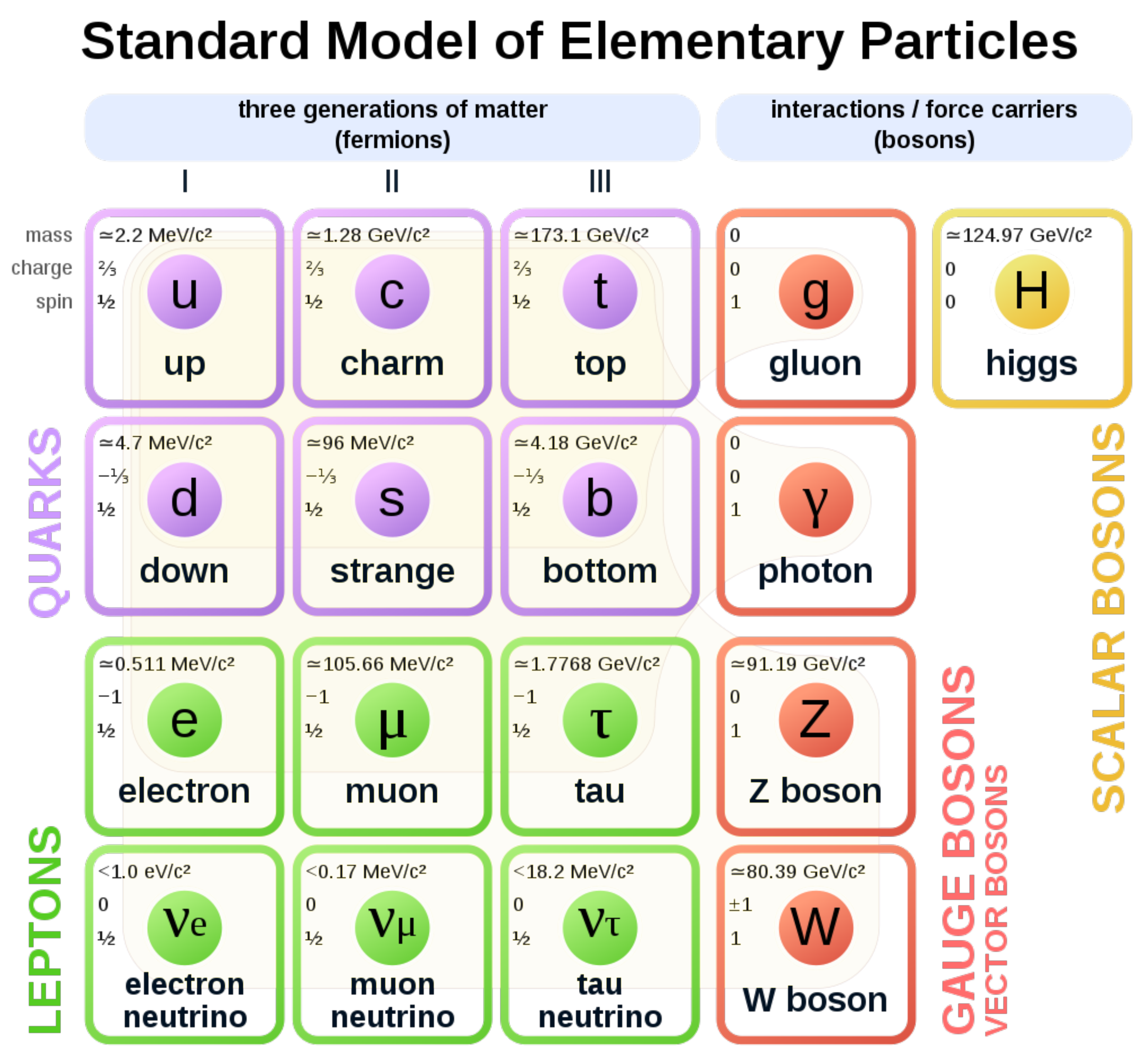


- Interaction strength given by α_{QED} and α_{QCD}



Large distances ⟷ Small distances





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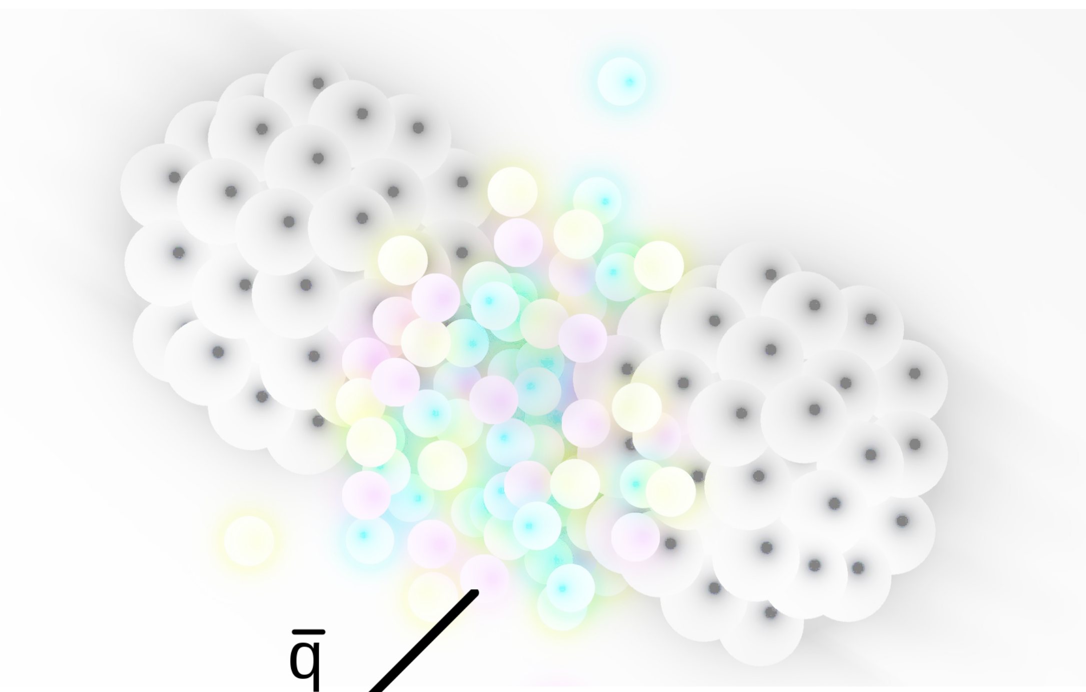

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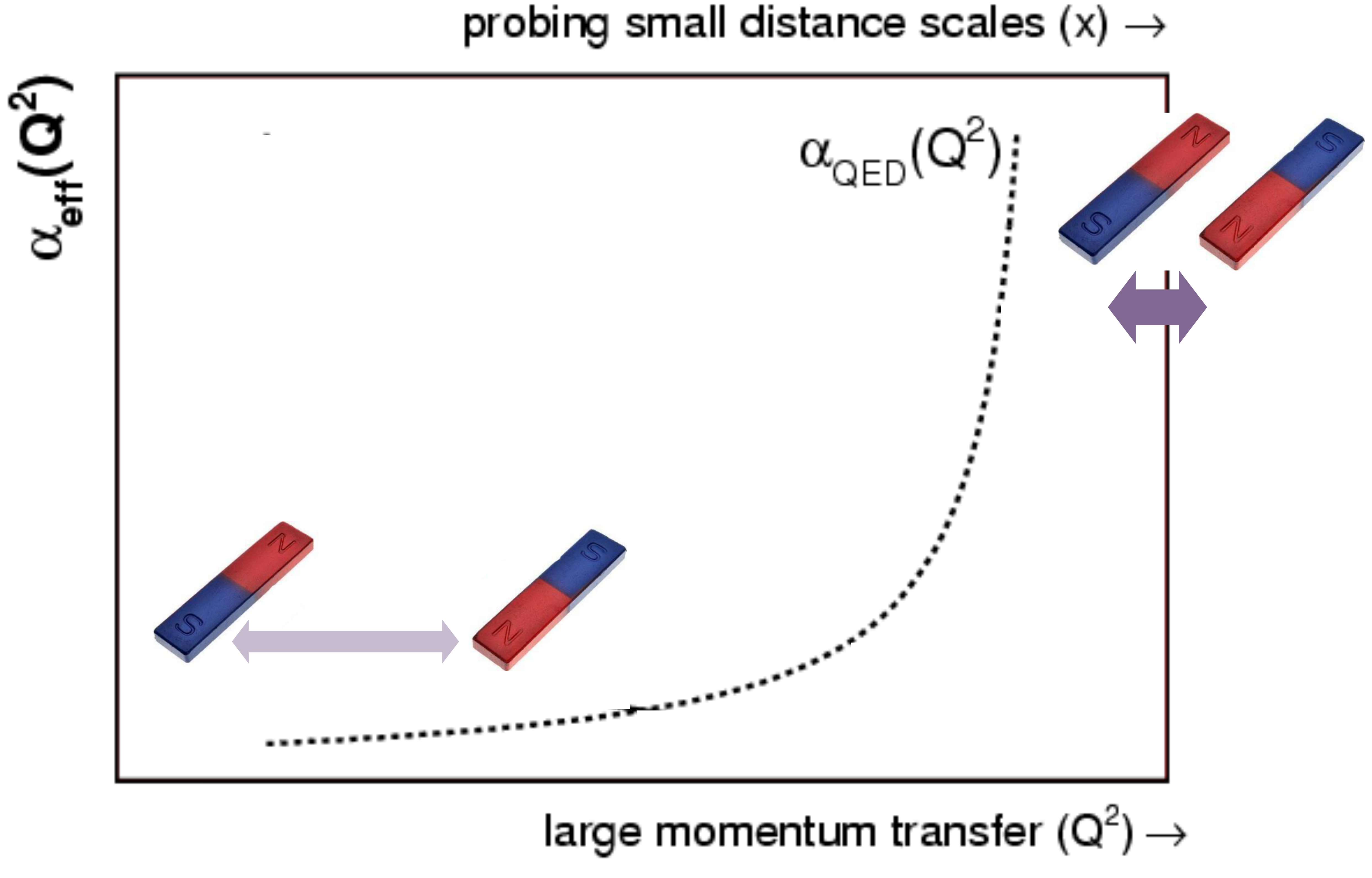

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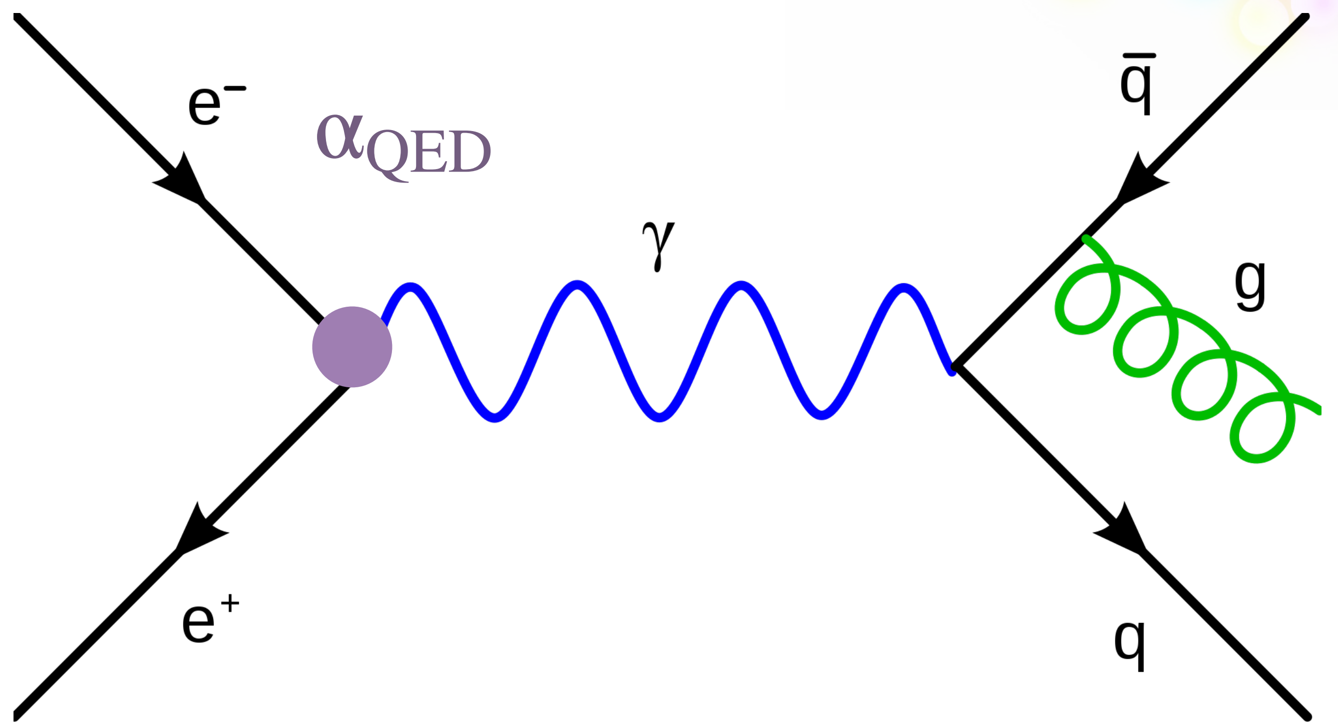

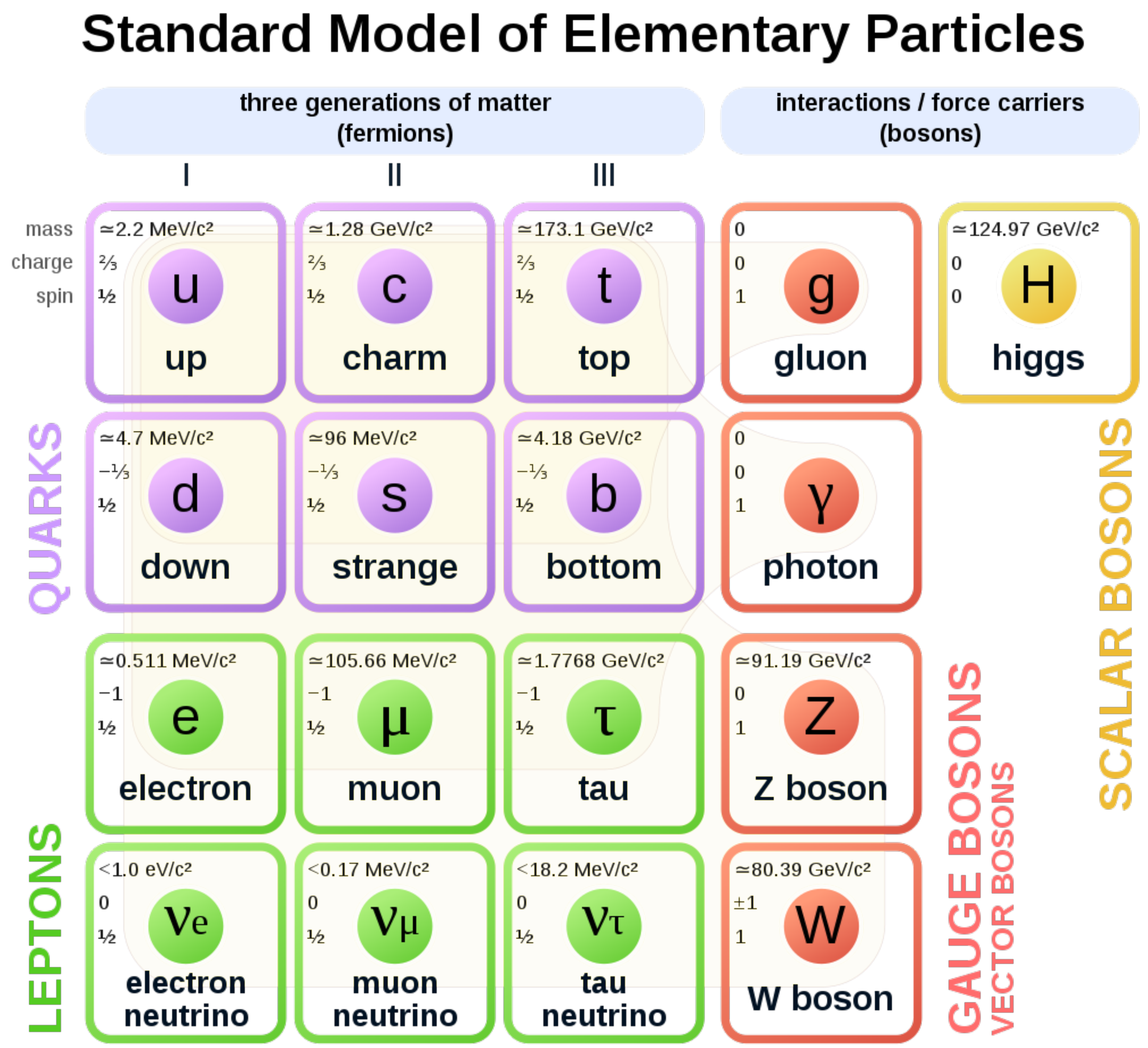

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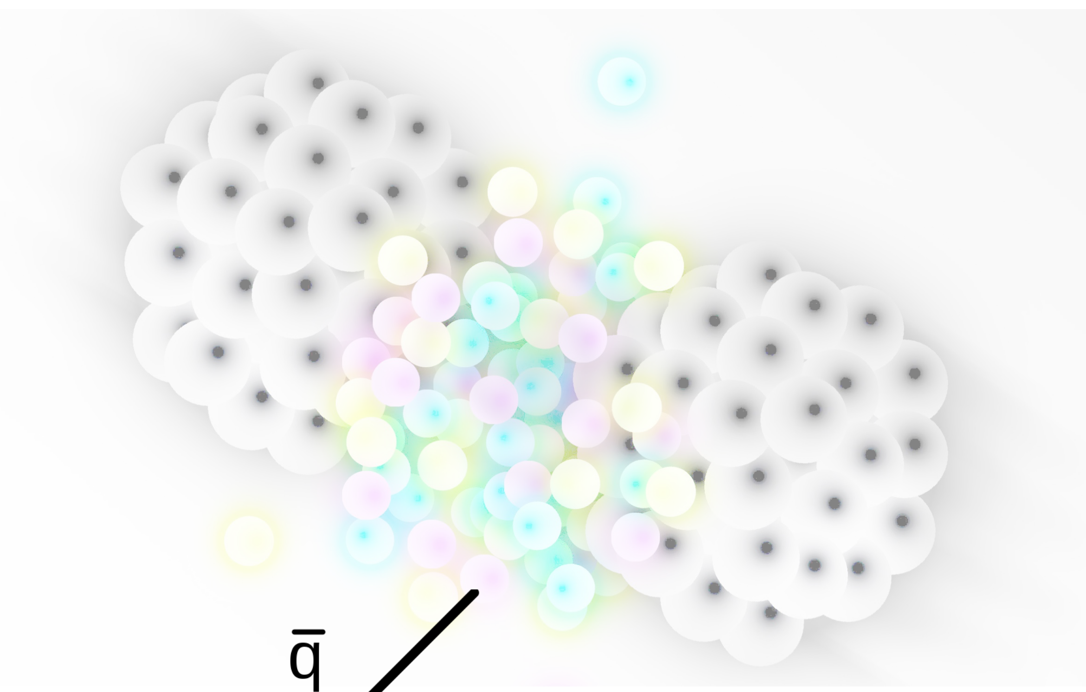

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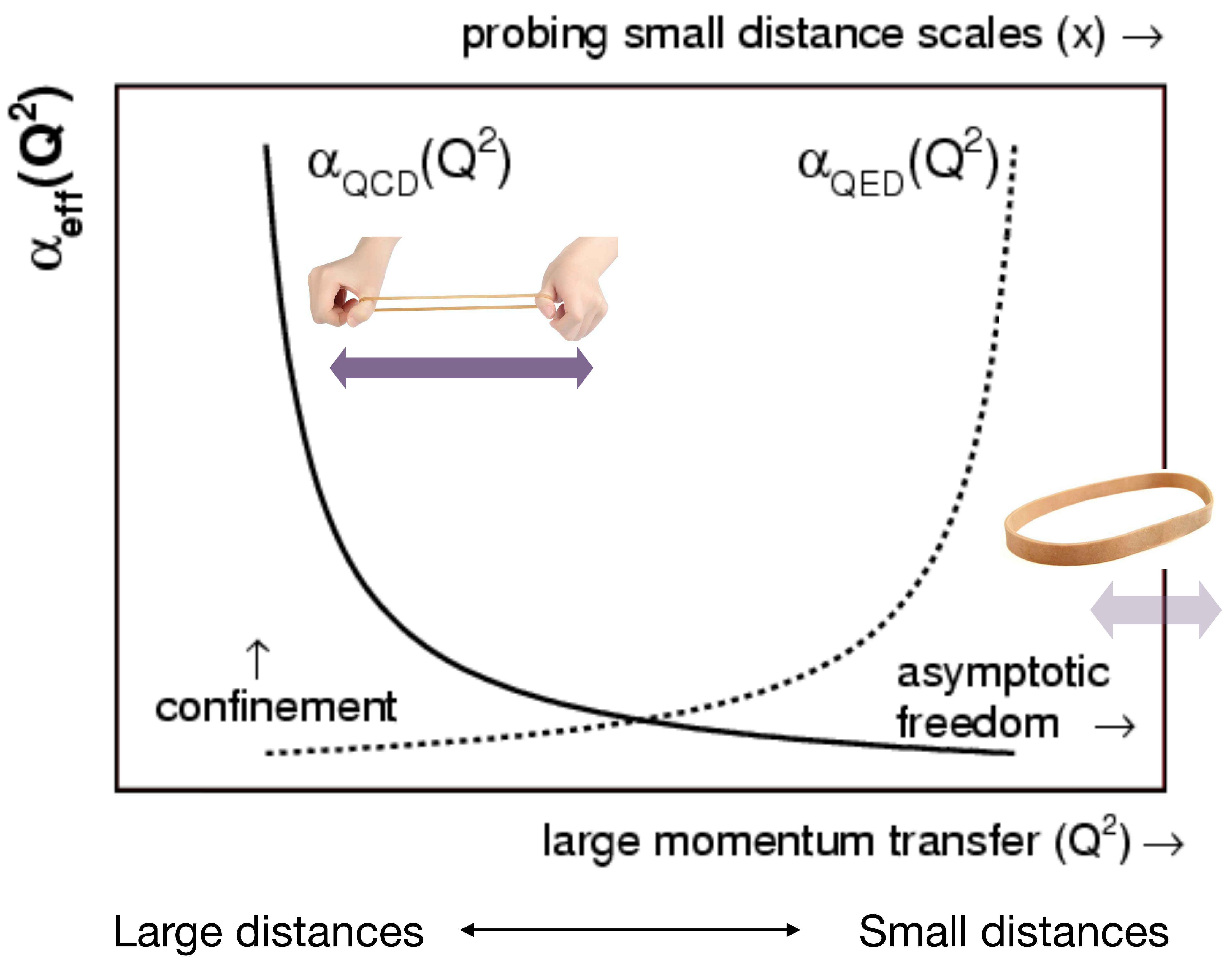

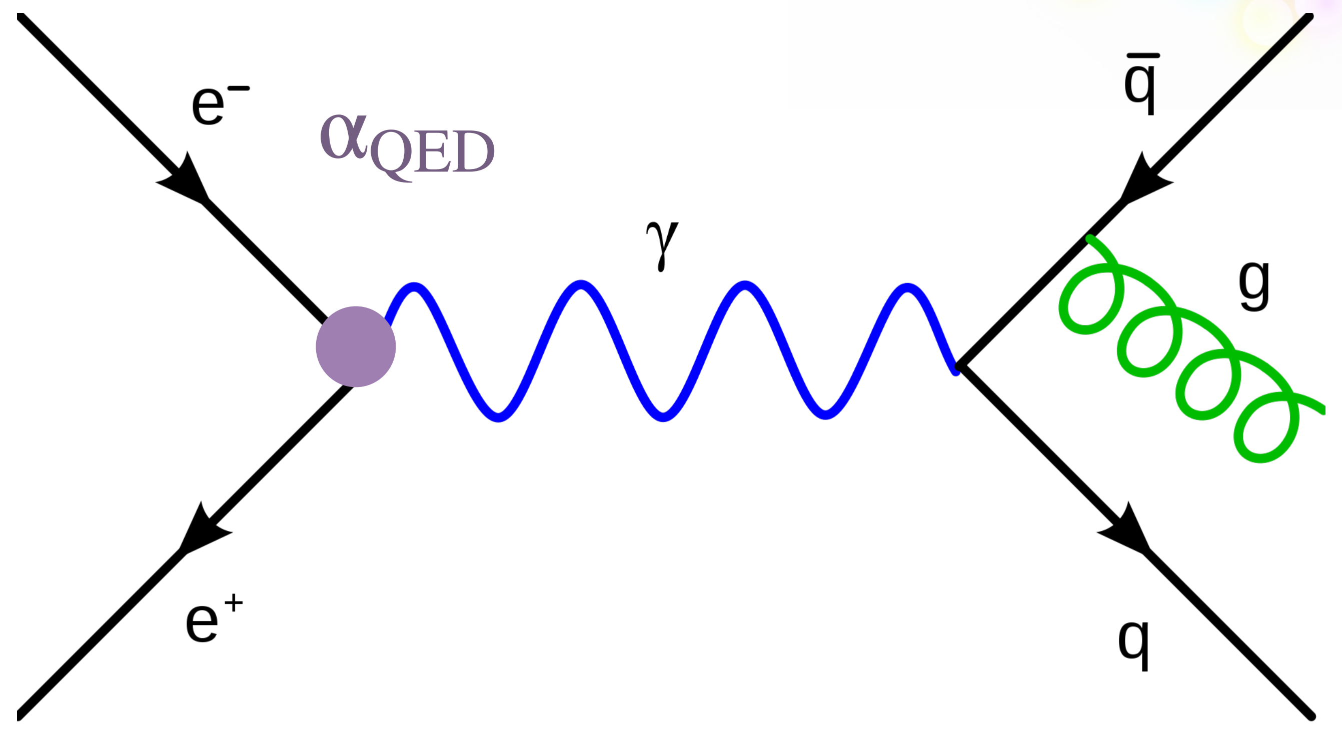

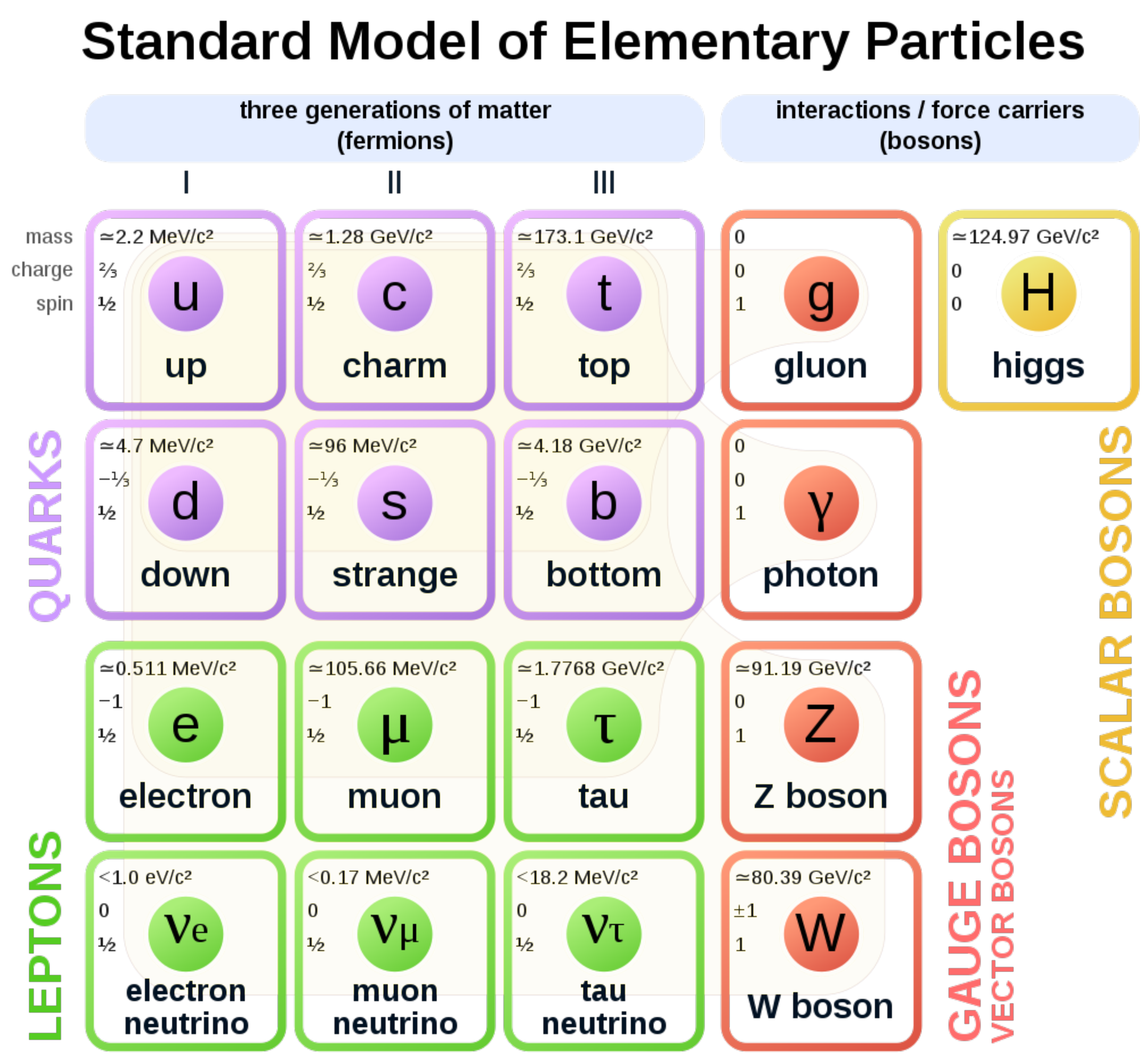

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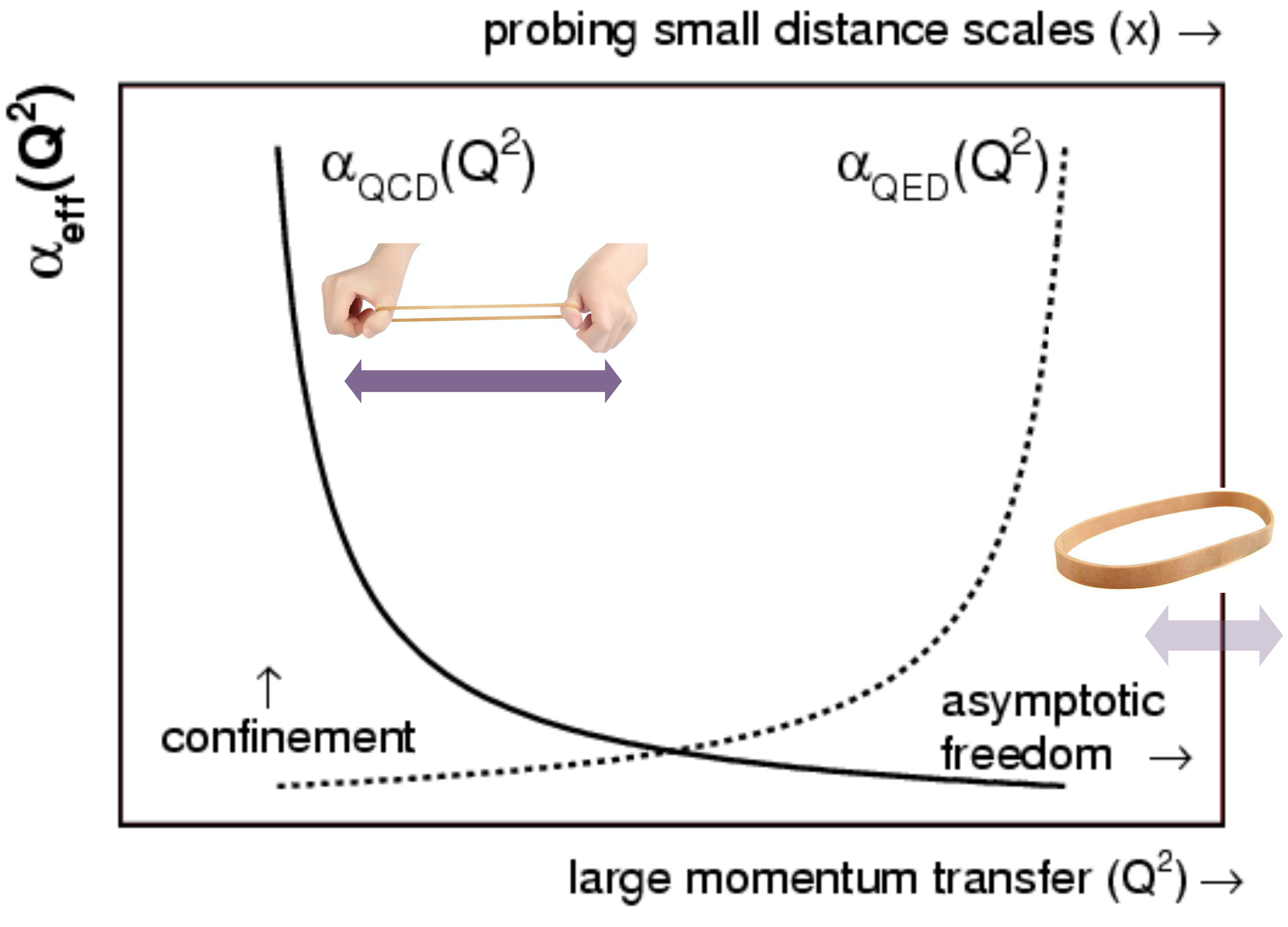

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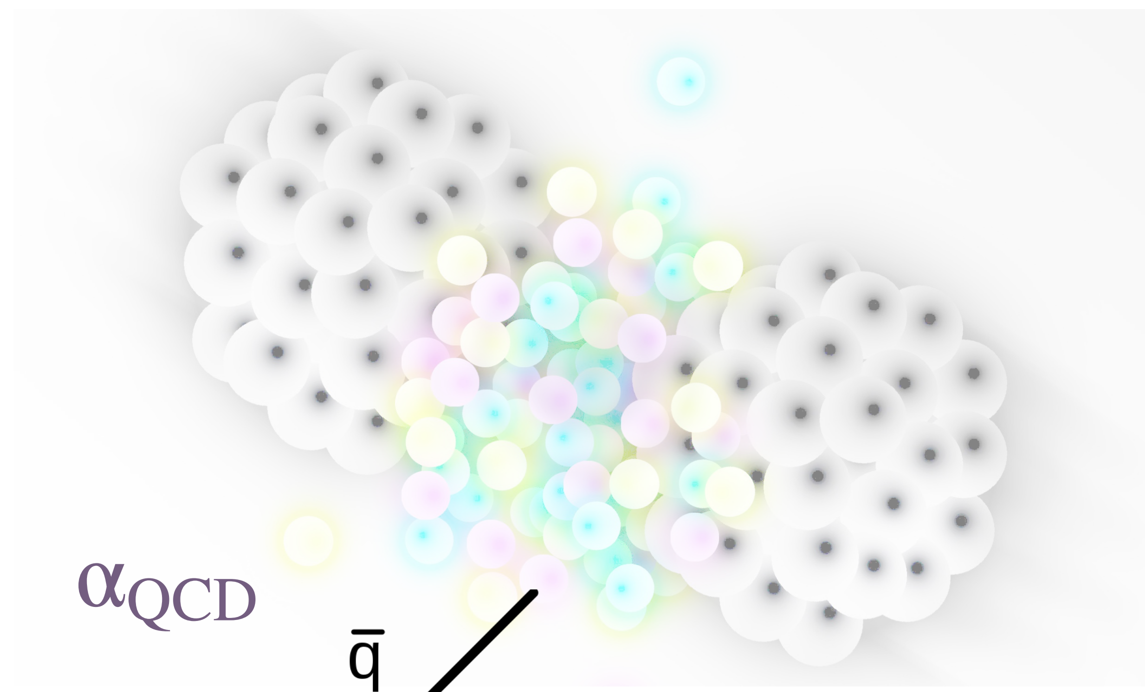
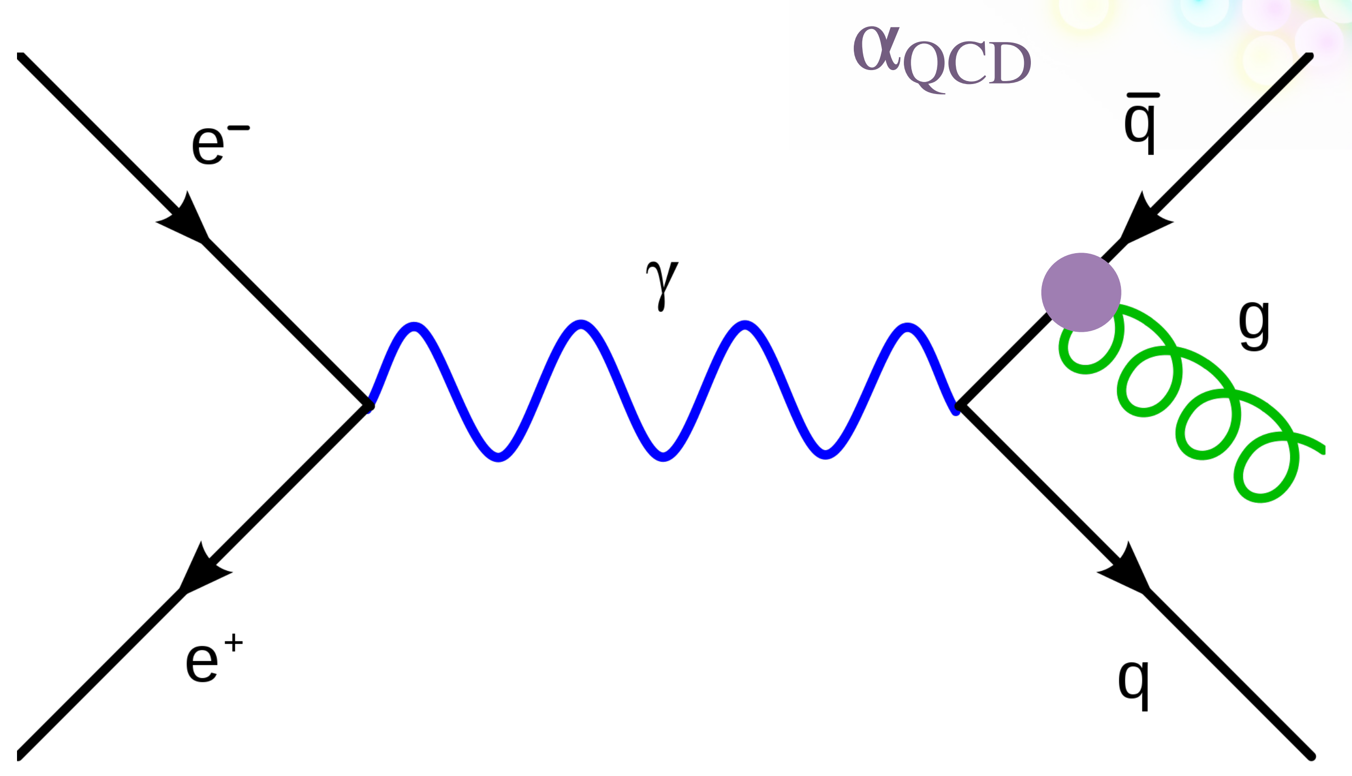
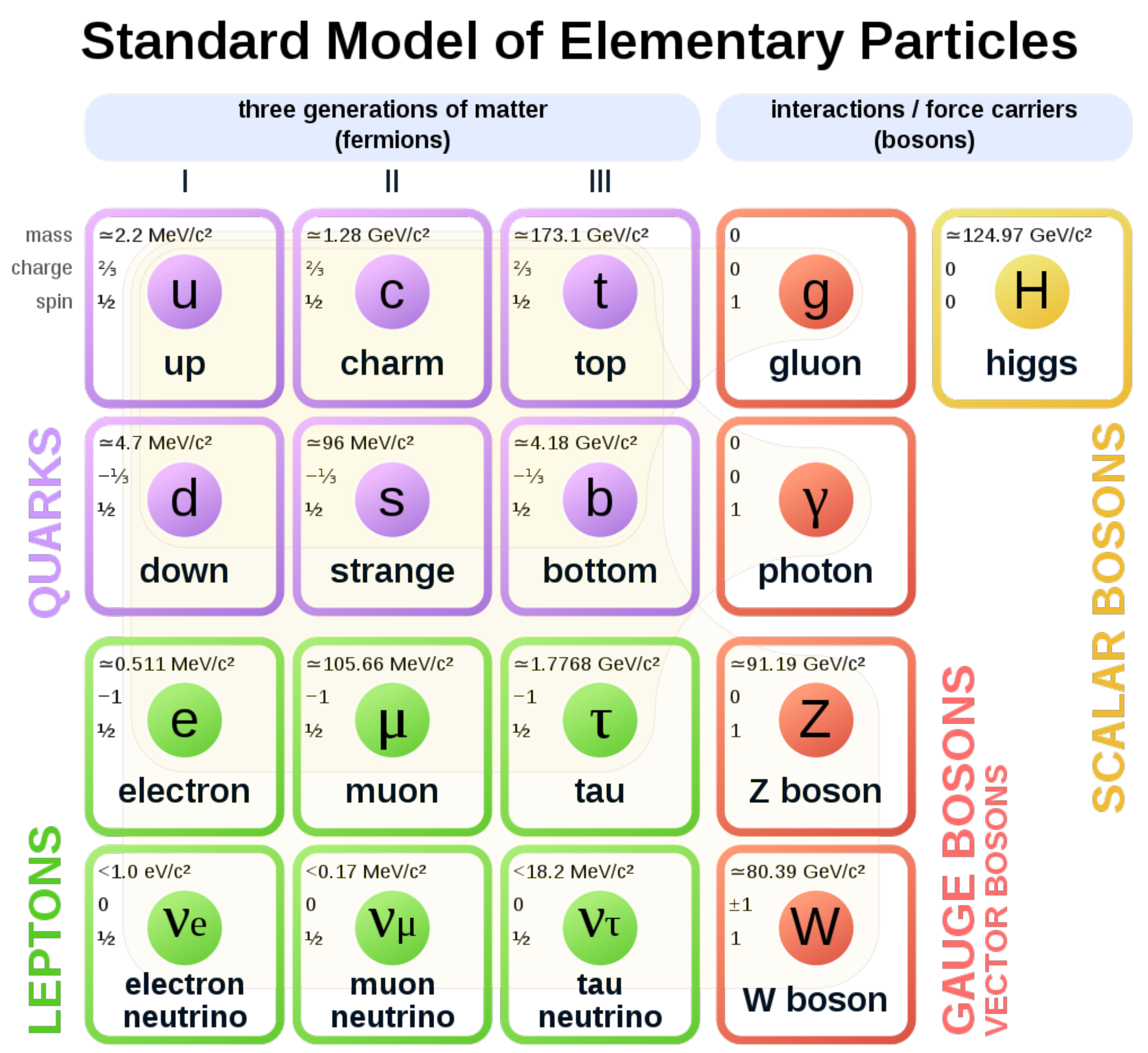
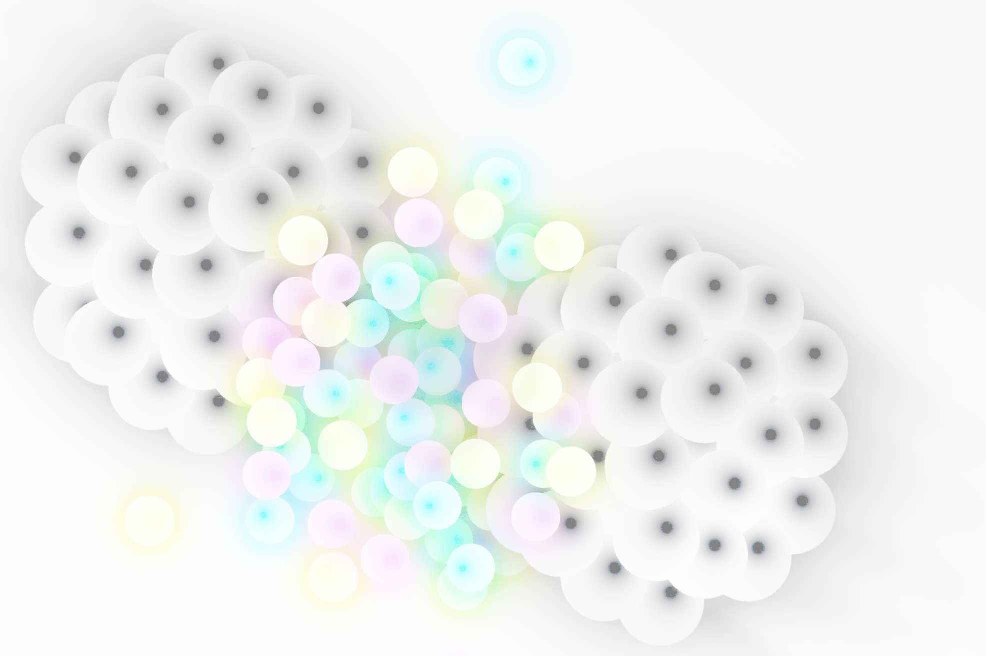






Quantum Chromodynamics



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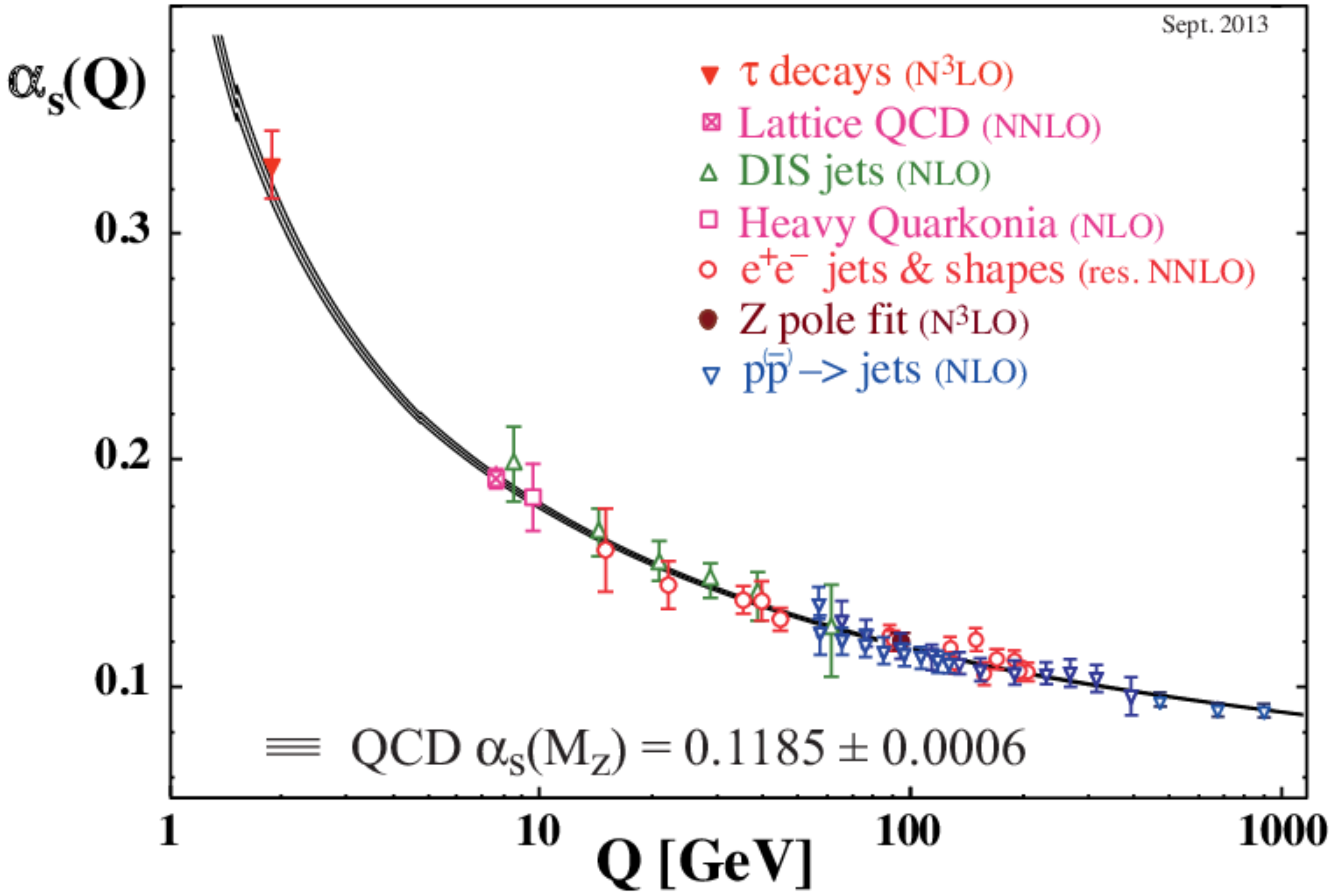

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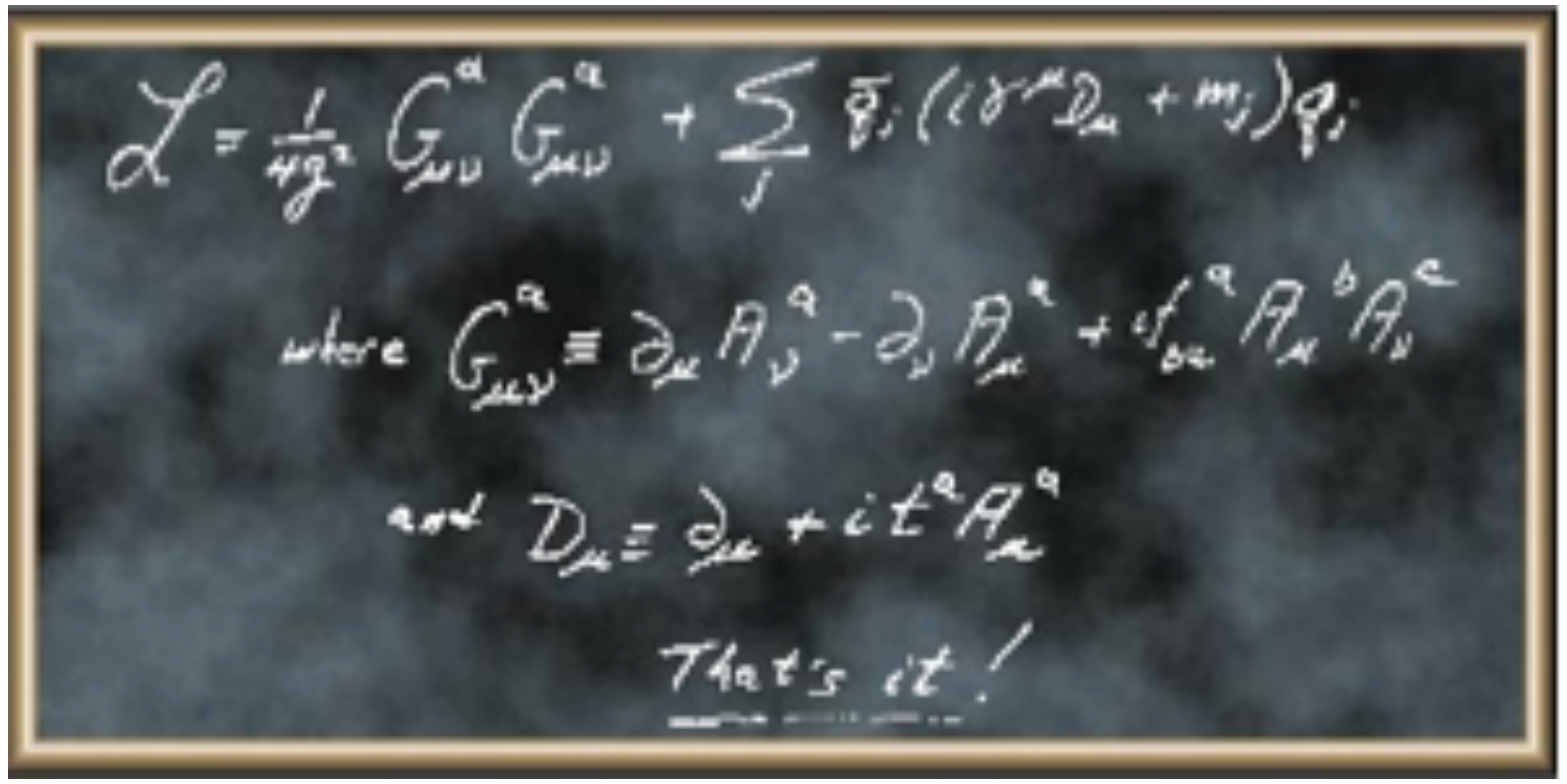

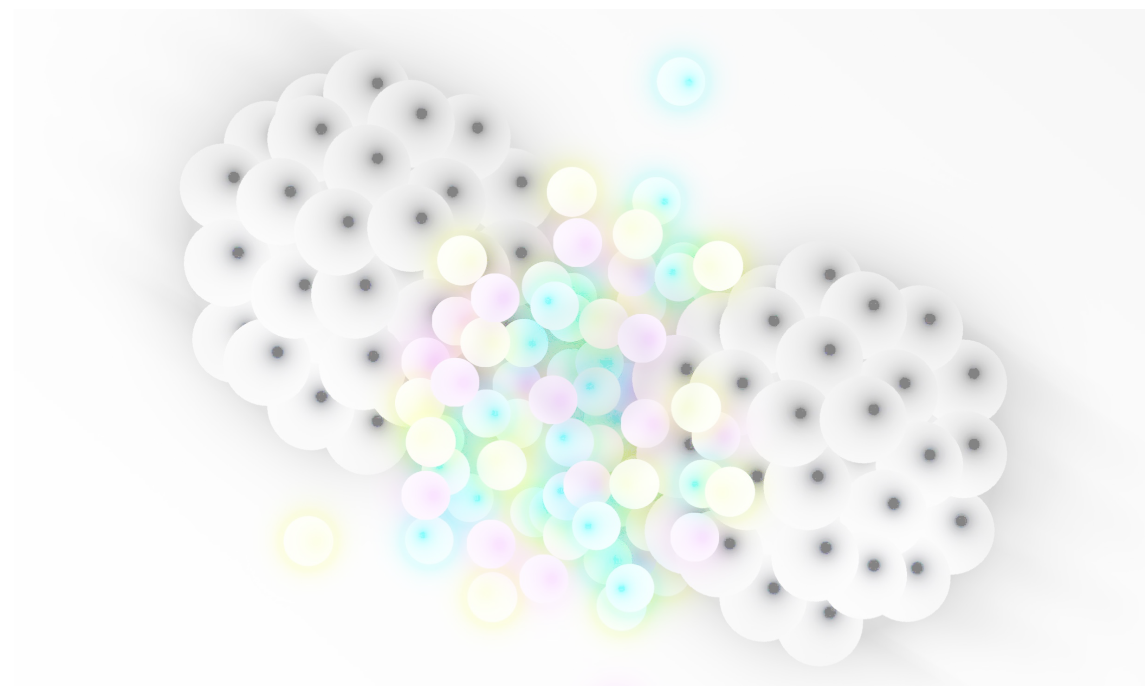

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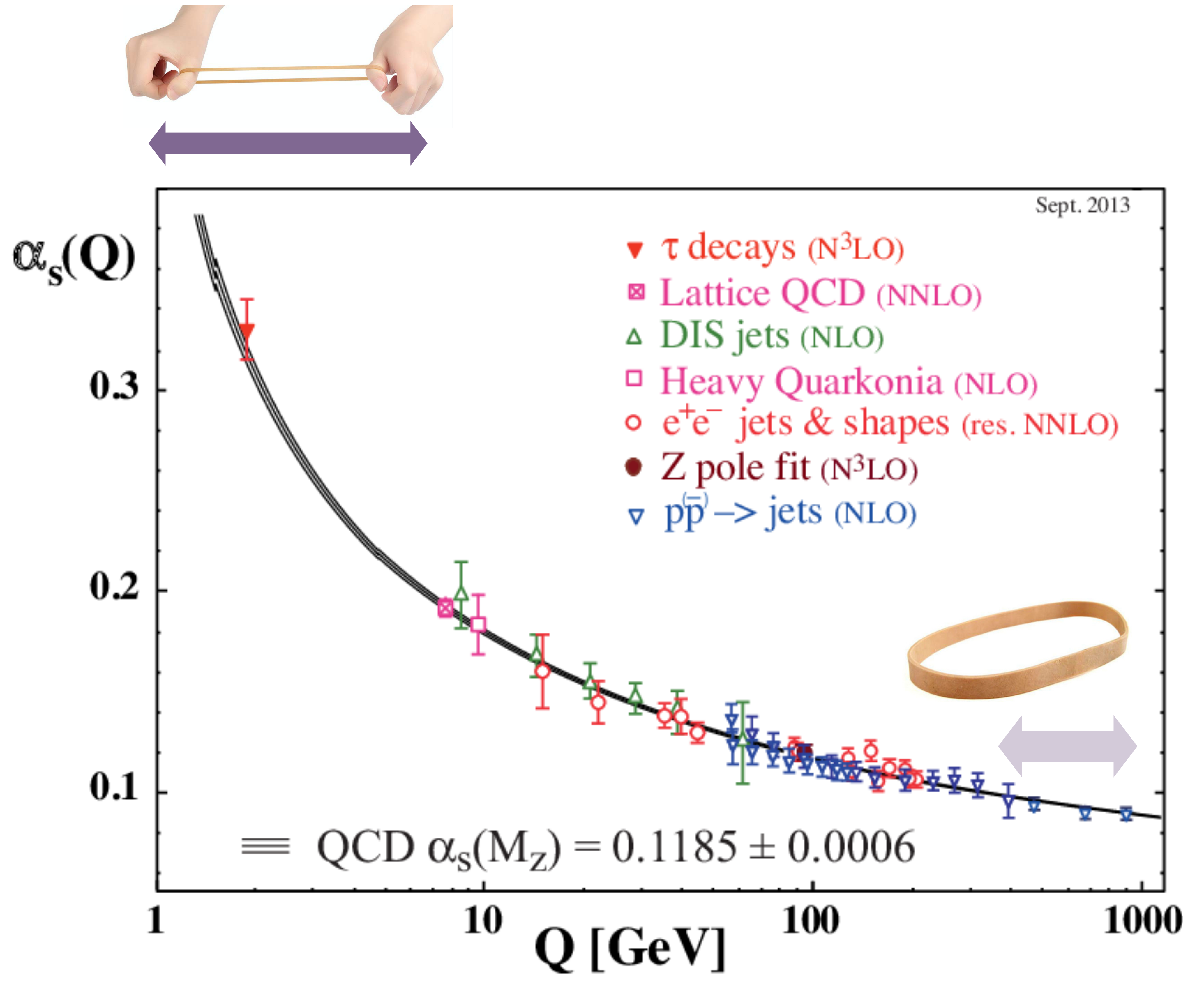

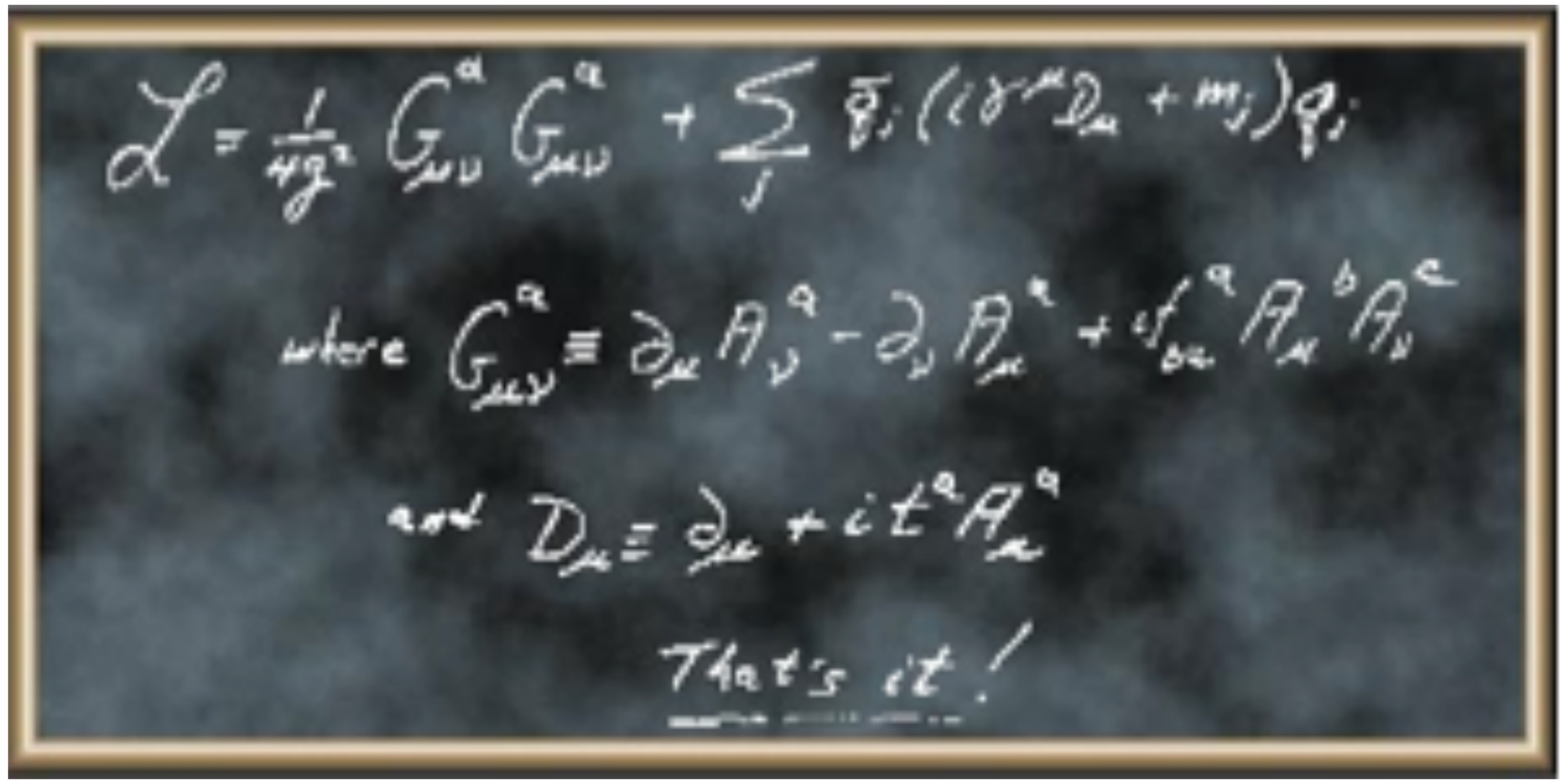

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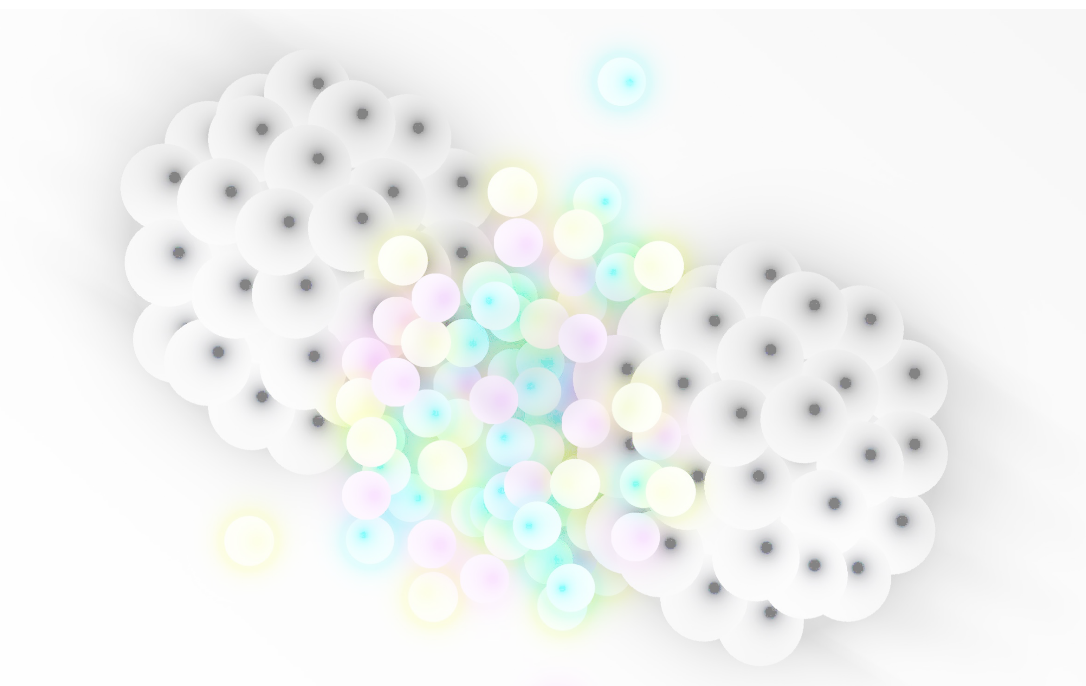

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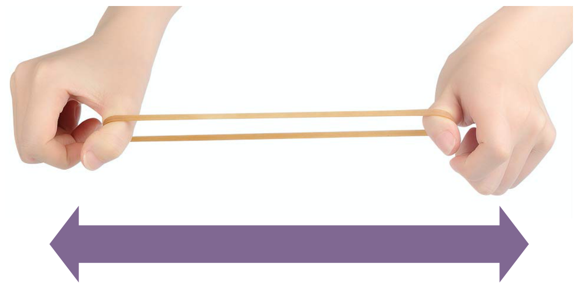

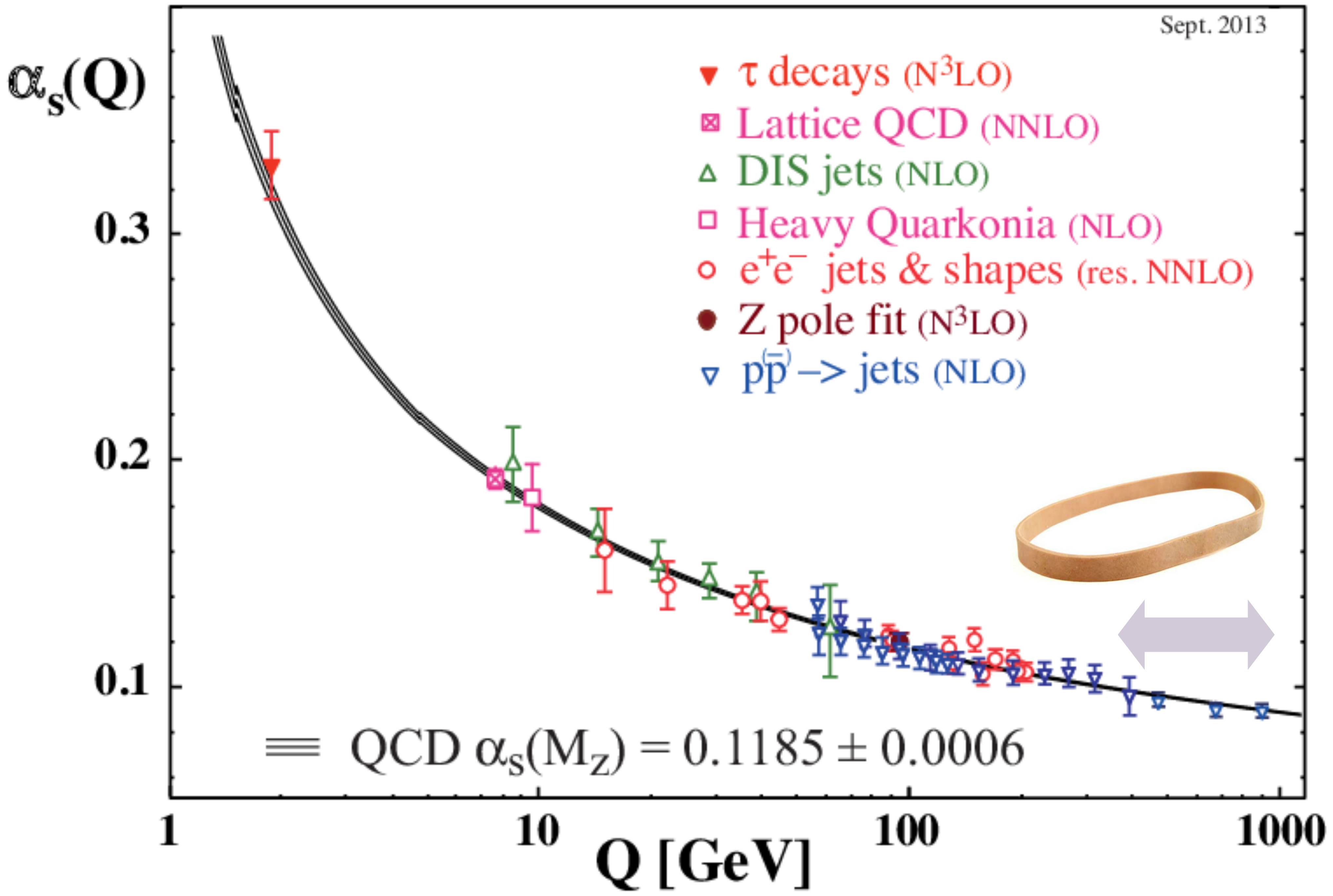

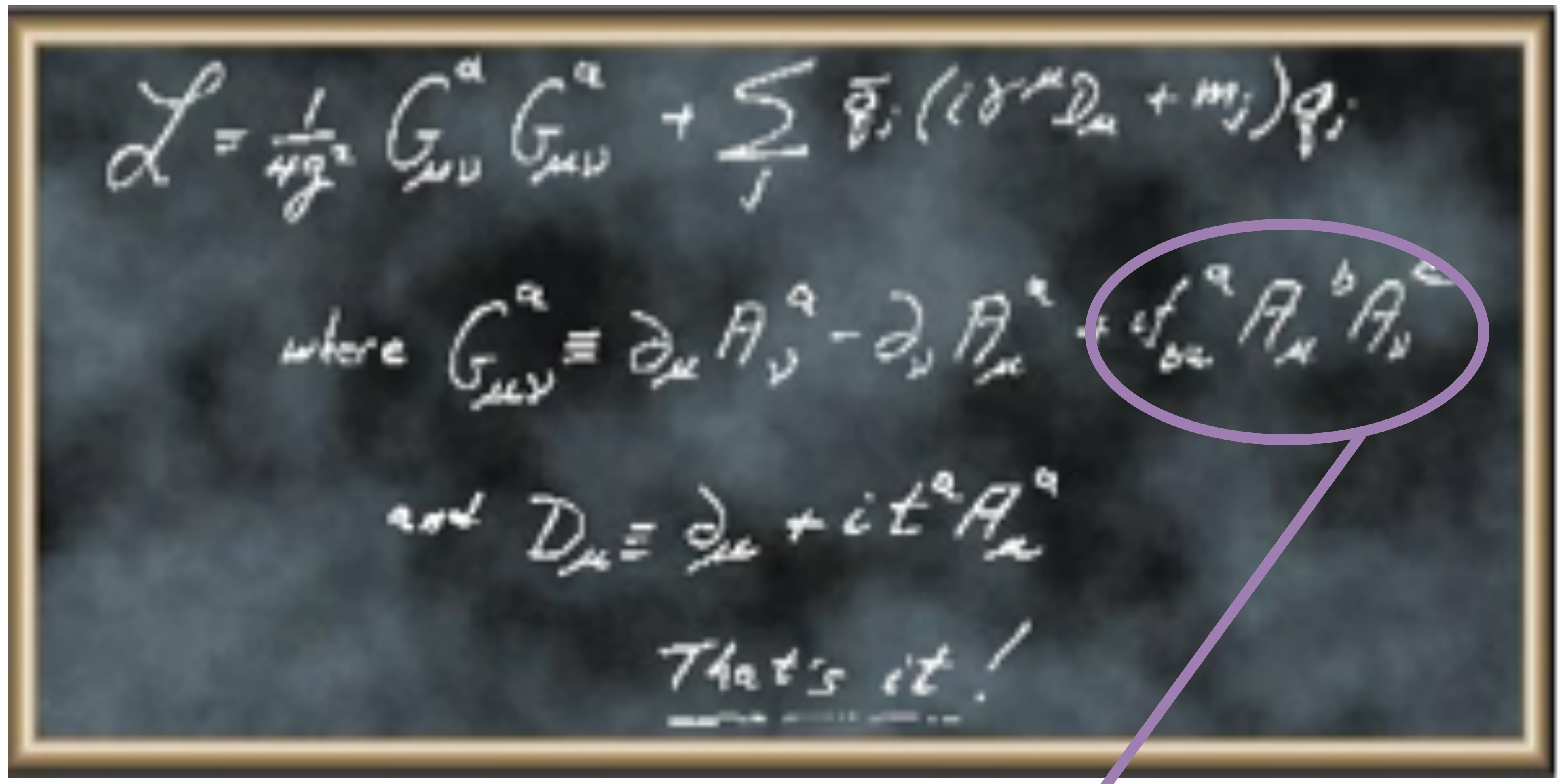

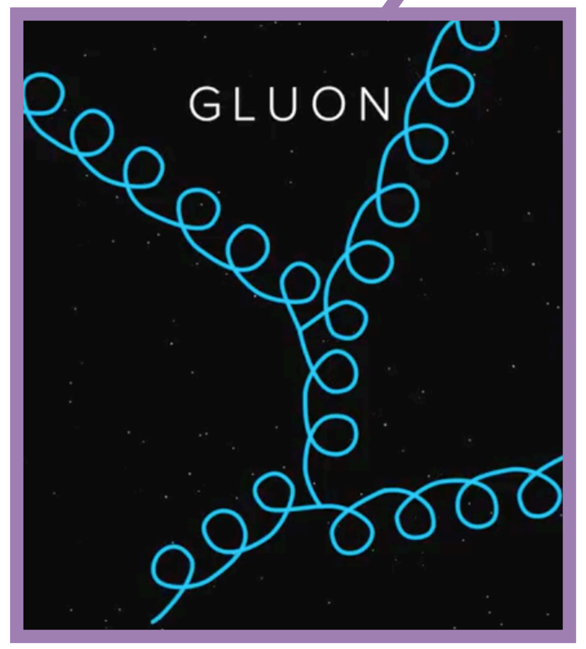

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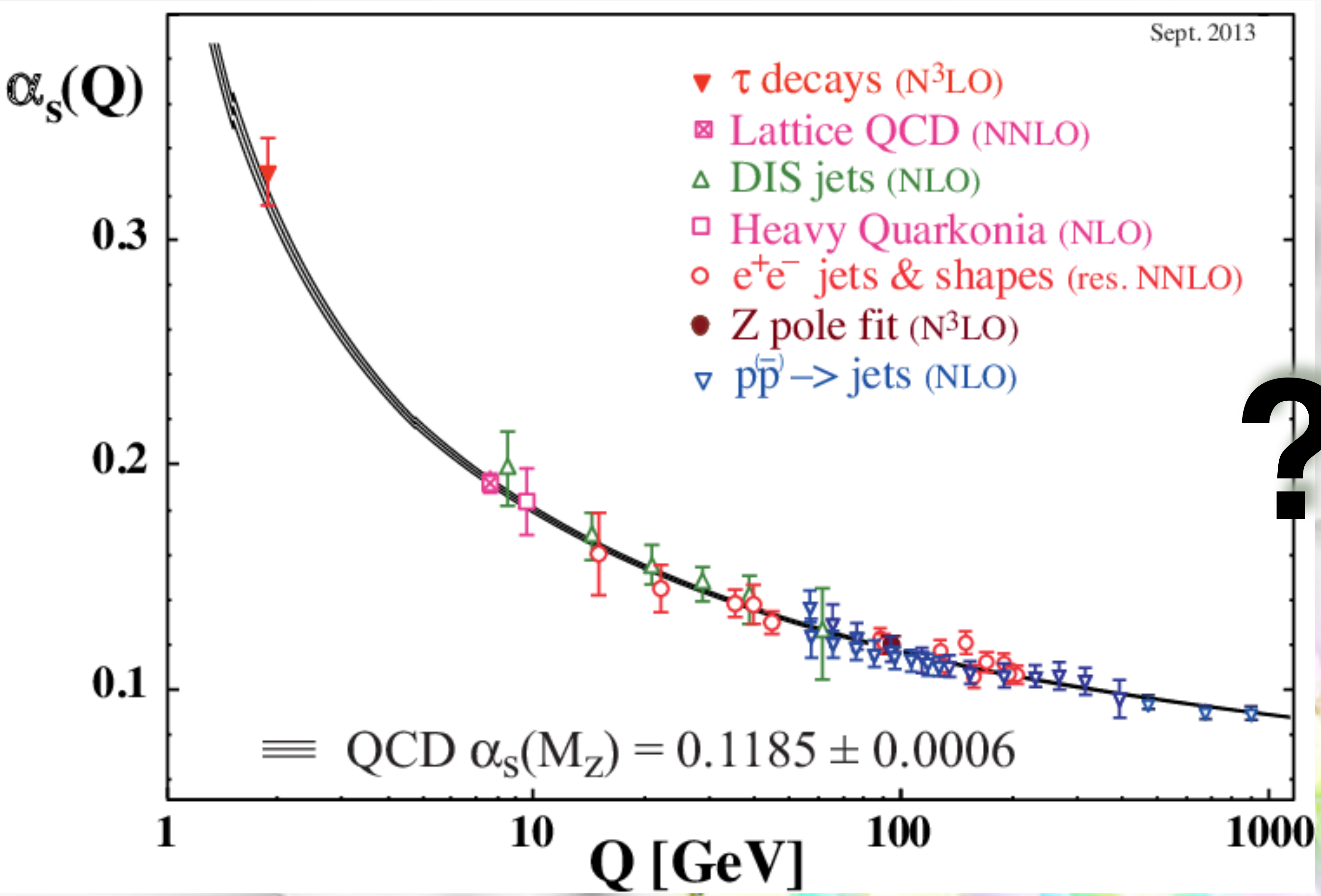
How do we “work” with QCD?



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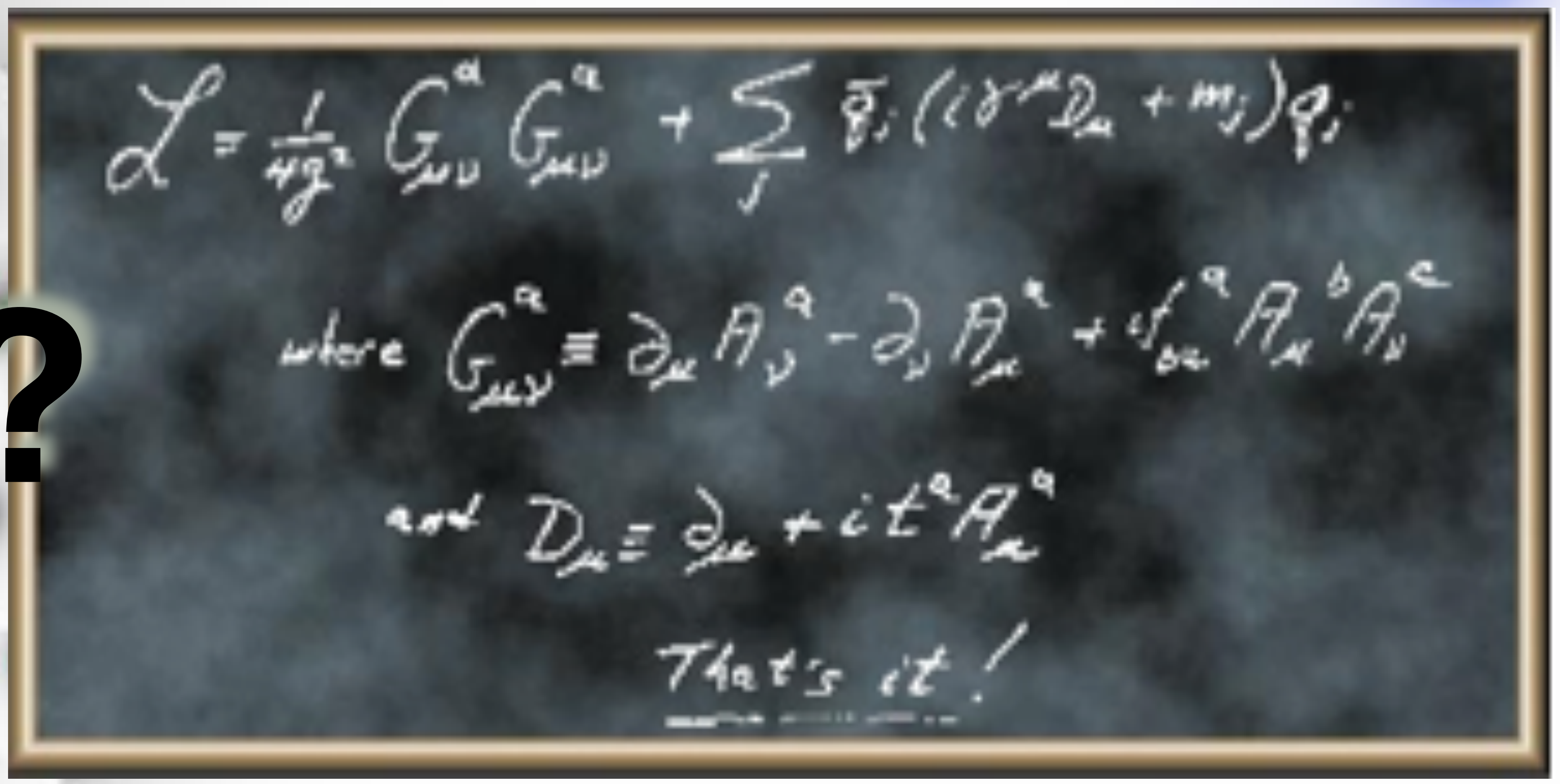
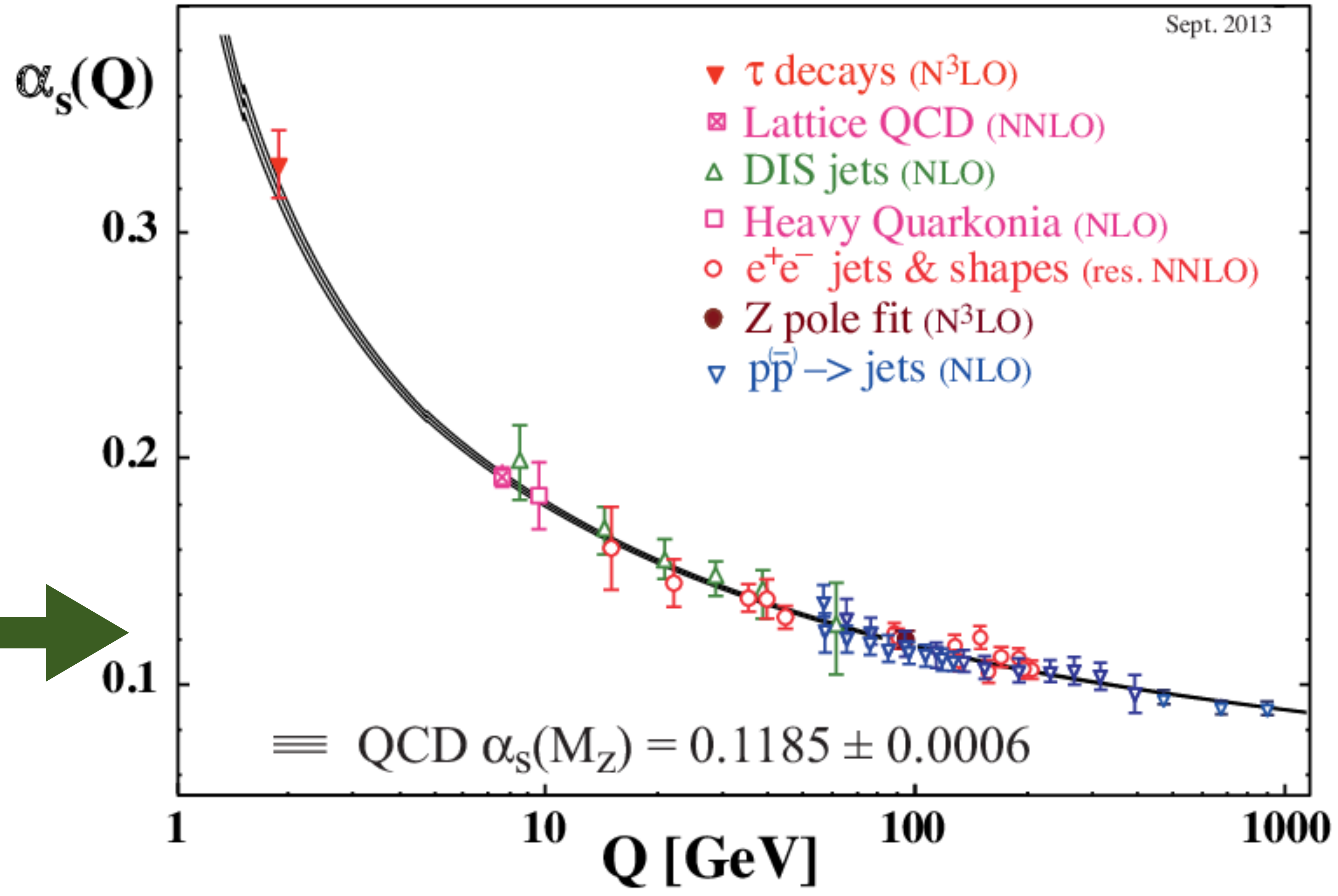


Asymptotic Freedom



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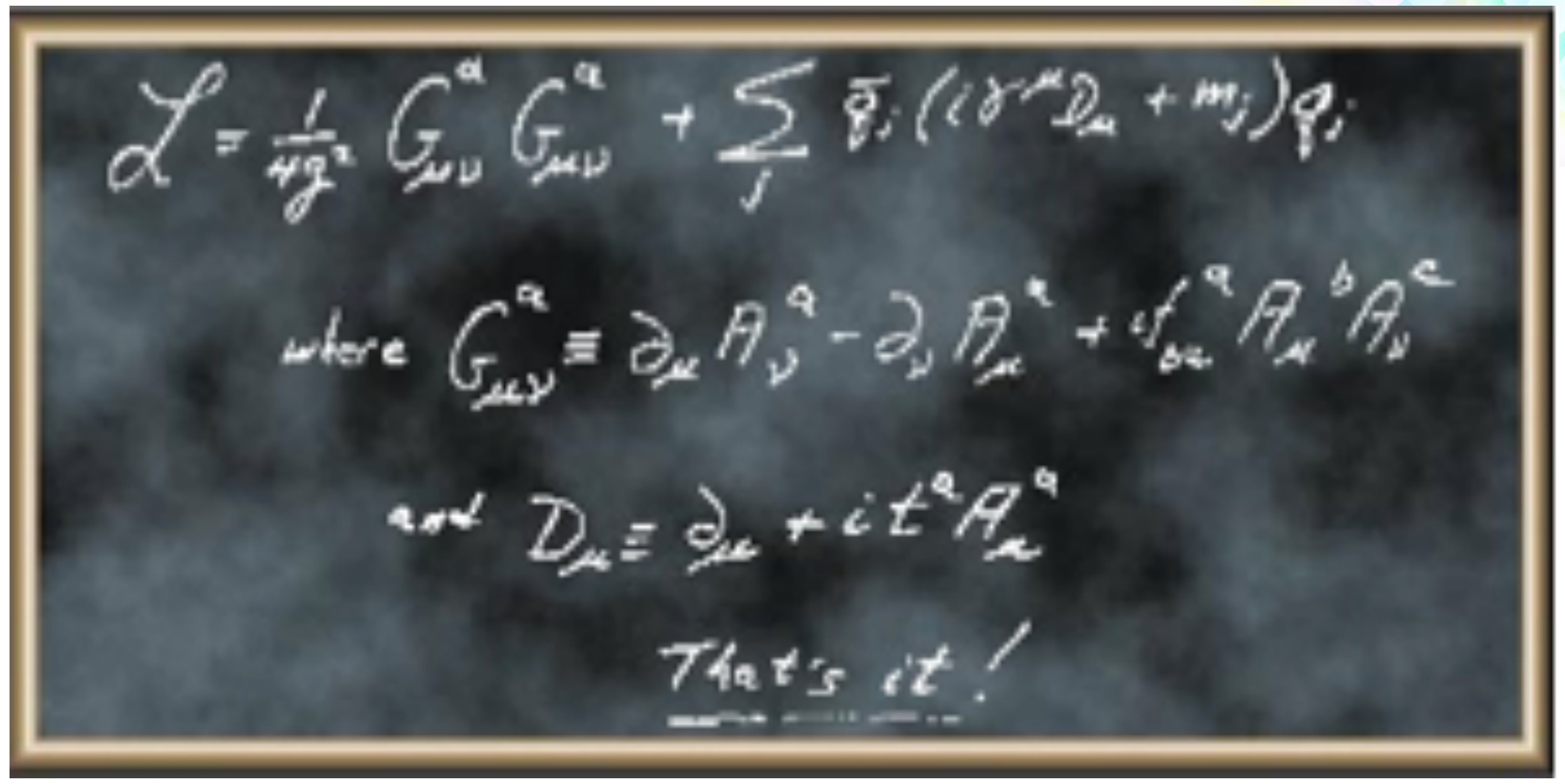


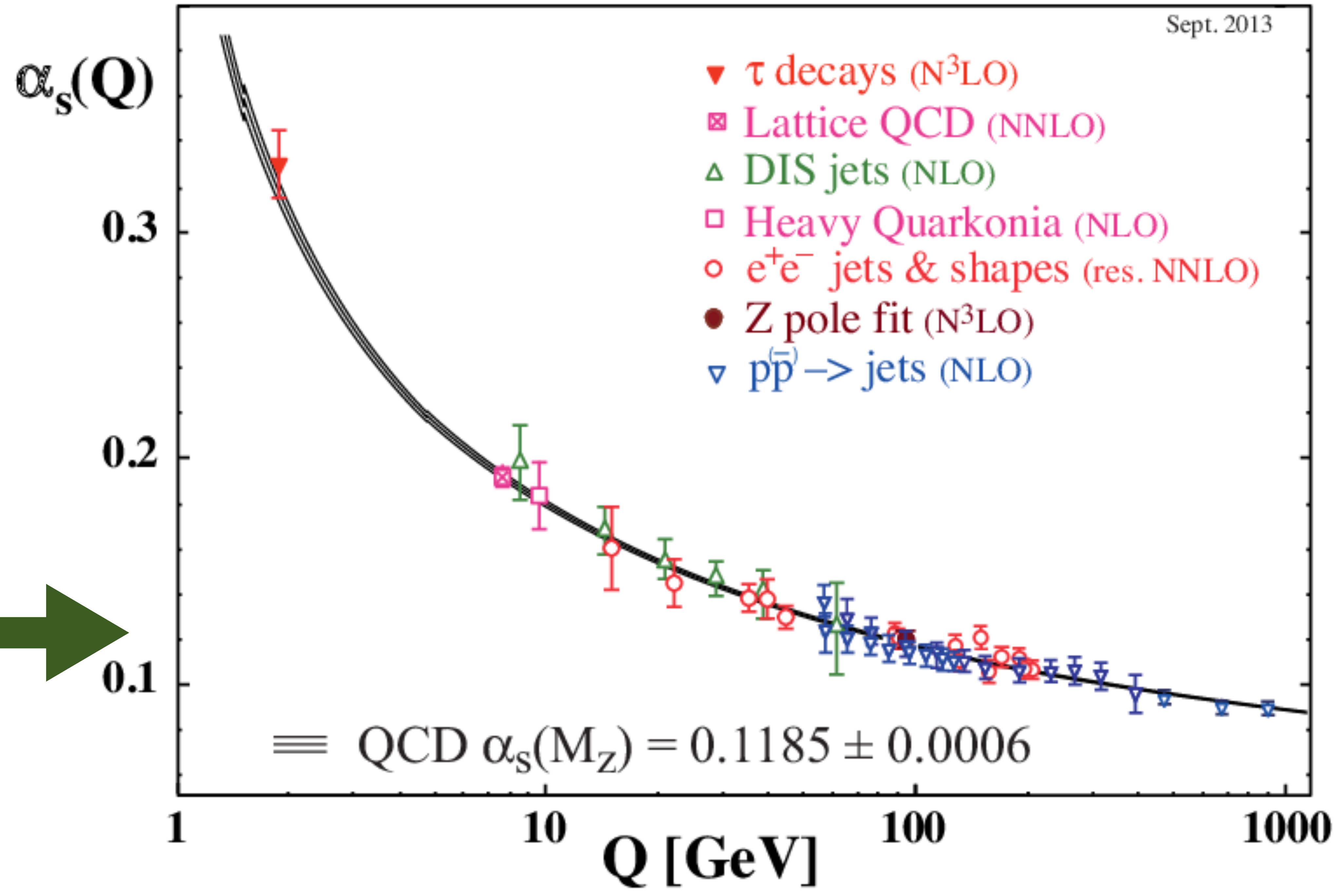
Example: Taylor Series of $f(x)$

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

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

Higher order terms can be neglected for x << 1

Asymptotic Freedom



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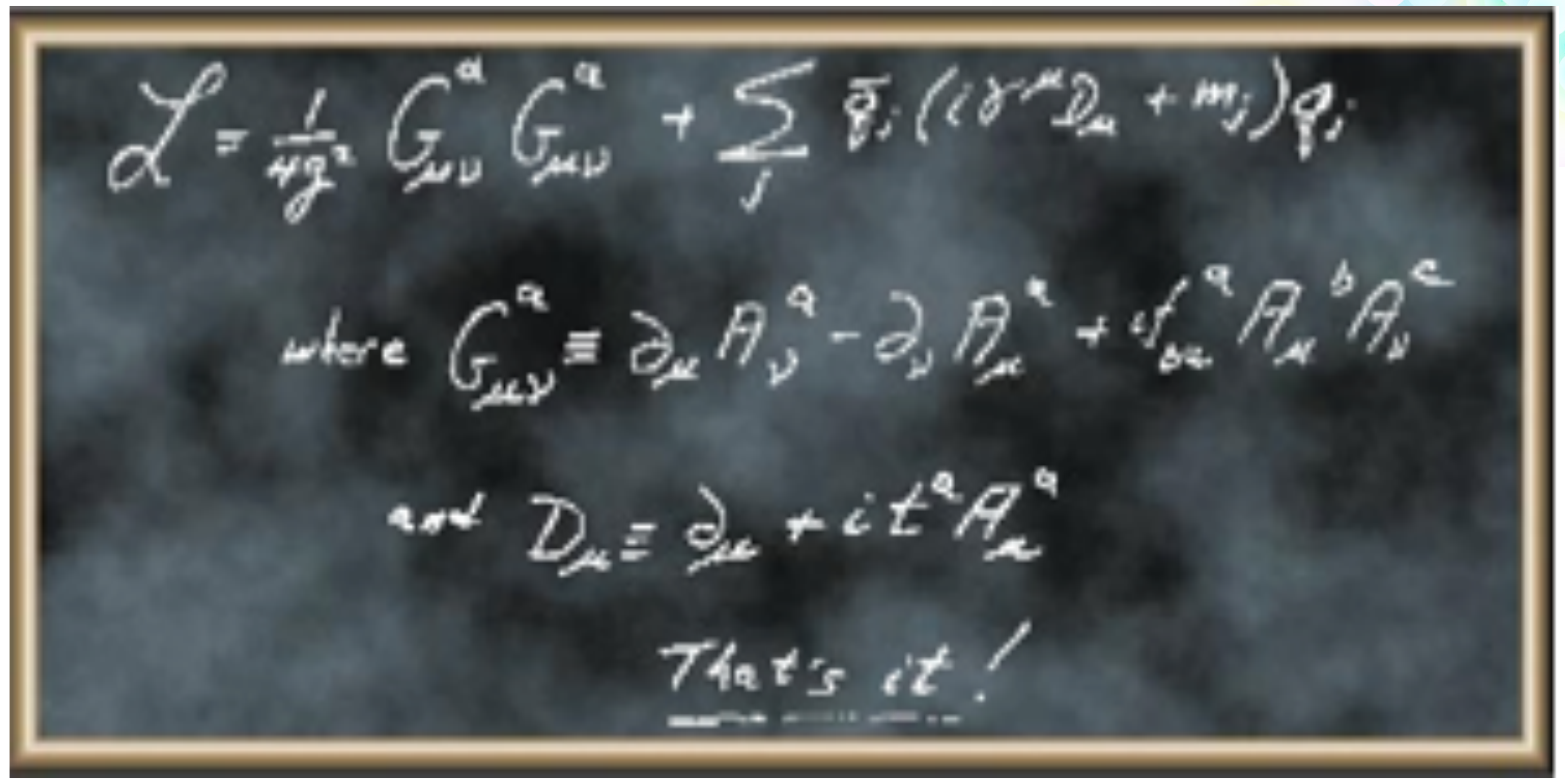
QCD Lagrangian within perturbation theory!

➜ perturbative QCD (pQCD)



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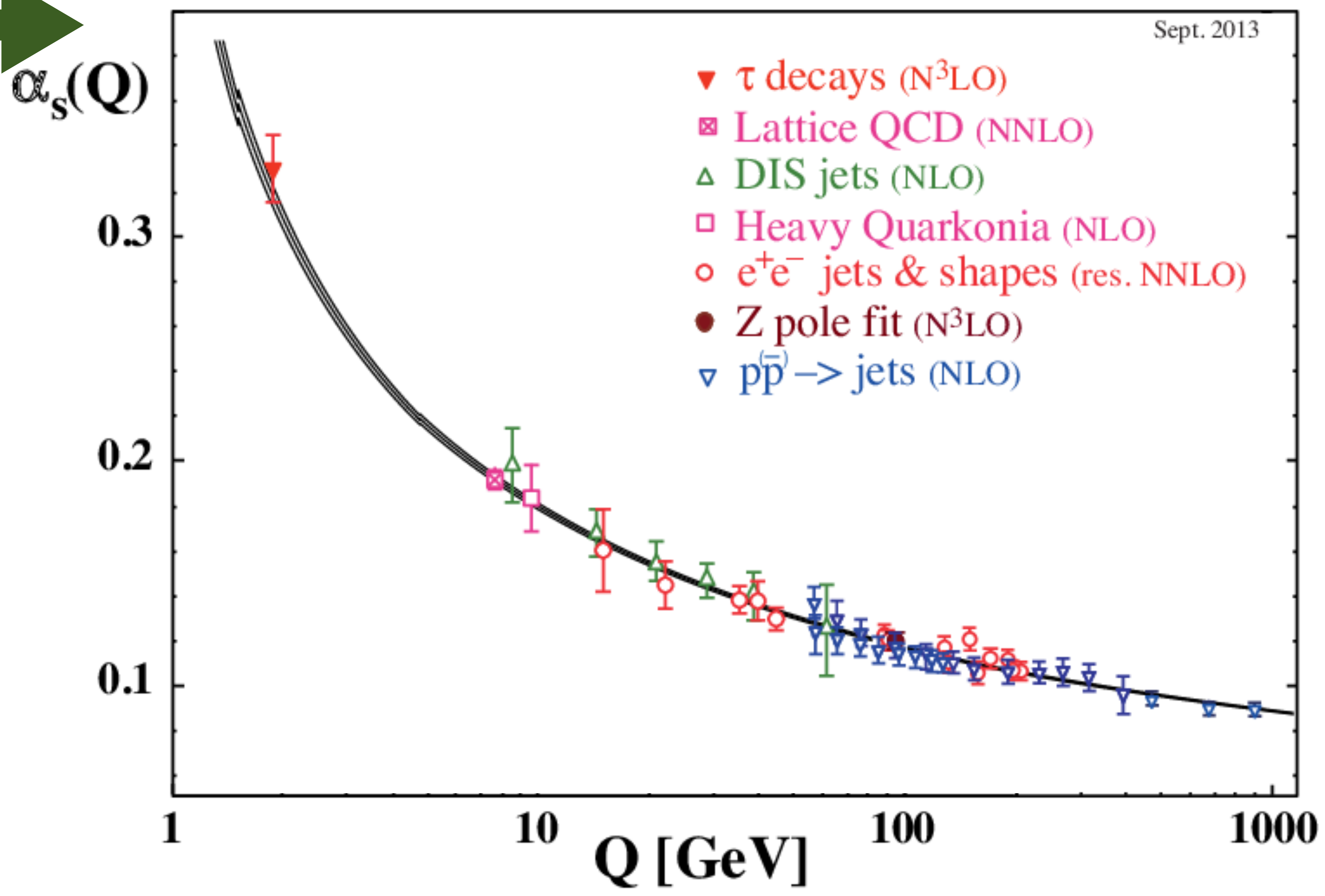
Confinement



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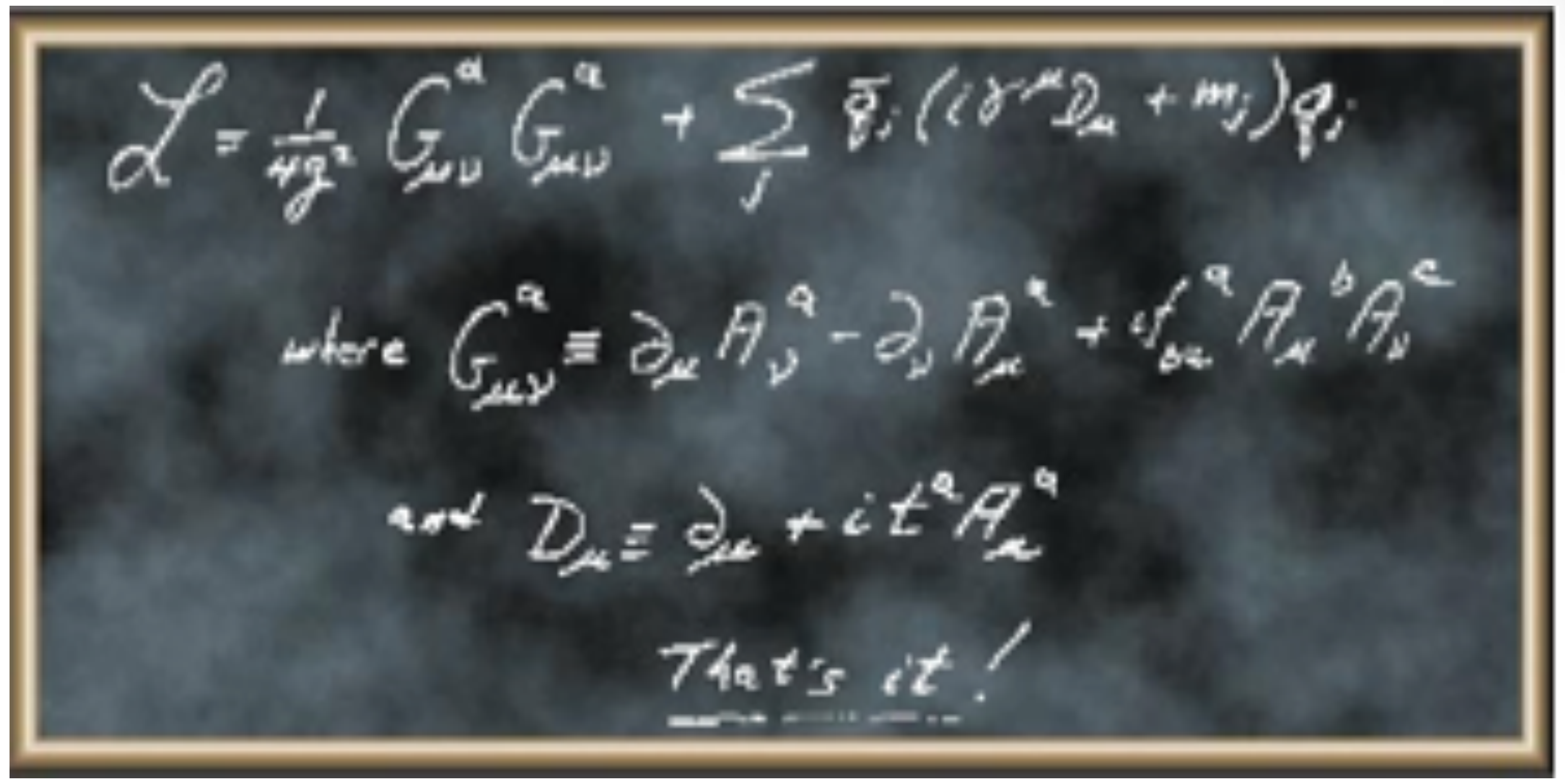

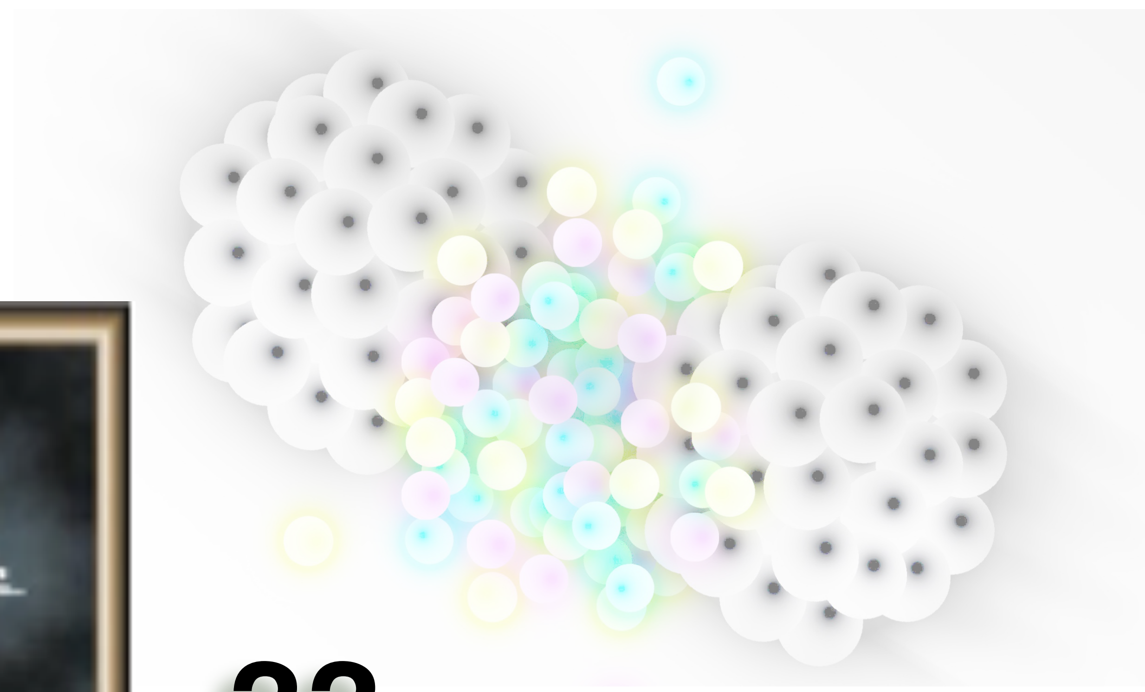

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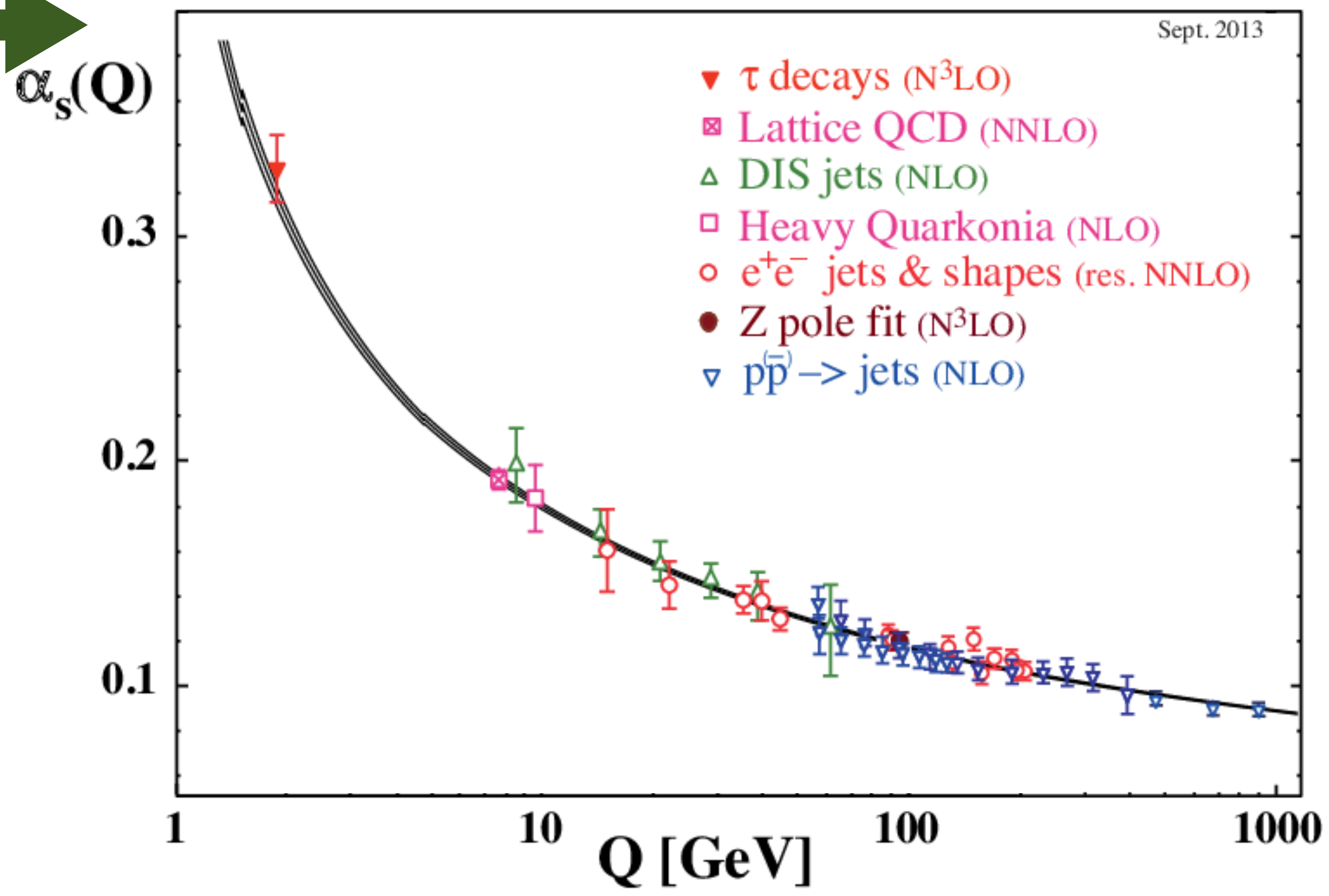

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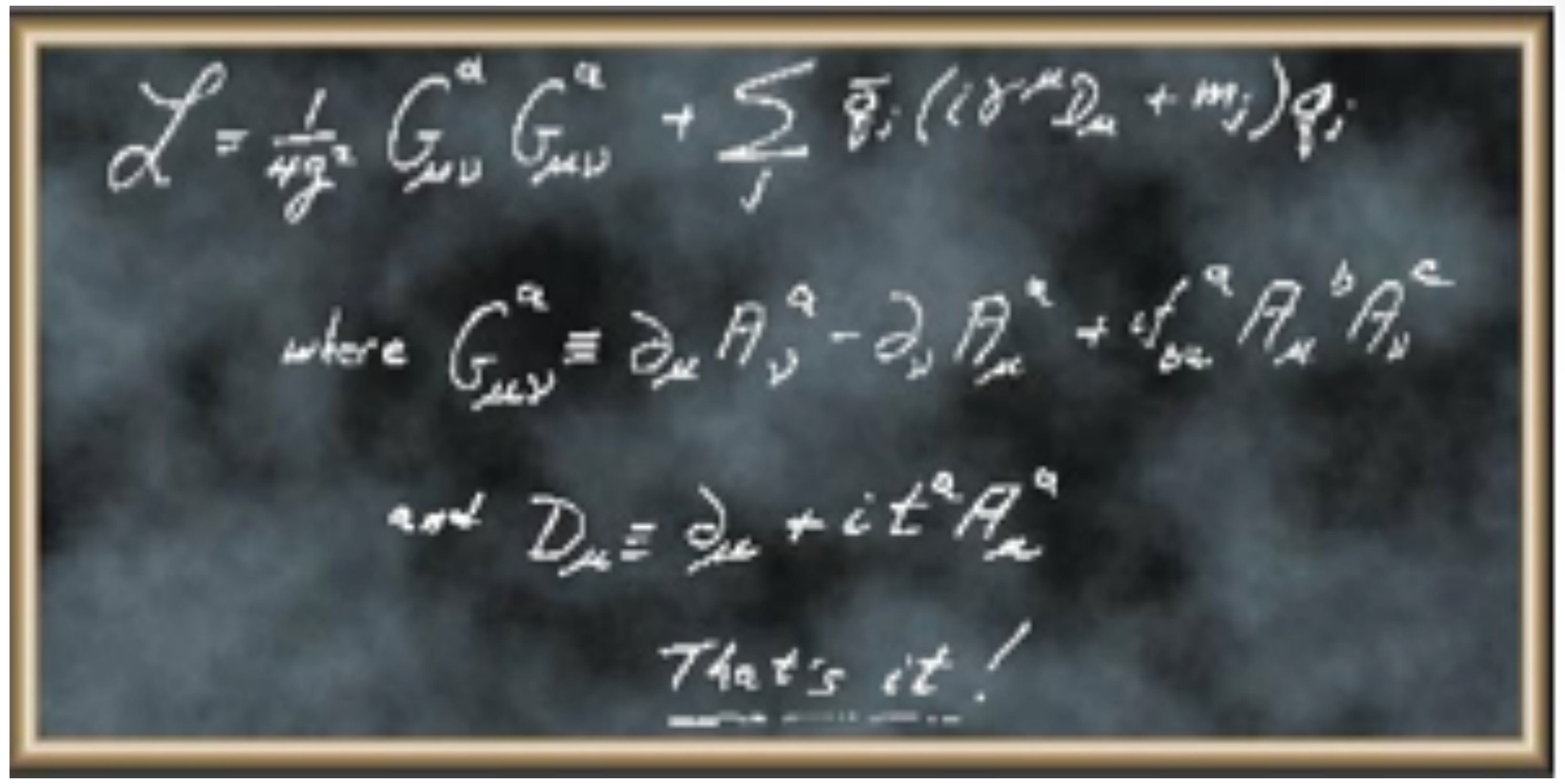

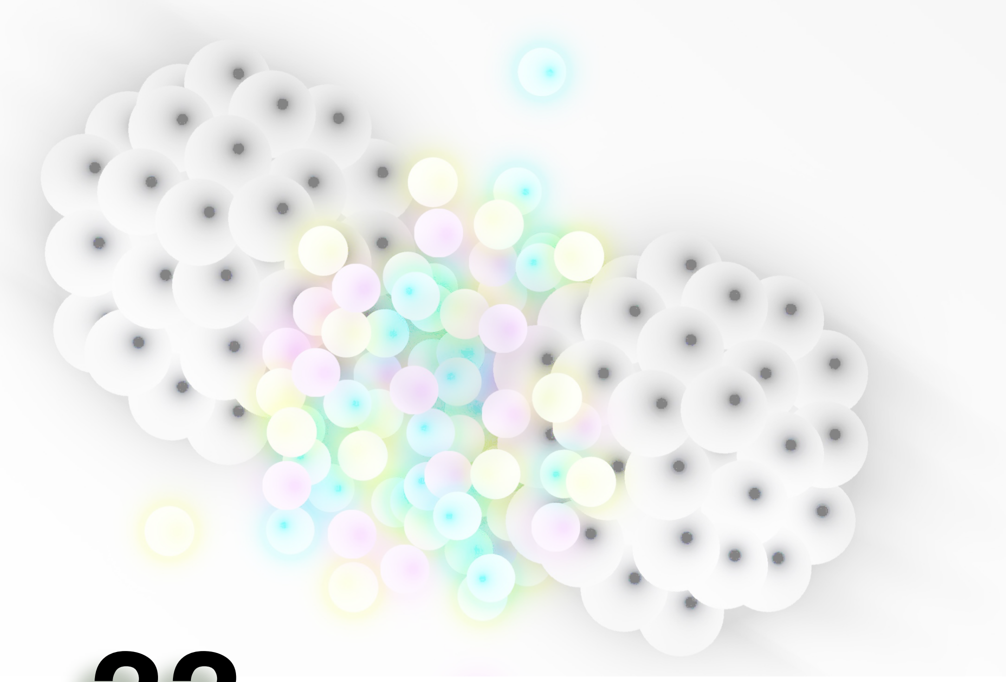

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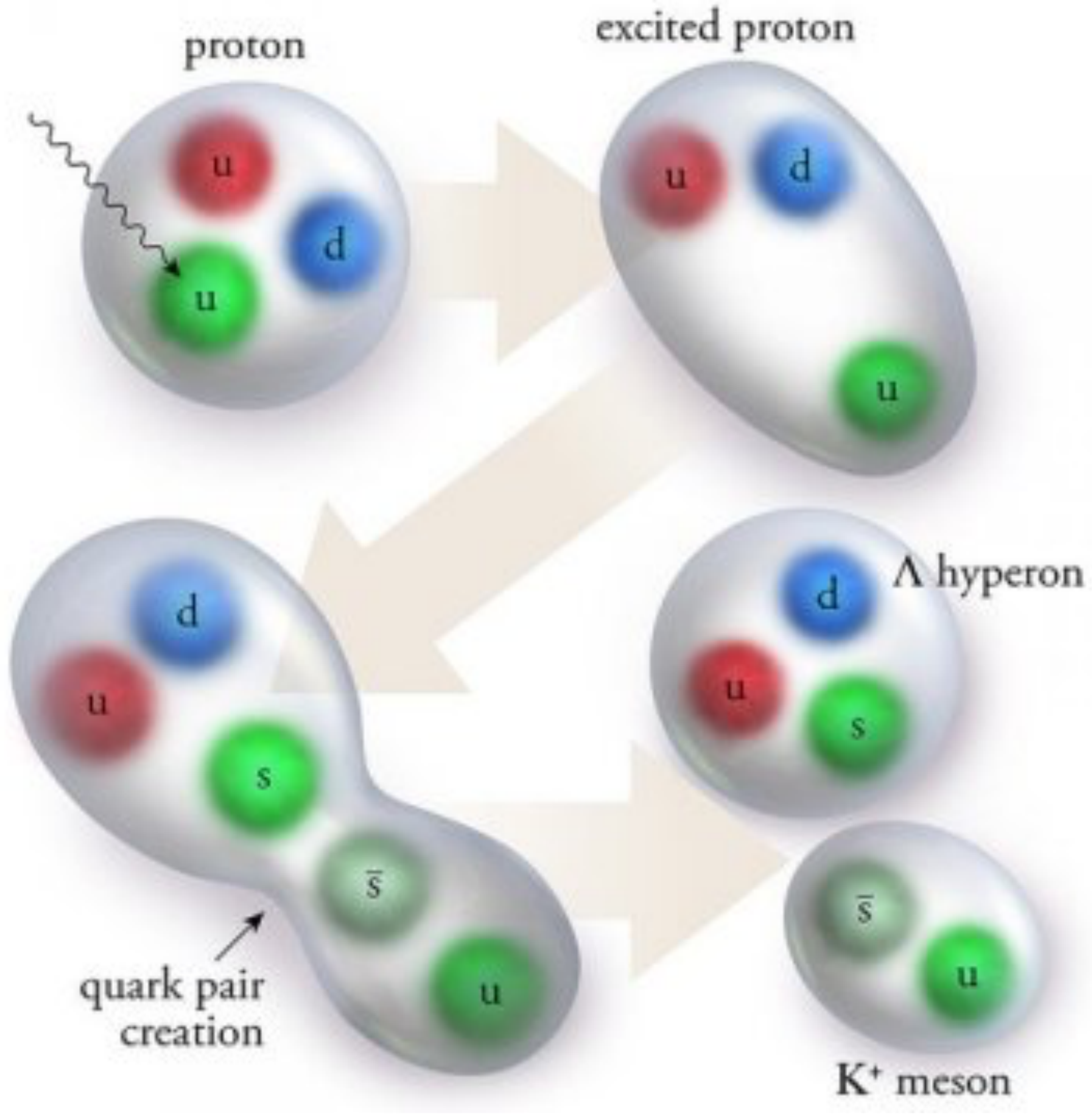
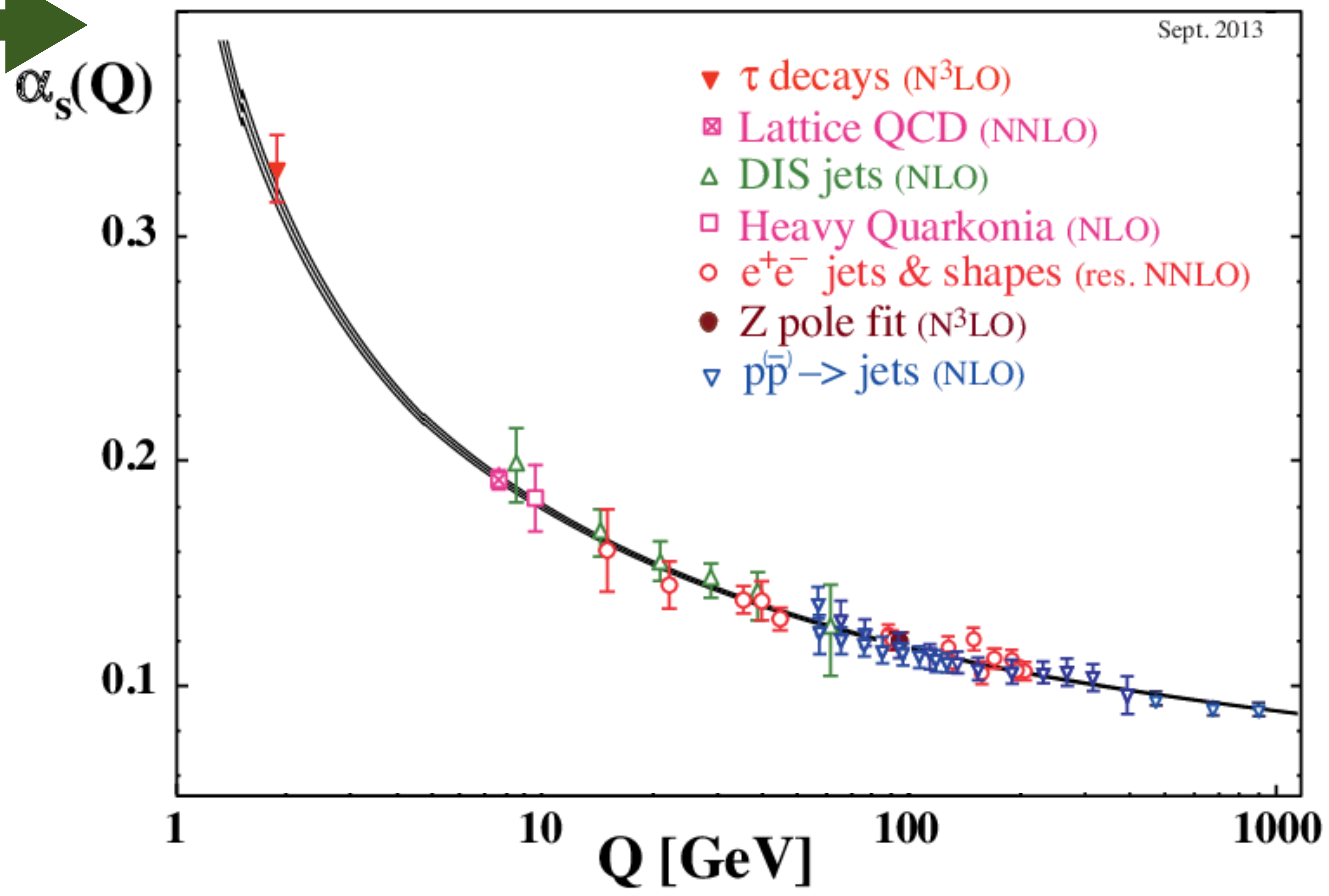


Confinement



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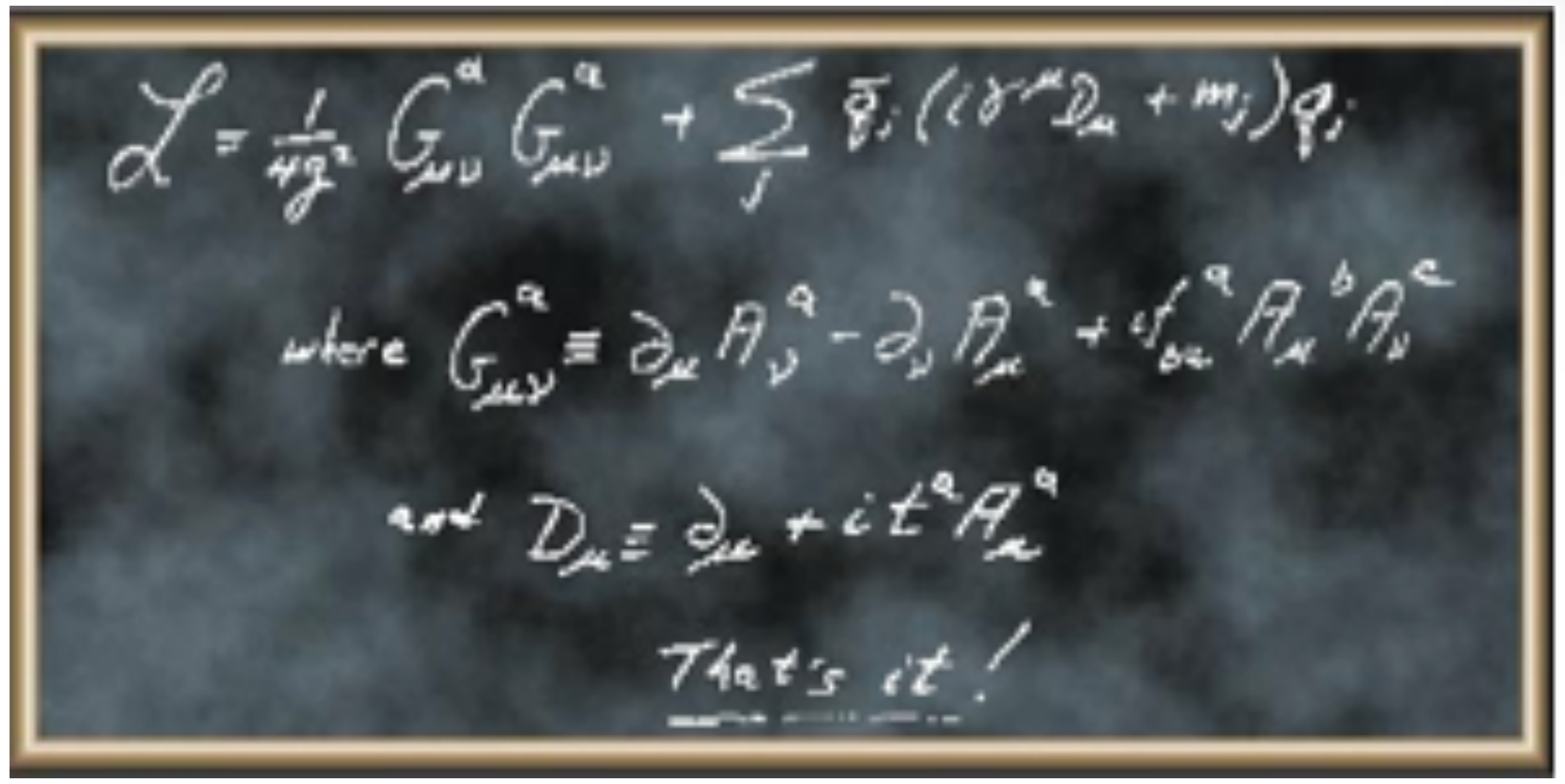

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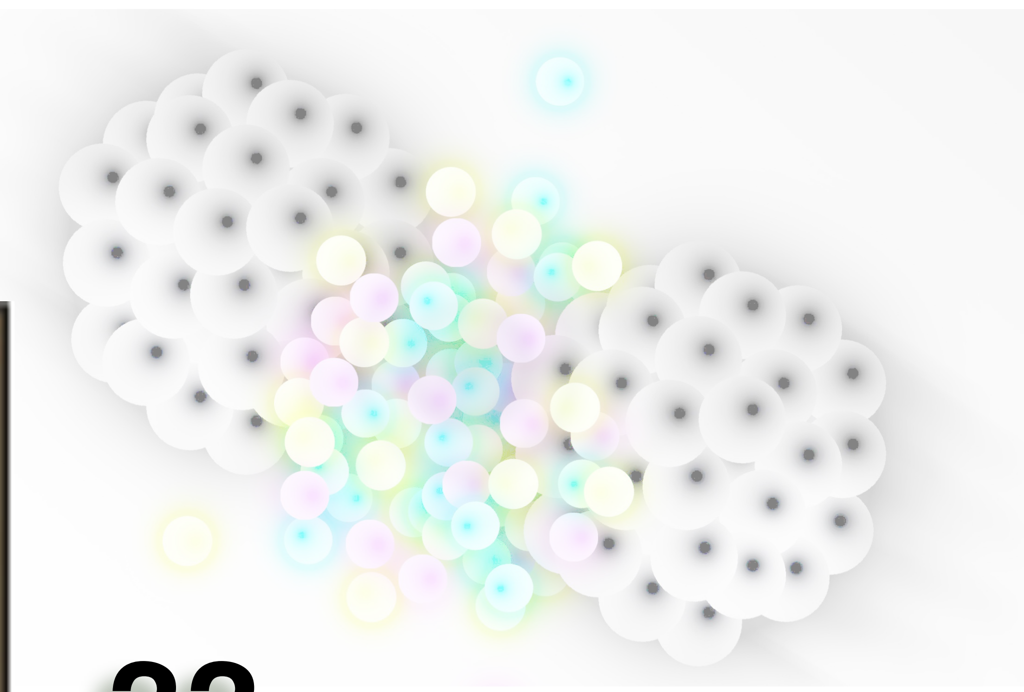
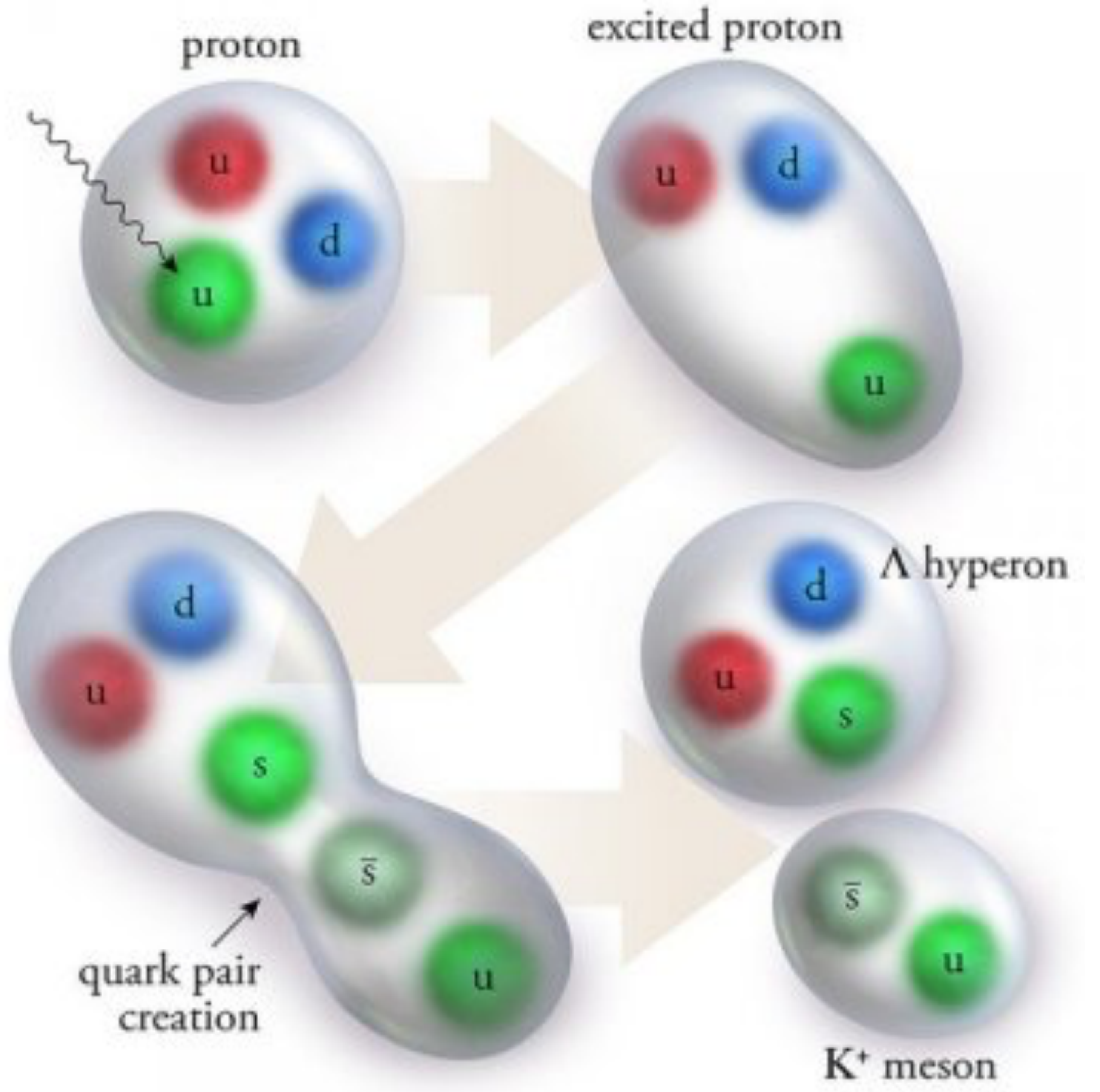
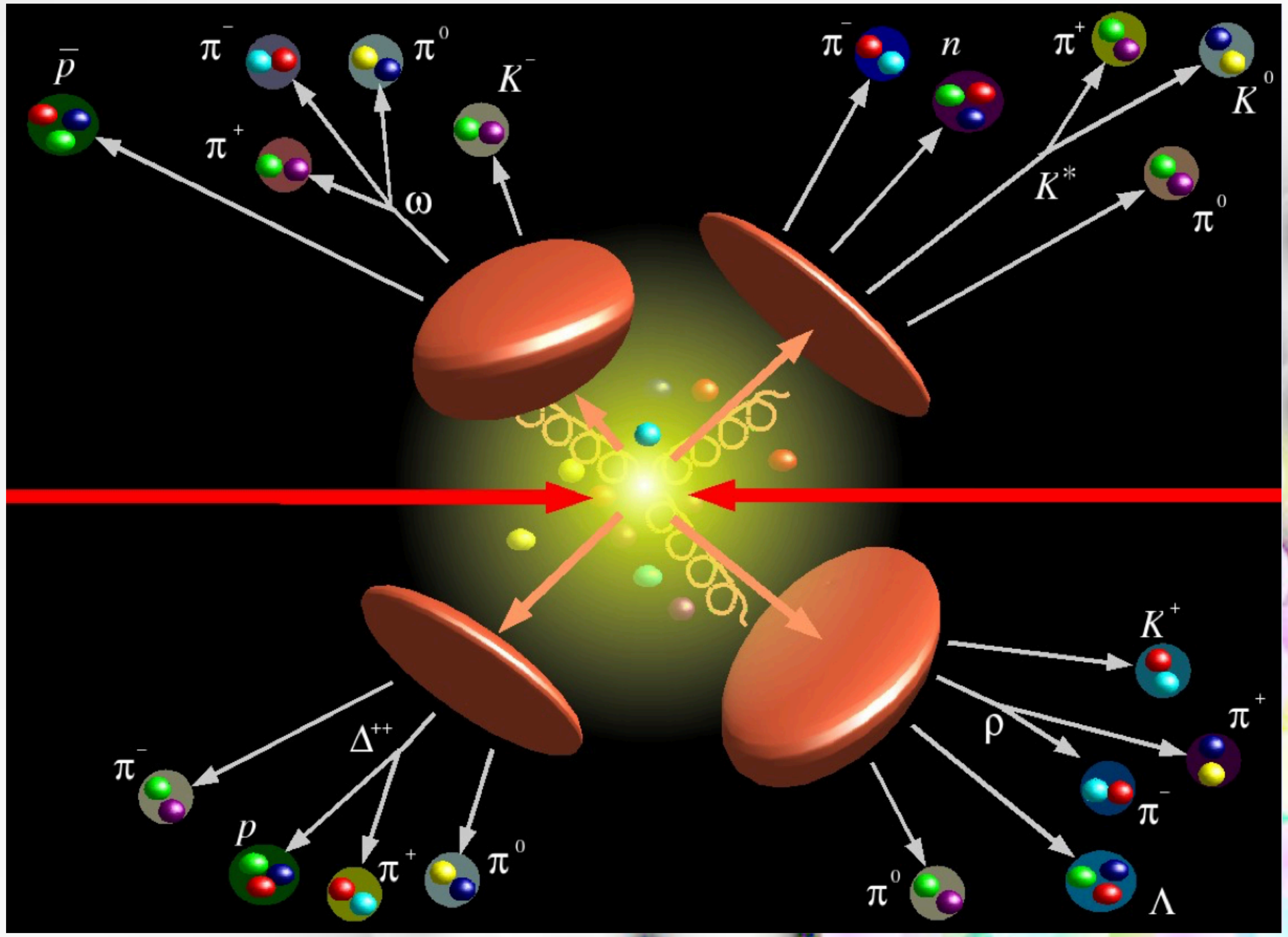


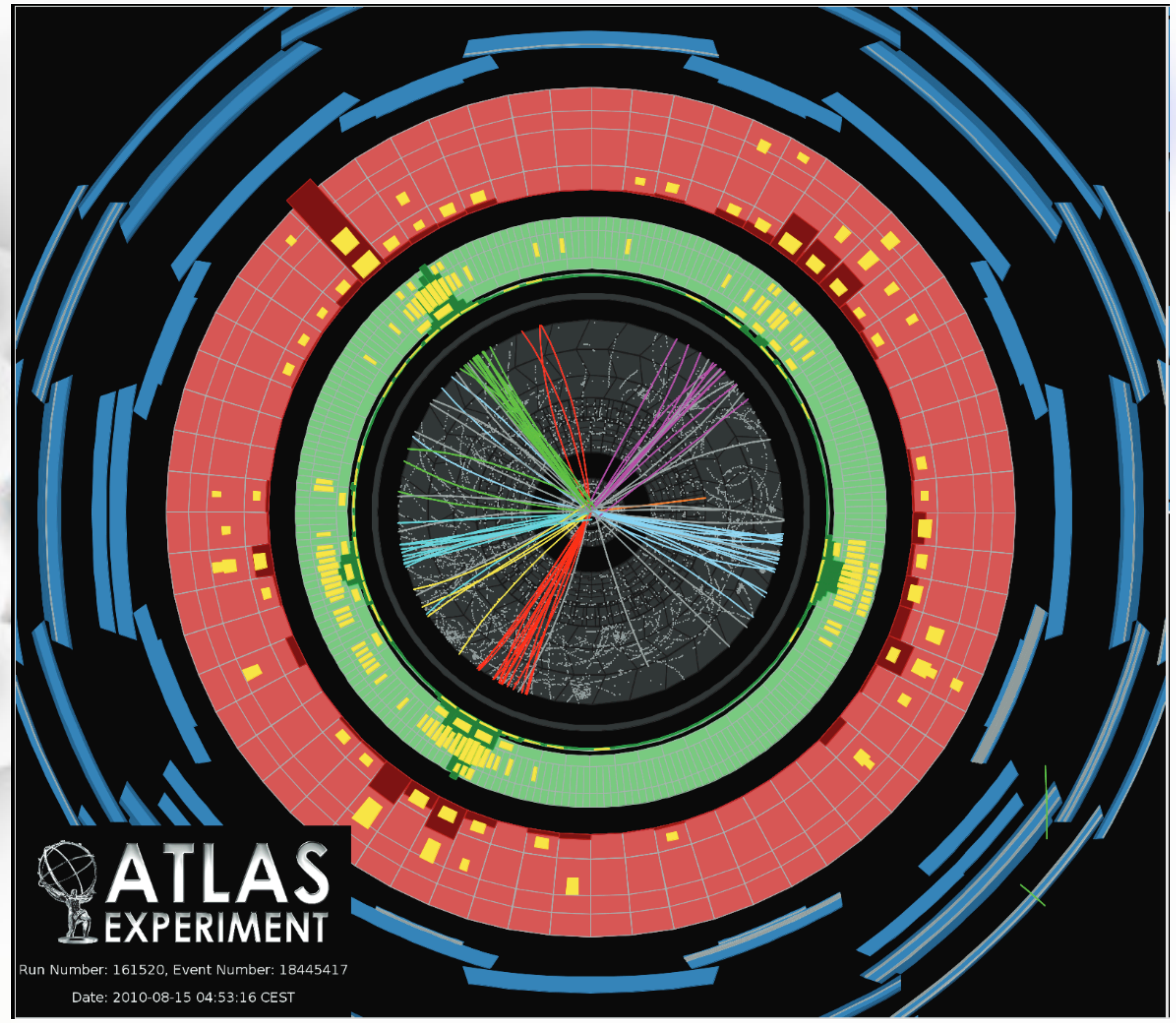


Perturbation theory not possible…

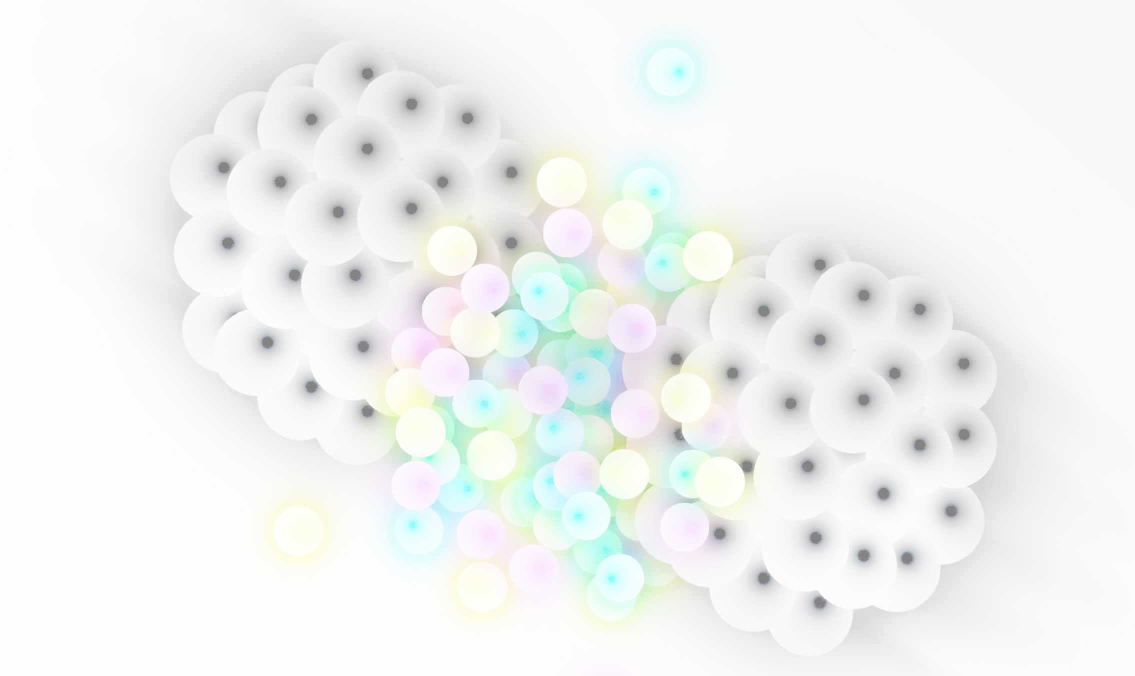
➜ Non-perturbative QCD (non-pQCD)

QCD: Two limits, same theory



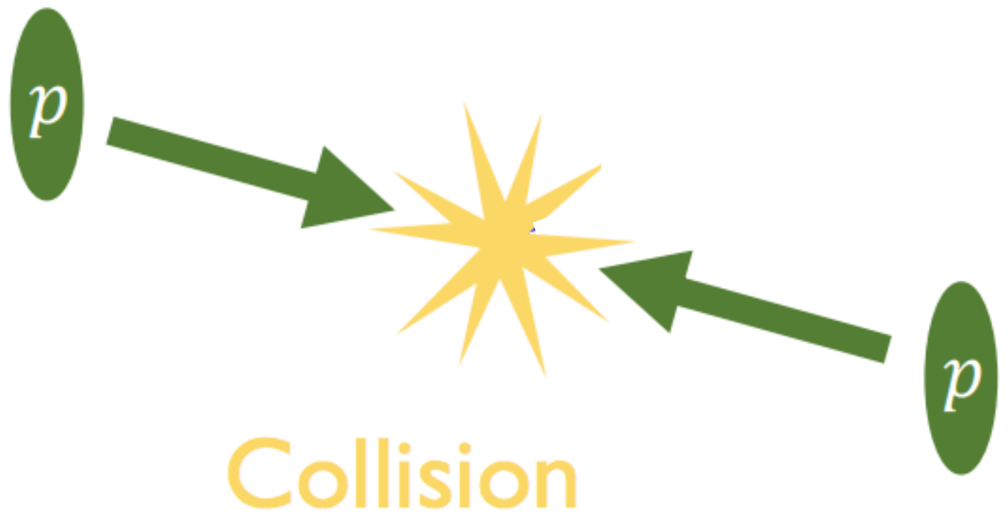


Quarks & gluons ⟷ Hadrons ⟷ What we detect experimentally?



QCD Parton Shower

- Process with a large momentum transfer:



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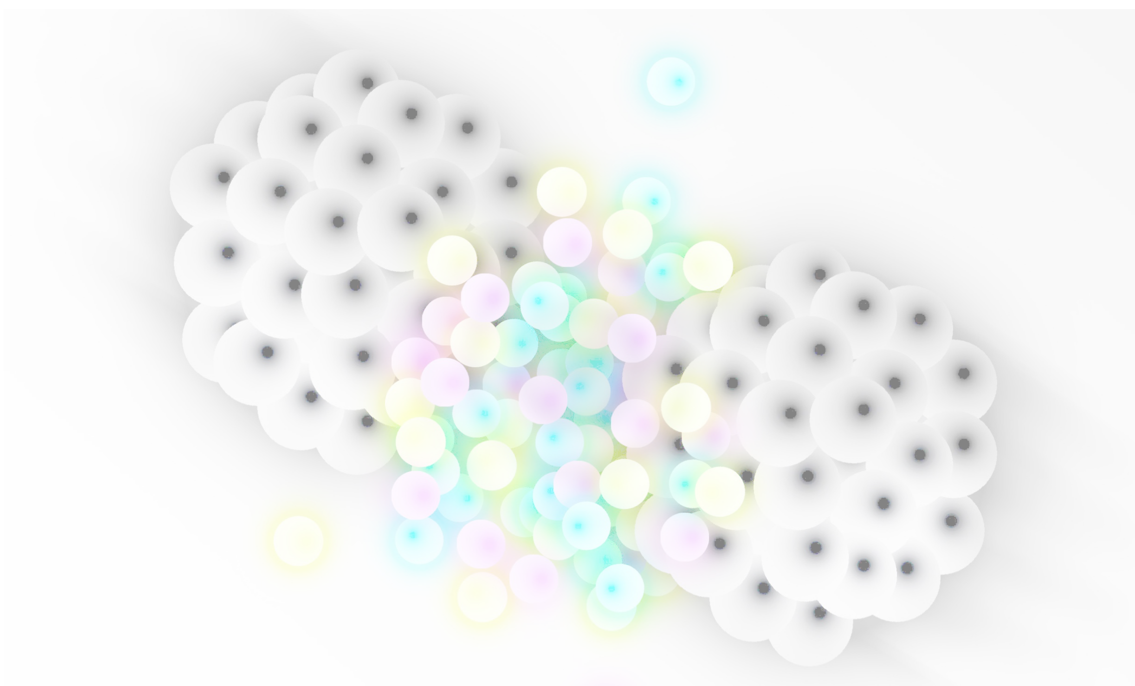

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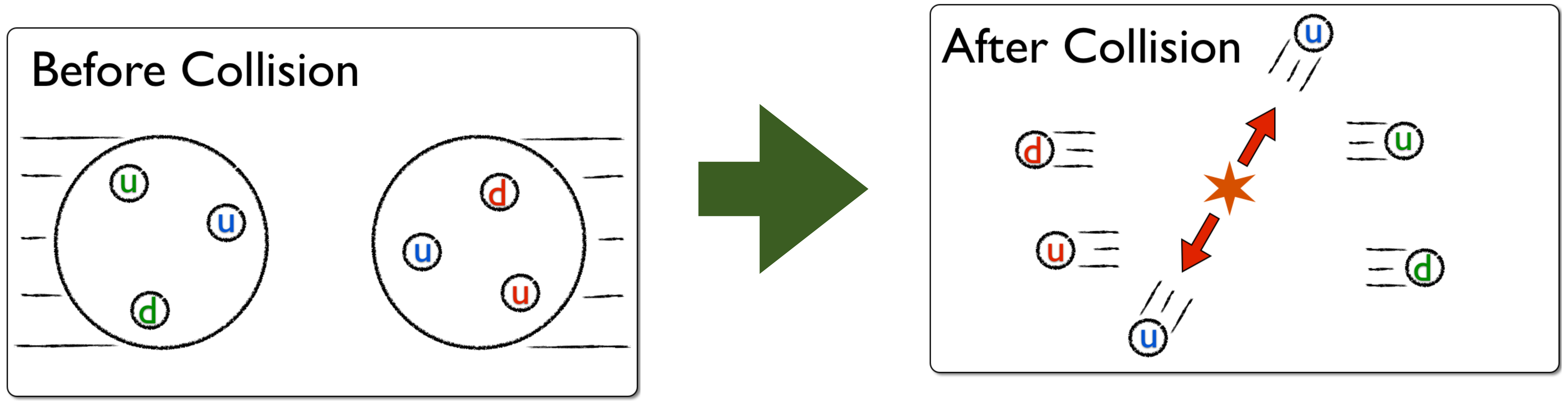

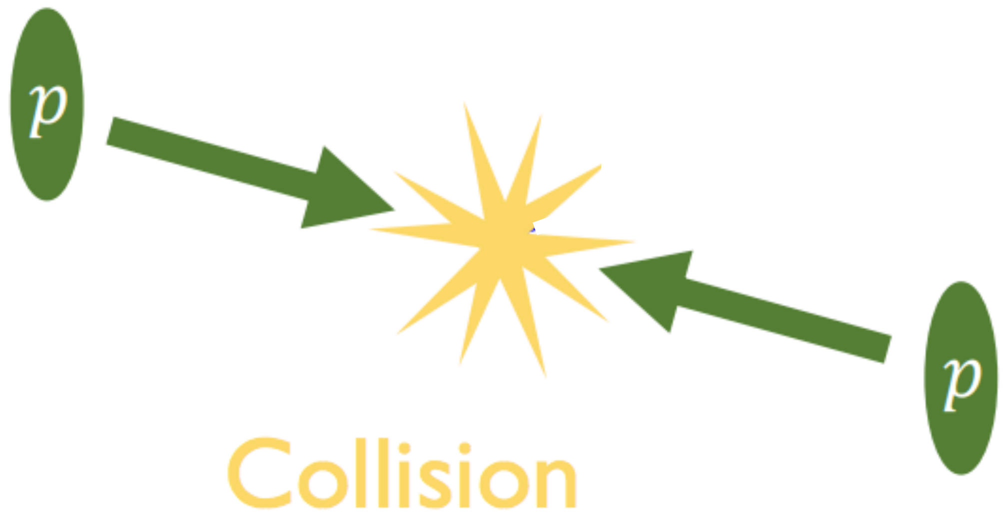

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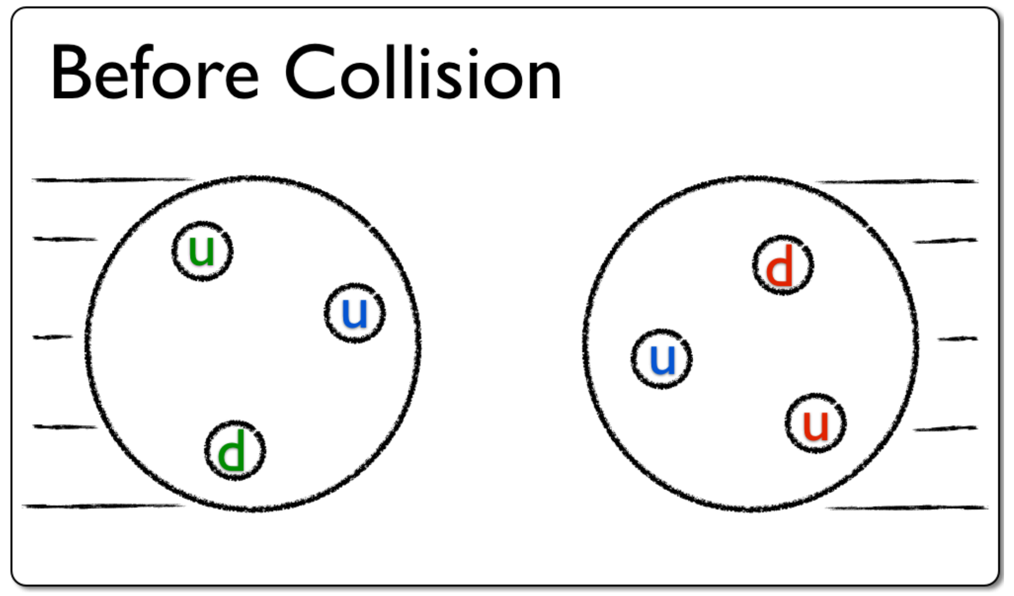

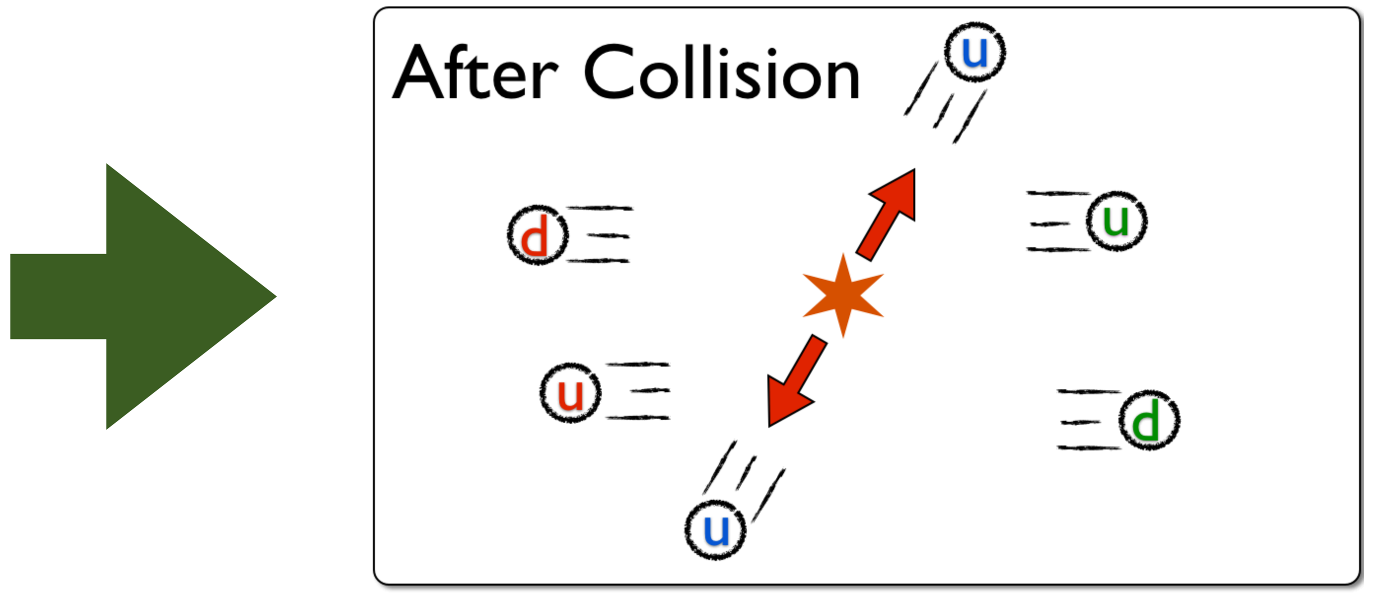

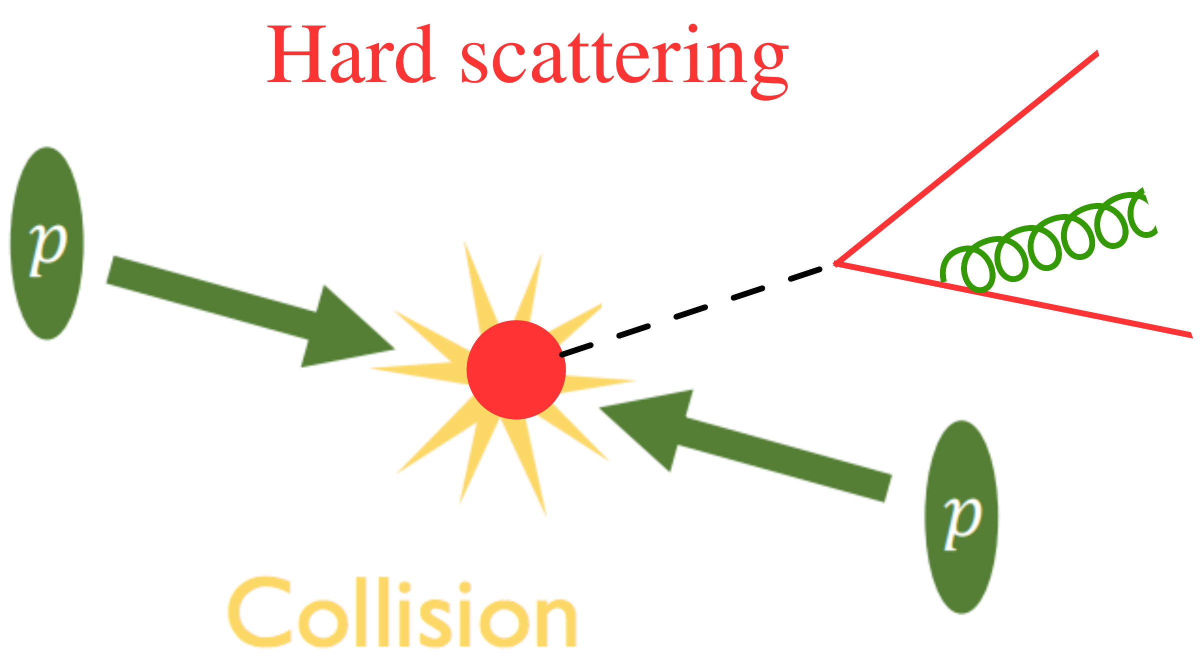

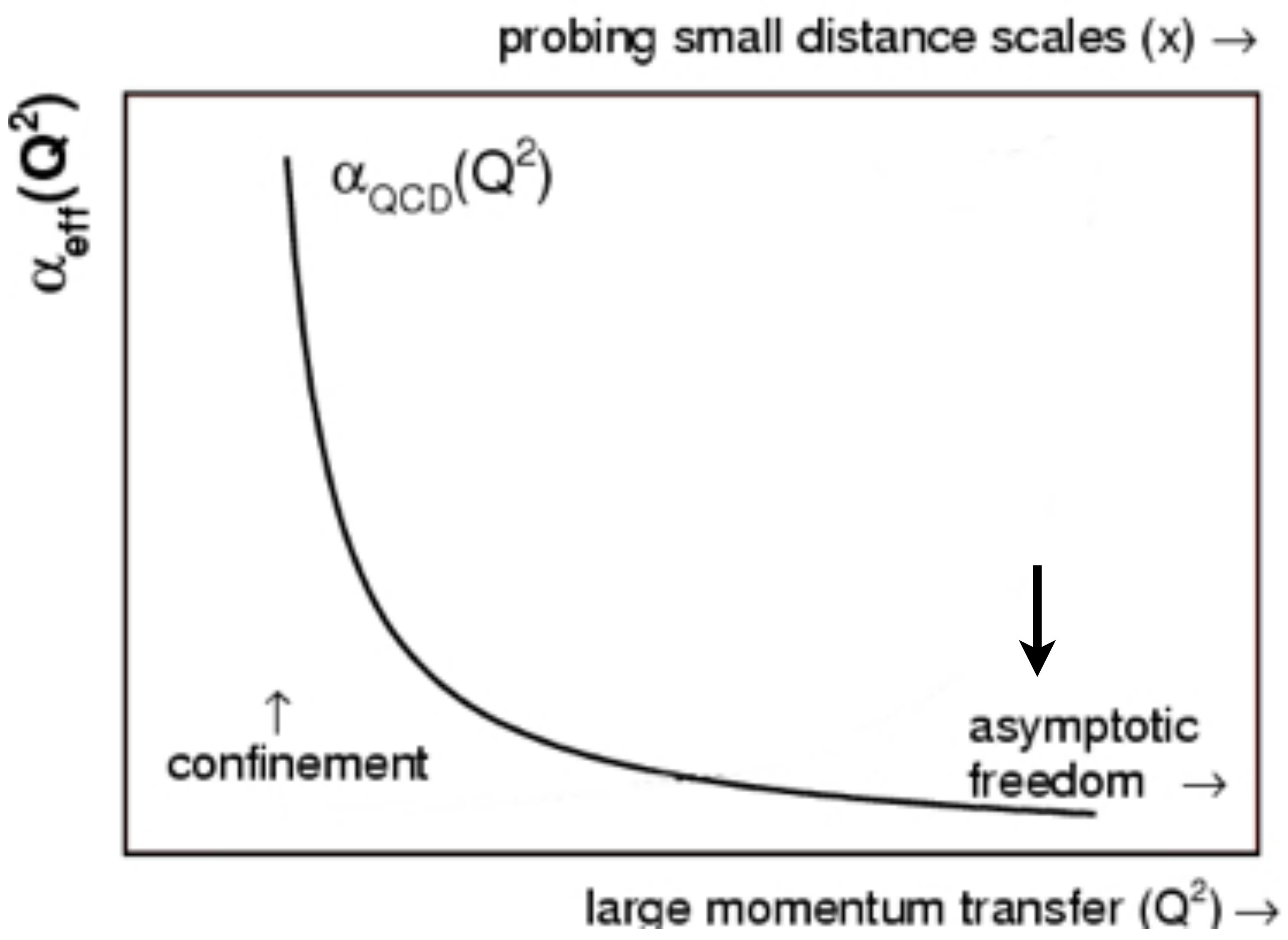

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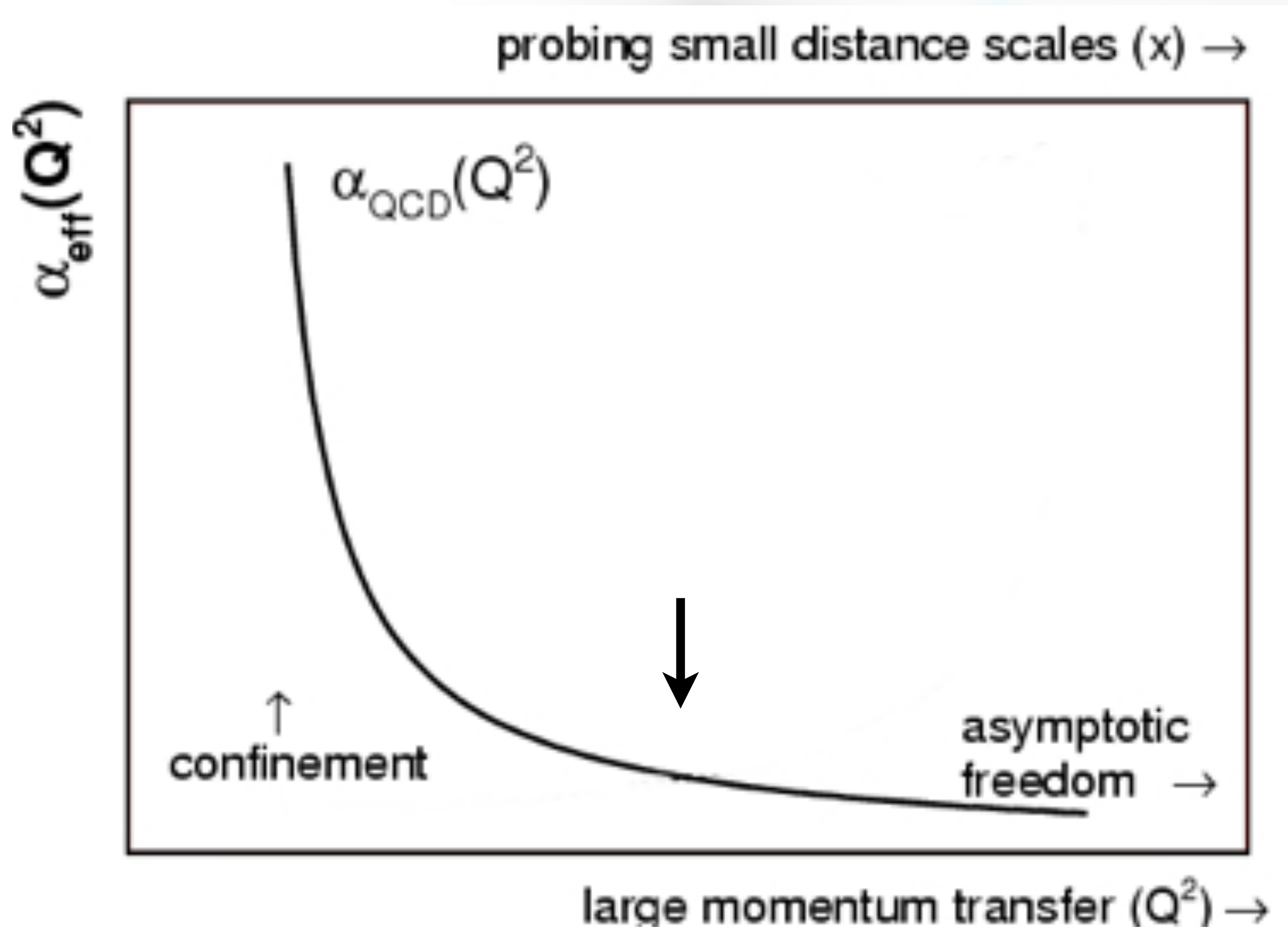

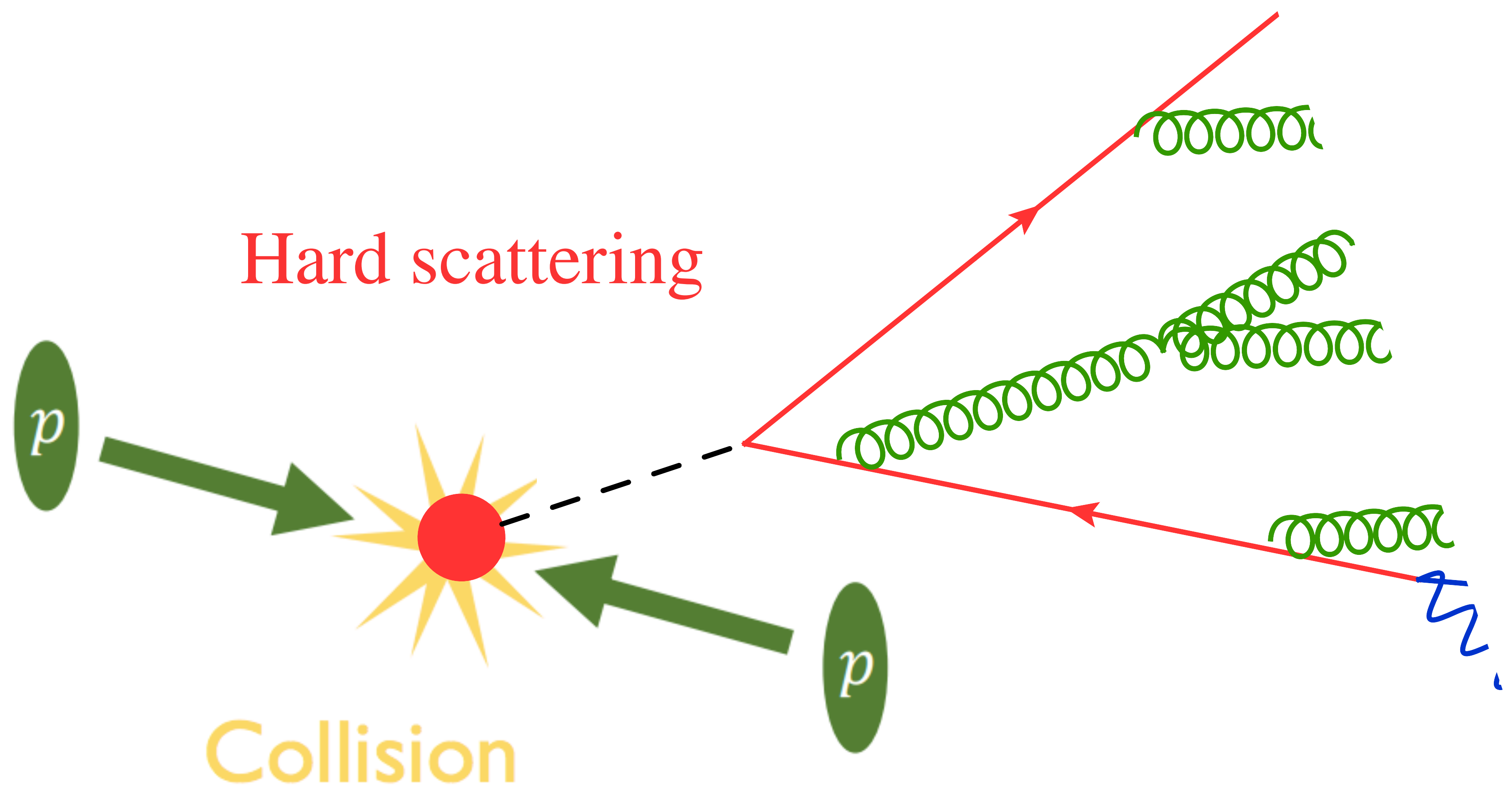

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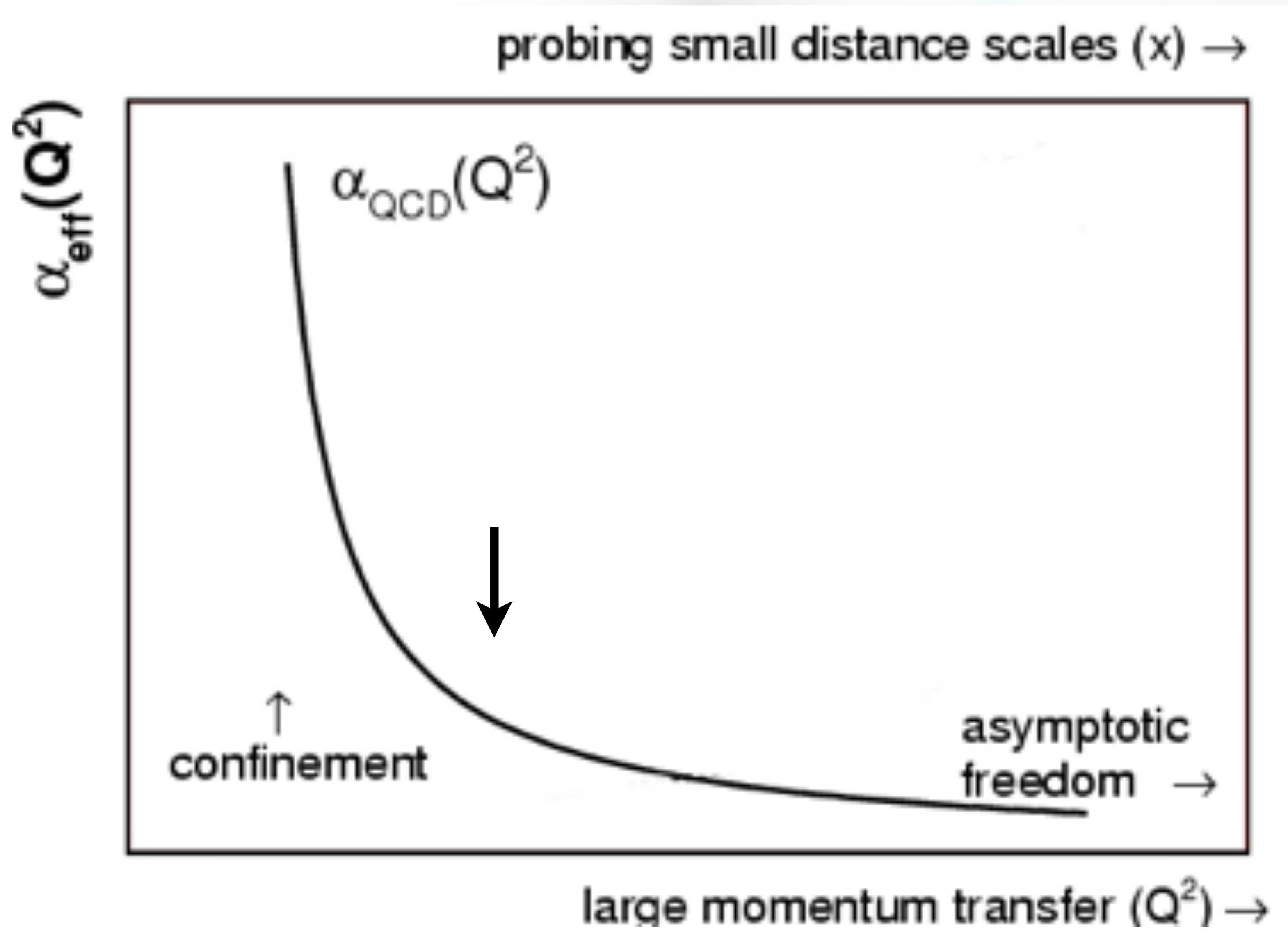

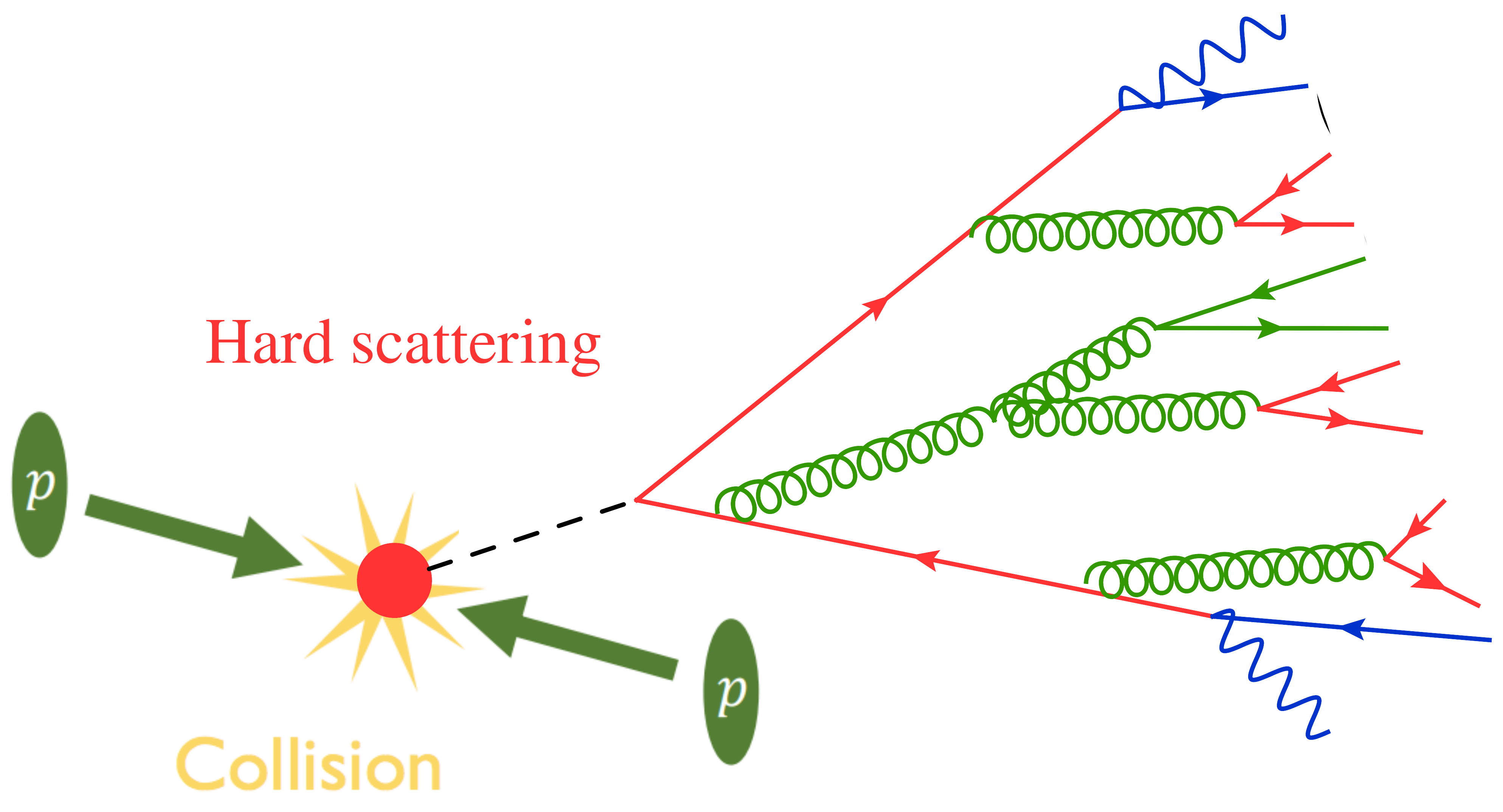

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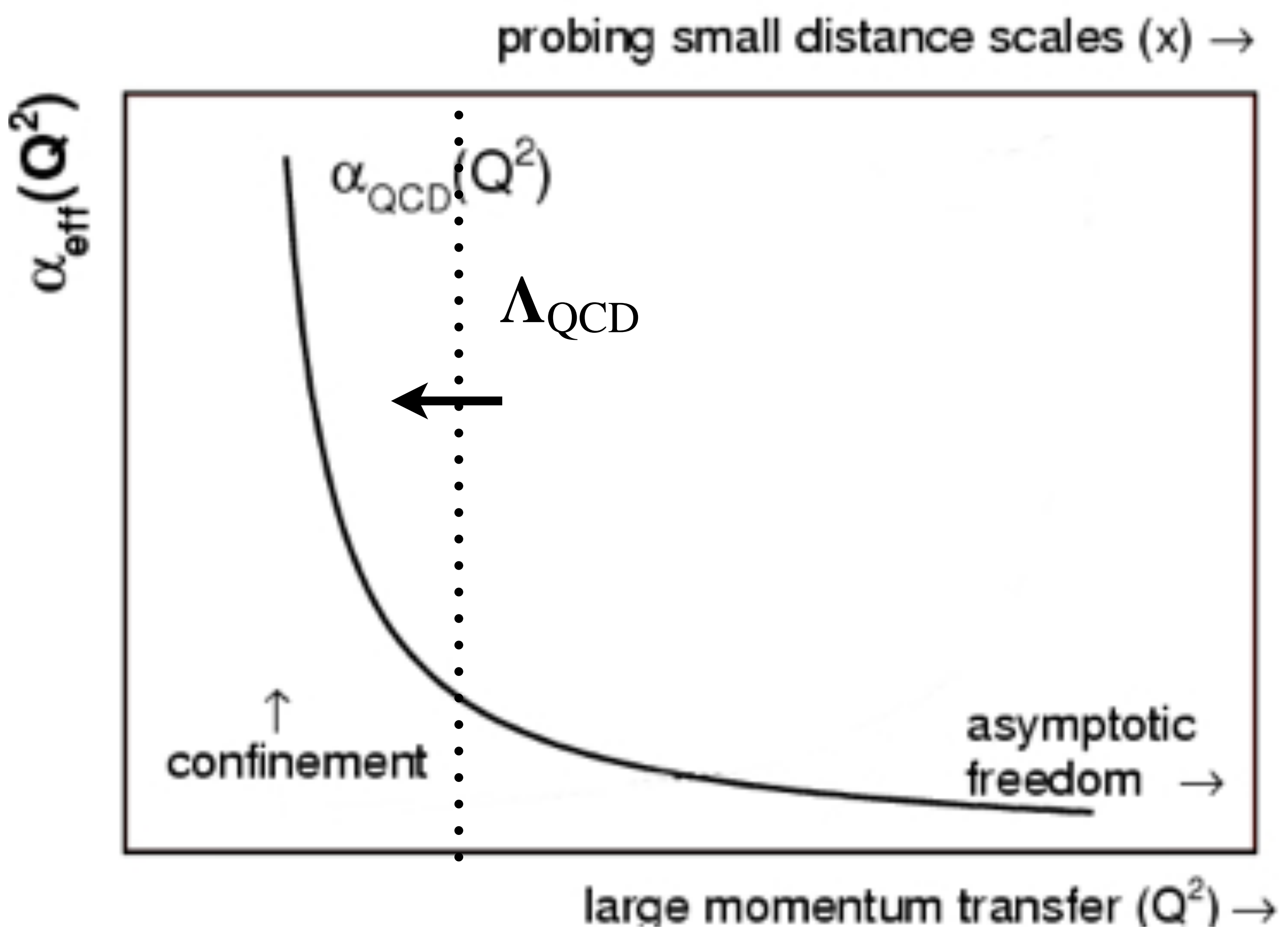
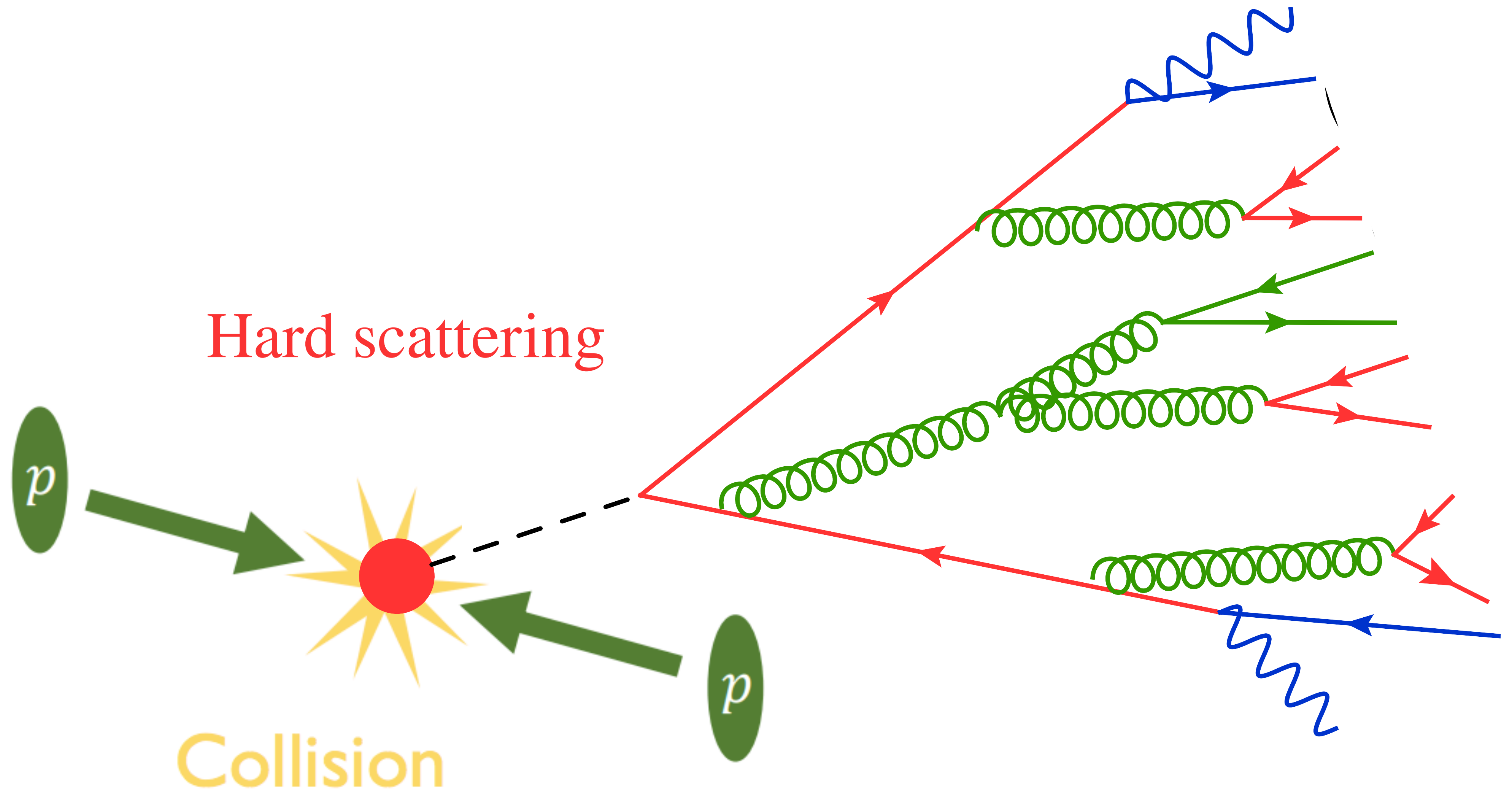


α_{QCD} no longer << 1



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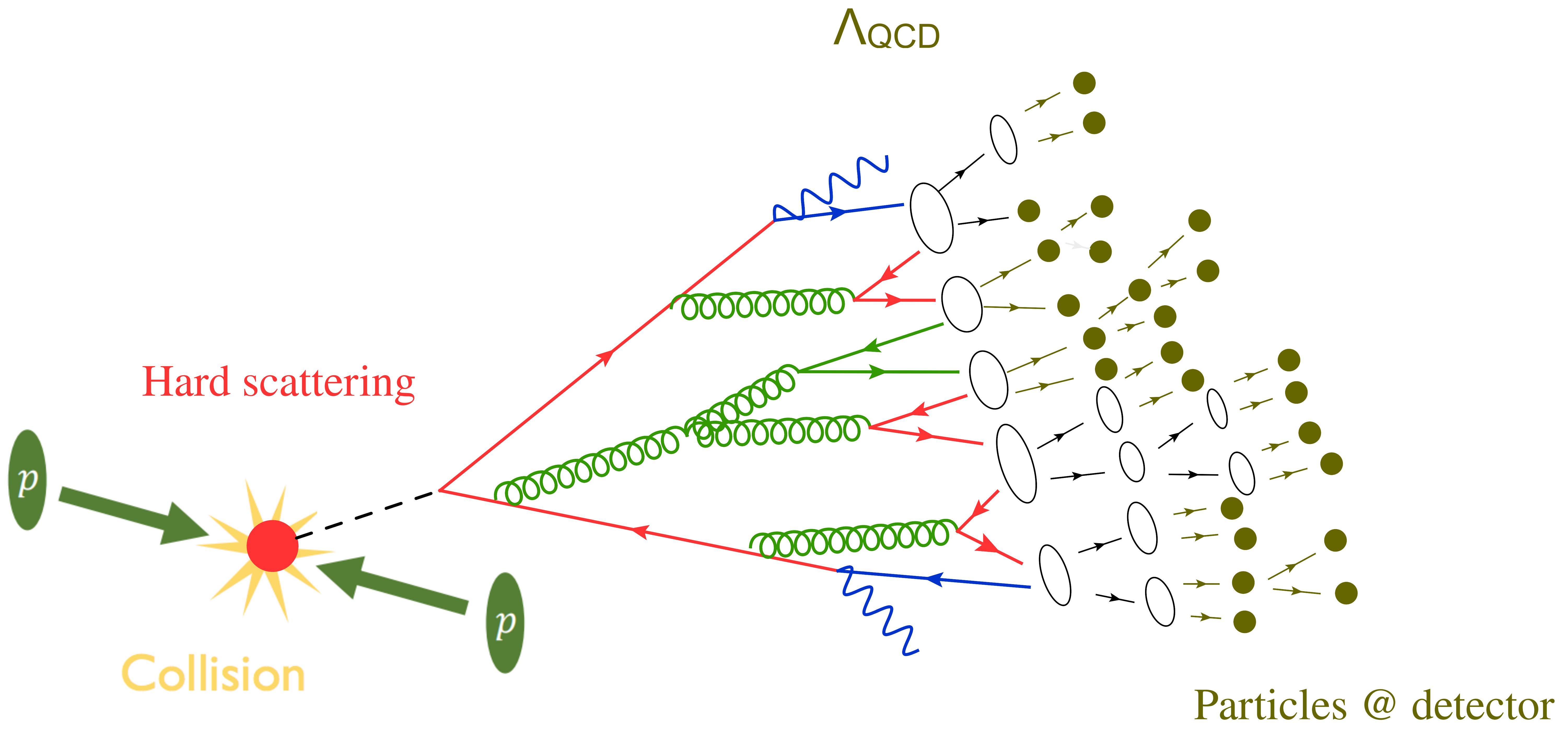

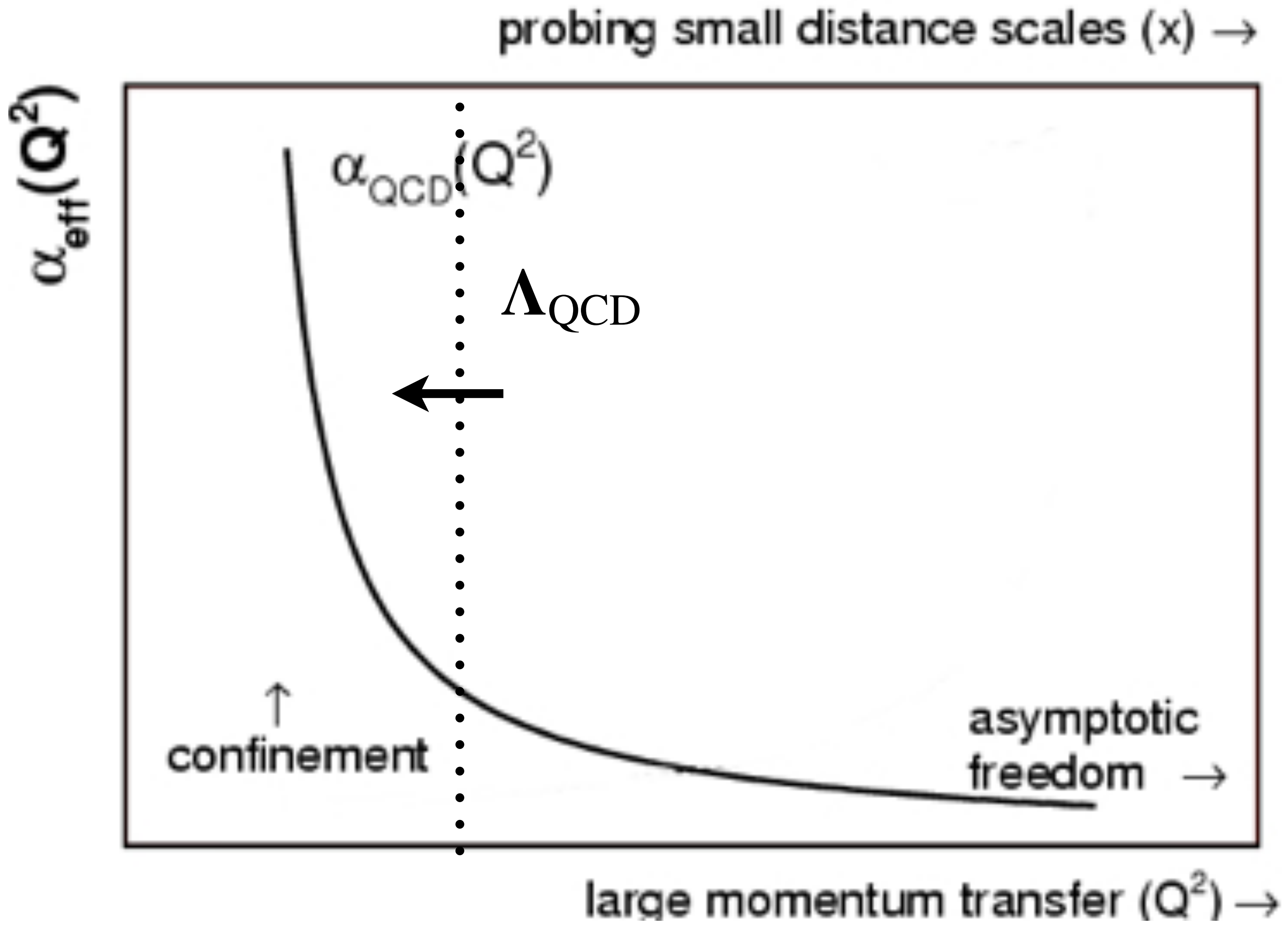

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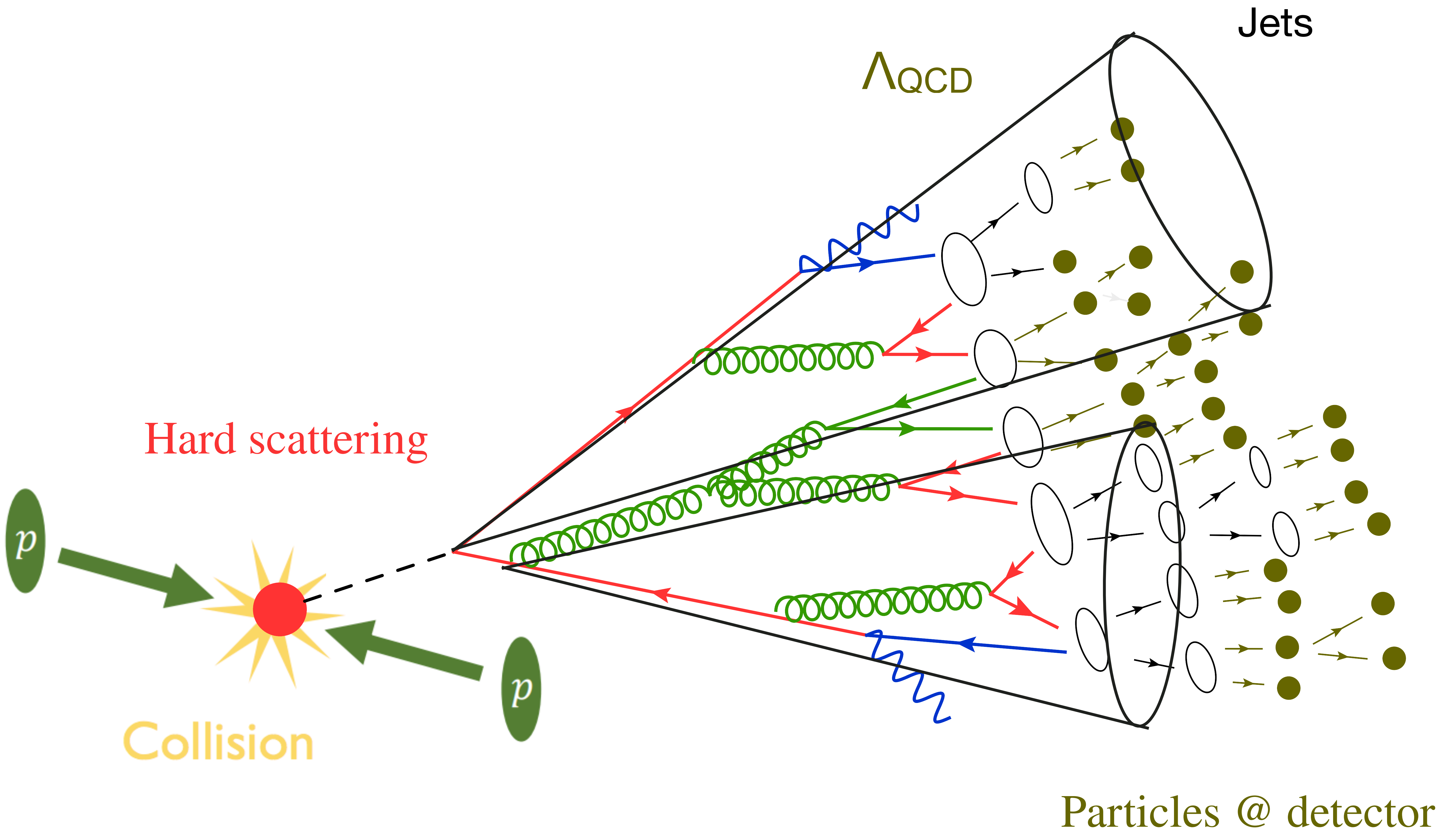

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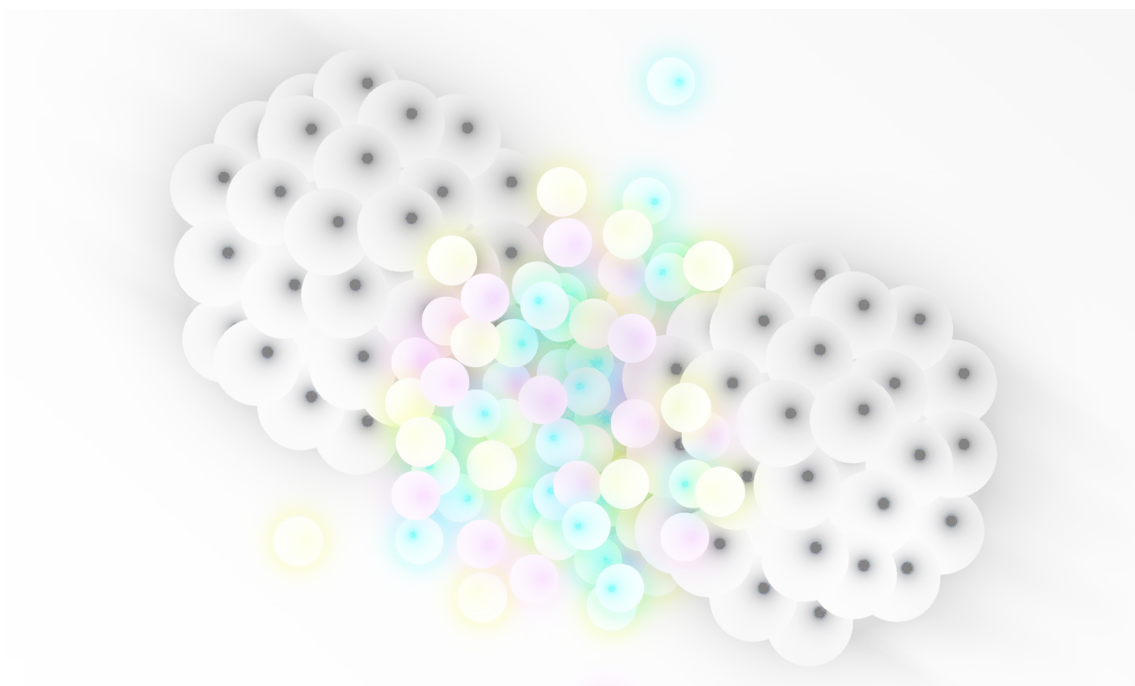
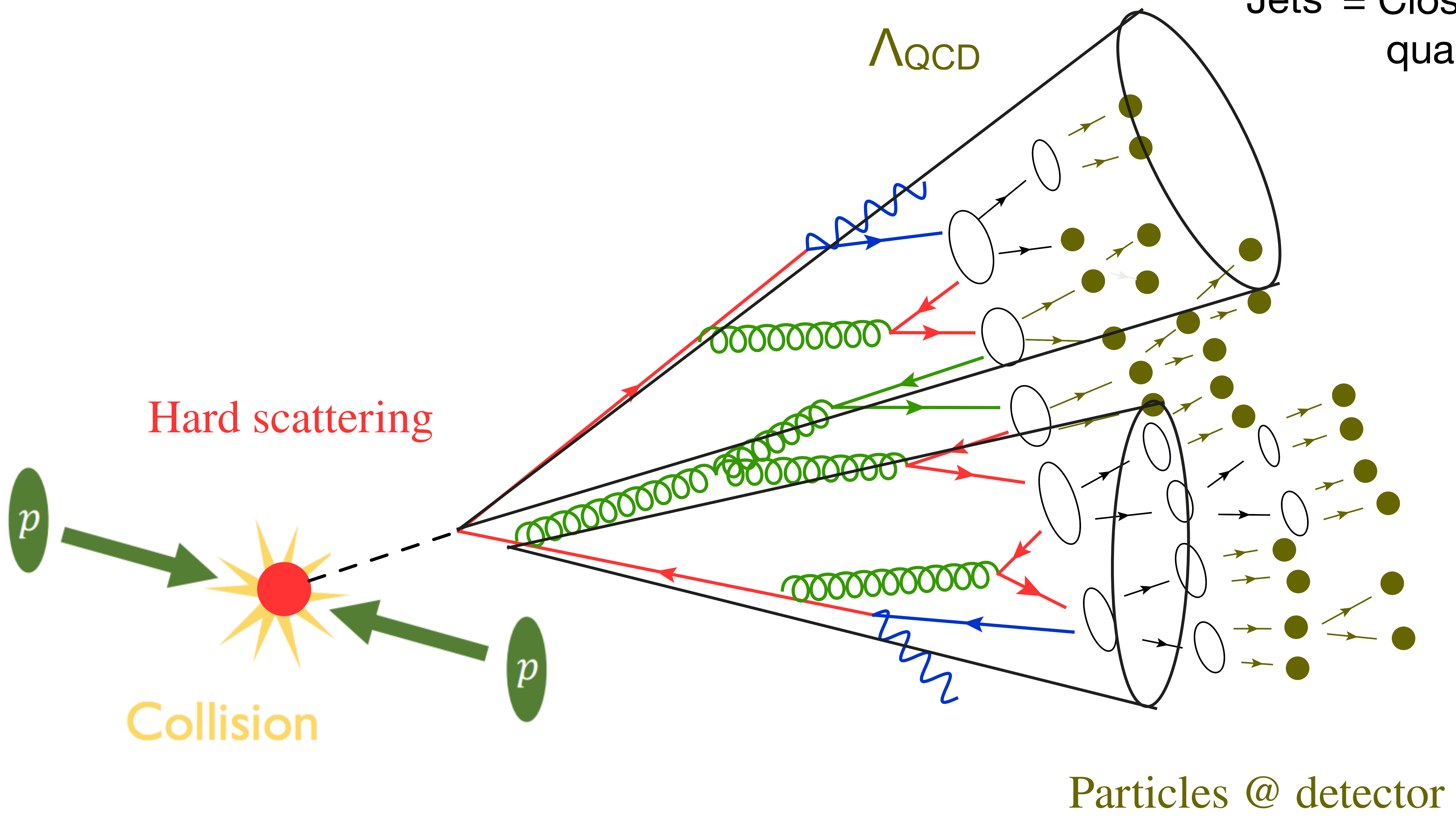
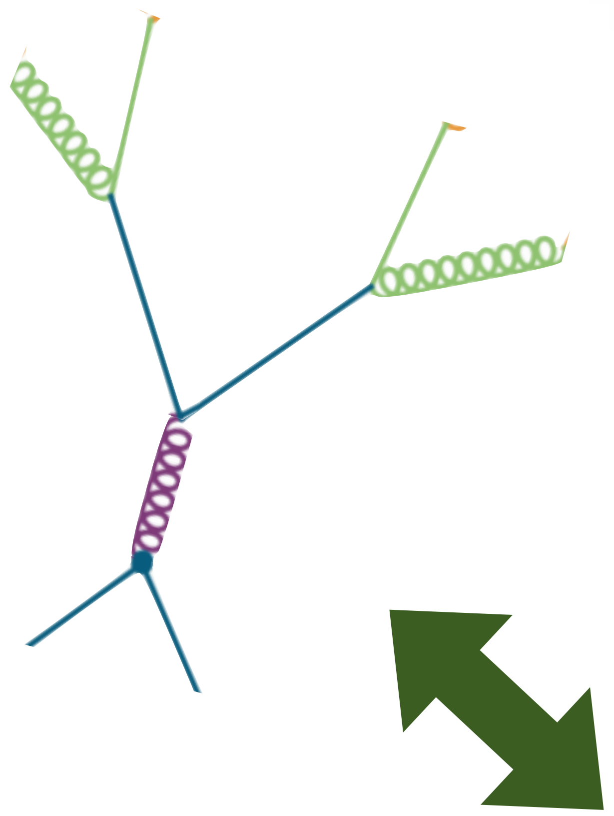


- Process with a large momentum transfer:

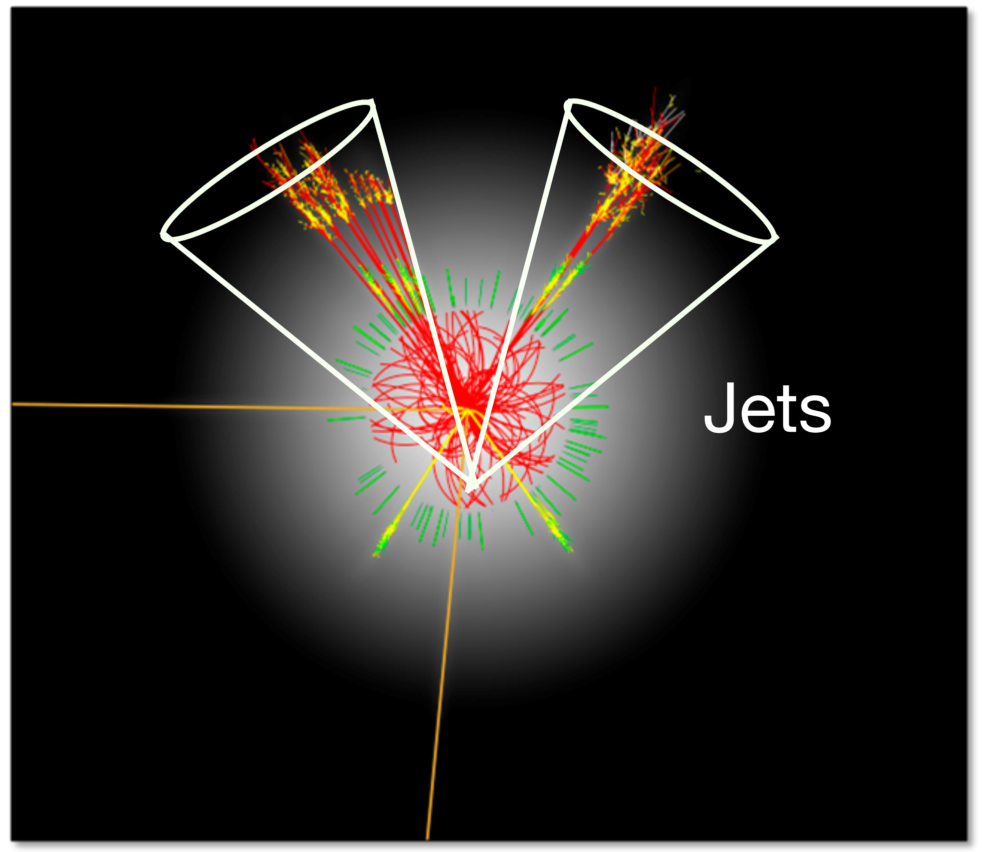
Jets = Closest proxy for quarks/gluons



What we calculate



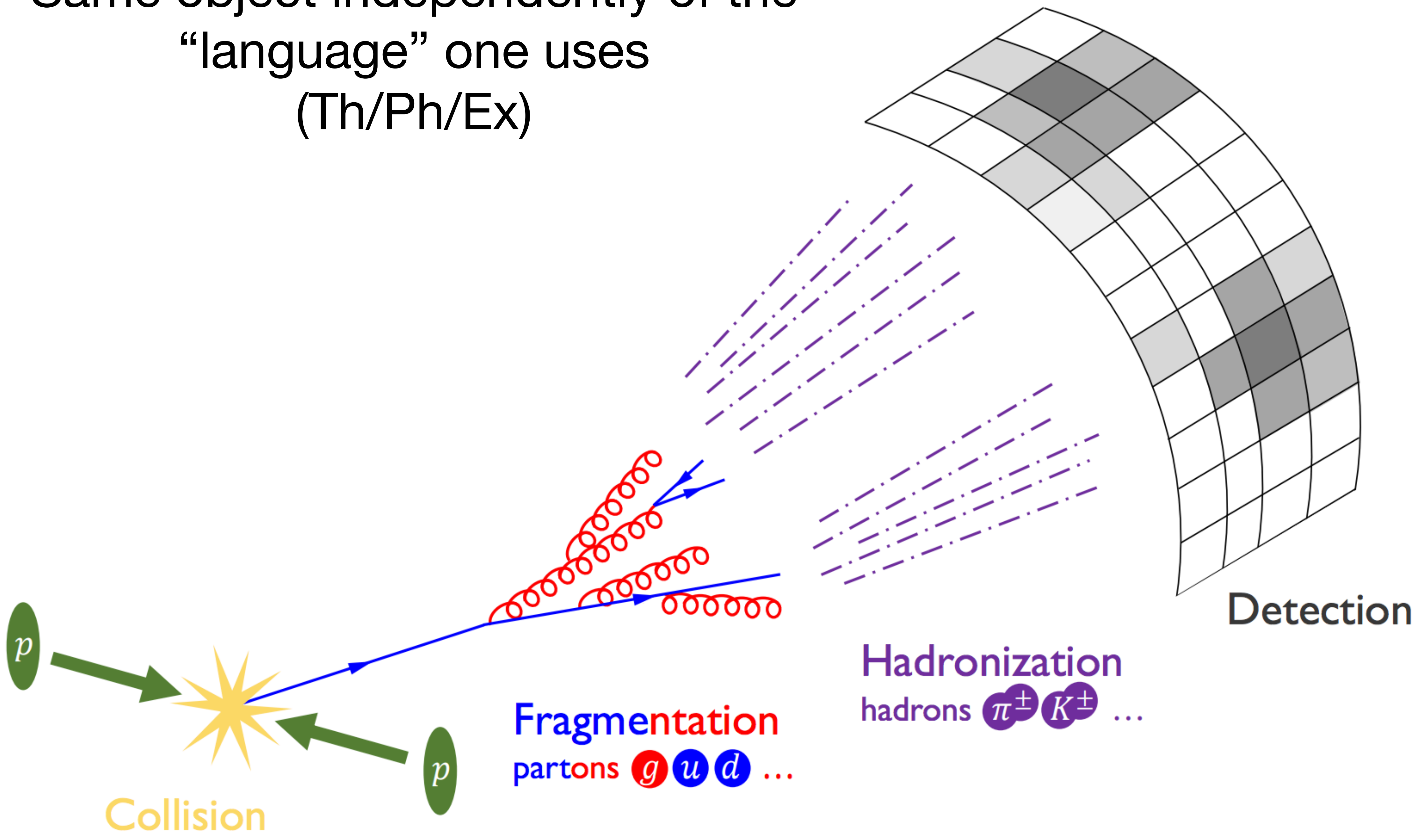
What we measure

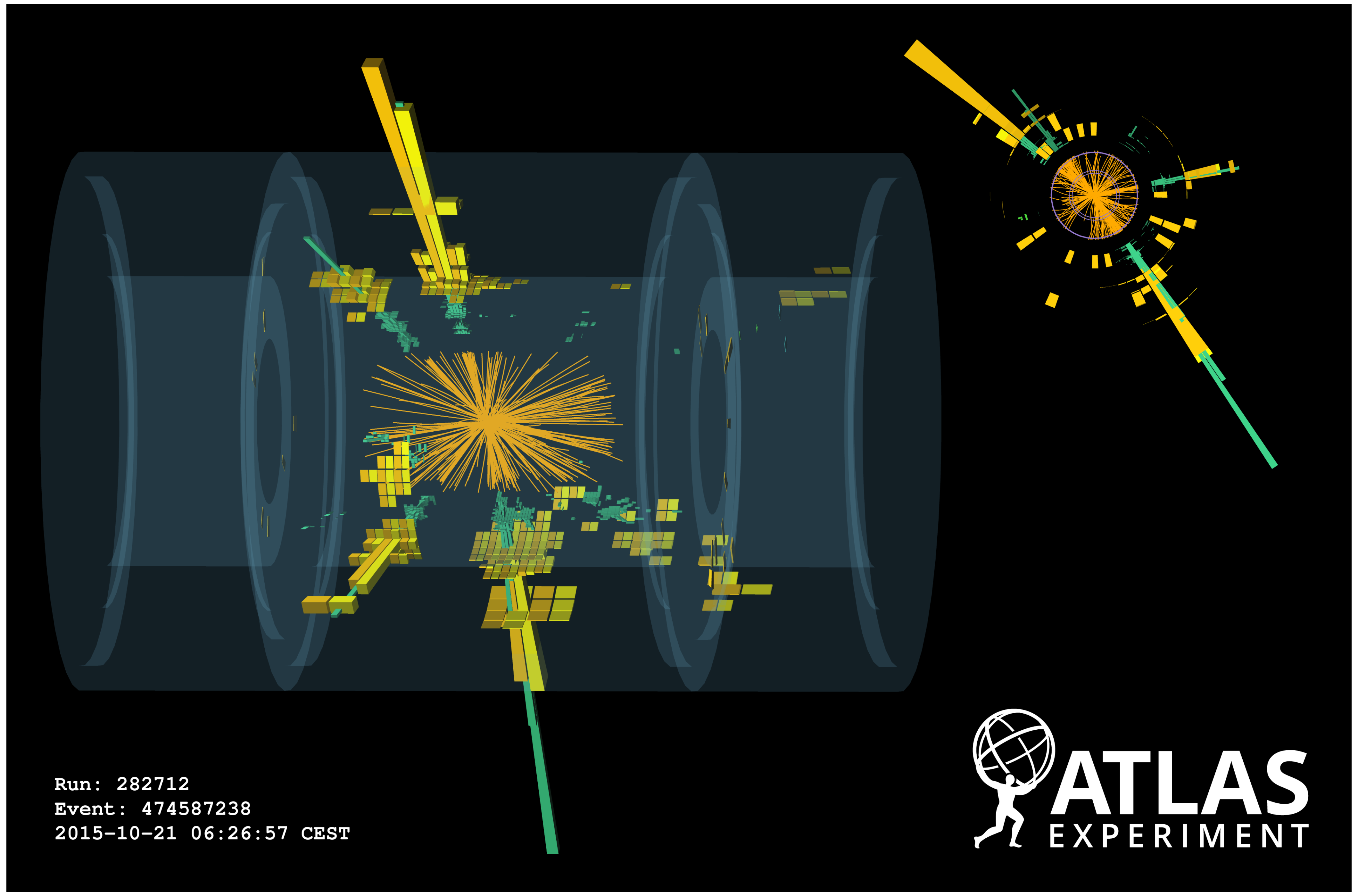


QCD Parton Shower to Jets

- 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)





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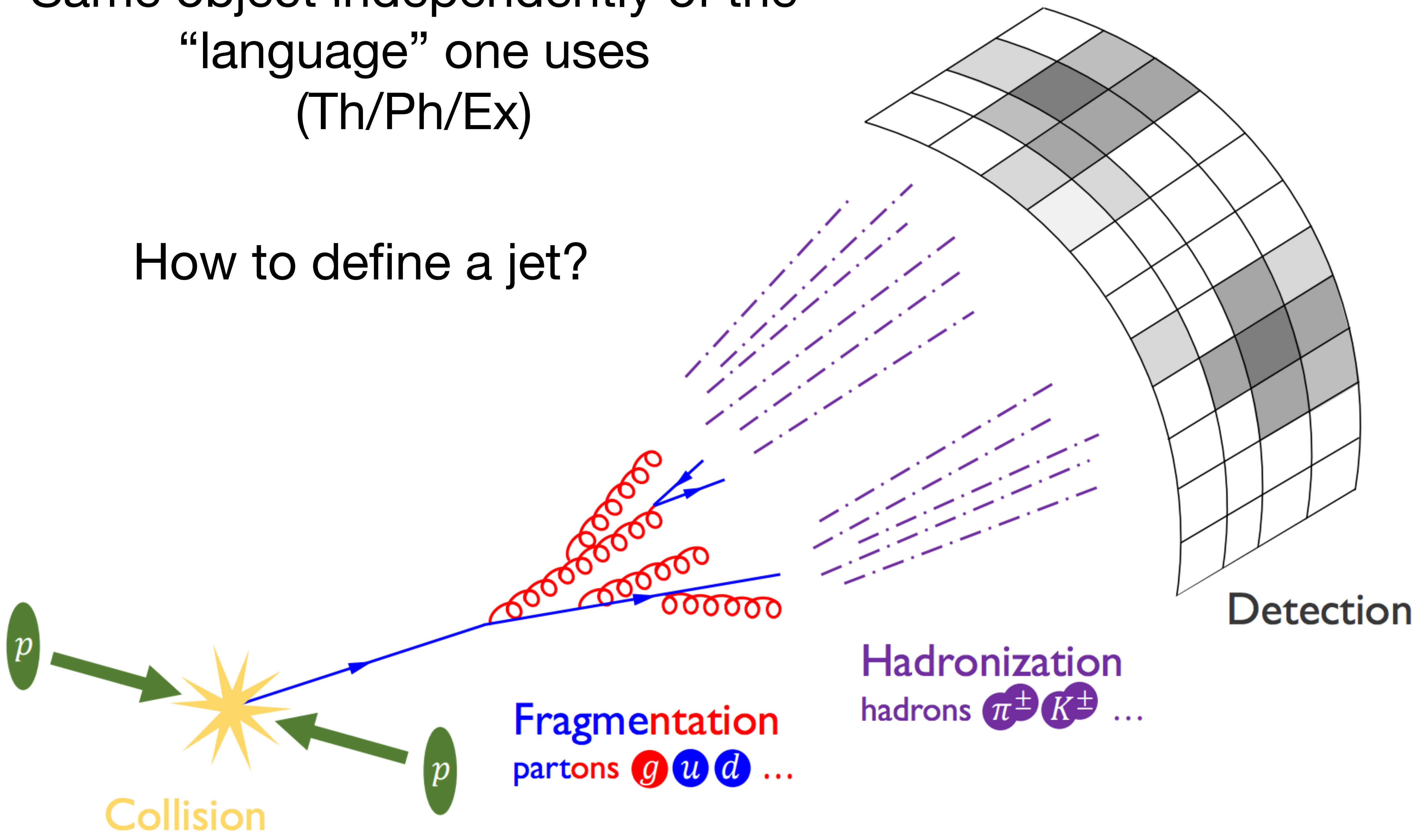
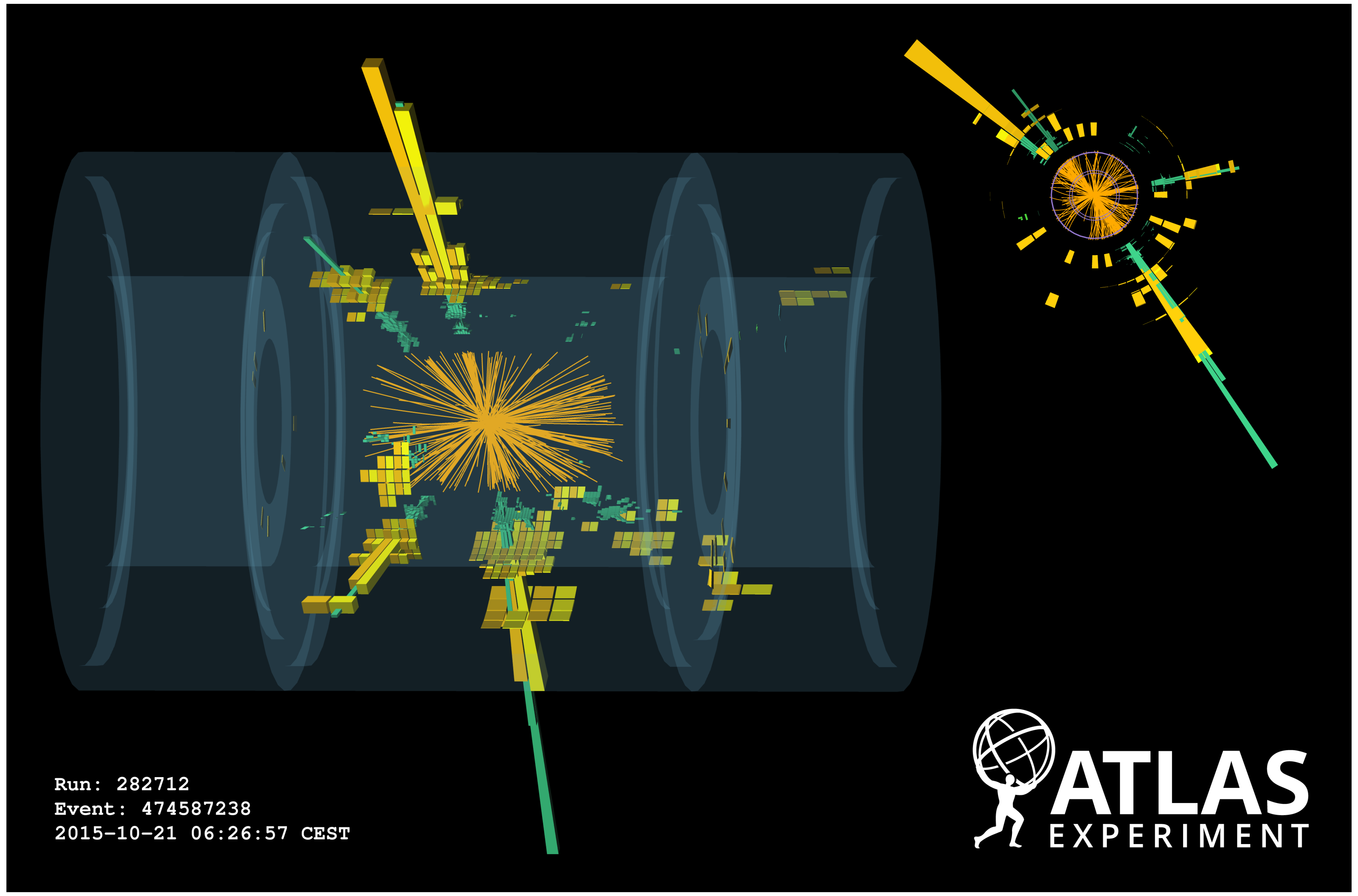
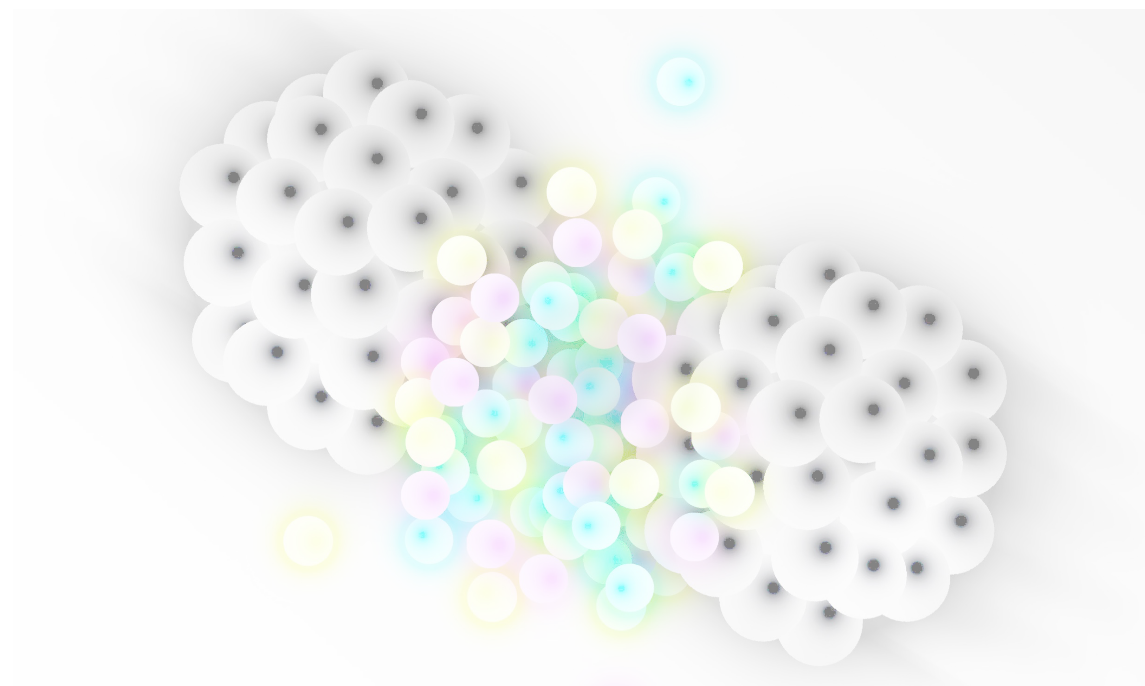
How to define a jet?



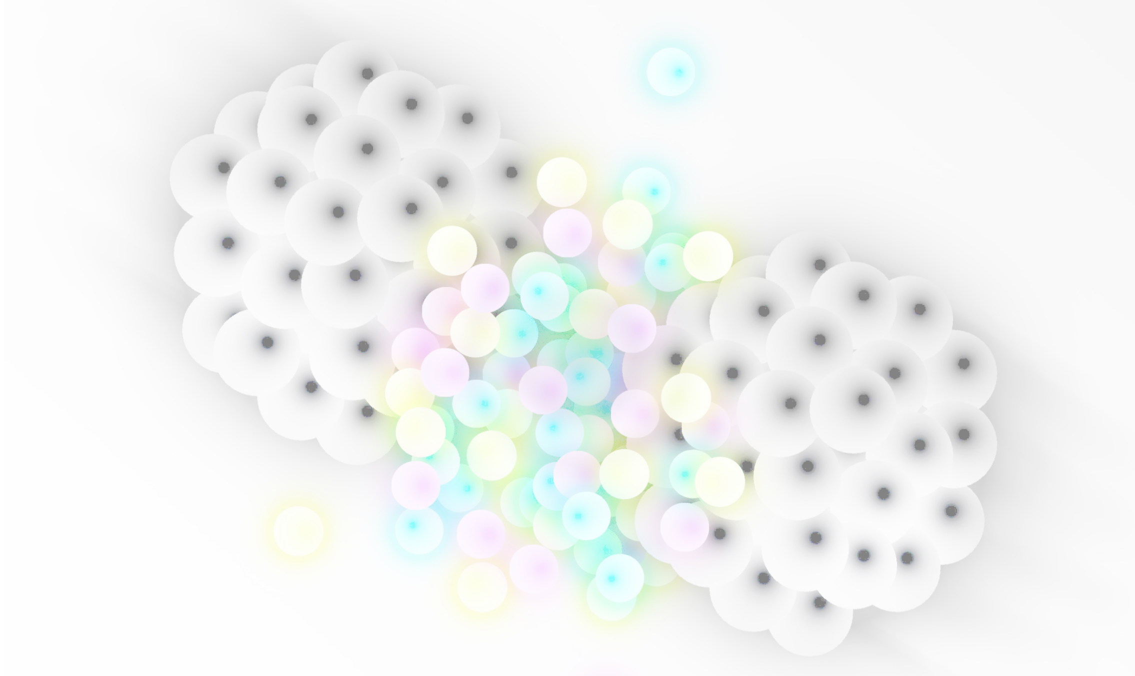


Jet algorithms



- Need a recipe to define a jet:
  - Jet size (radius): maximum "distance" that two particles can be to be considered as part of the same jet
  - Jet clustering algorithm: define criteria to decide which particles are going to be clustered in the same jet

Jet algorithms



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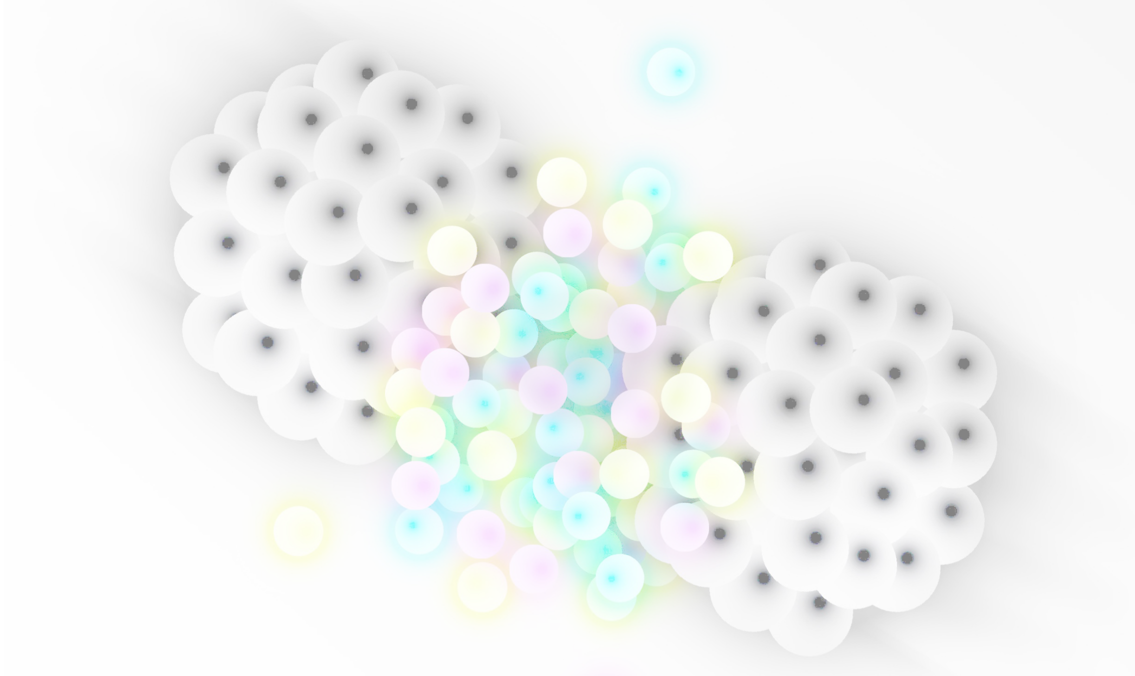

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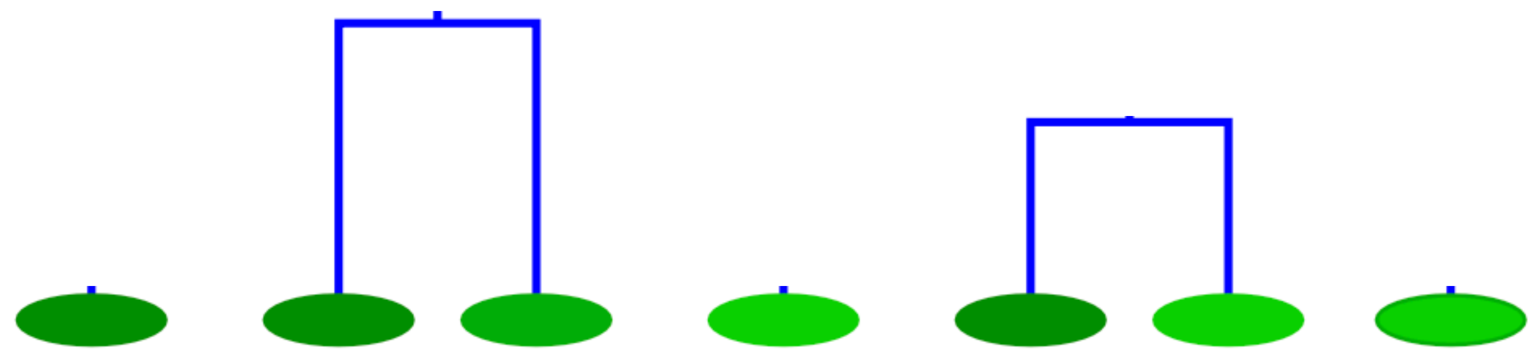

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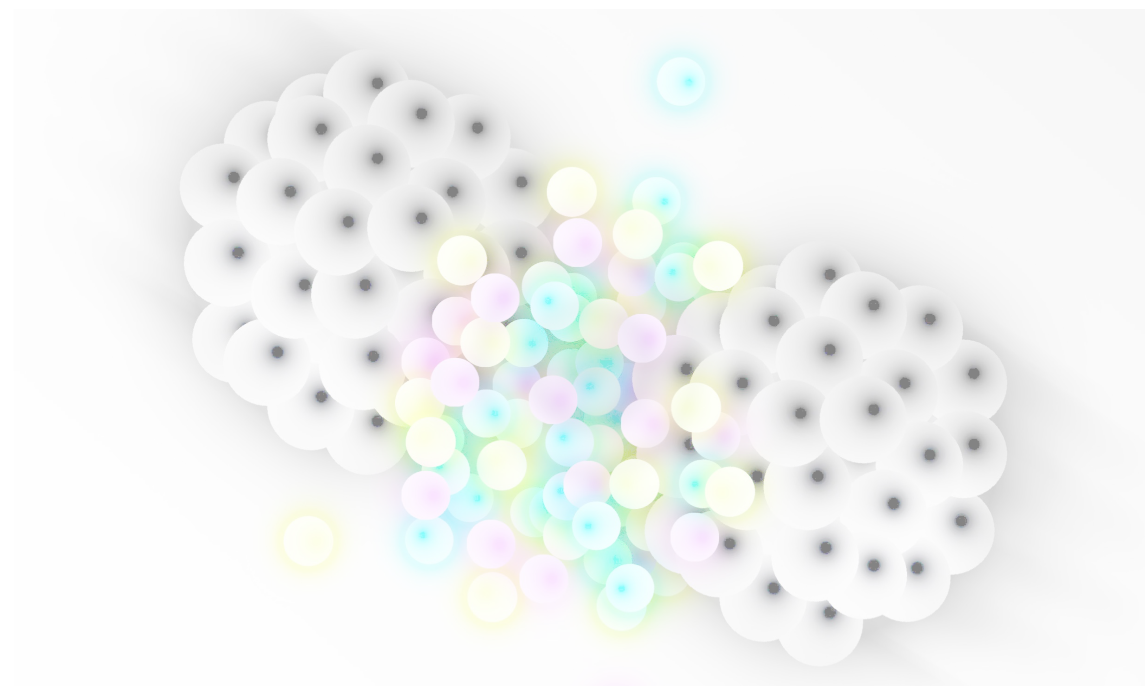

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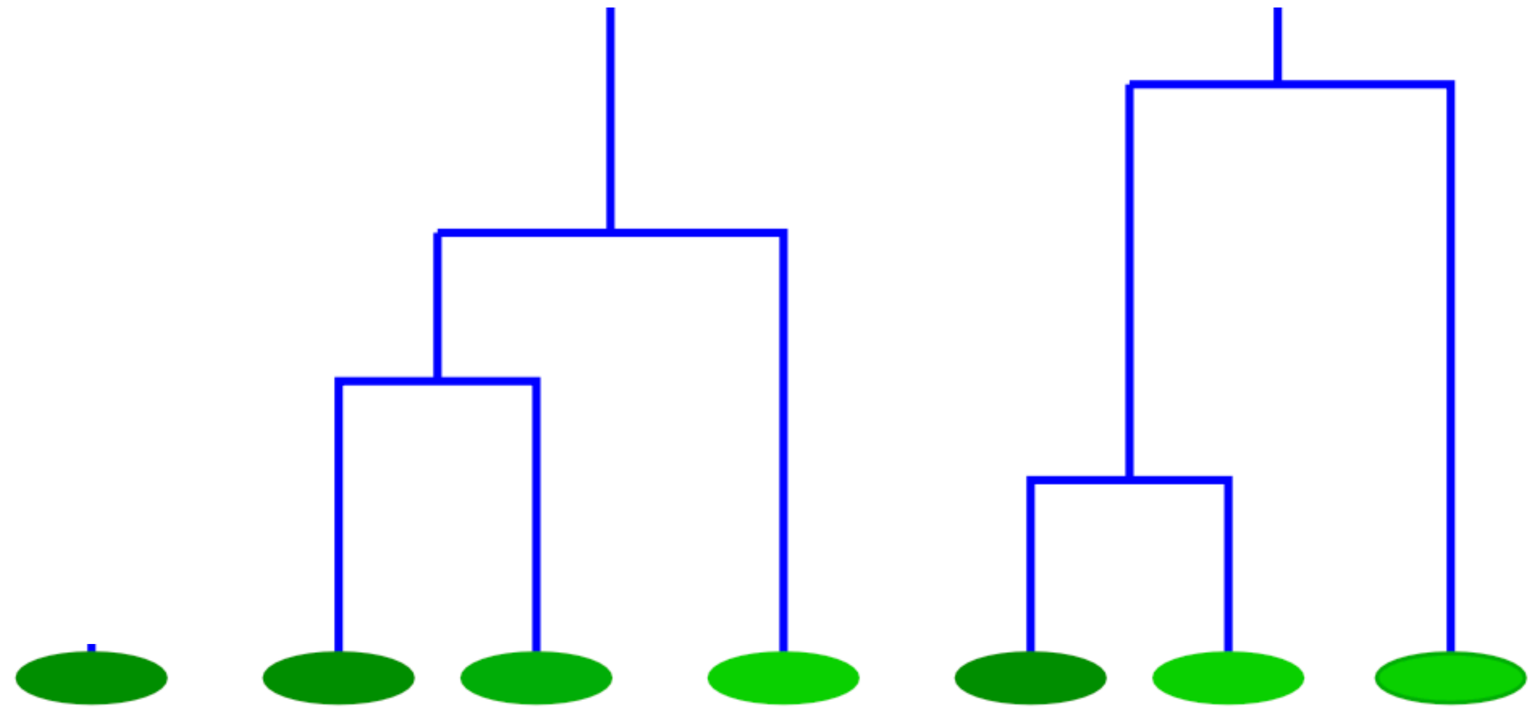

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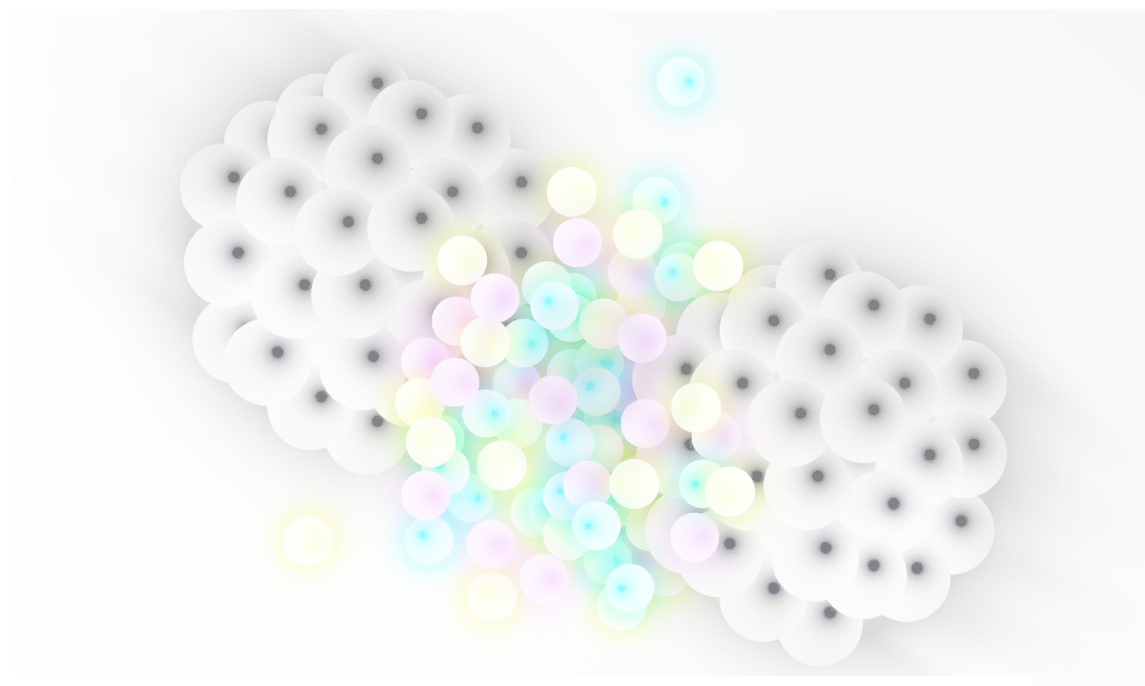

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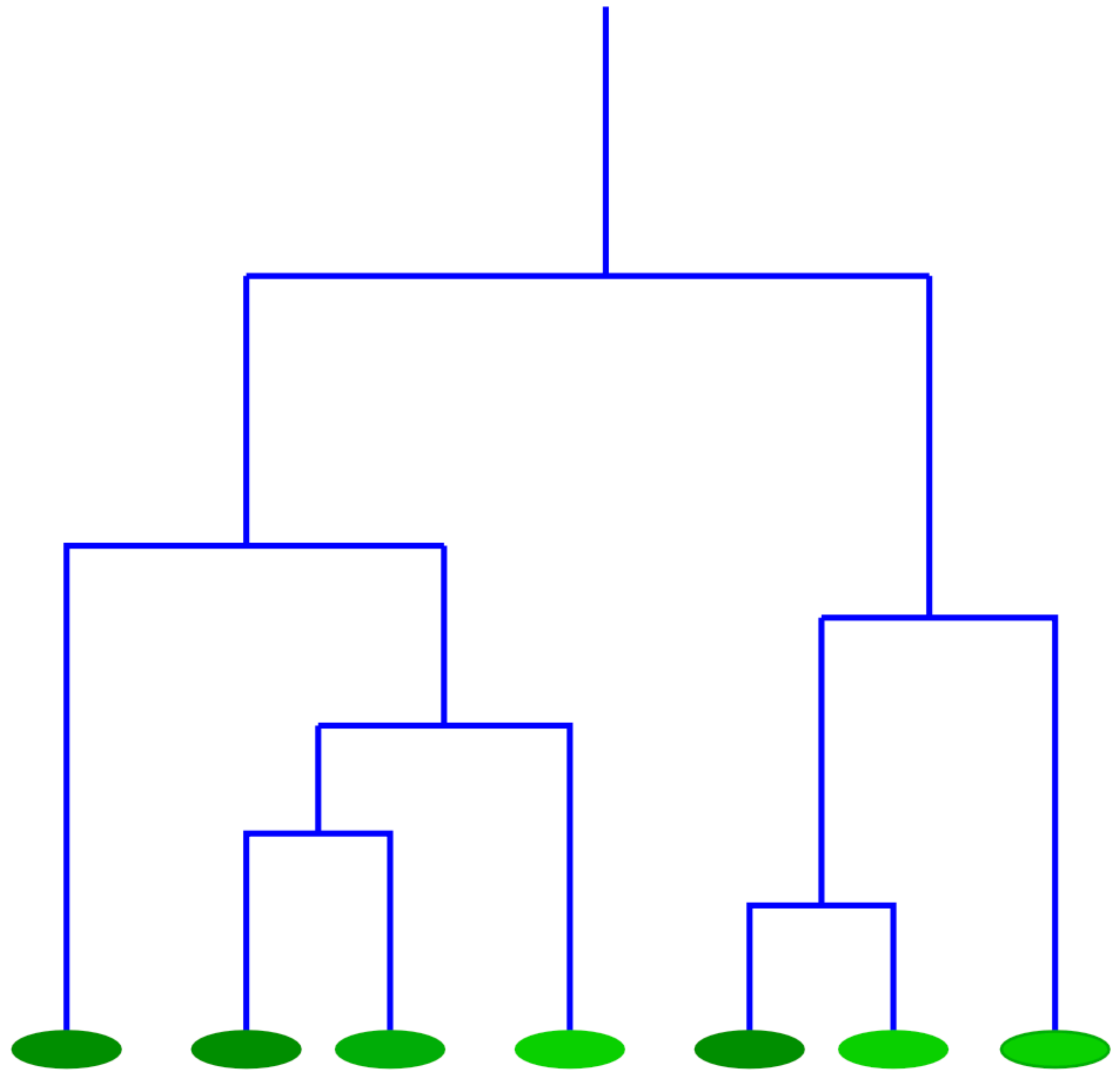

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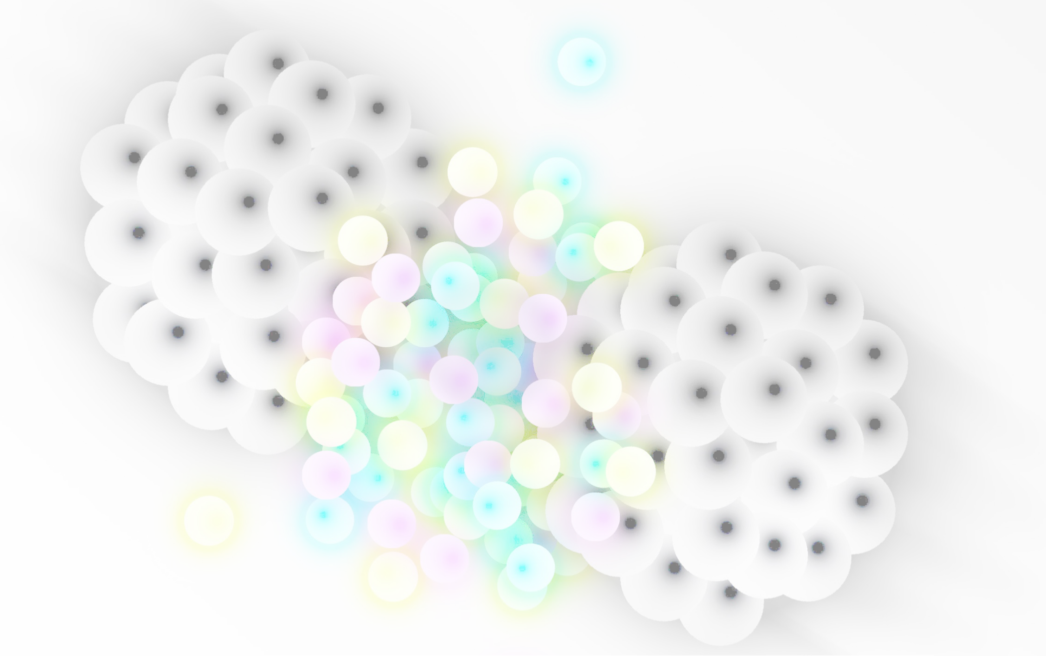

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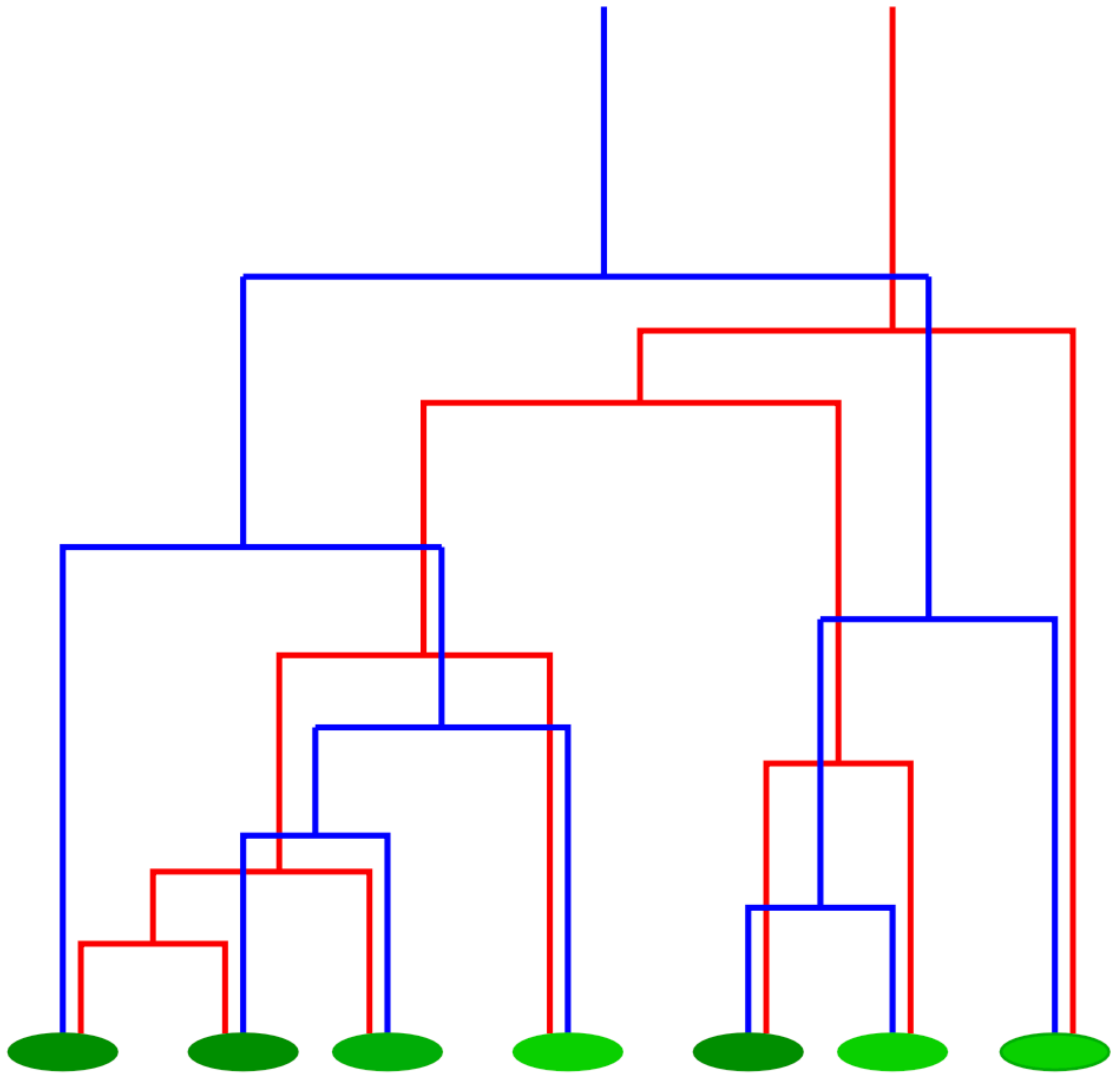

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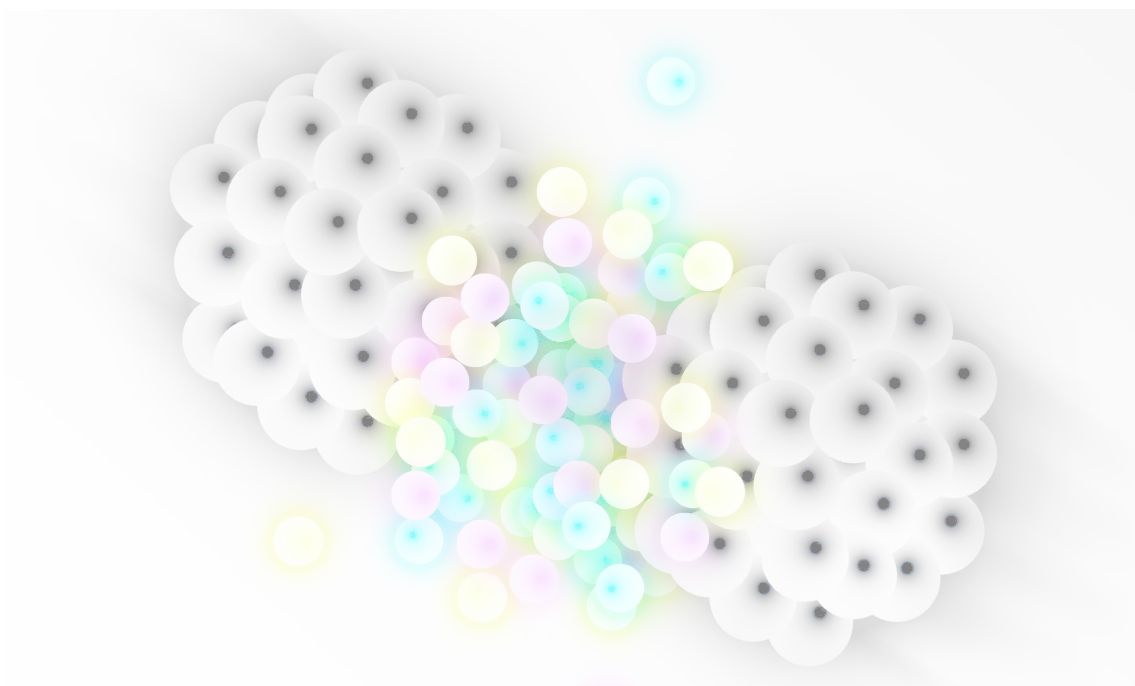

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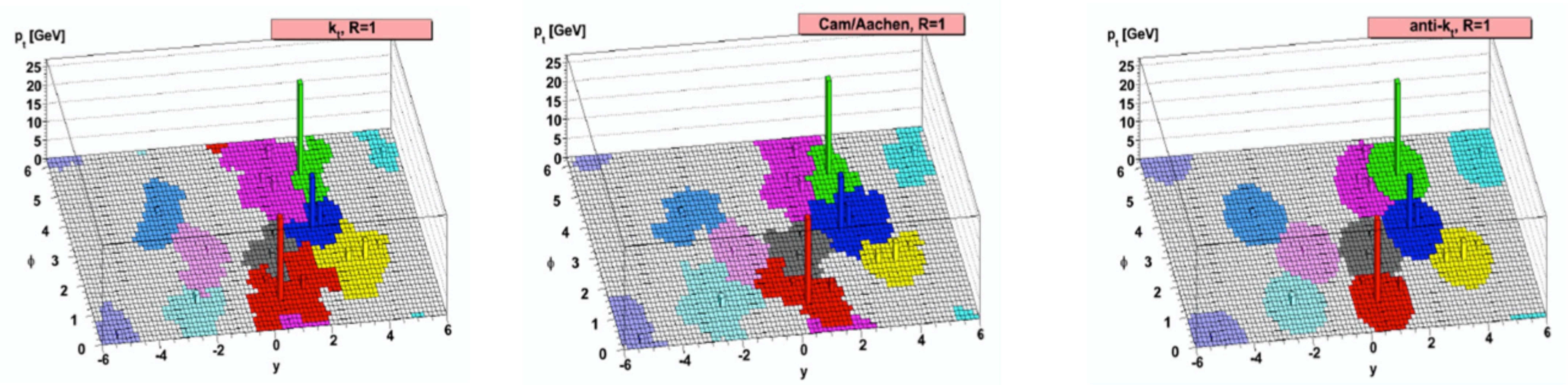
Same event, different jets



Jet algorithms

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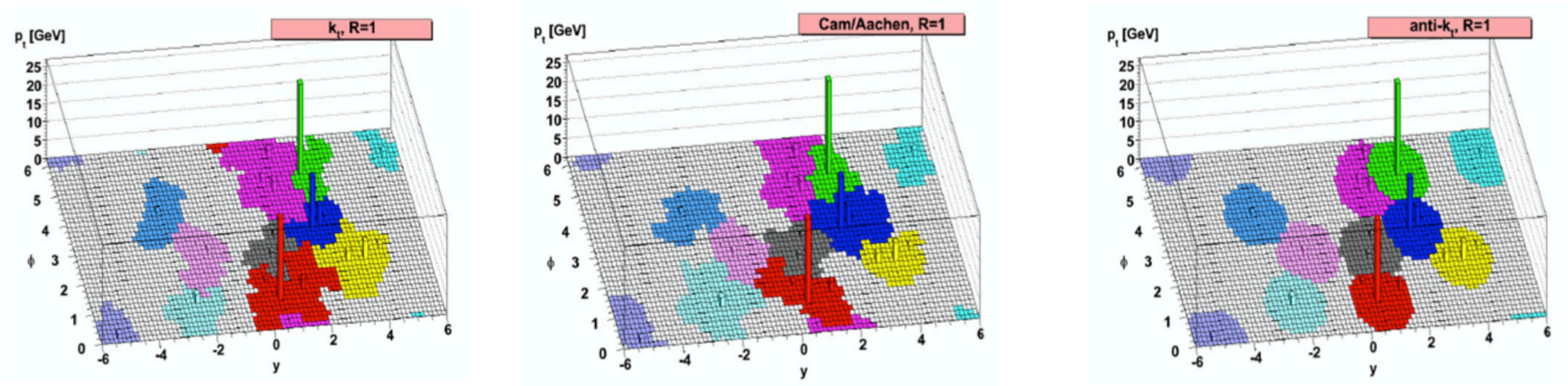
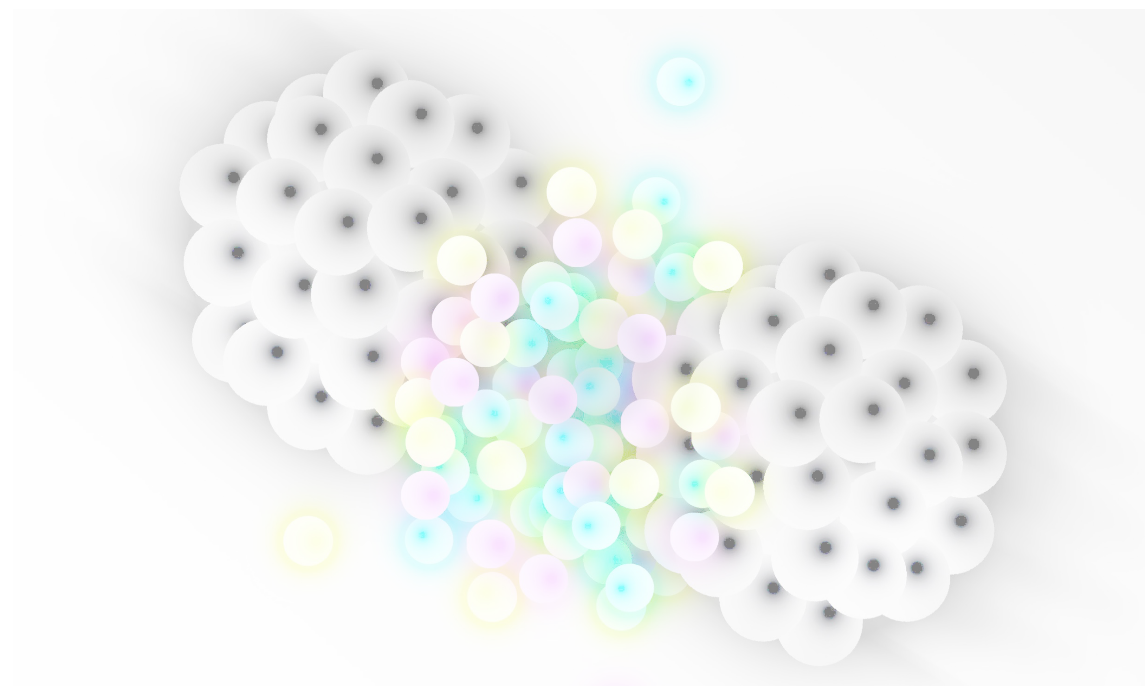
$$R_{ij}^2 = (y_i \; y_j)^2 + (\phi_i - \phi_j)^2$$

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

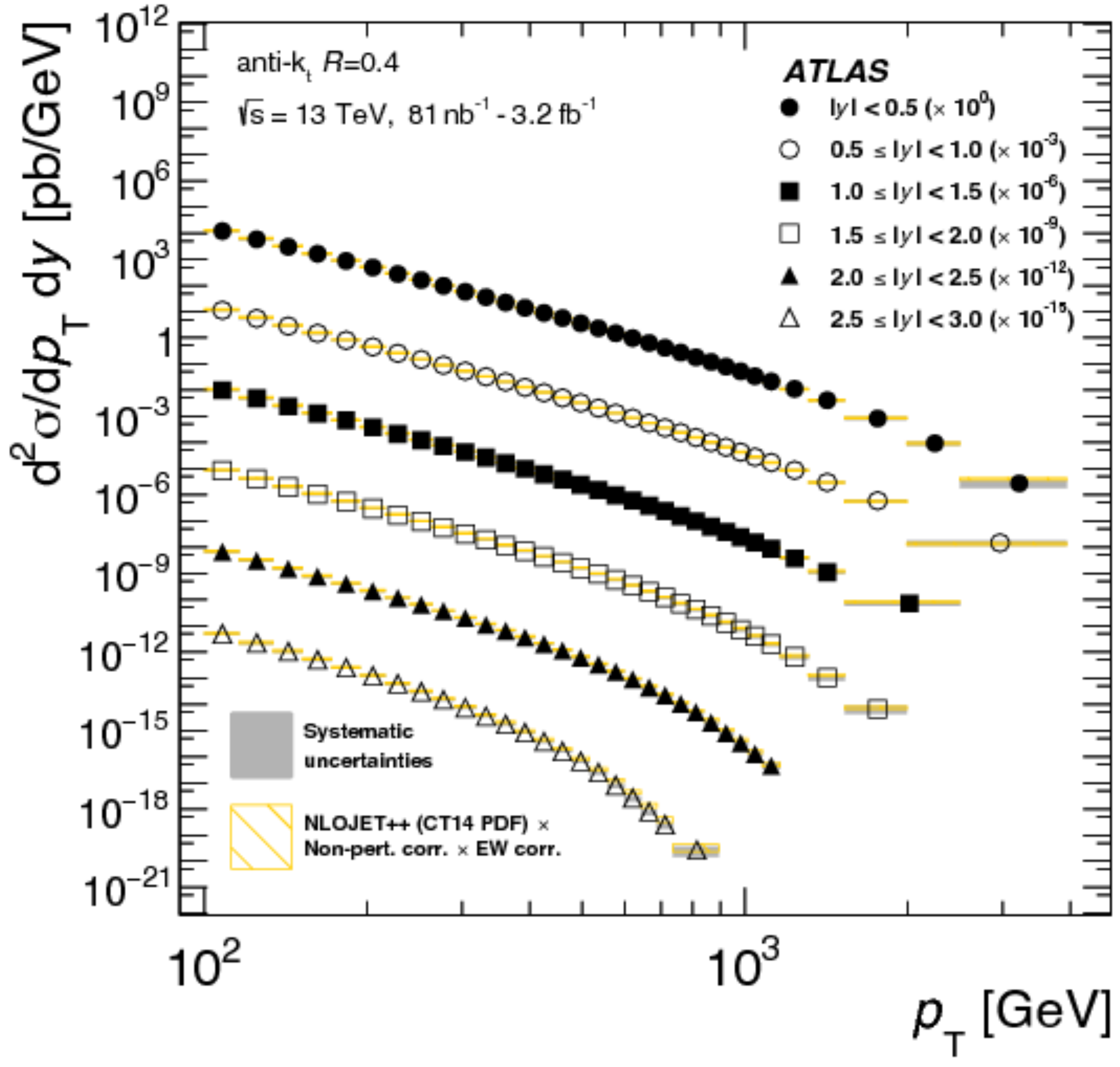
Same event, different jets



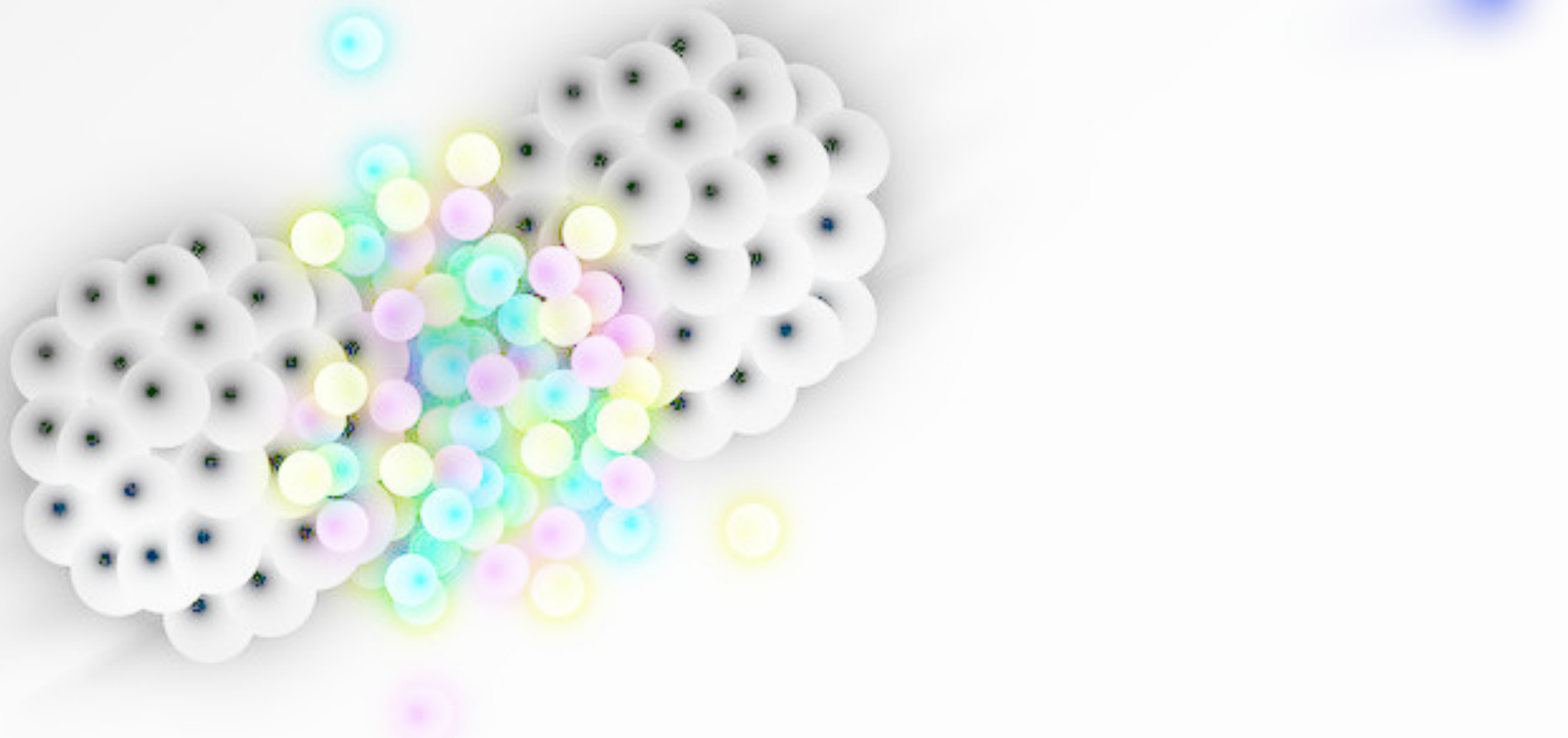
An example of QCD success



- 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, …)

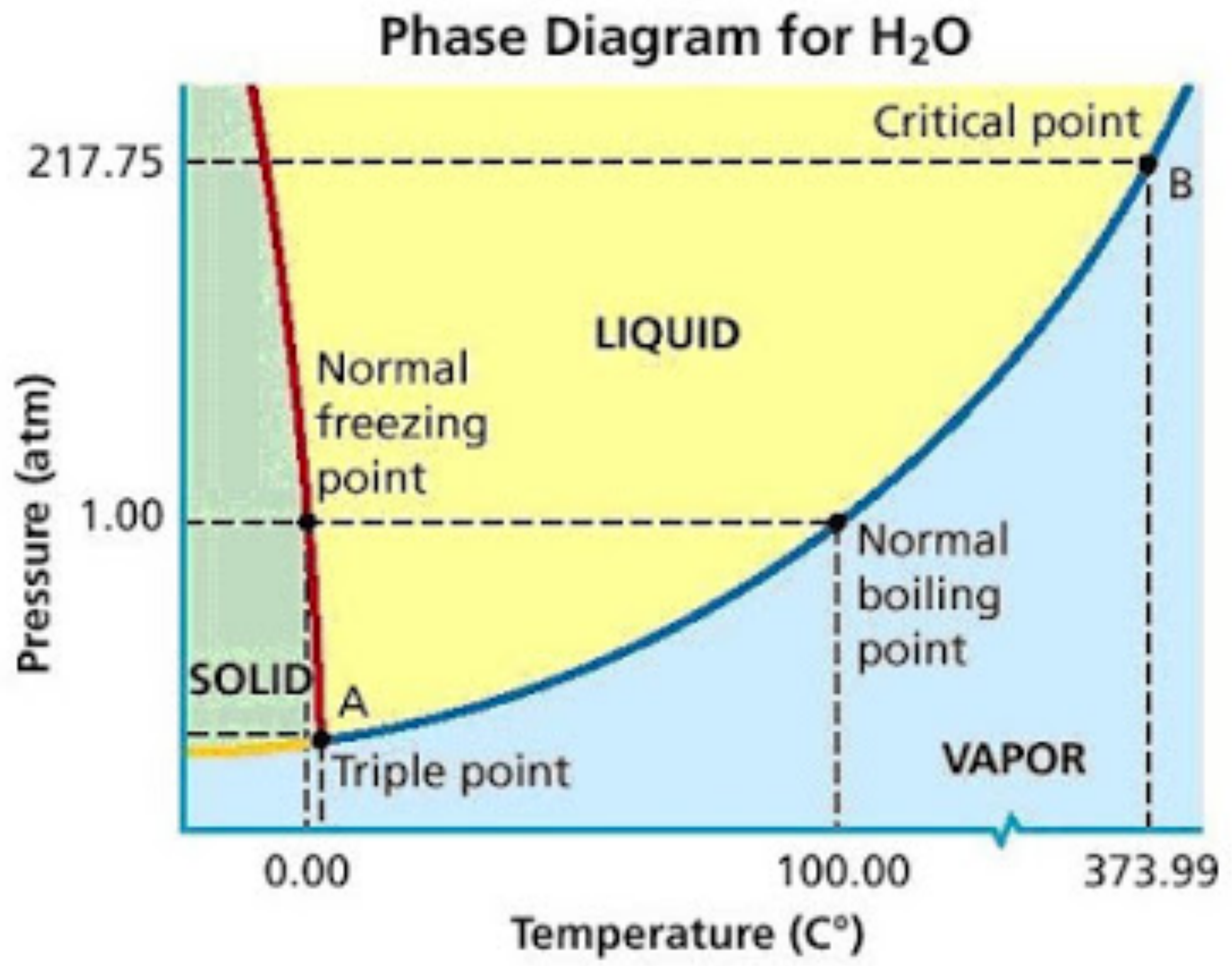


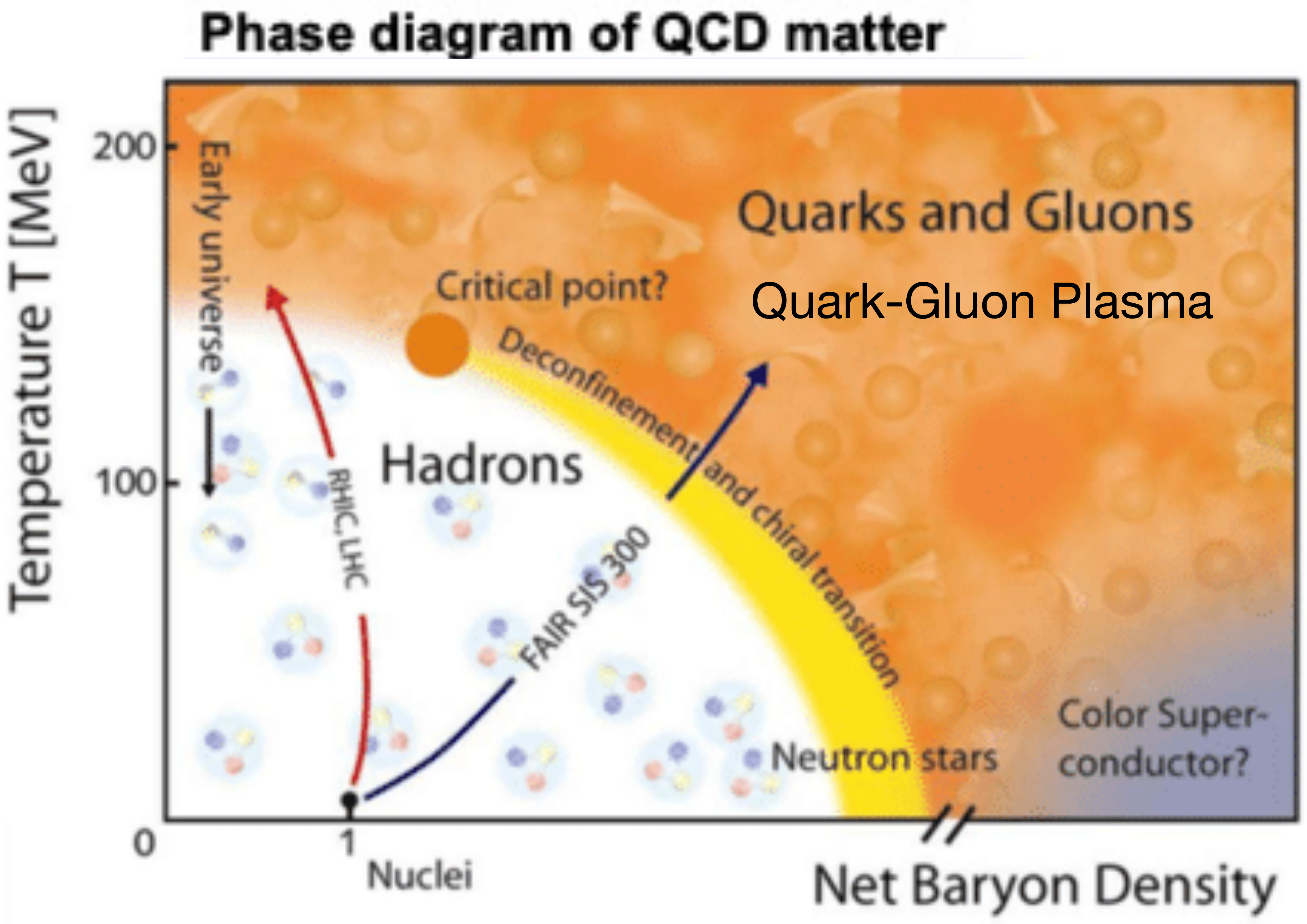
Is QCD limited to a collection of small particles?



From dilute QCD to dense QCD

- QCD matter has a rich and vast phase diagram:





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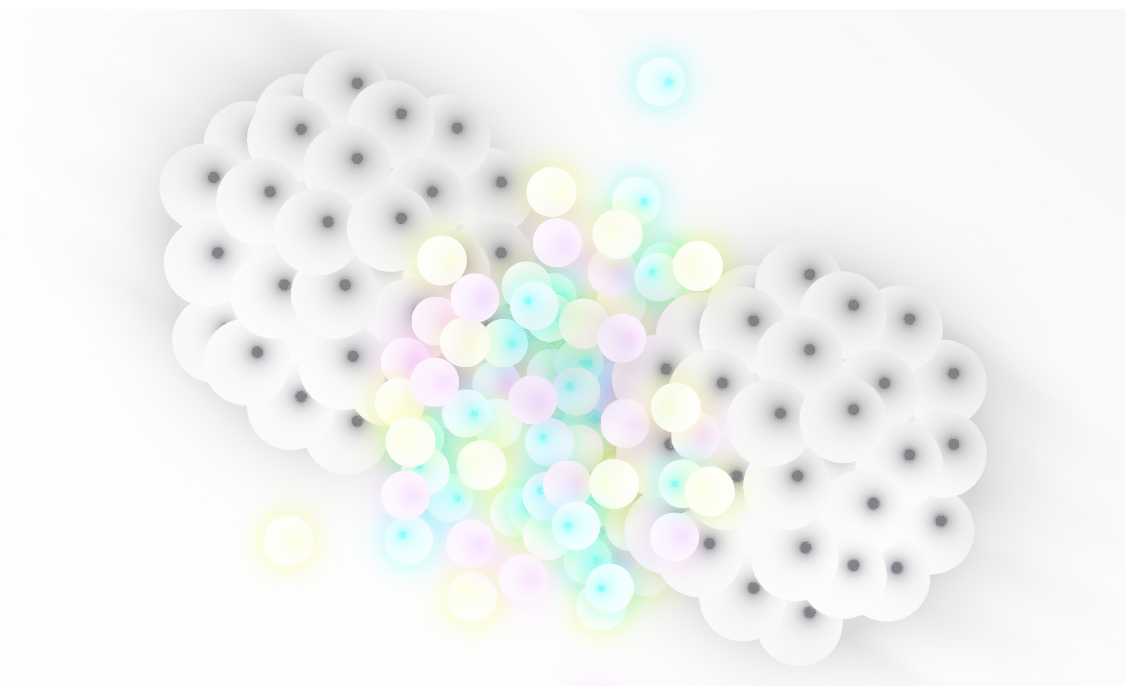
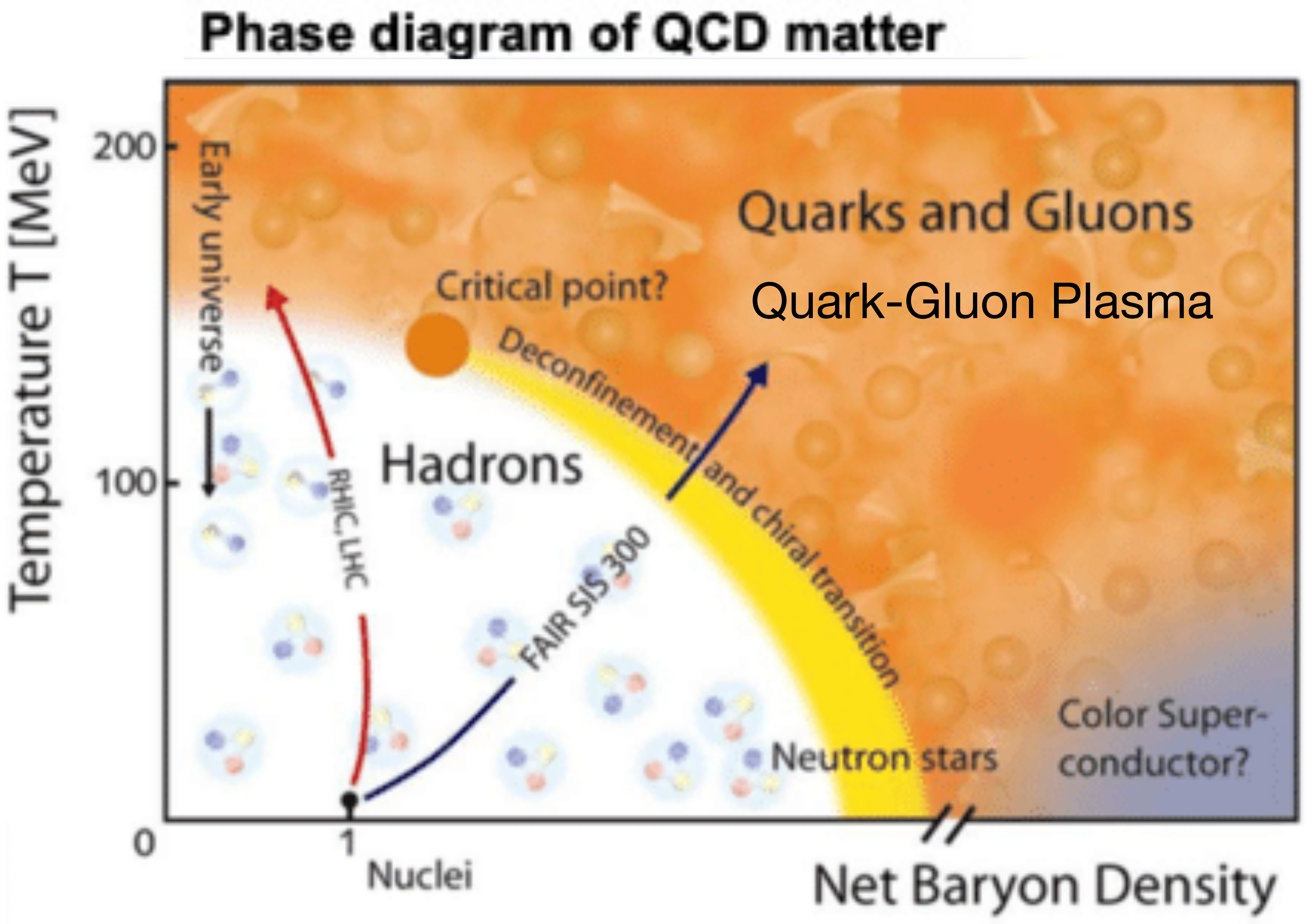


- QCD matter has a rich and vast phase diagram:

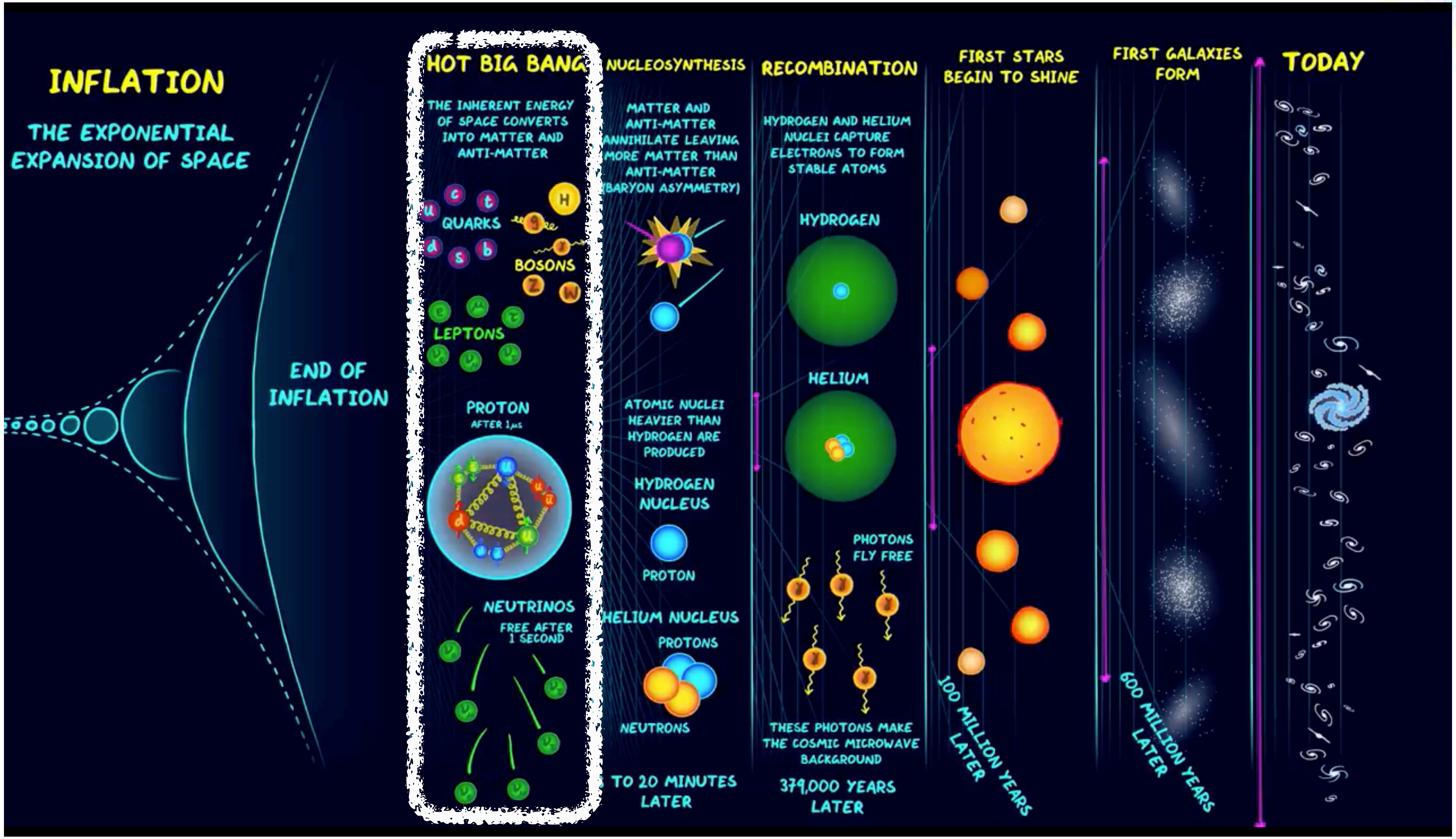
QCD theory (*1973*)
SU(3) Color symmetry; confinement; asymptotic freedom, …

QGP initial idea (*1975*)
“Weakly coupling quark soup”

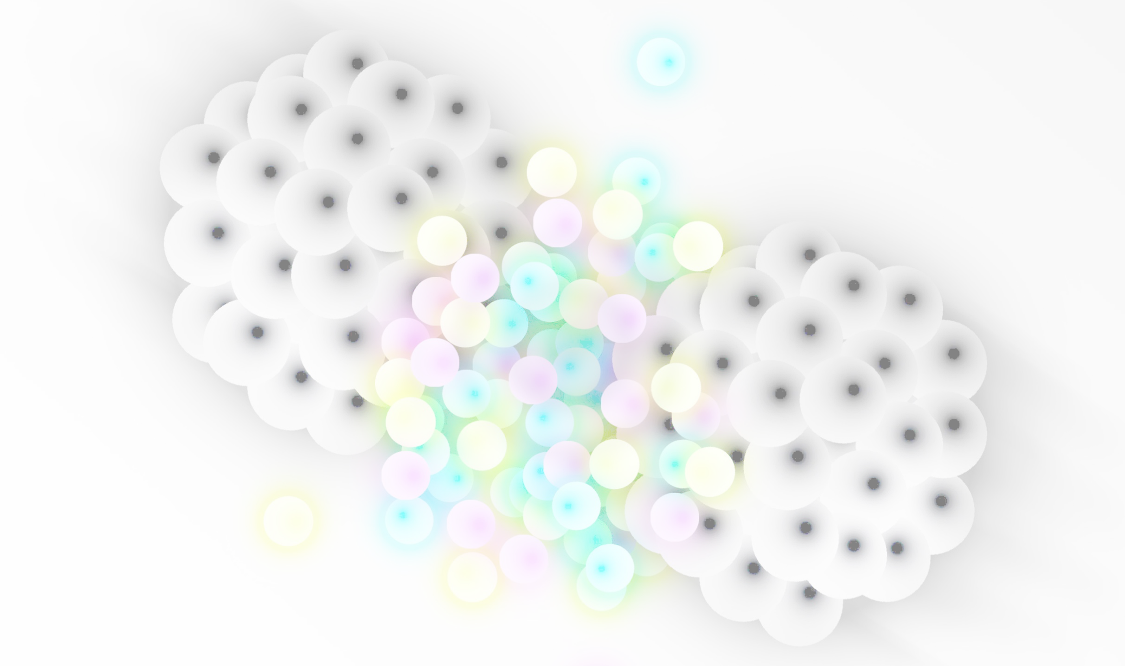
State of matter where quarks and gluons are asymptotically free



QGP @ Early Universe



QGP @ Heavy-Ion Collisions



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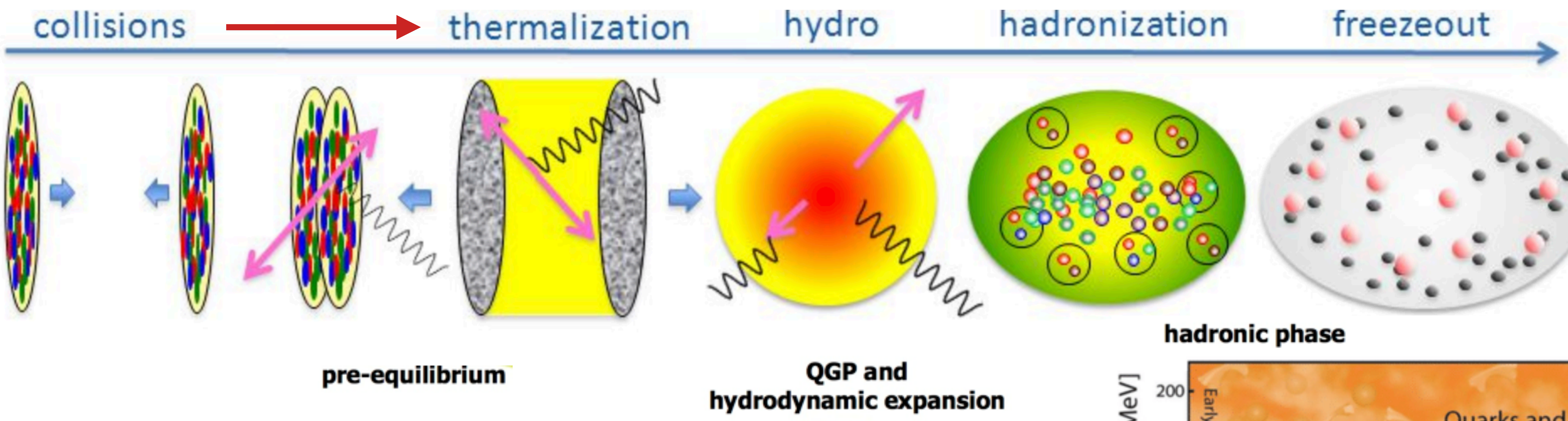
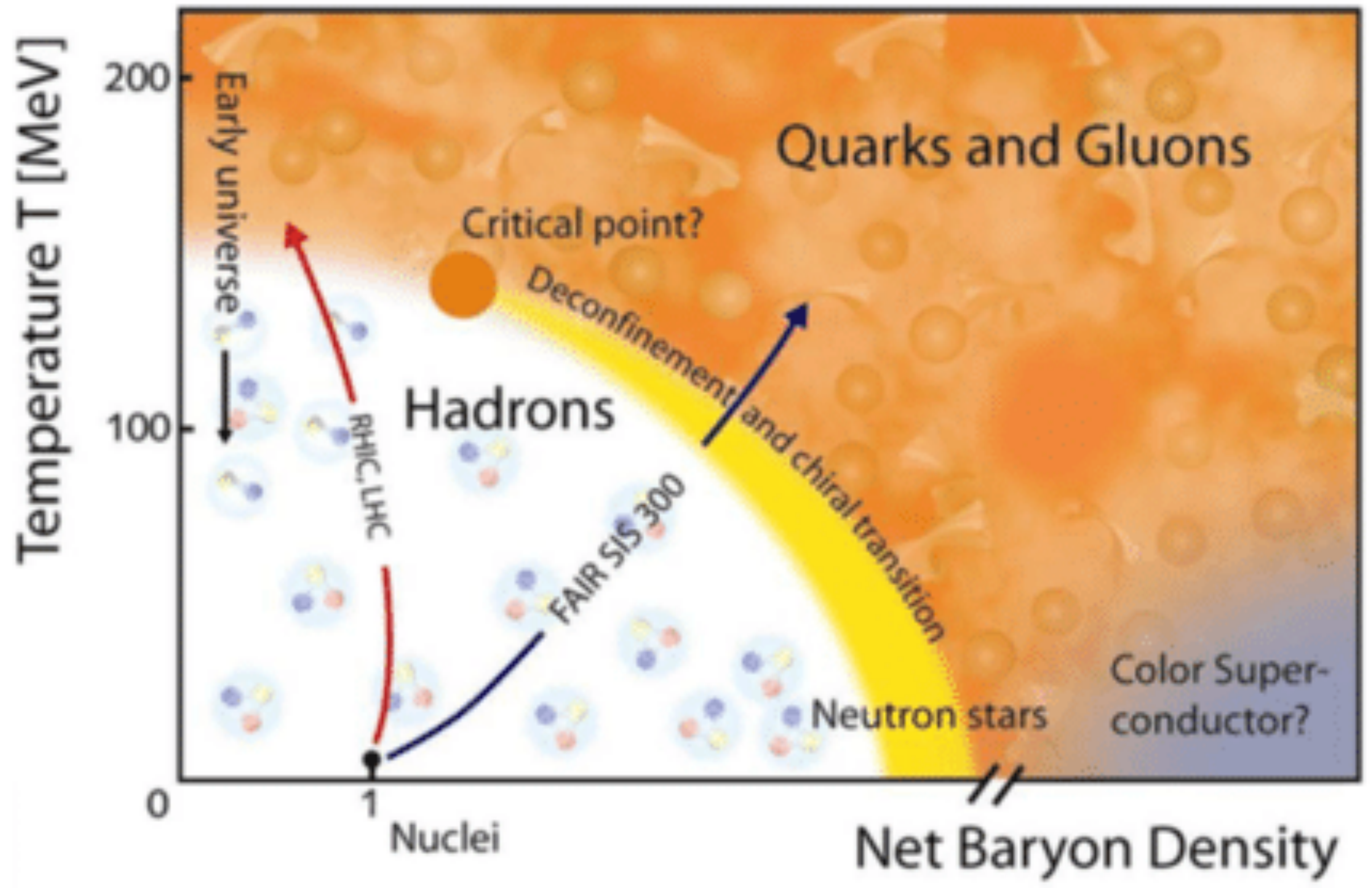


FCC?:
PbPb @ 39 TeV

RHIC (~2000):
AuAu @ 200 GeV

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



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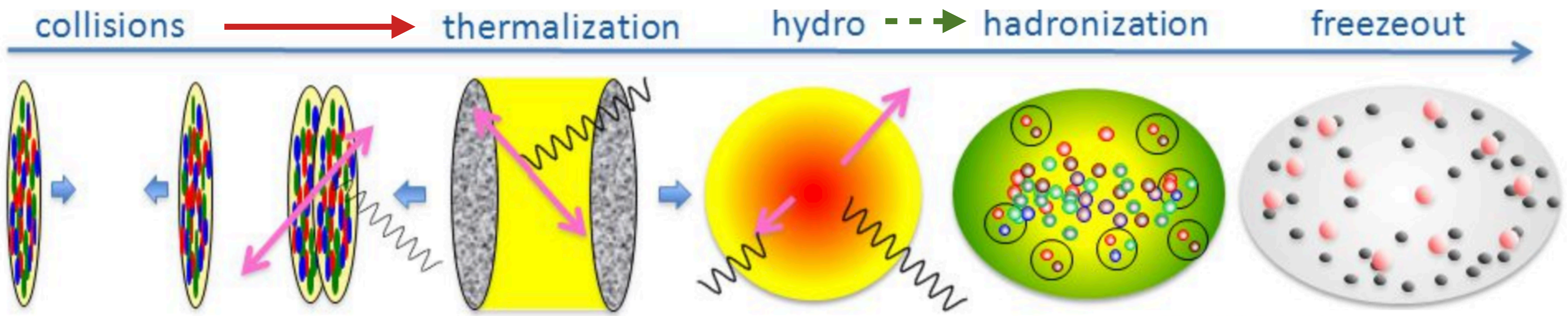

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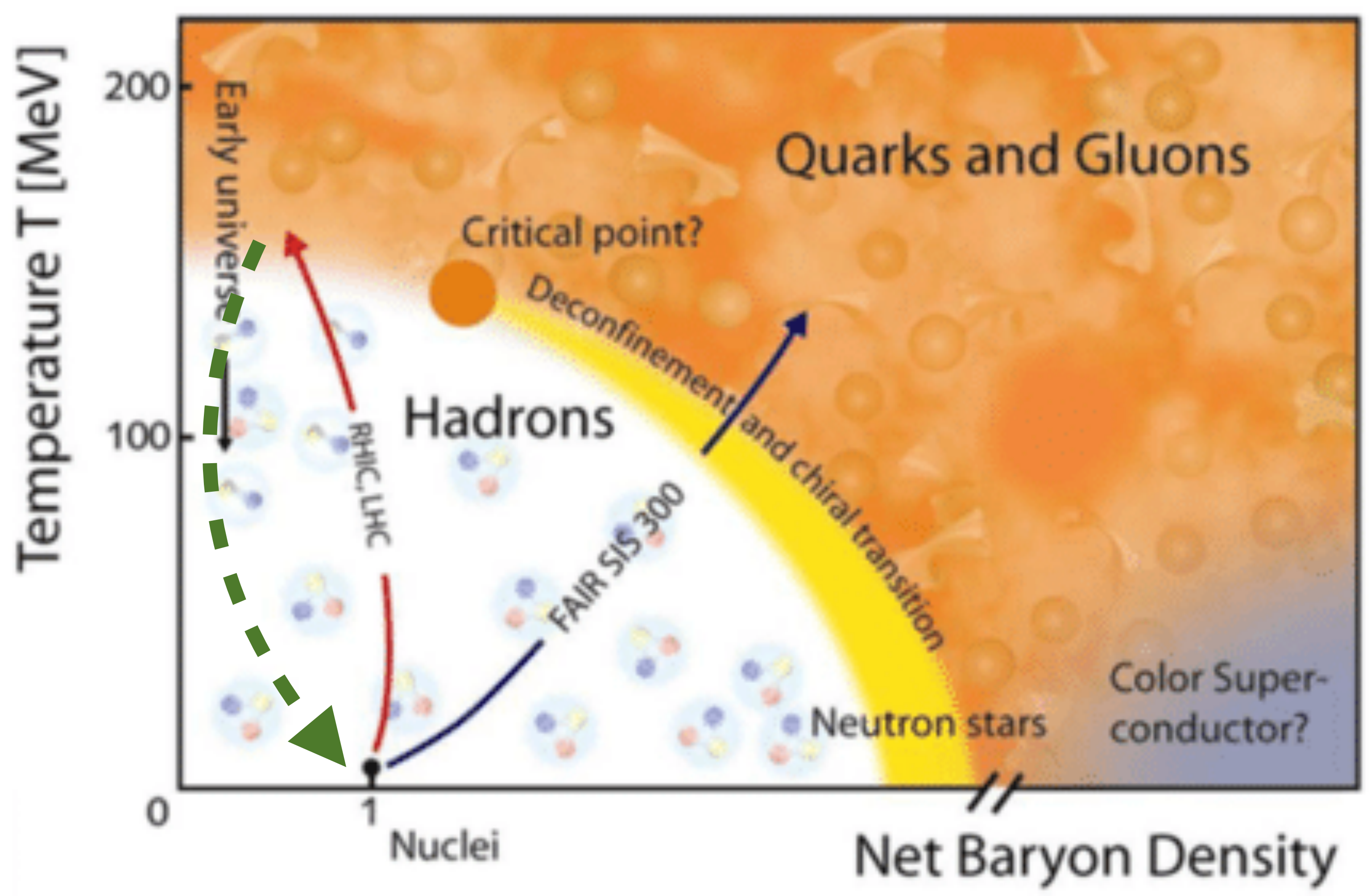
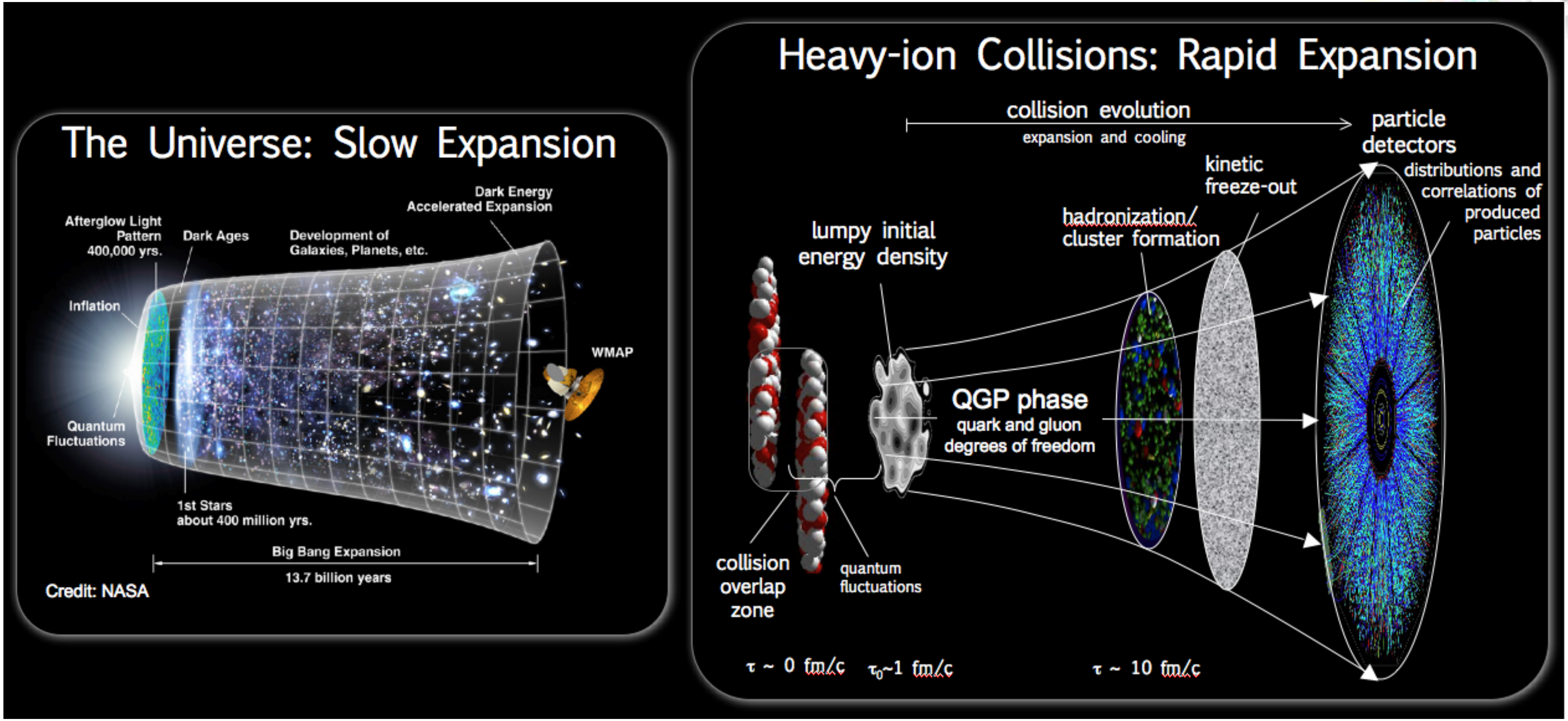


“Big-Bang” vs “Mini-Bang”



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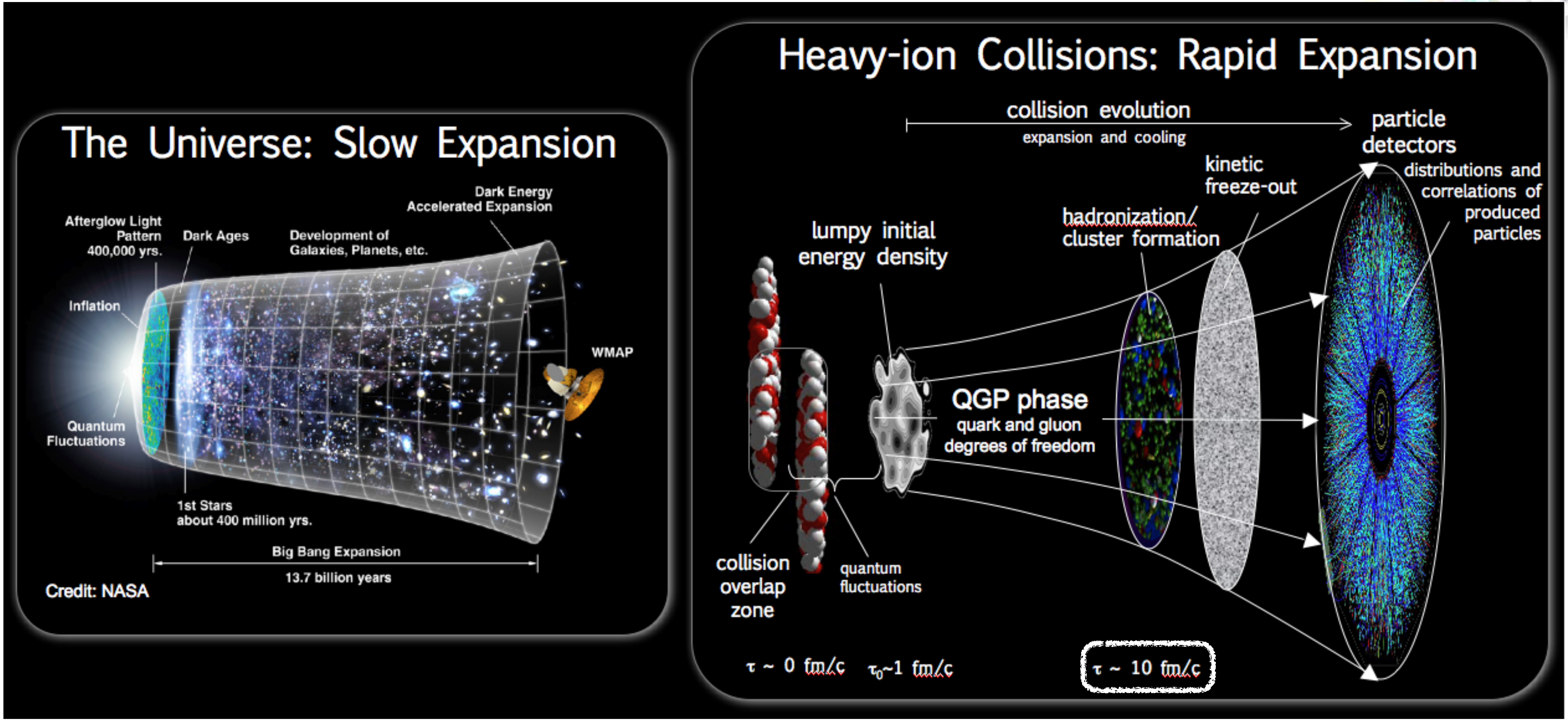
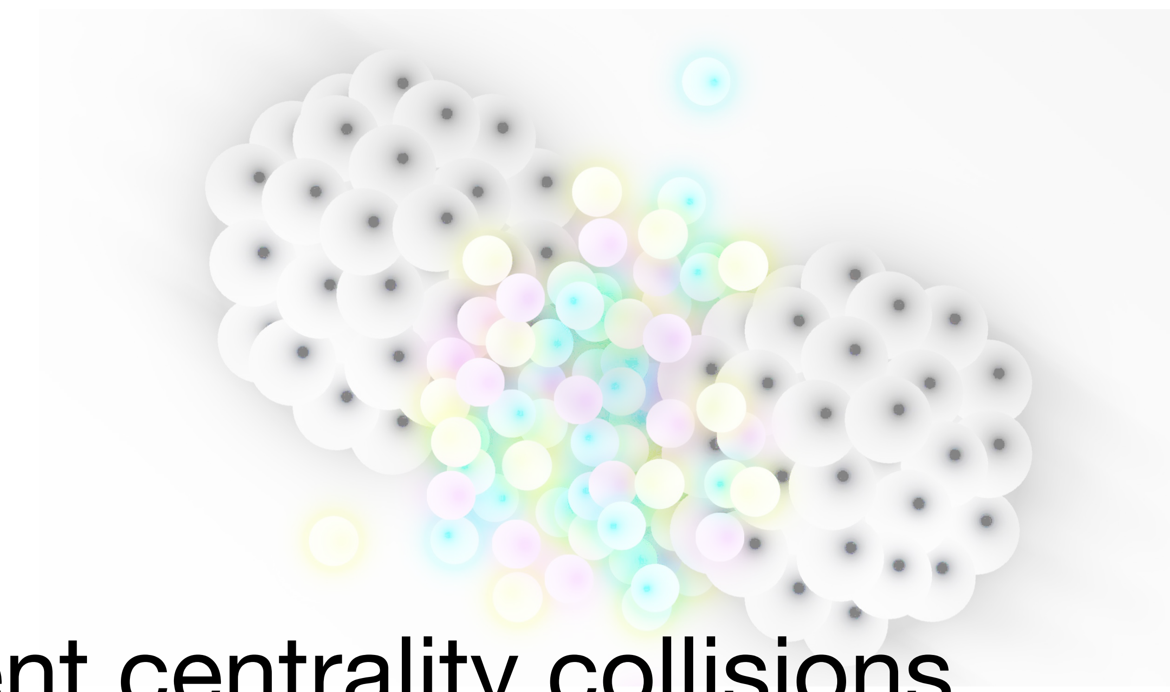
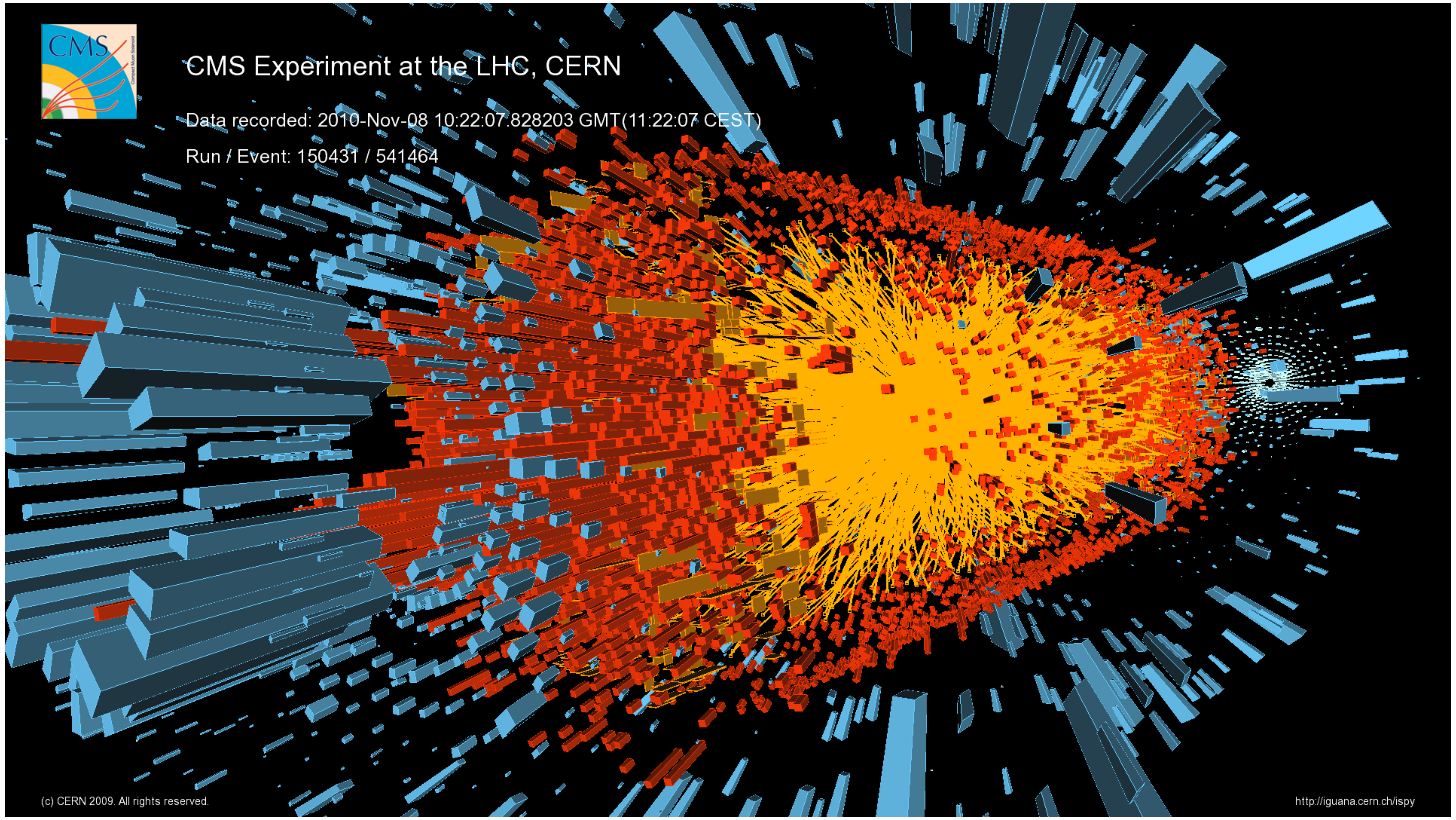


??? (fm/c = 10^{-24} s)

How to probe the QGP @ lab?

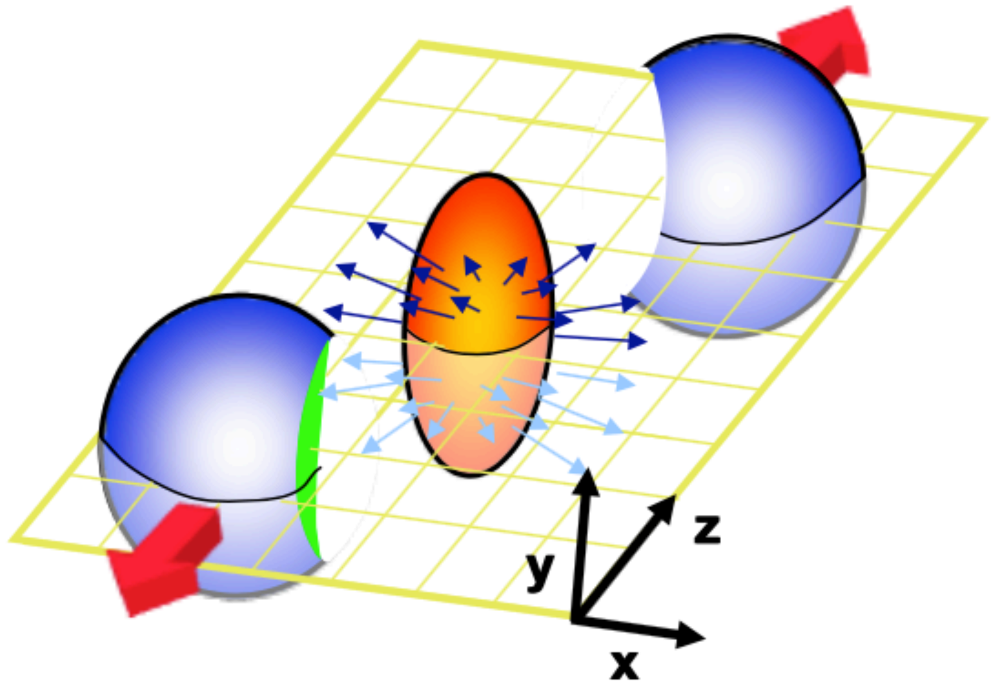


- Look to the result of the collision (Soft probes)

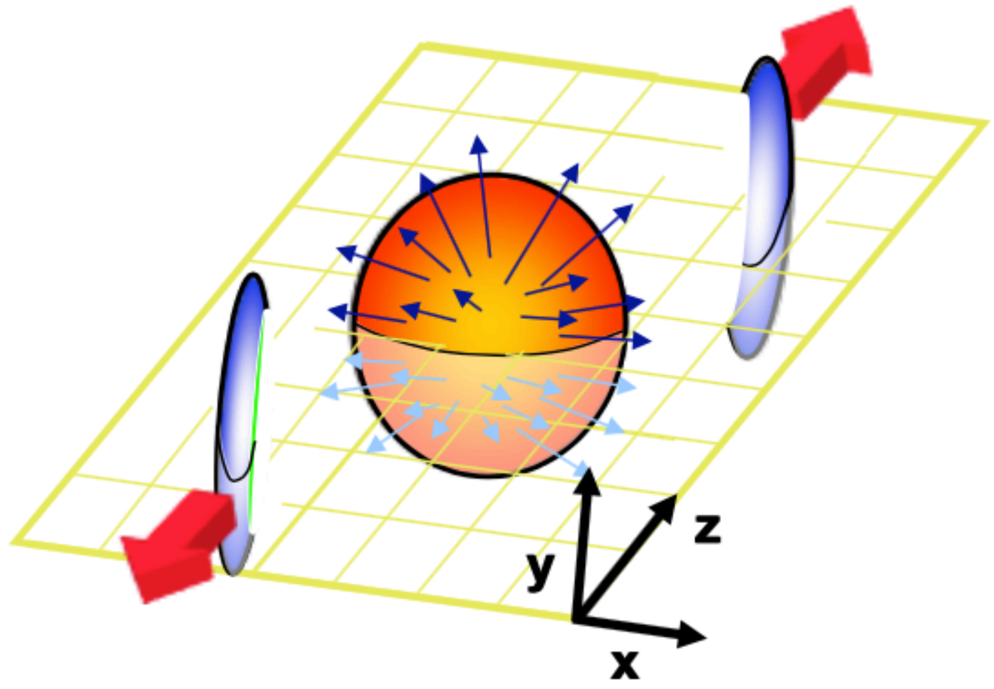


Try different centrality collisions

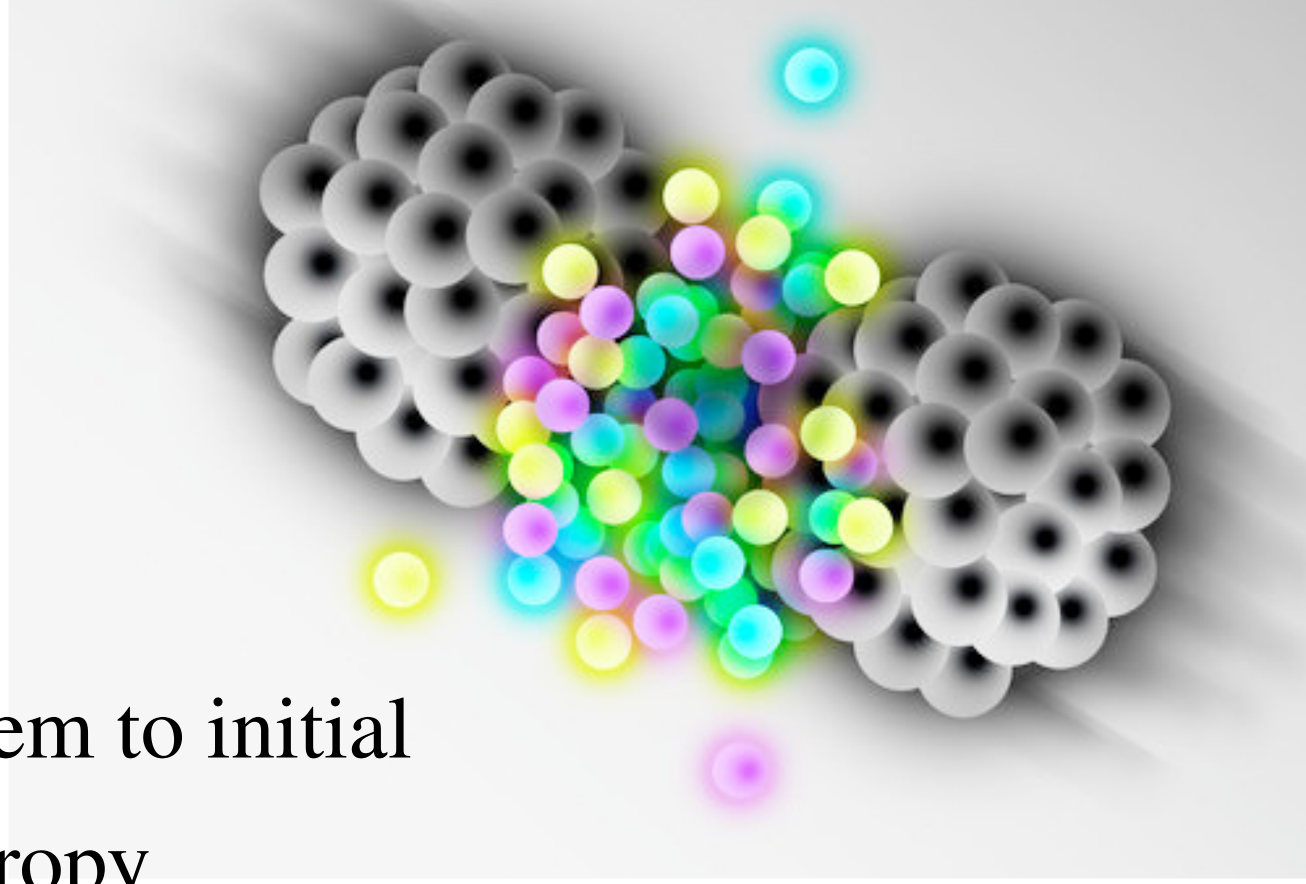
Peripheral Collision



(near) Central Collision



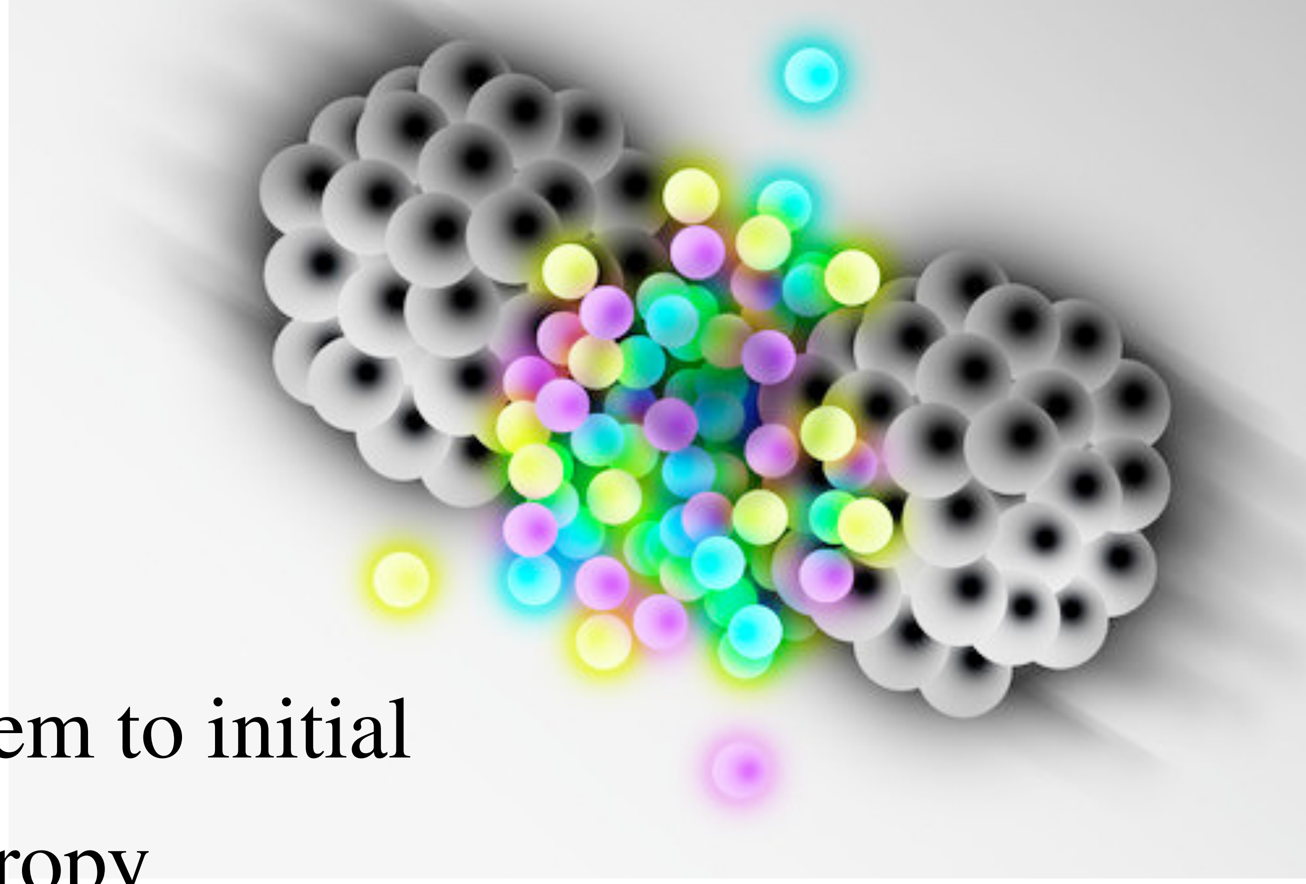
Soft probes



- 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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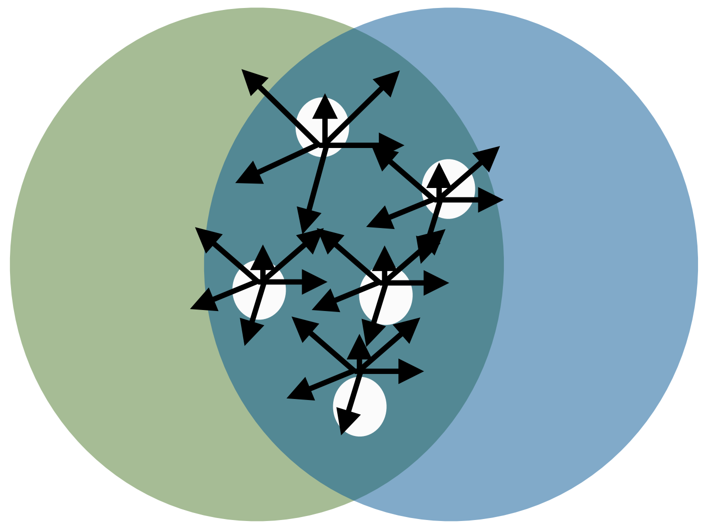
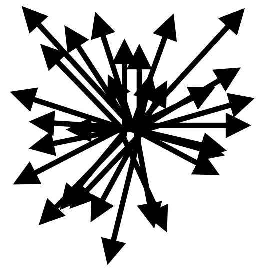
Response of the system to initial spatial anisotropy

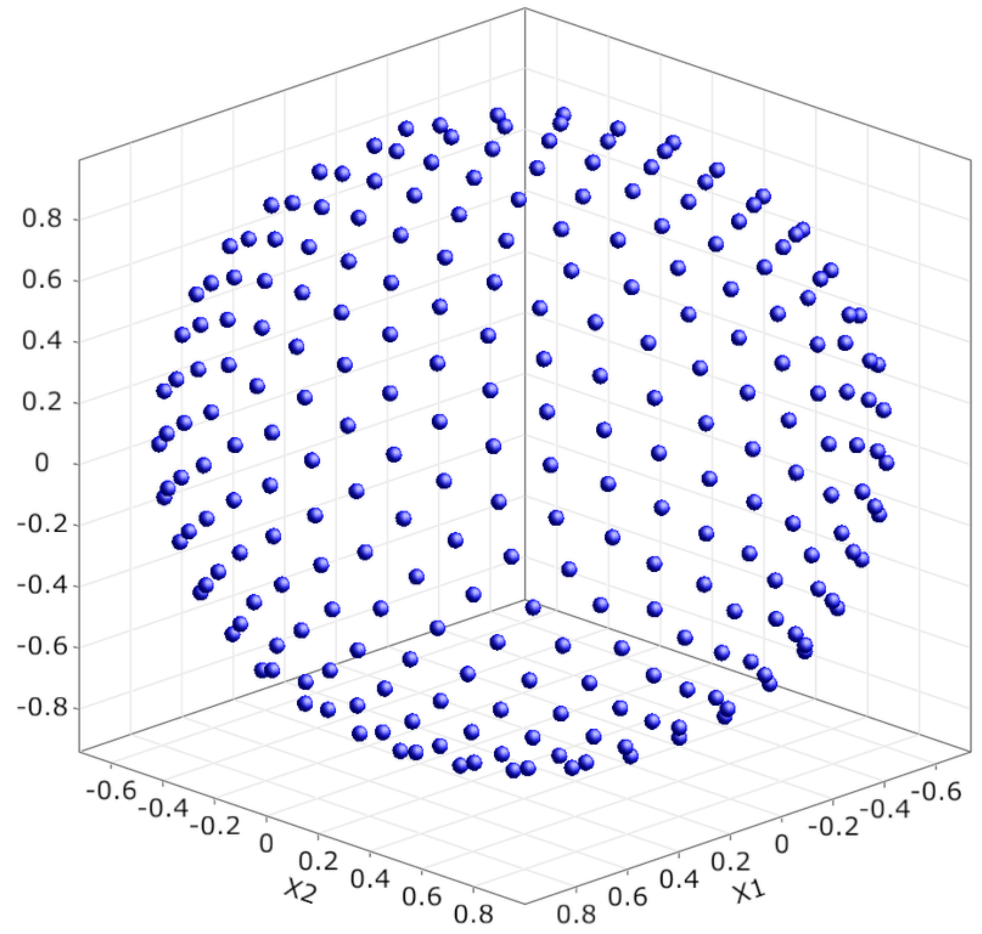
Superposition of multiple pp collisions



“Gas-like” behaviour?



Uniform distribution of final particles



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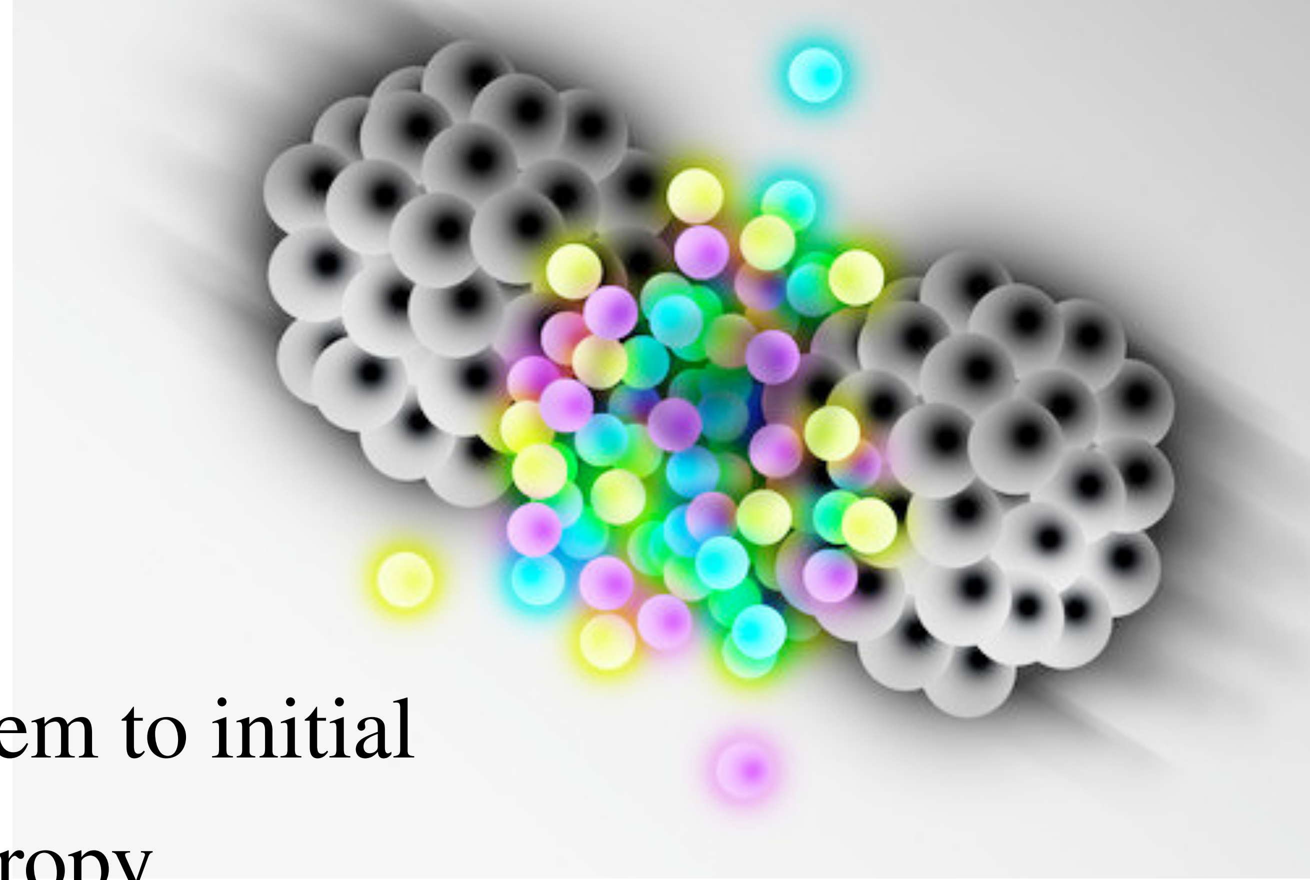

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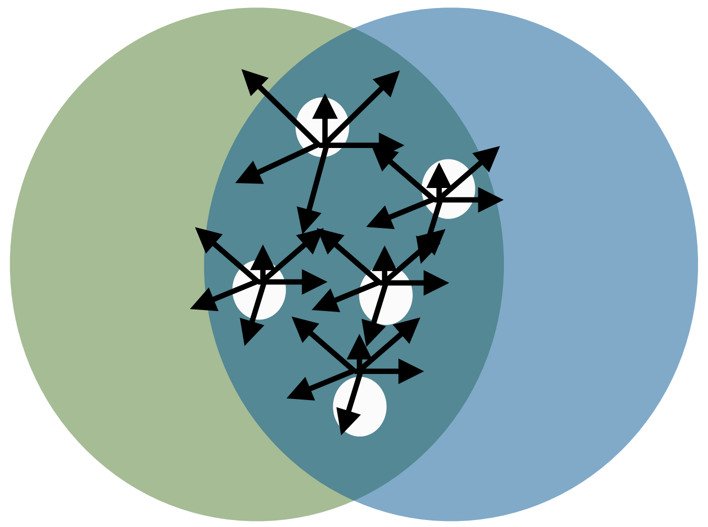

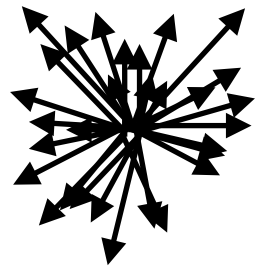

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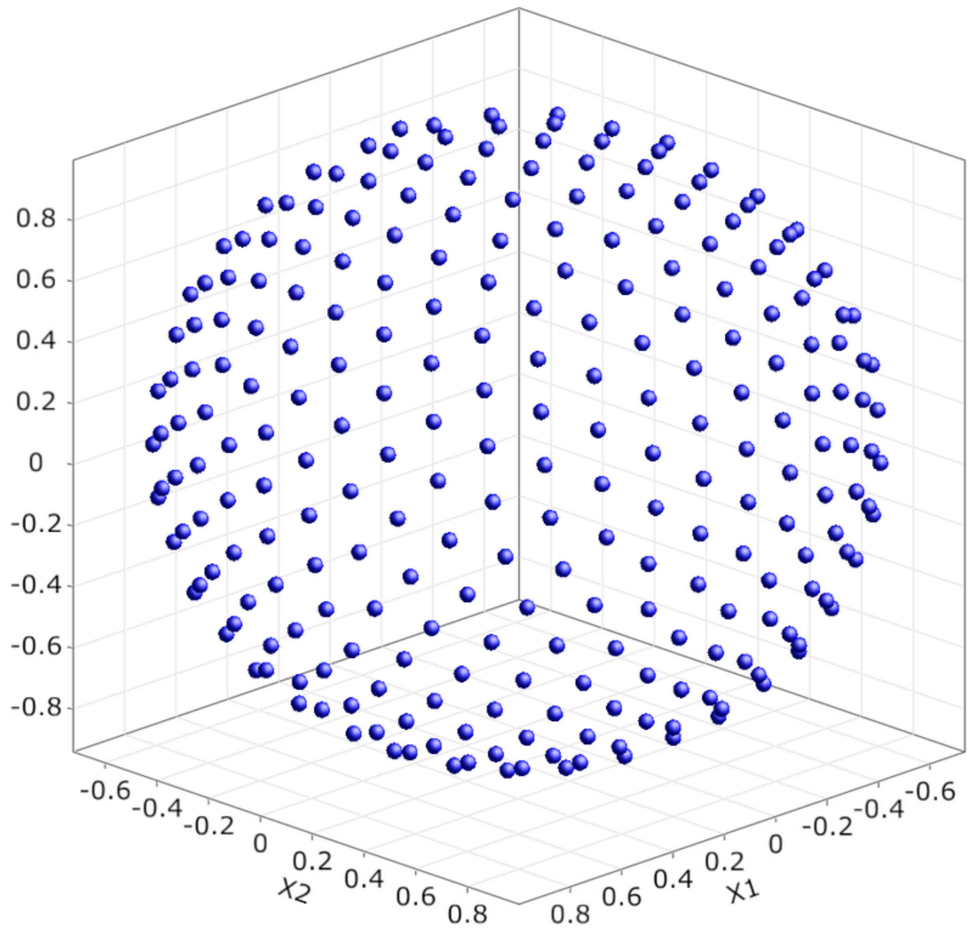
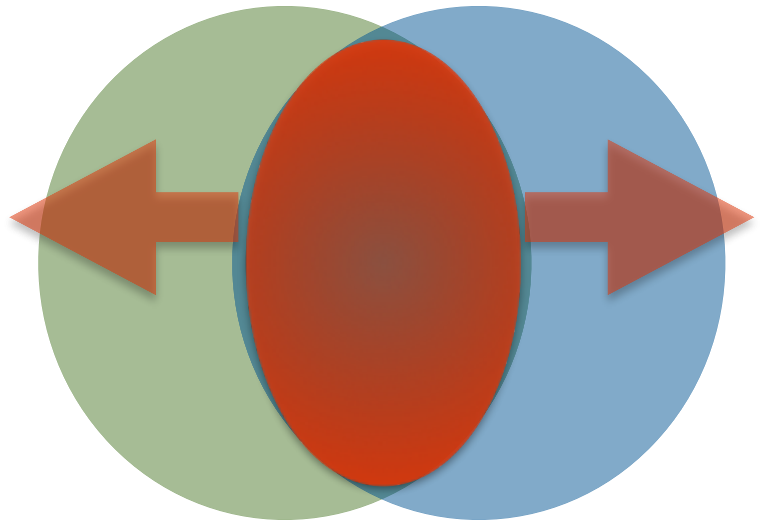


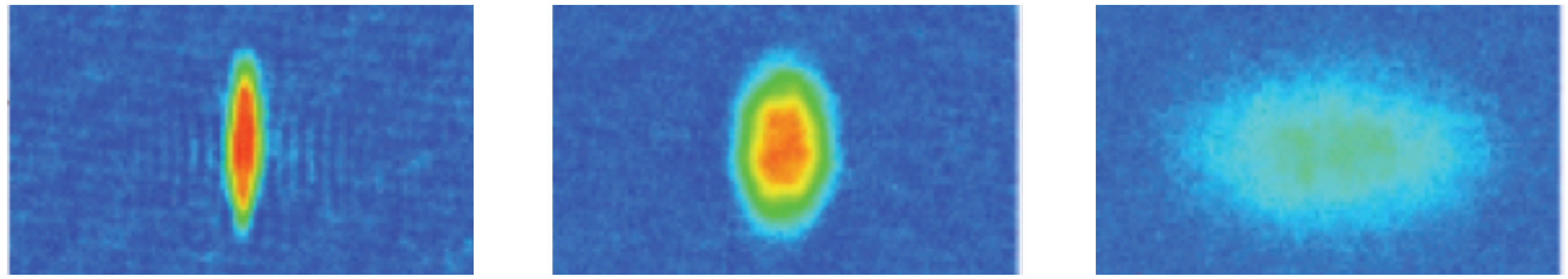
"Gas-like" behaviour?

Collective bulk

"Liquid-like" behaviour?



Initial anisotropies also present in the distribution of final particles



Soft probes

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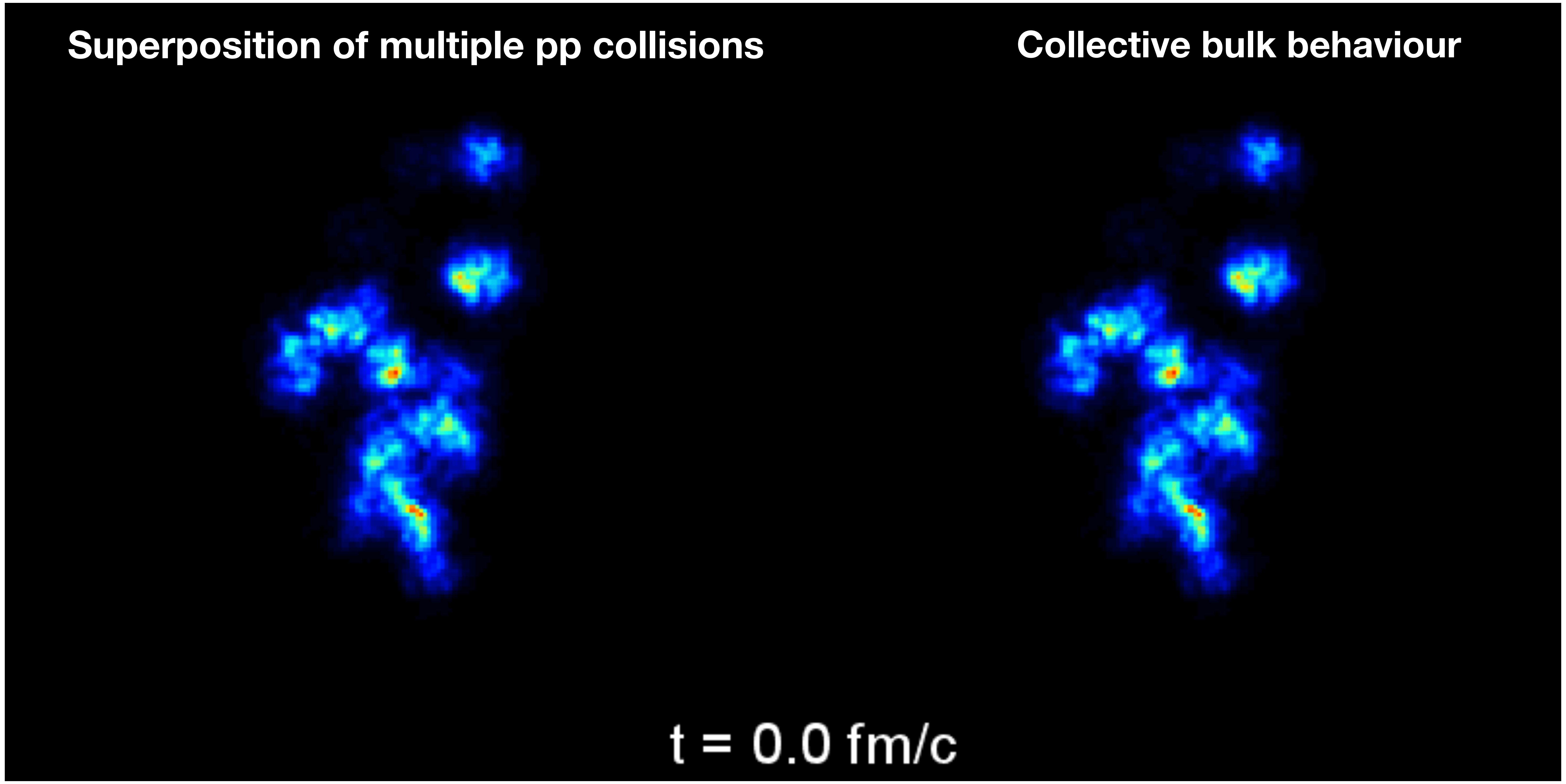

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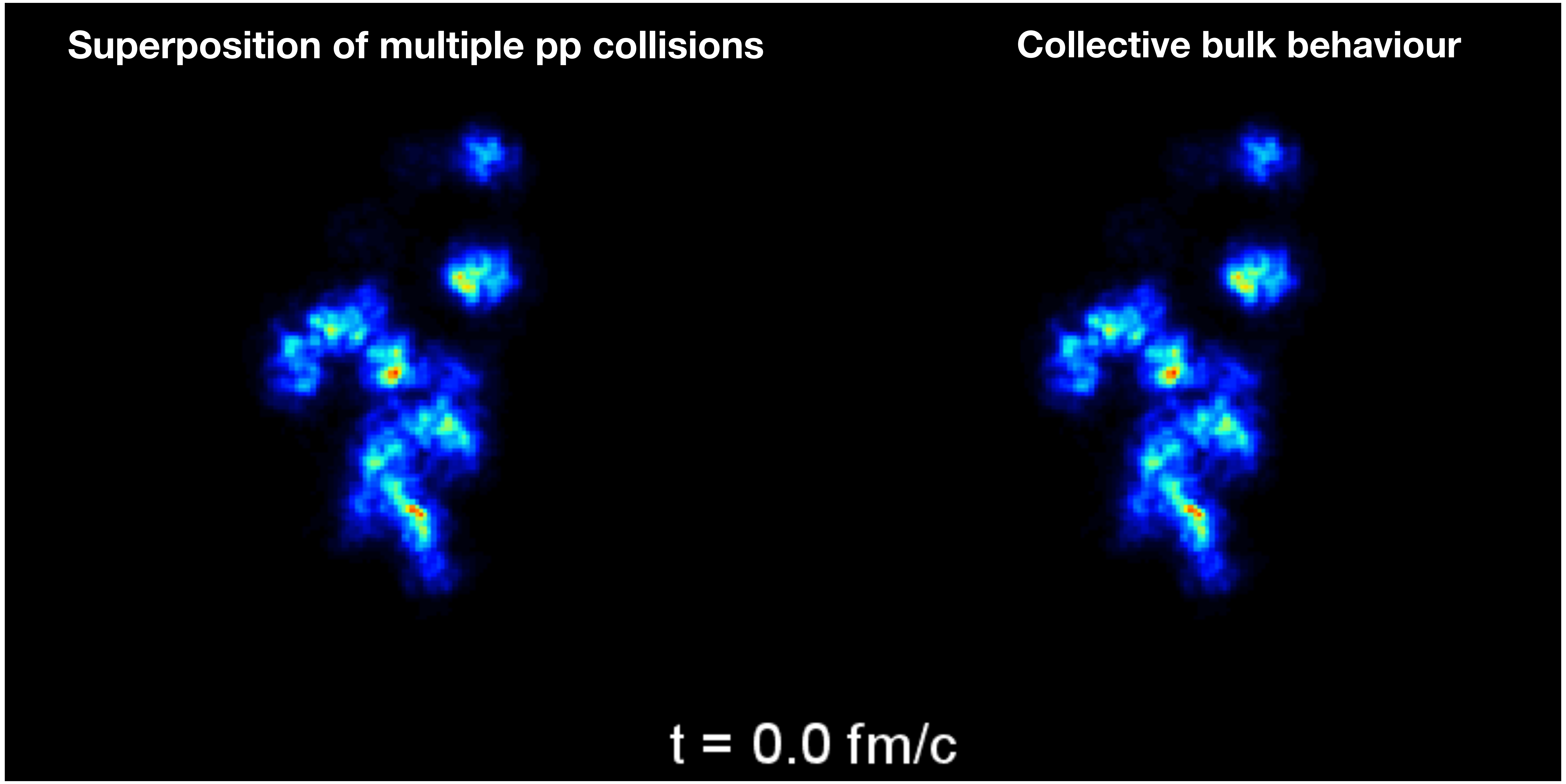
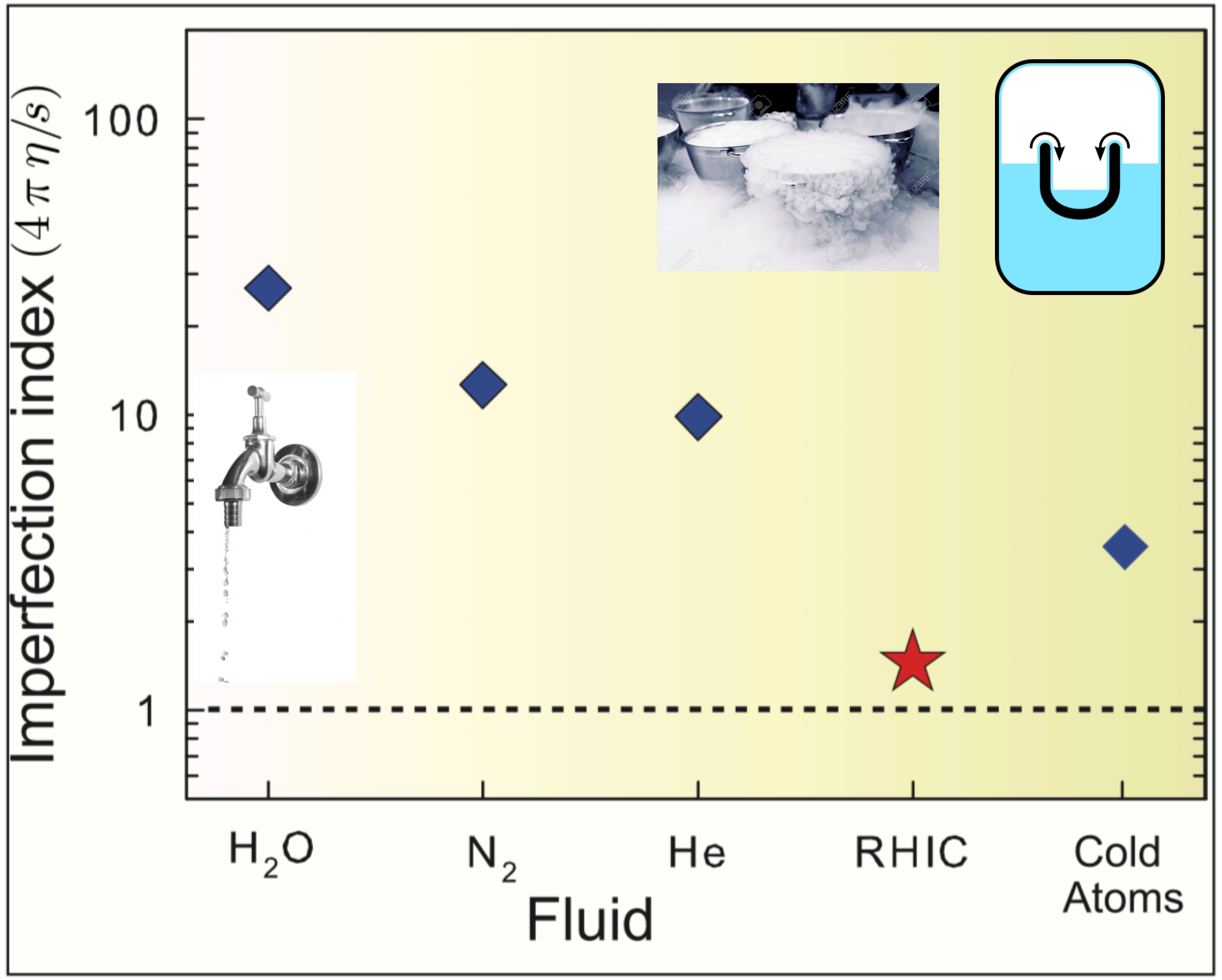
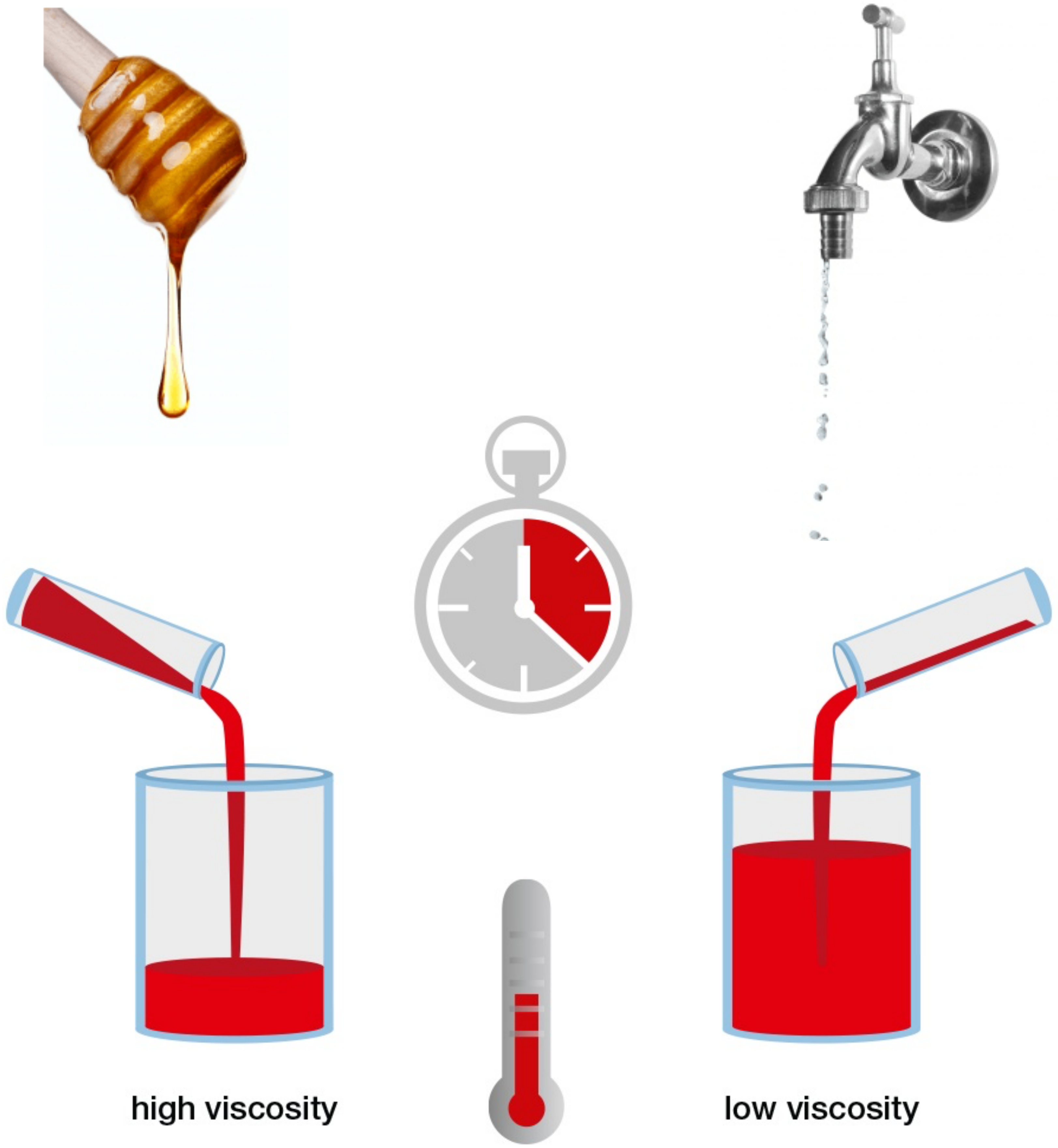


QGP: an almost perfect liquid

- Measuring the imperfection factor (viscosity)….





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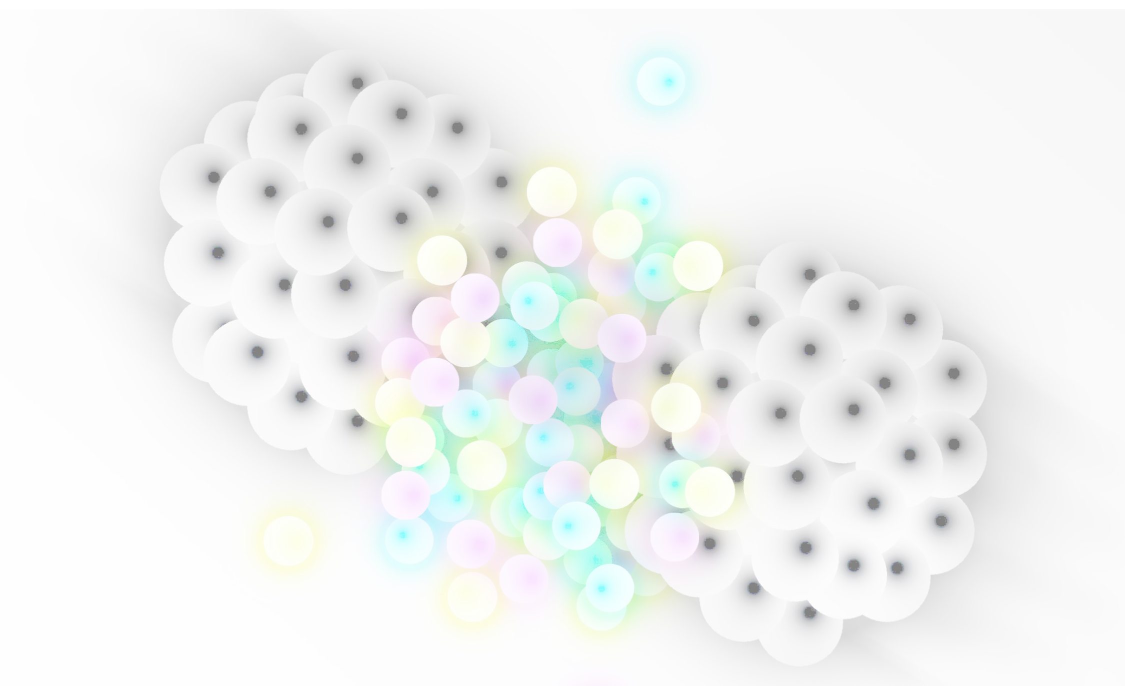

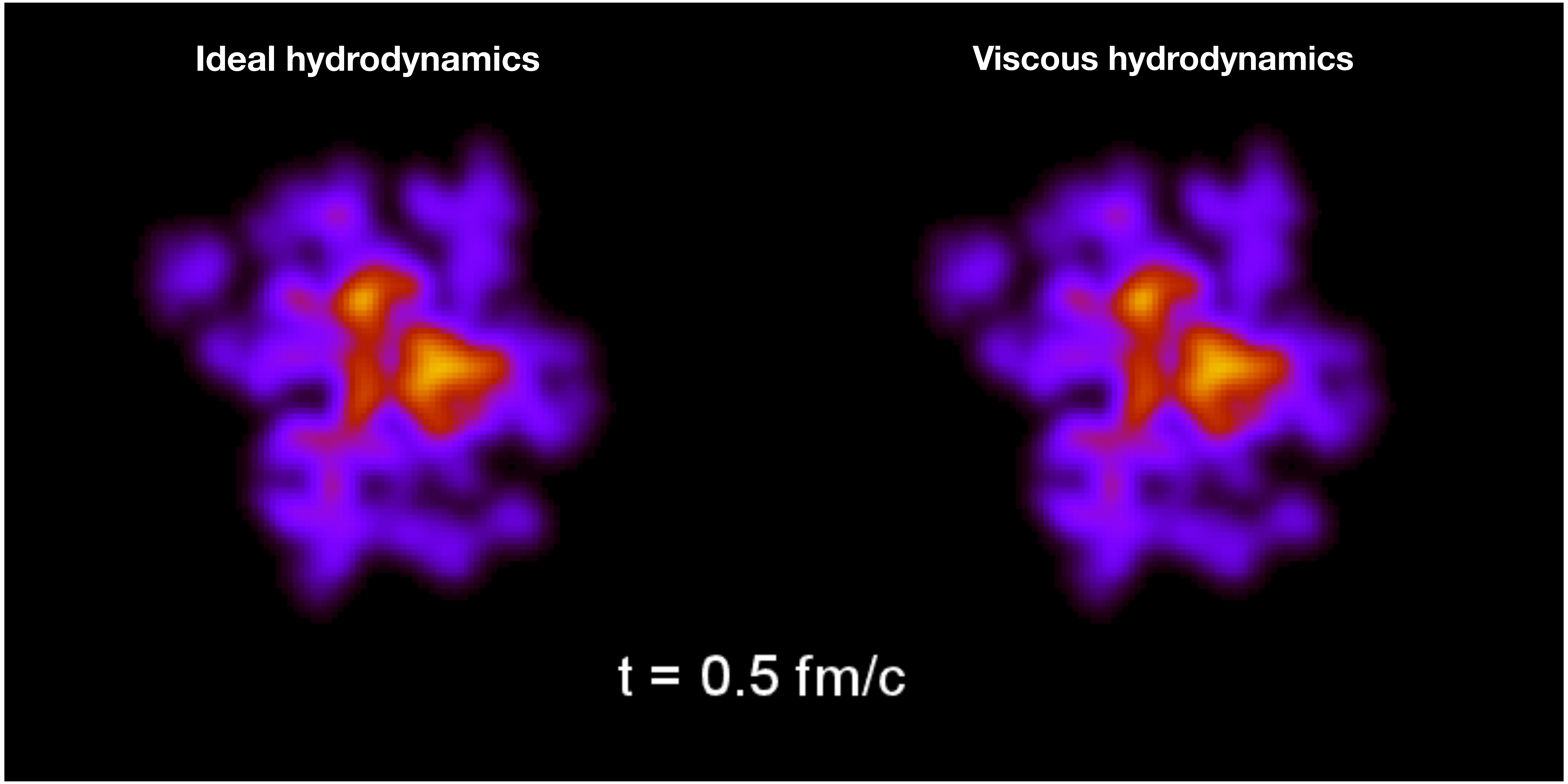

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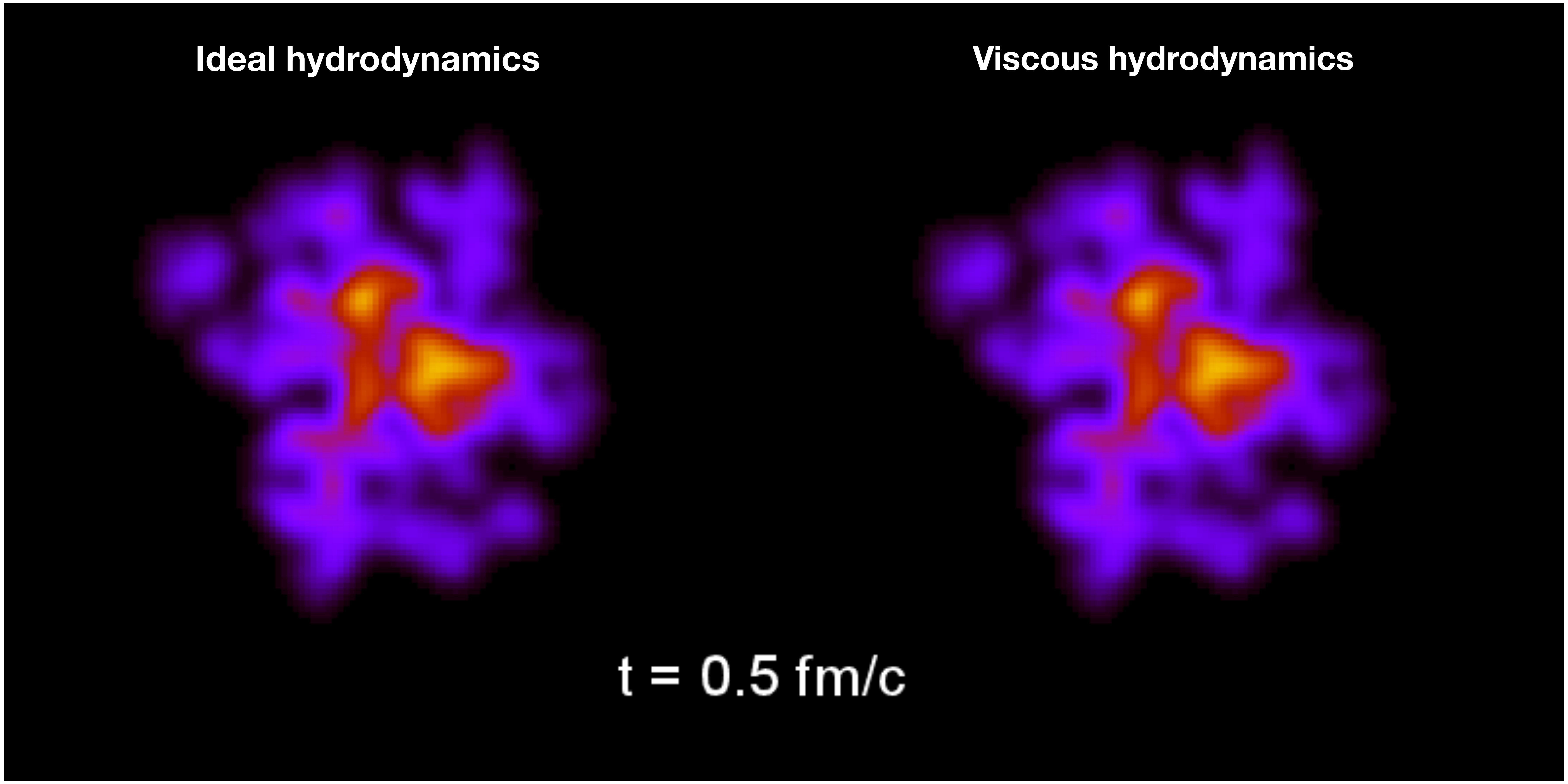
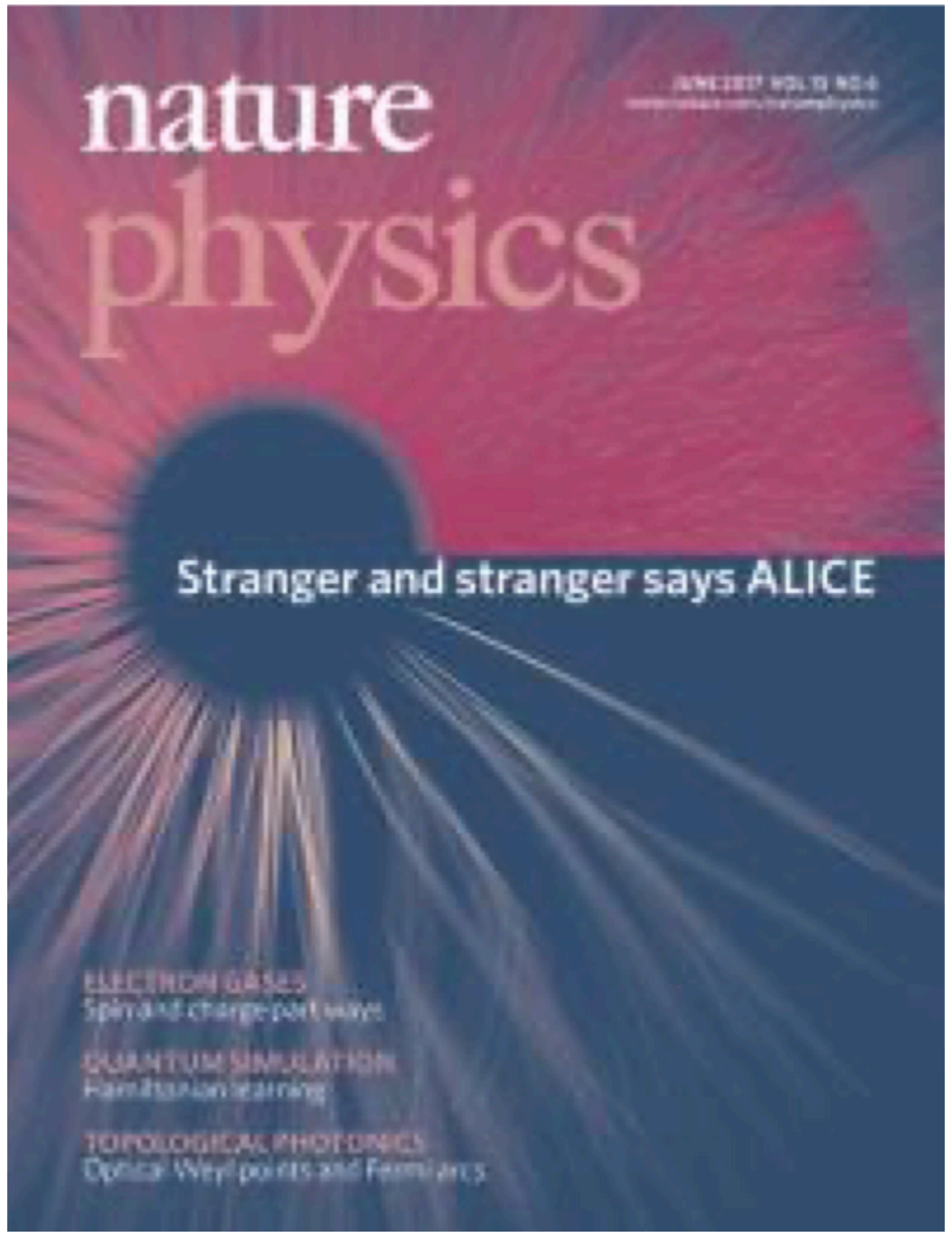
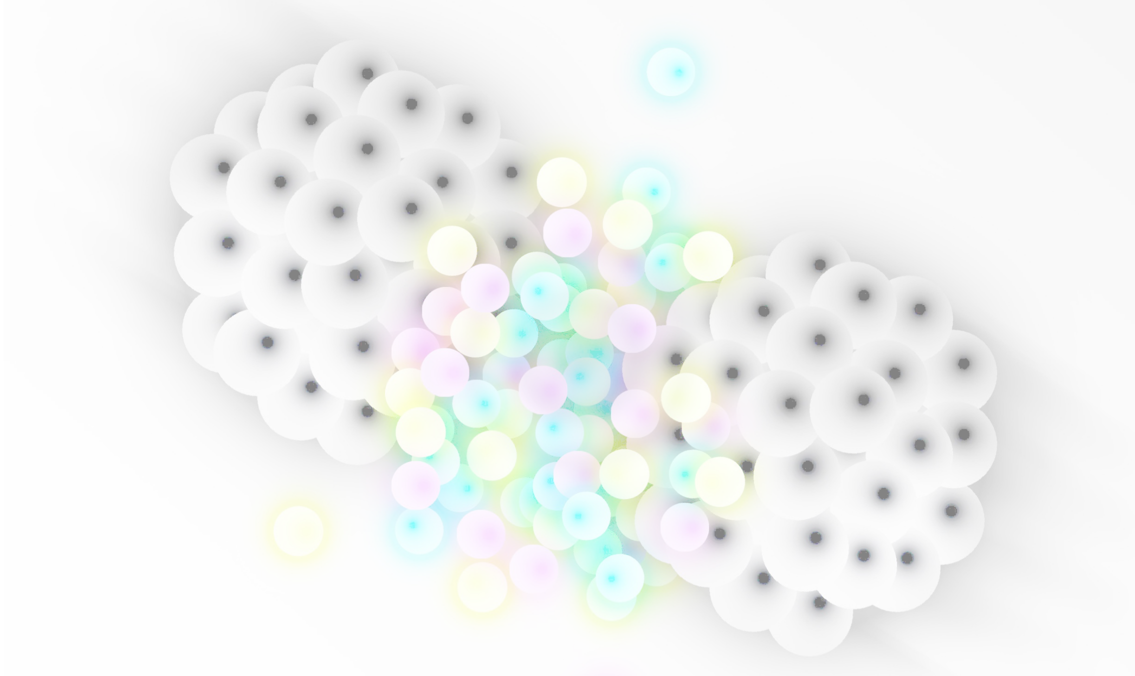


QGP properties:

Most perfect liquid:
$\eta/s \sim 0.8$



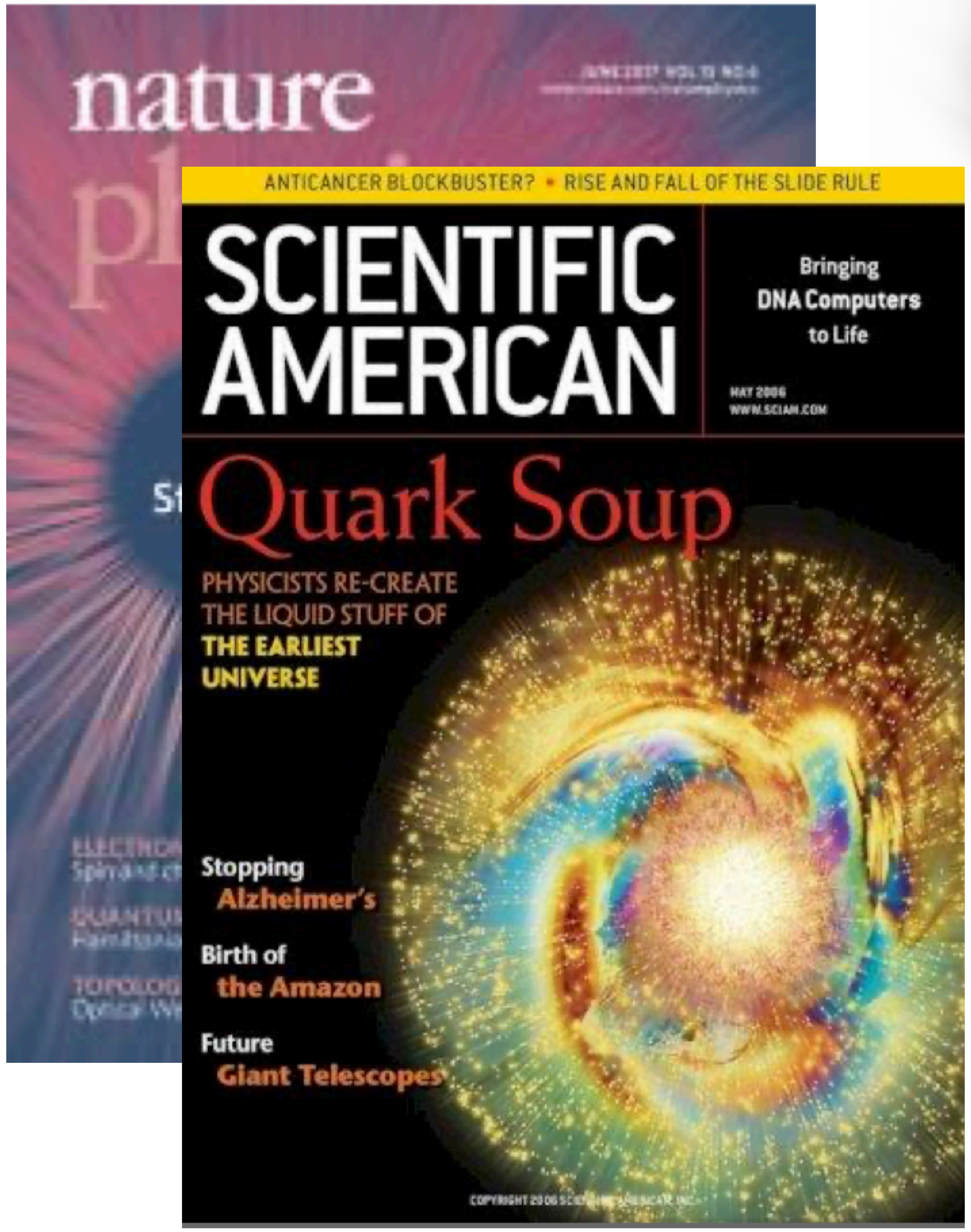


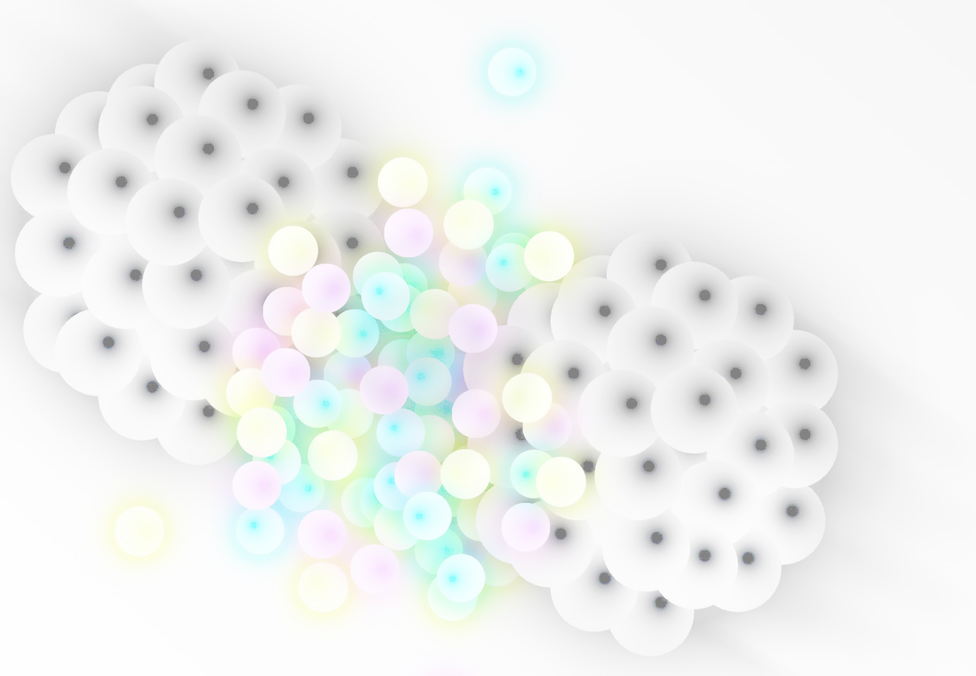
QGP properties:

Most perfect liquid:
η/s ~0.8

Hottest liquid:
10^{12}K

(100,000 x temperature of the Sun core)





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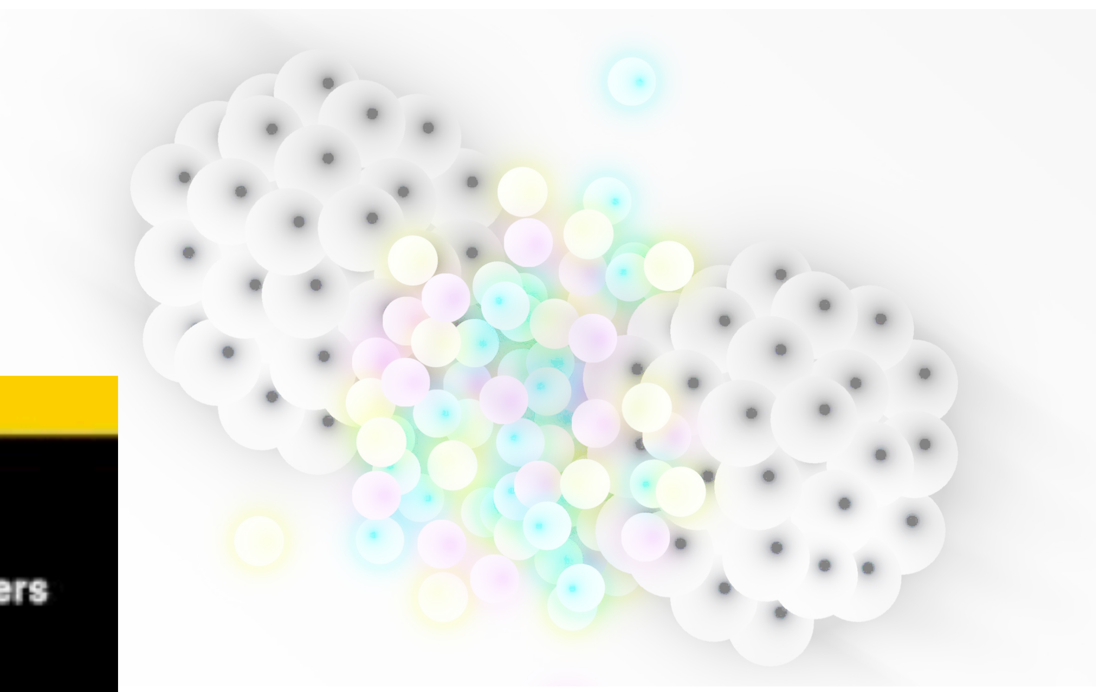

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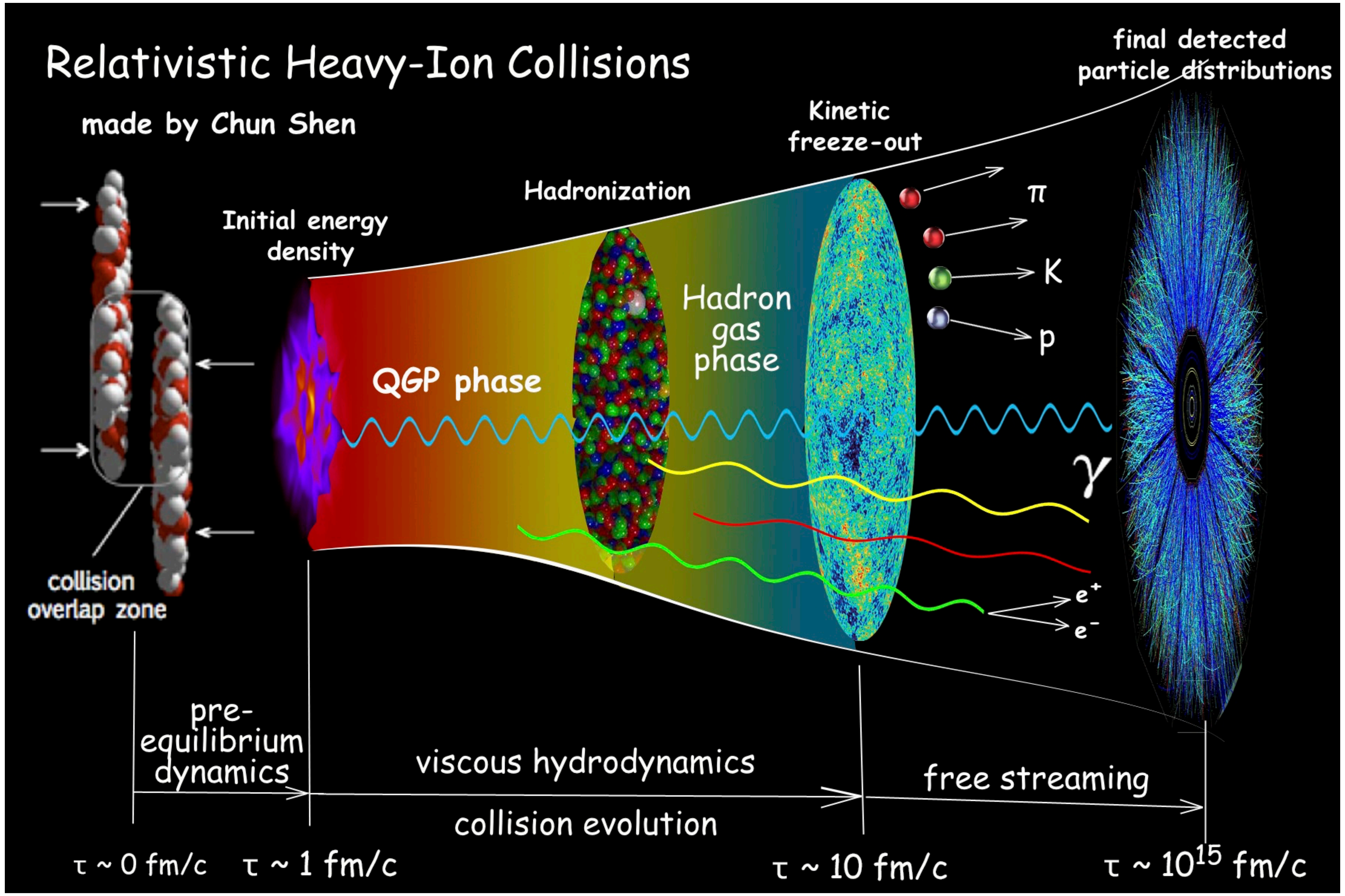
(100,000 x temperature of the Sun core)

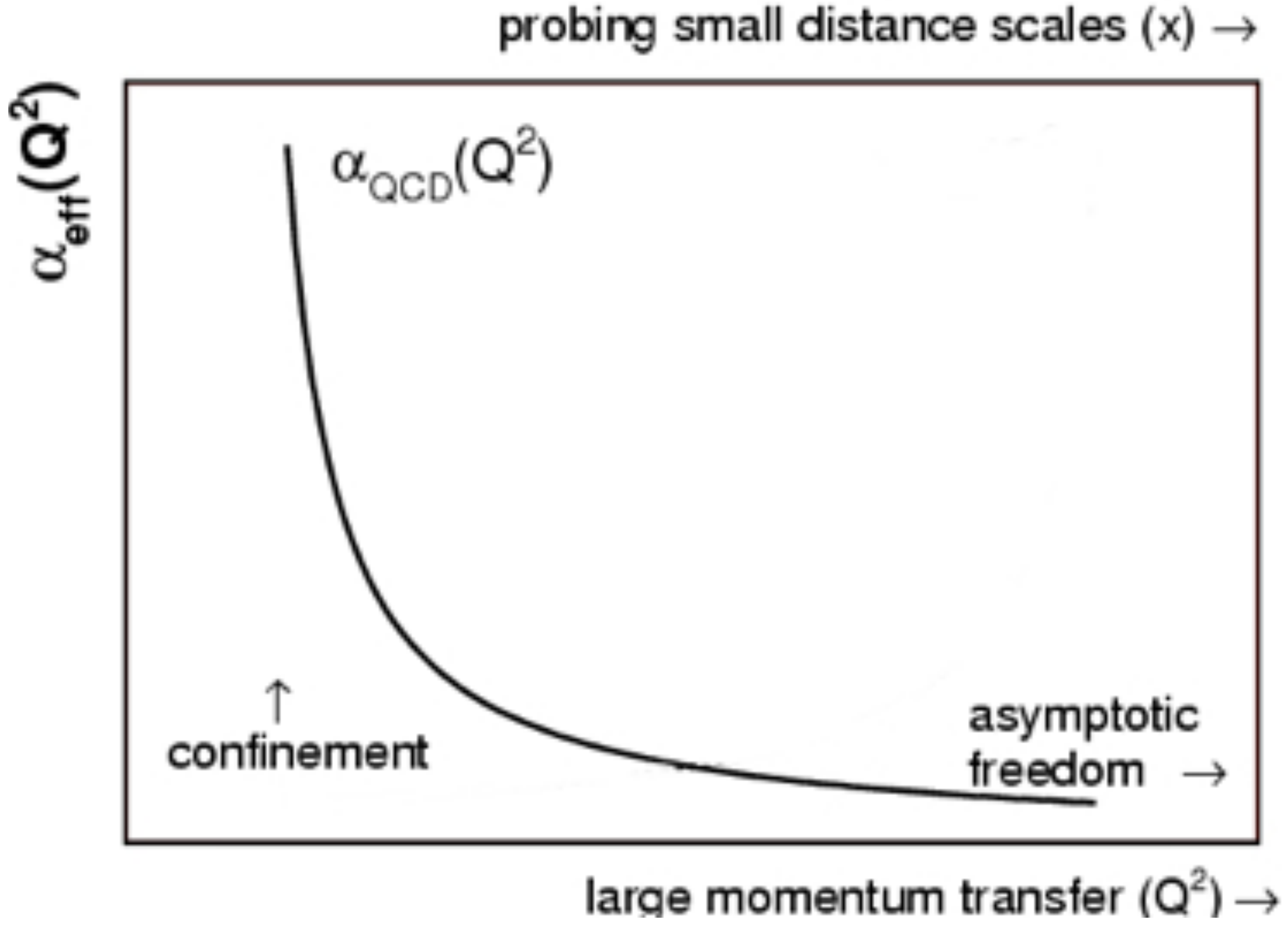
Smallest liquid:
~yoctosegundos (10^{-23})

Most vortical liquid:
$\omega \sim 10^{22}$/s

(Atmosphere: $\omega \sim 10^{-4}$/s
Tornado: $\omega \sim 10^{-1}$/s)

How to probe the QGP @ lab (v2)





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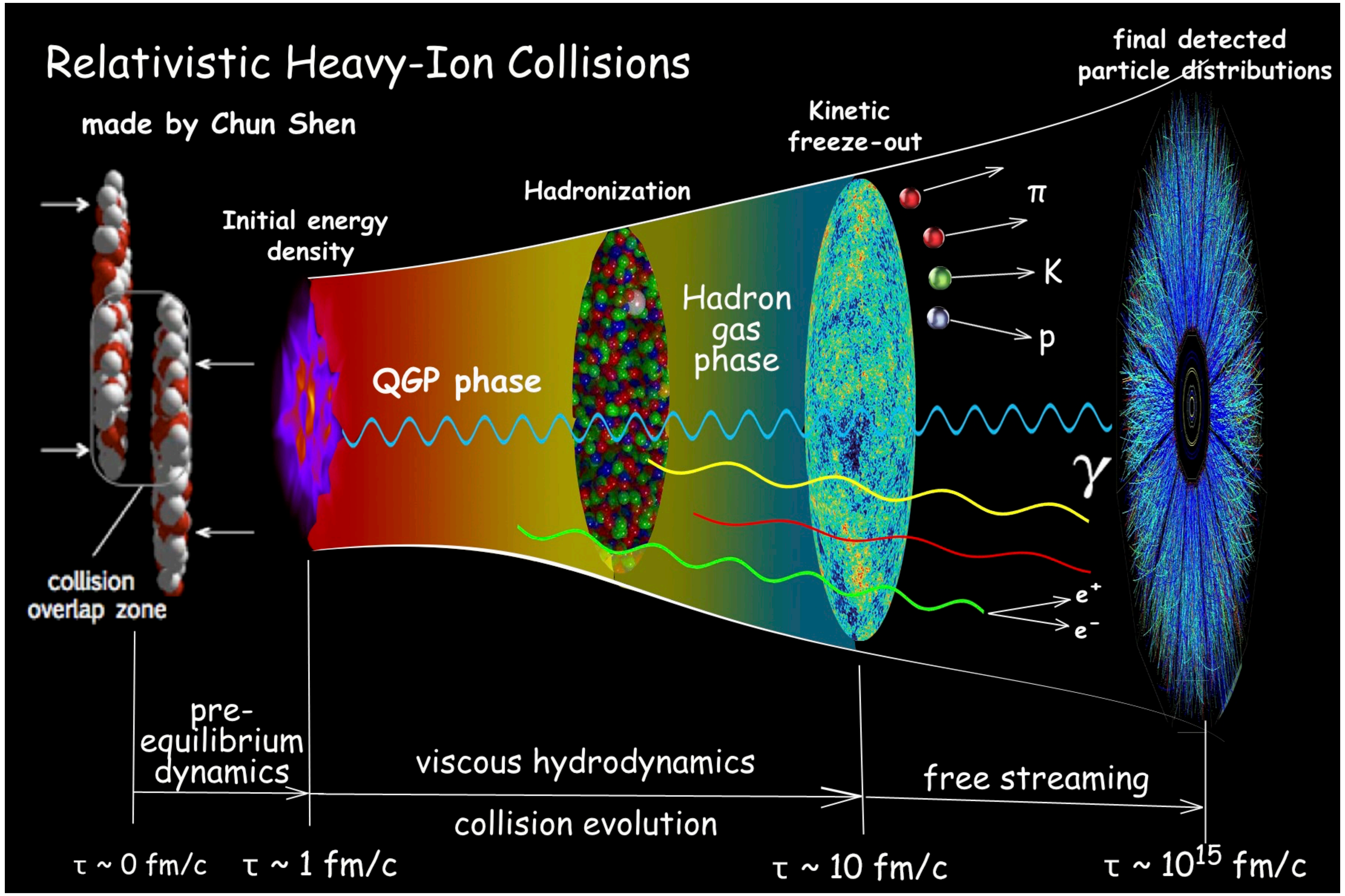

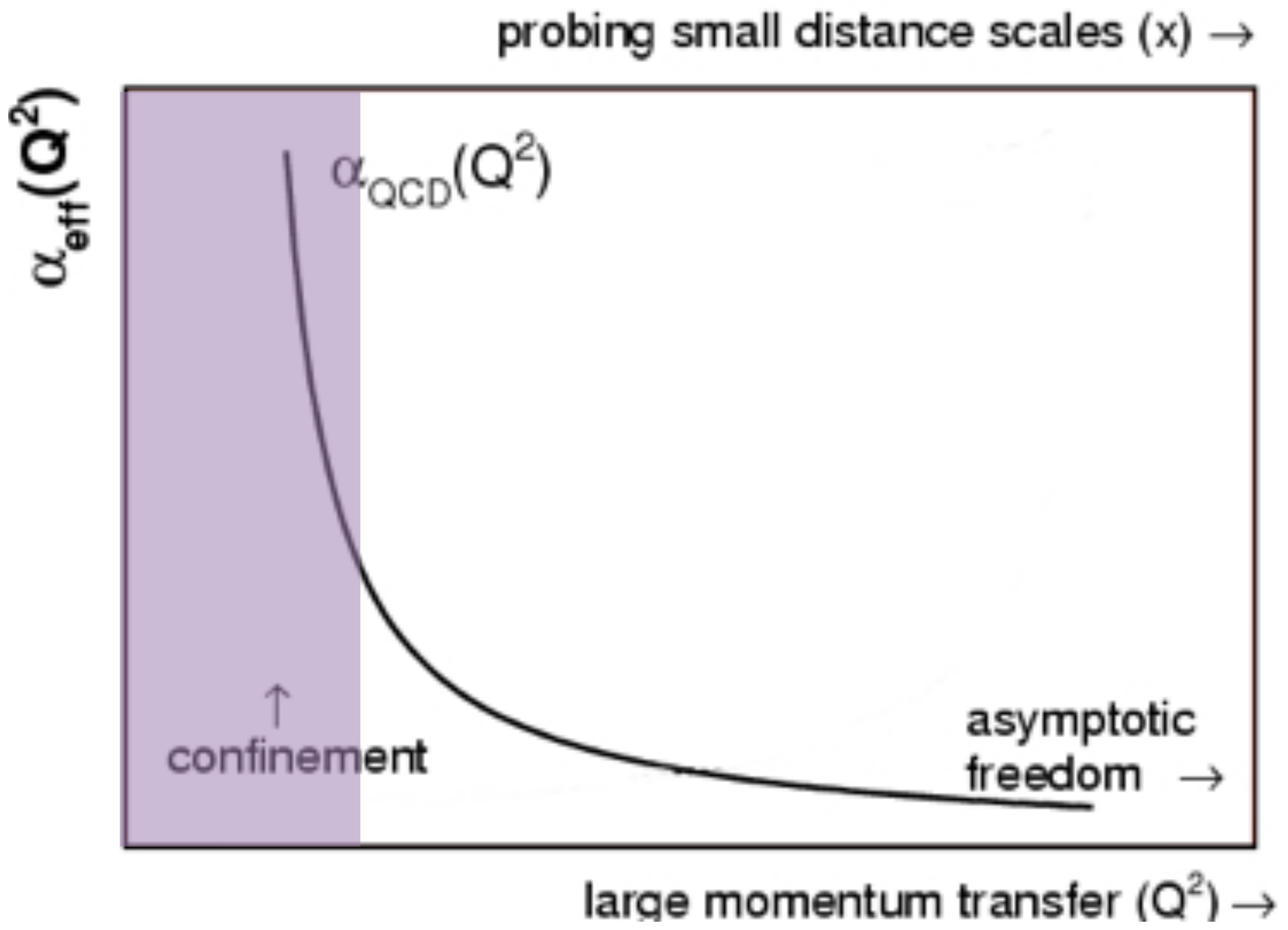

Soft probes

non-pQCD

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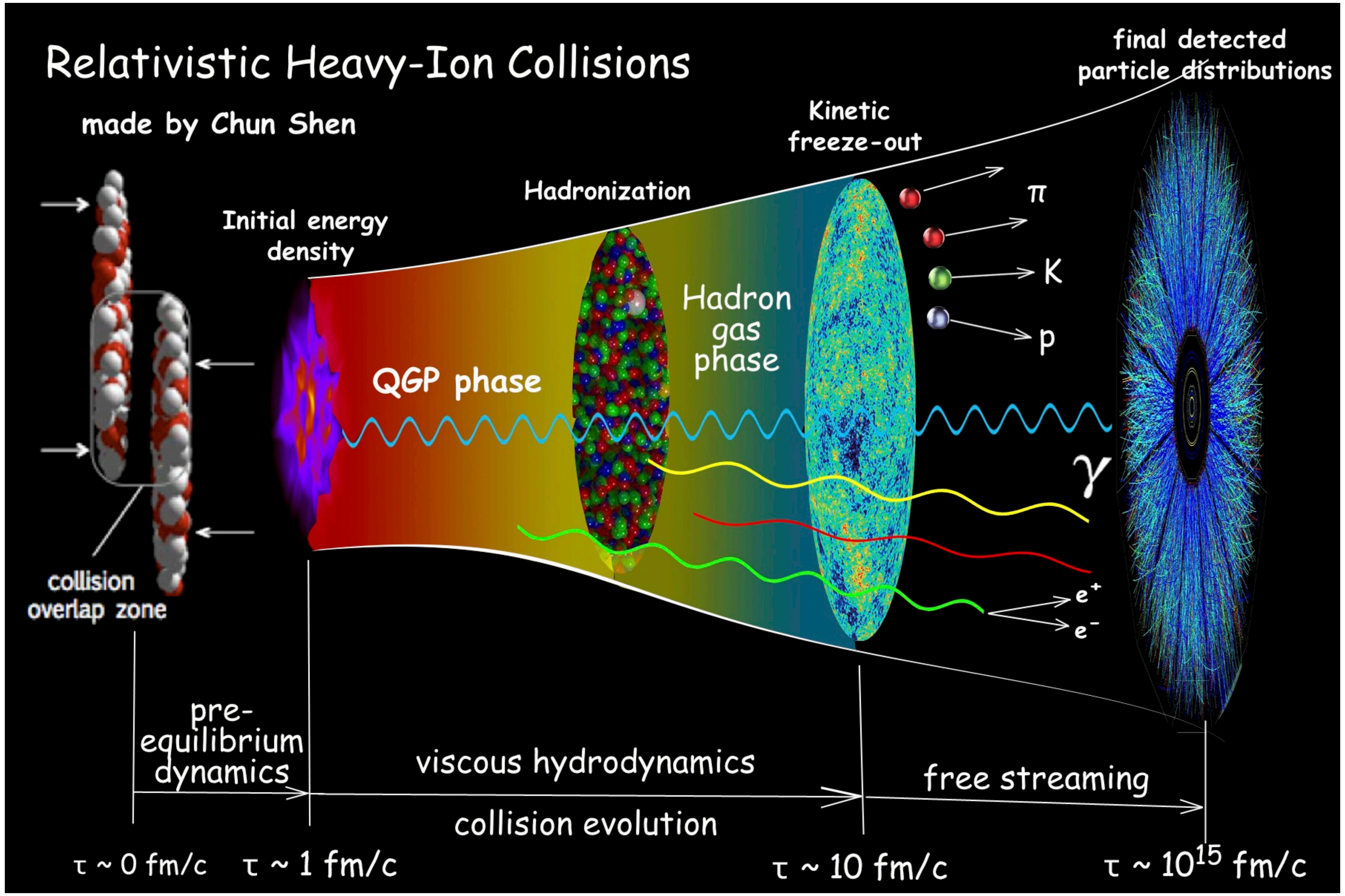

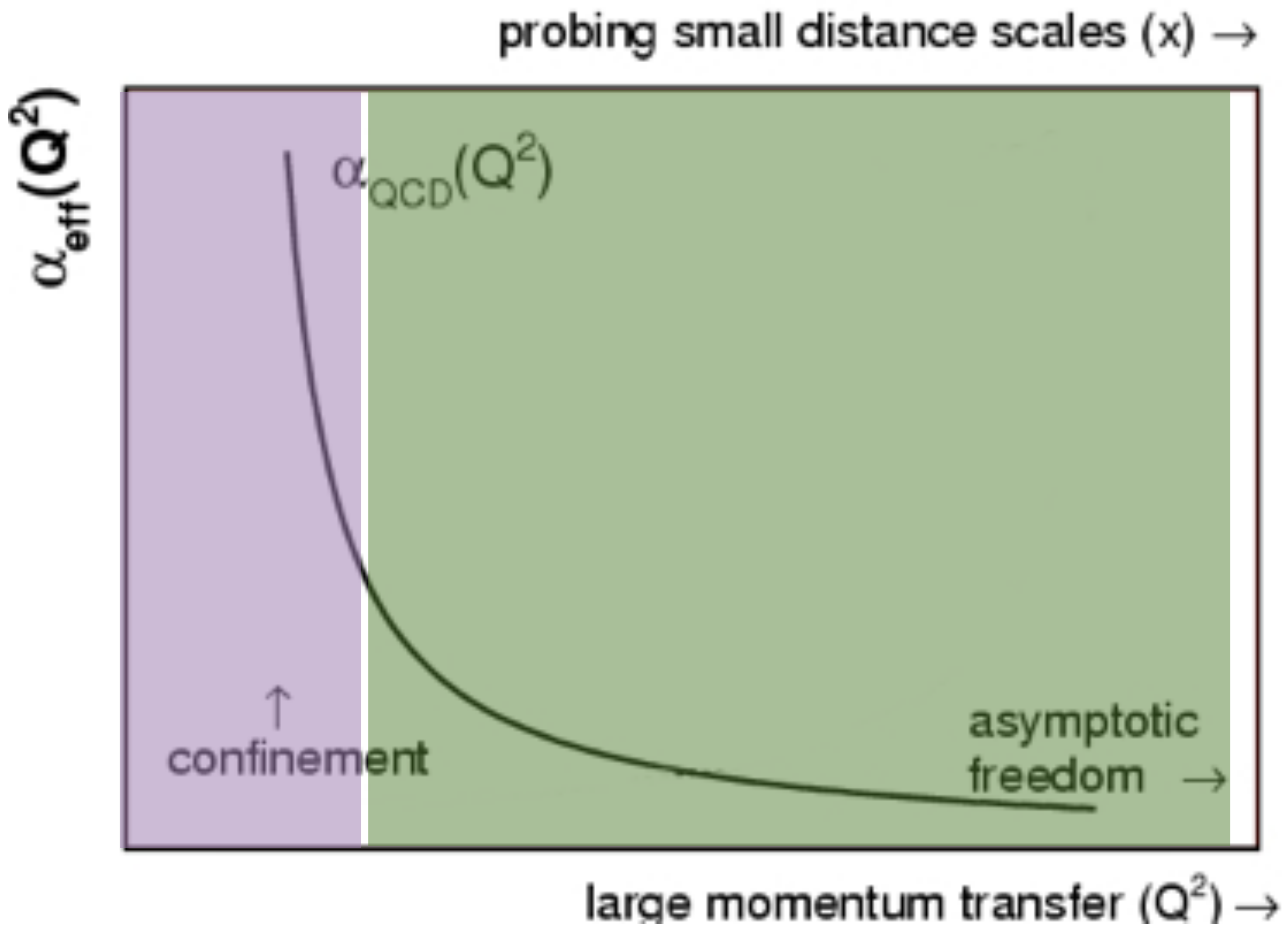

Soft probes

non-pQCD

Hard probes

pQCD

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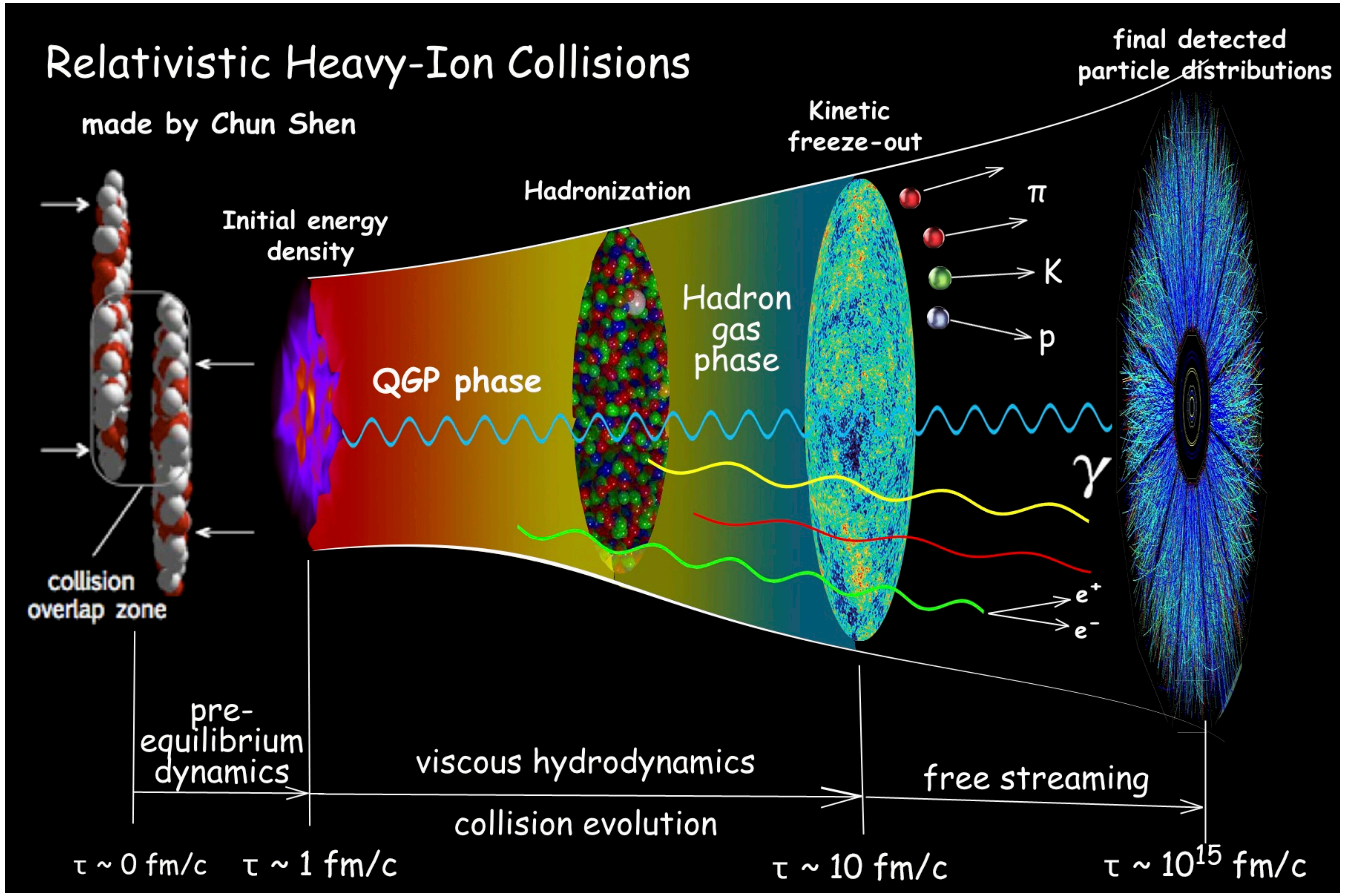
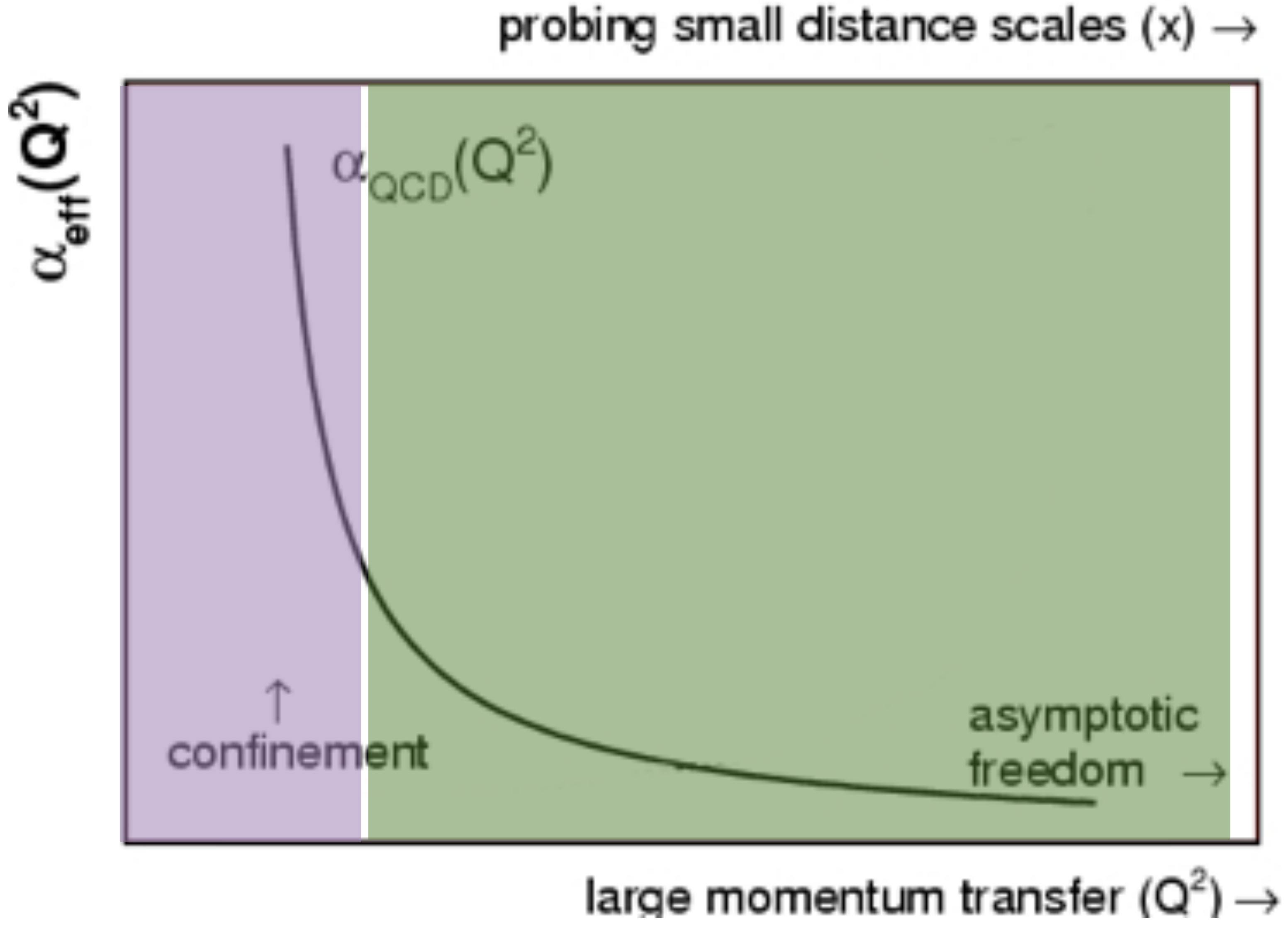


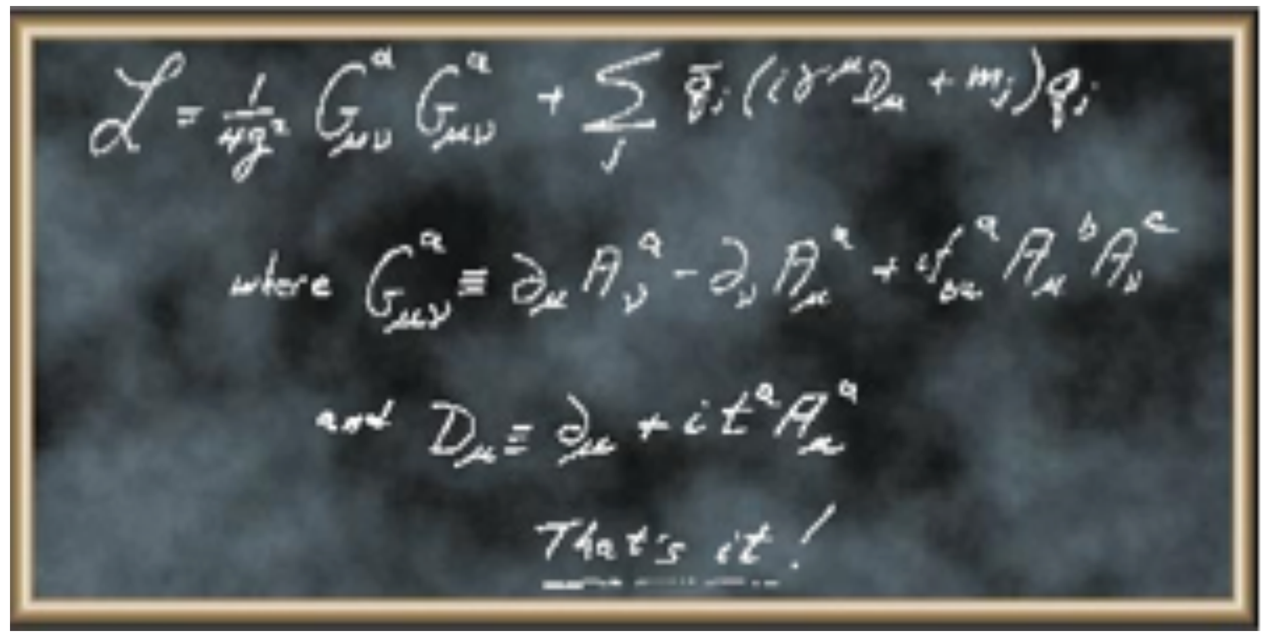


Soft probes

non-pQCD

Hard probes

pQCD



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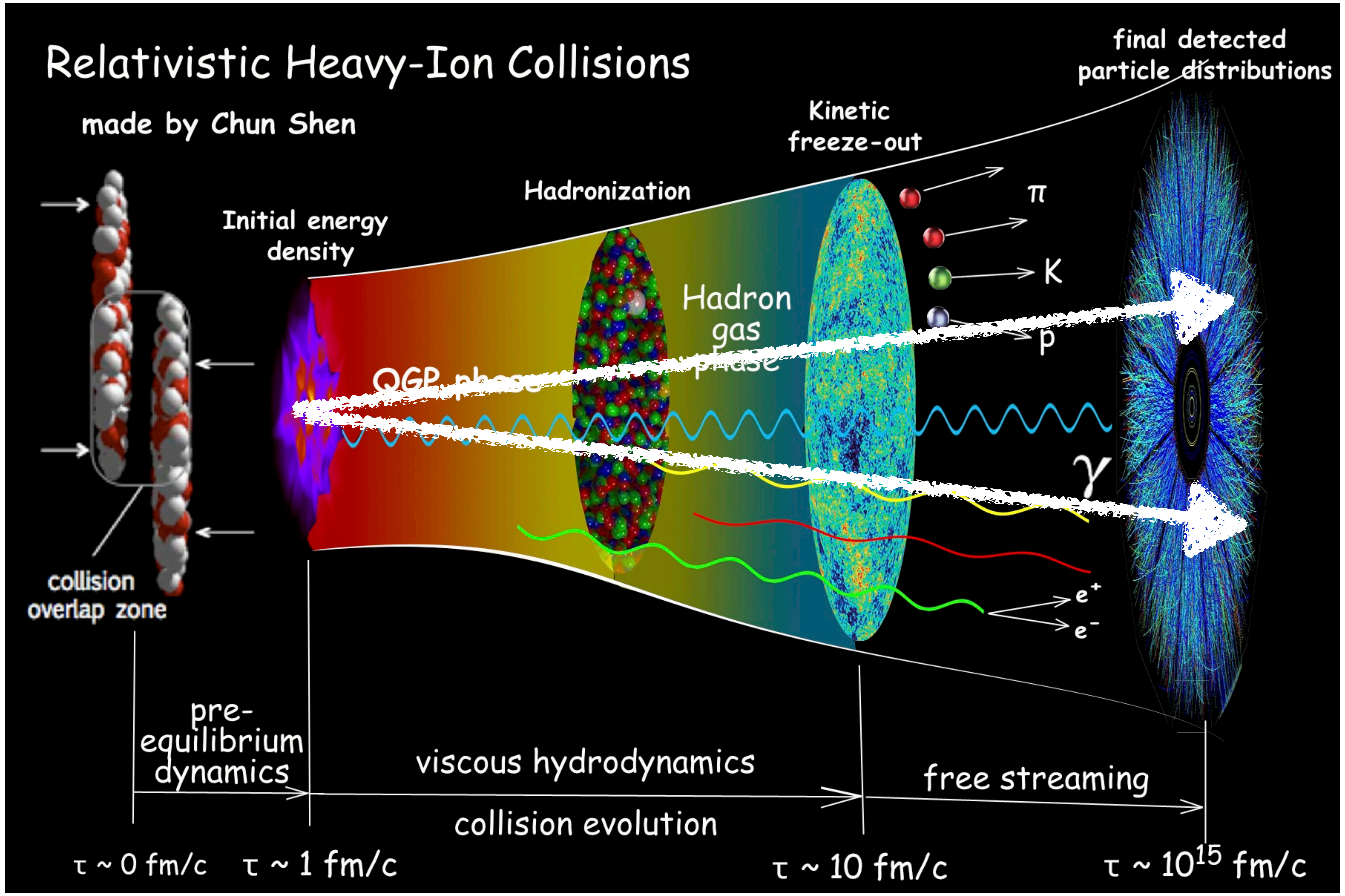

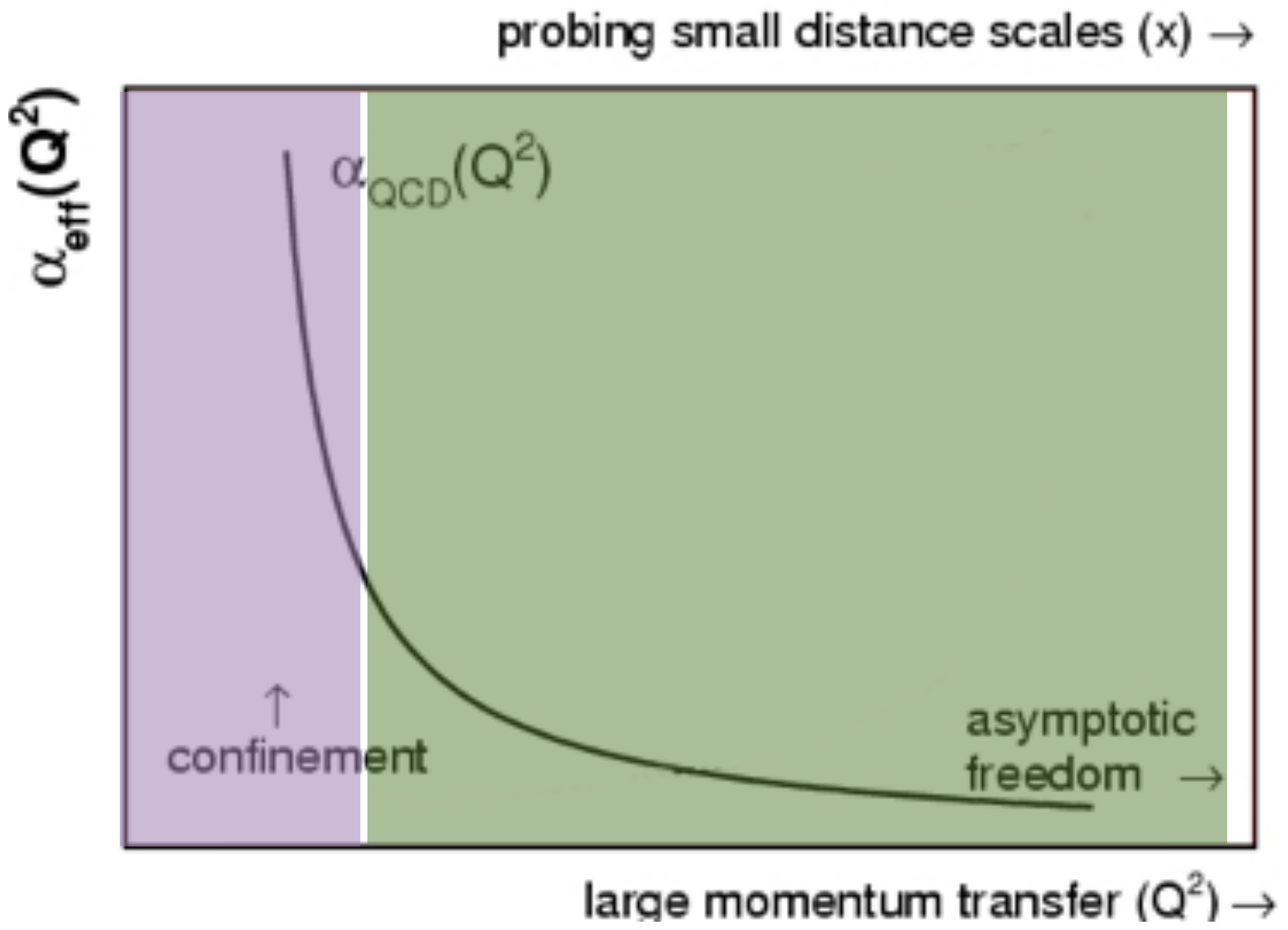

Soft probes

non-pQCD

Hard probes

pQCD

Caveat: need to rely on self-generated probes

How to probe the QGP @ lab (v2)

- Using internal probes that can be self-calibrated:

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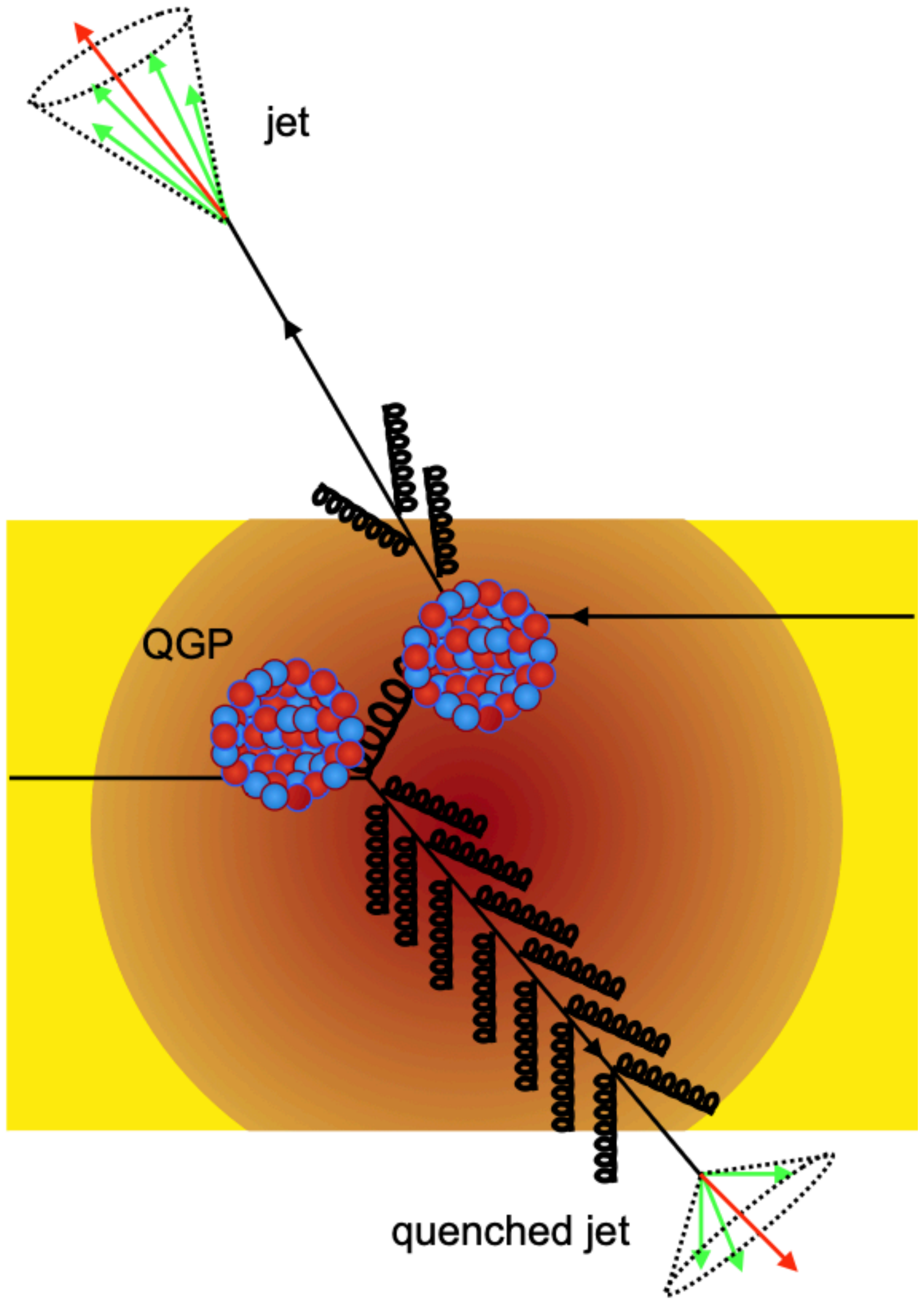
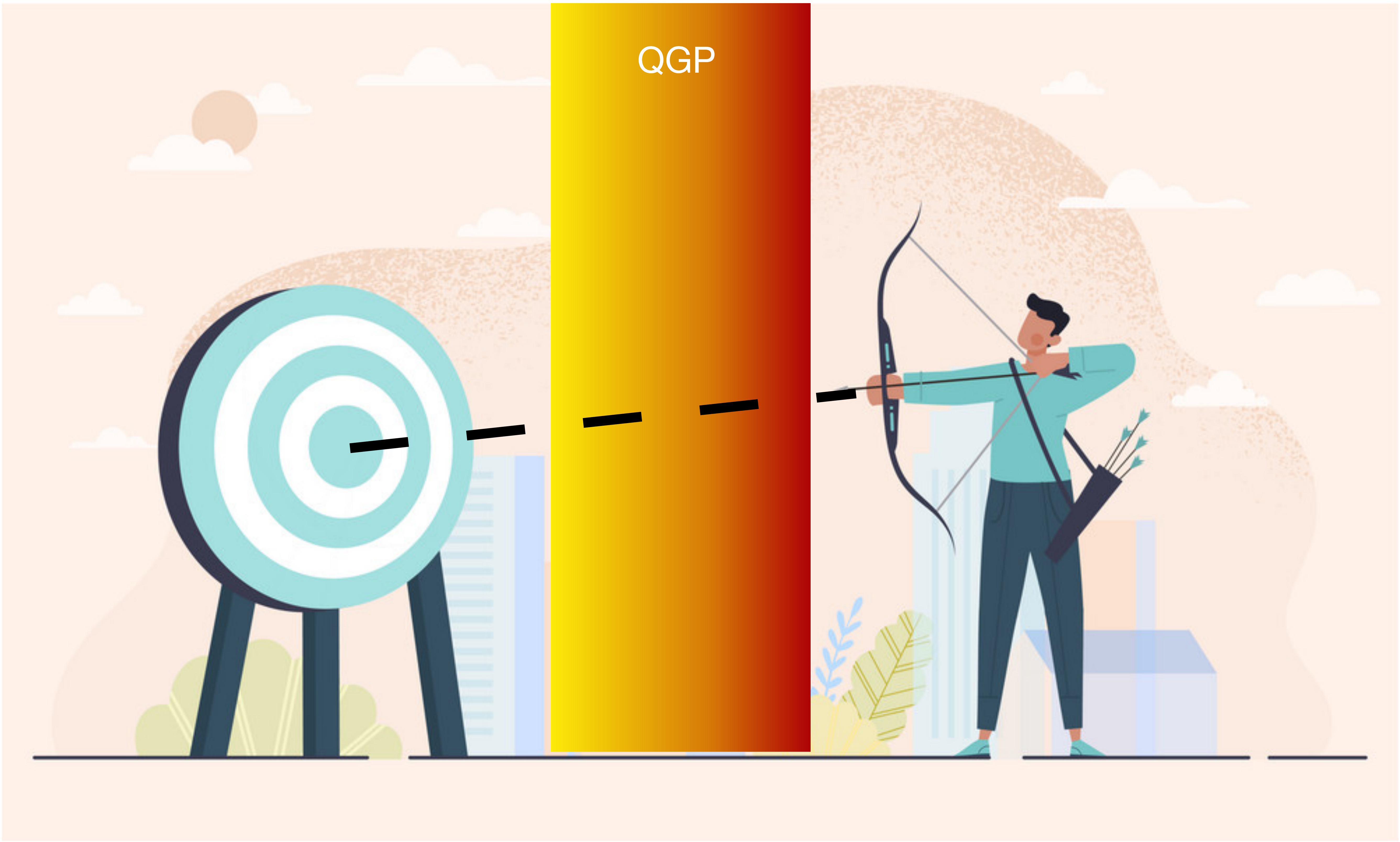
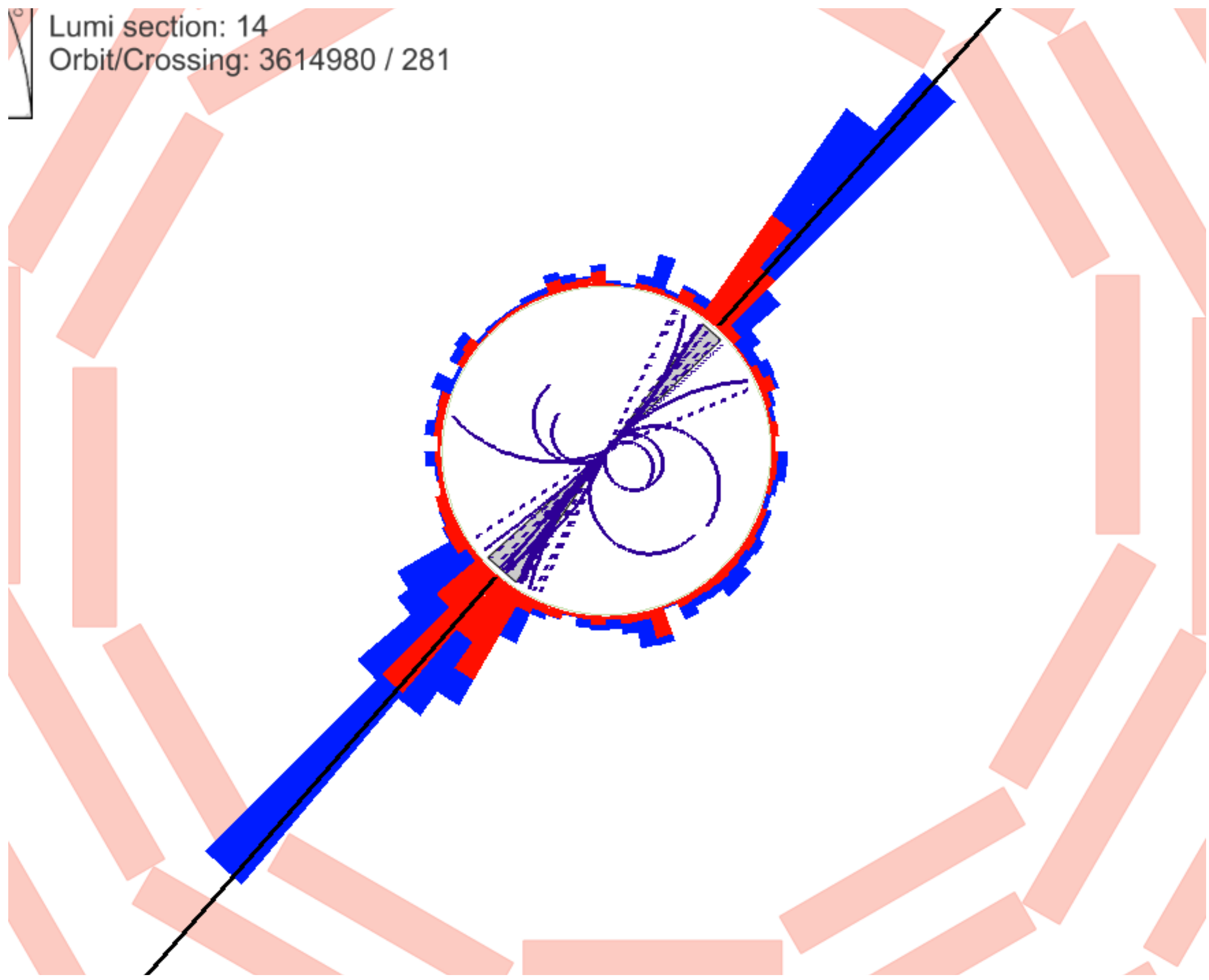


Jets in PbPb



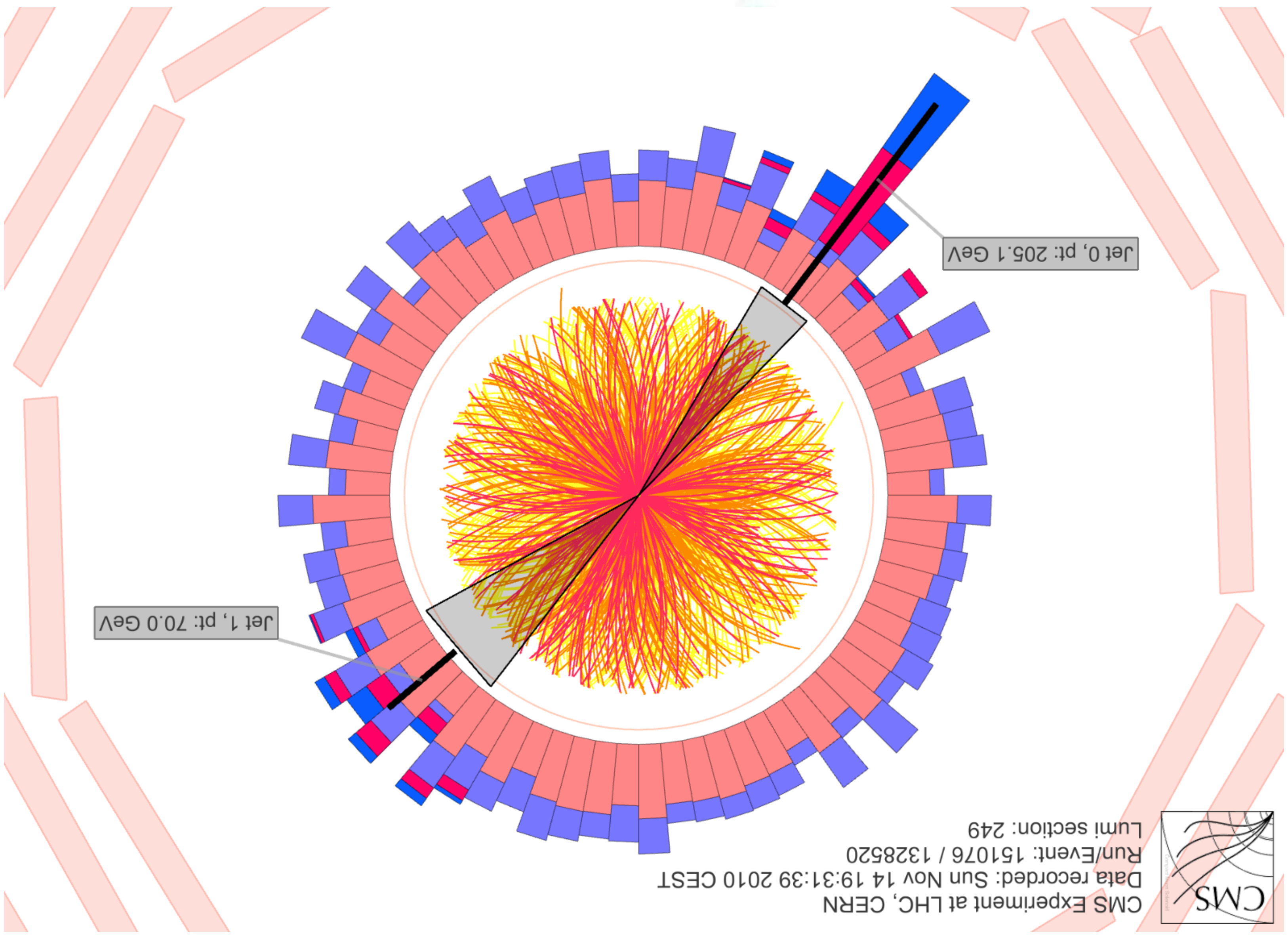
Hard Probes

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



Example: jets in pp

(well known and theoretically understood)



Example: jets in PbPb

(modifications related to the QGP microscopic properties)

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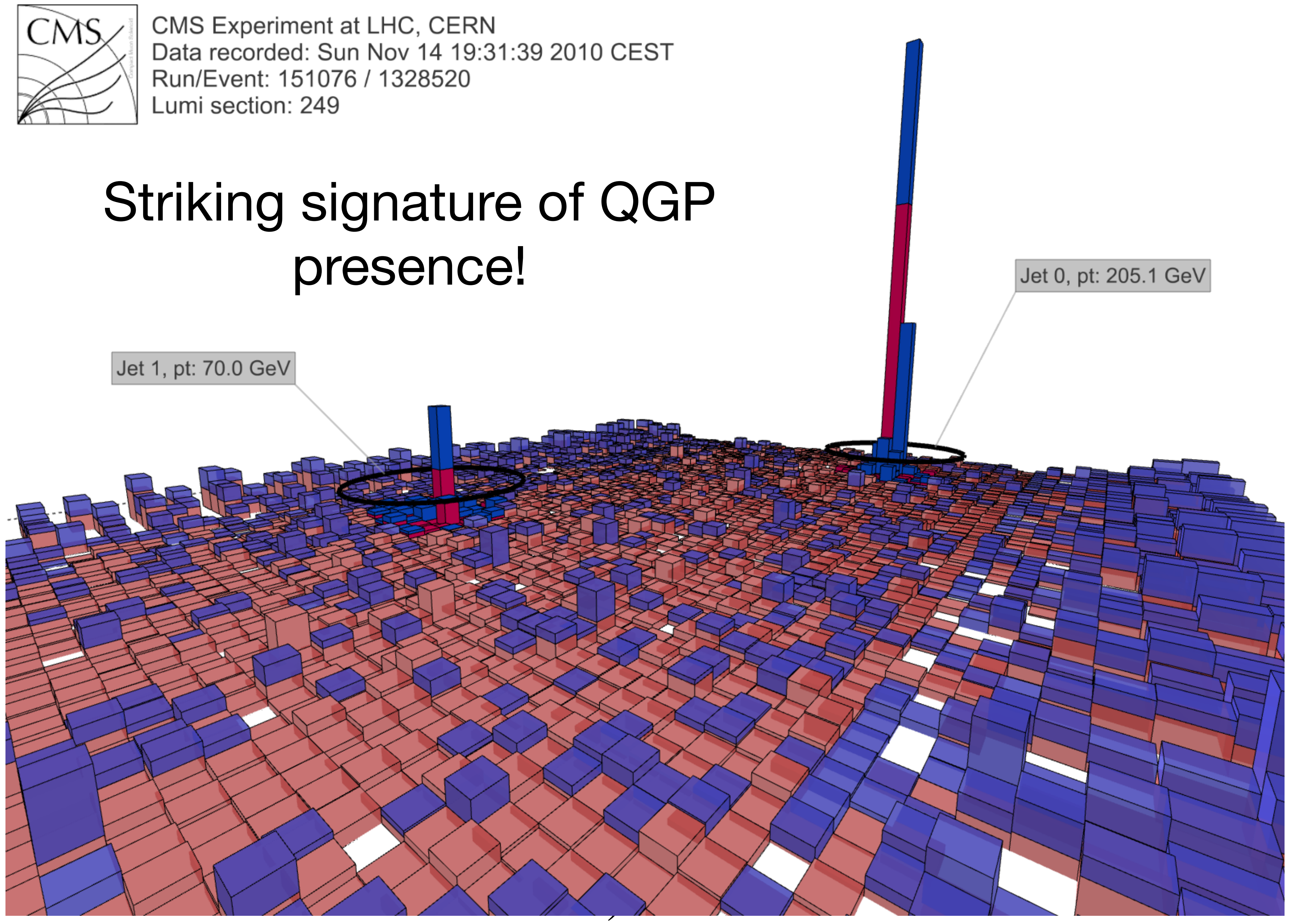
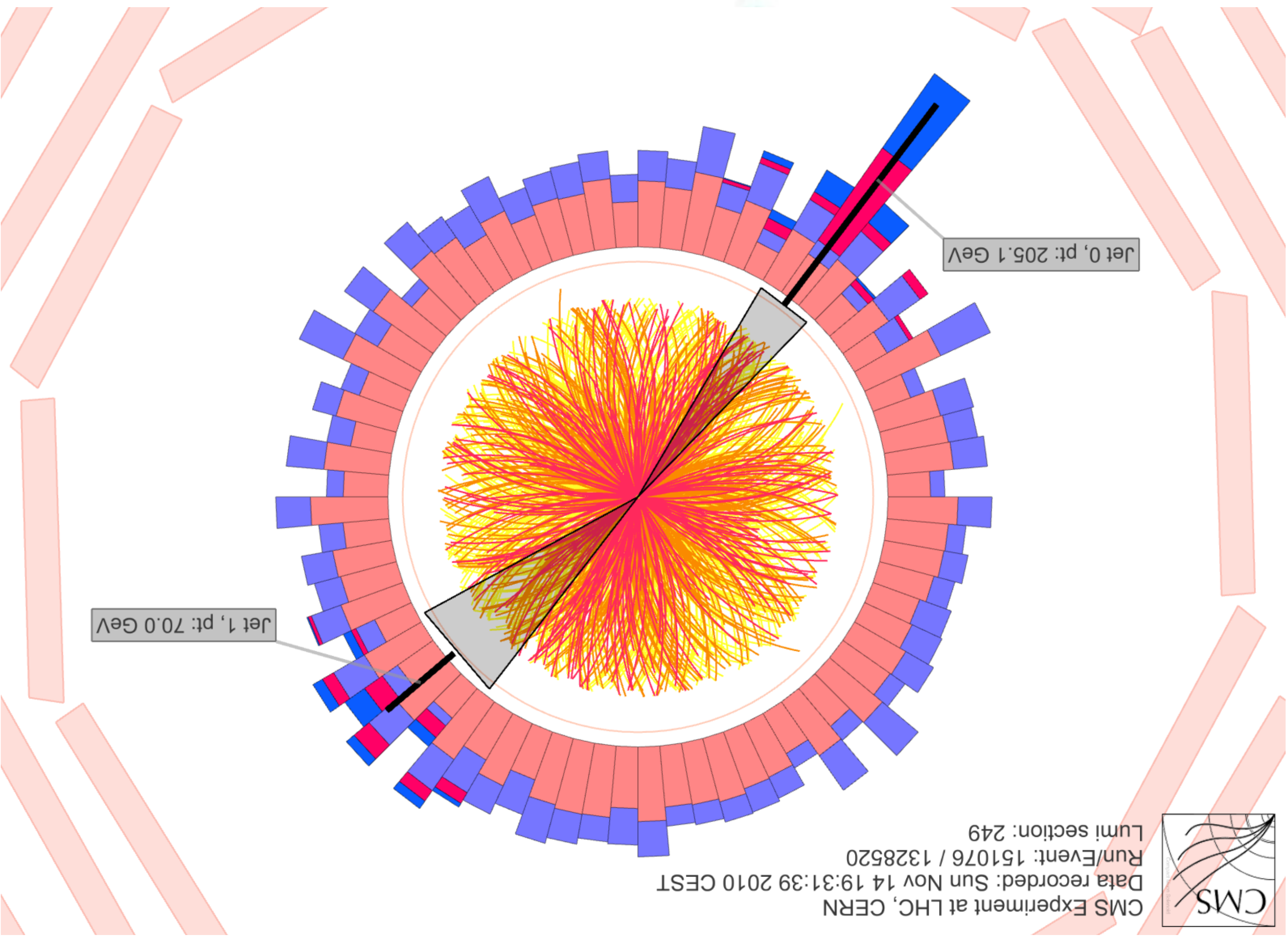


Striking signature of QGP presence!



Example: jets in PbPb

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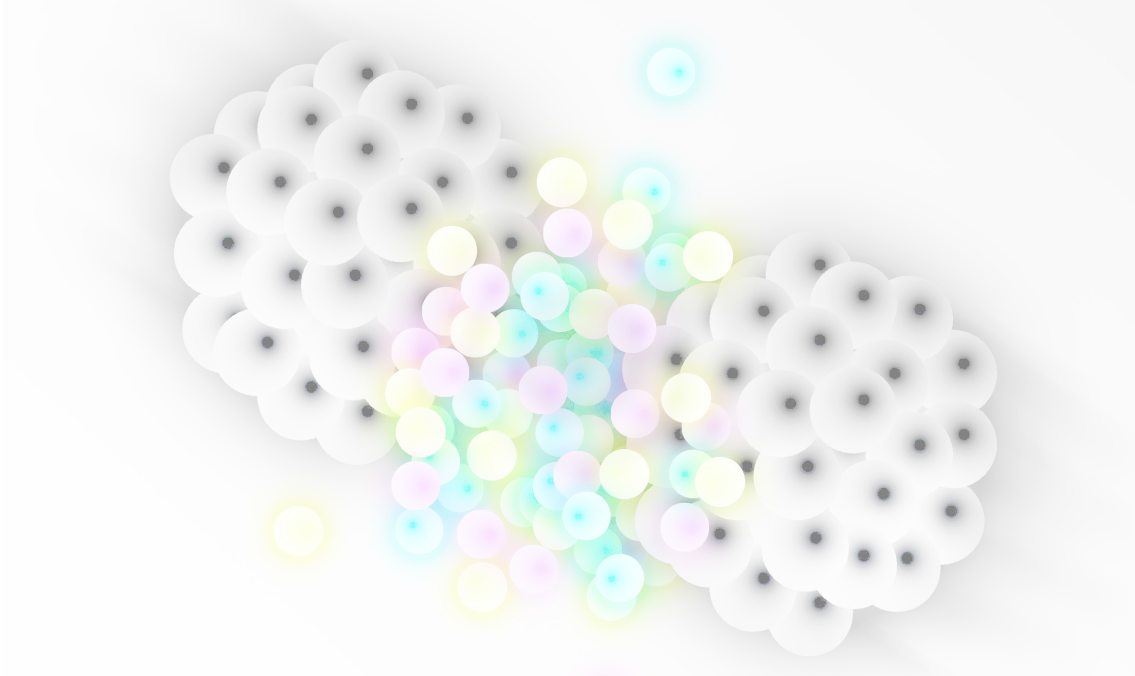
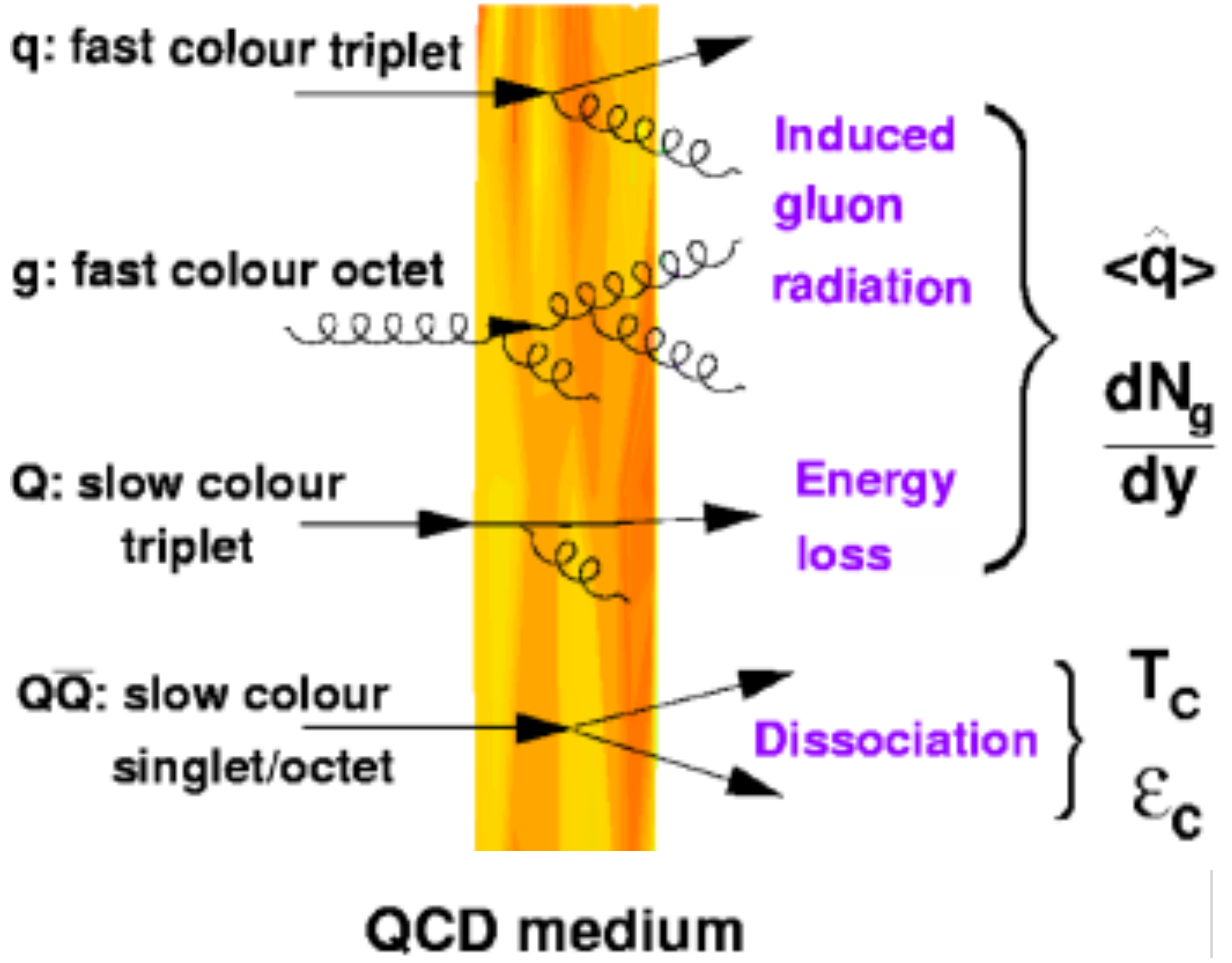


- Rare processes of high energy that are produced within the collision (hard scattering) and propagate through the QGP:
  - High momentum coloured objects:
    - Single particle measurements (B-meson, quarkonia,…)
    - Jets (Inclusive jets, b-initiated jets, …)



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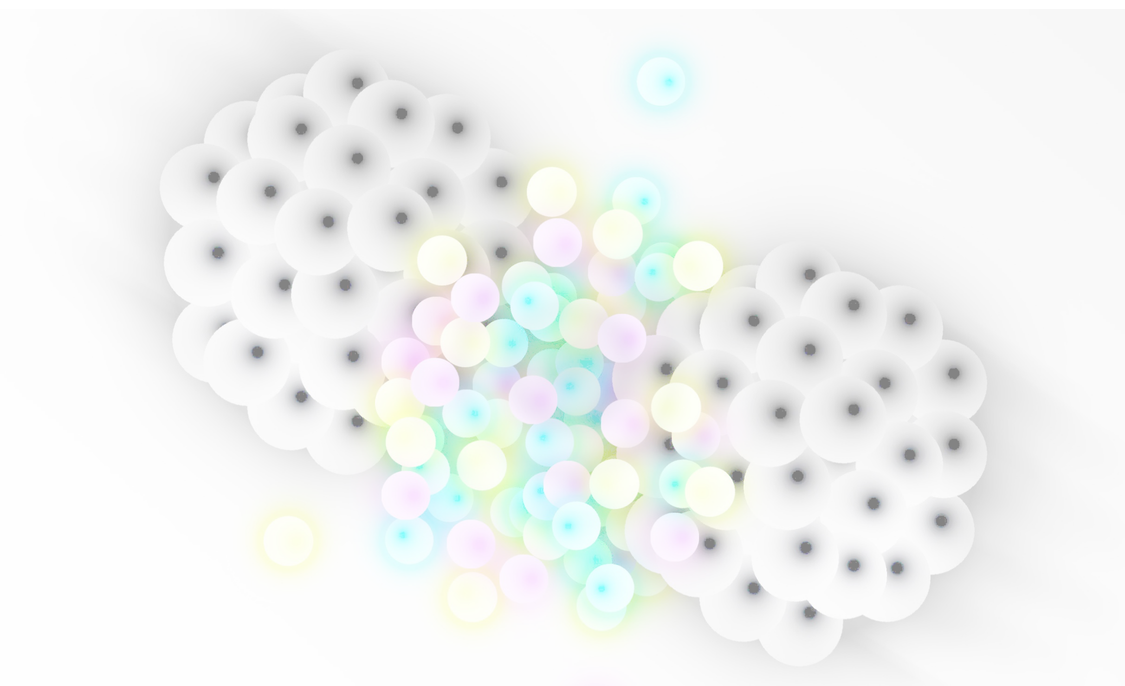

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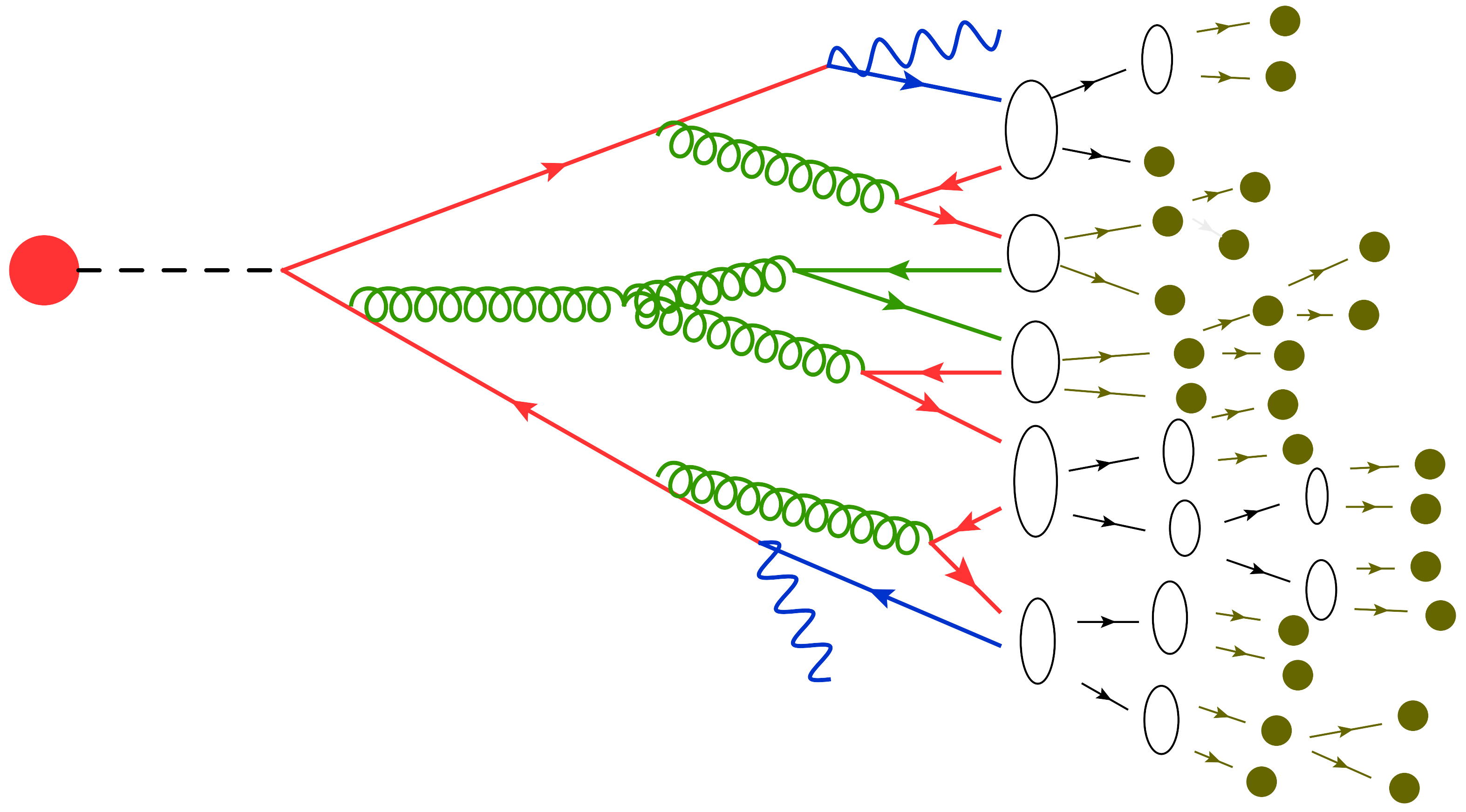

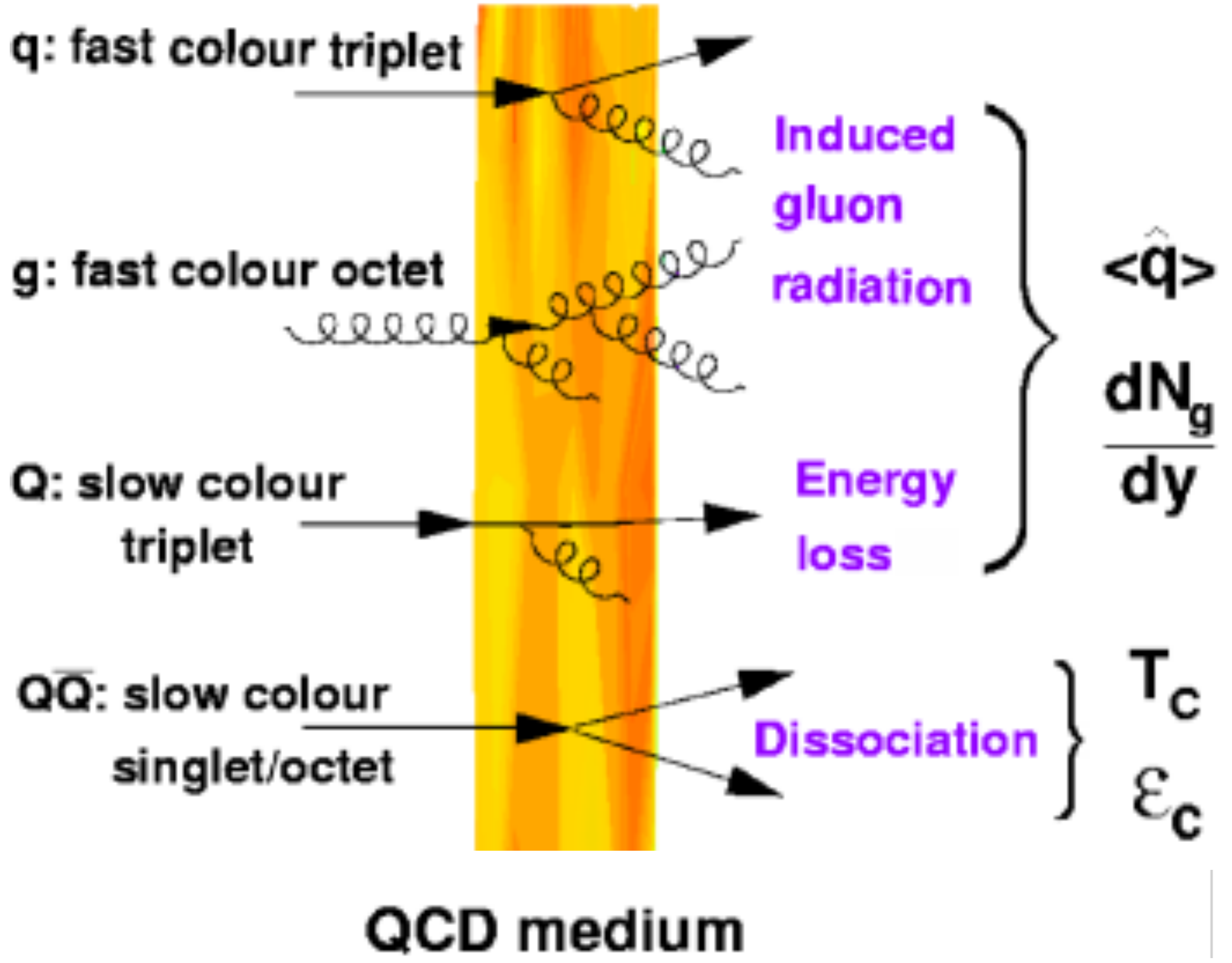

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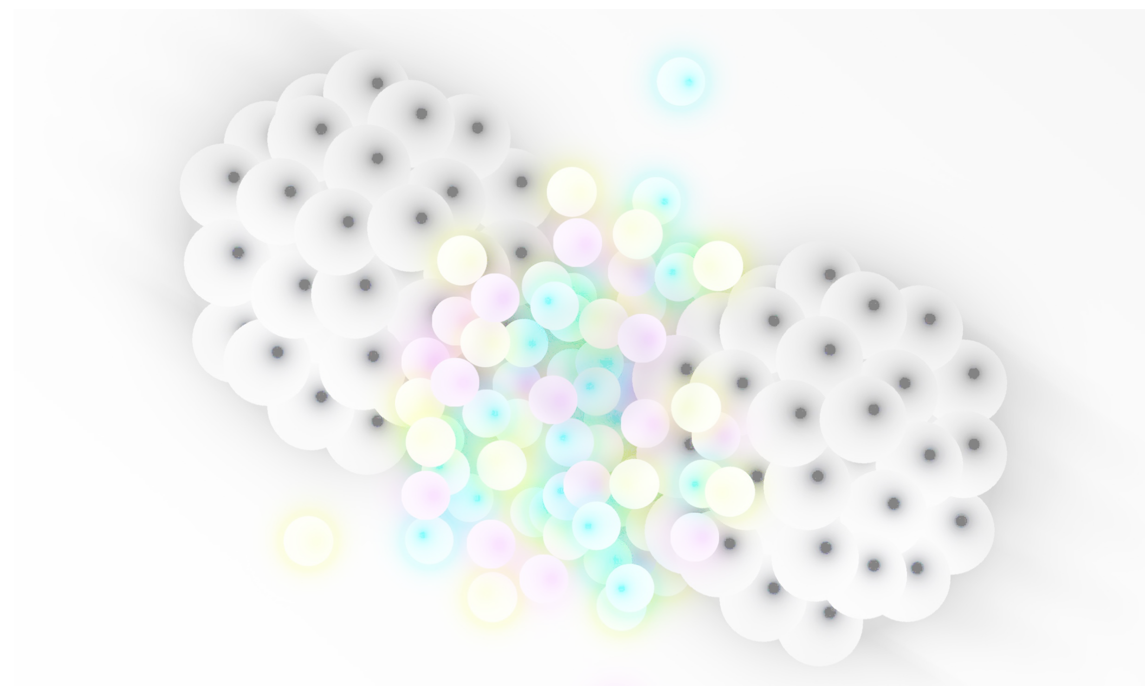

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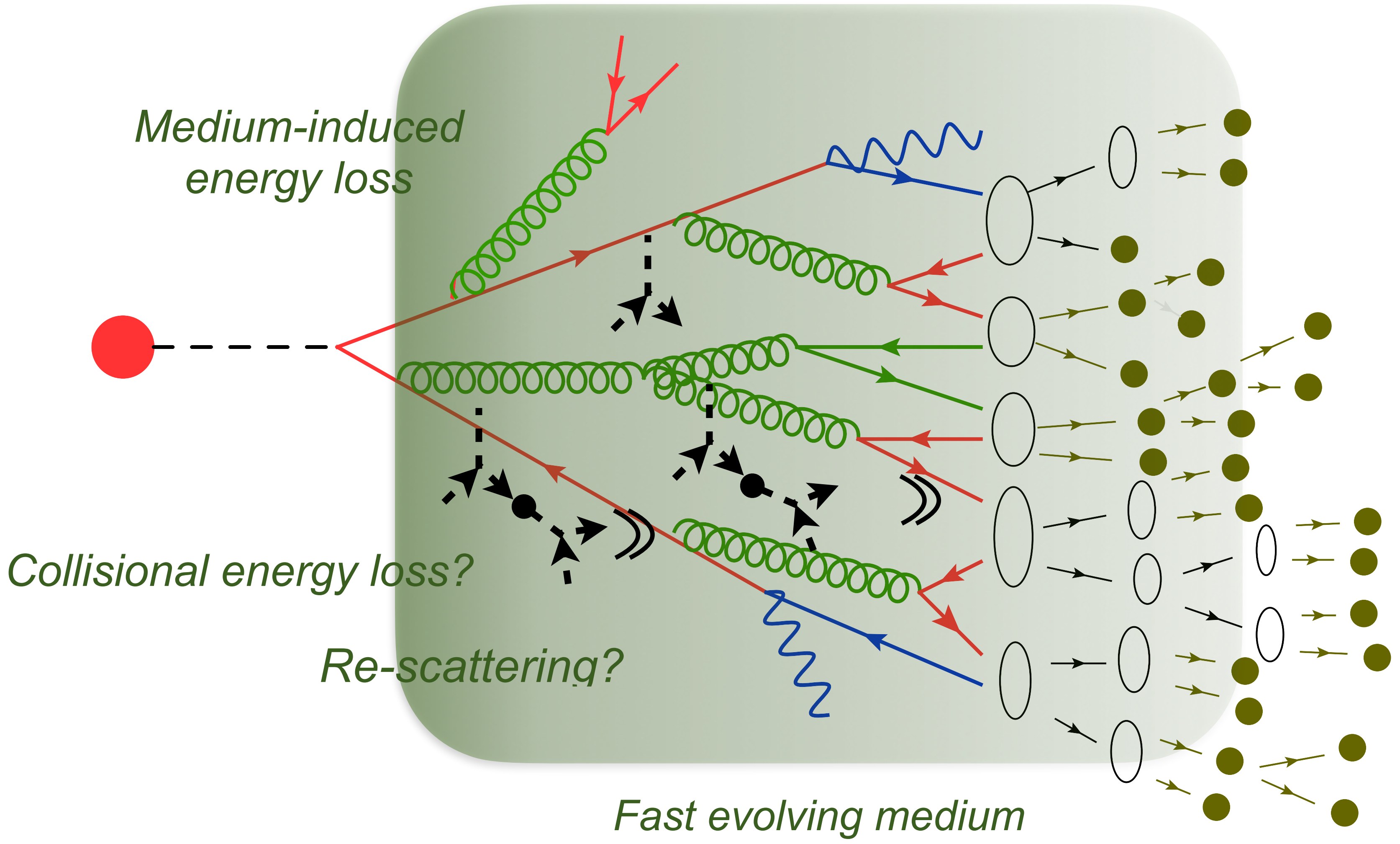

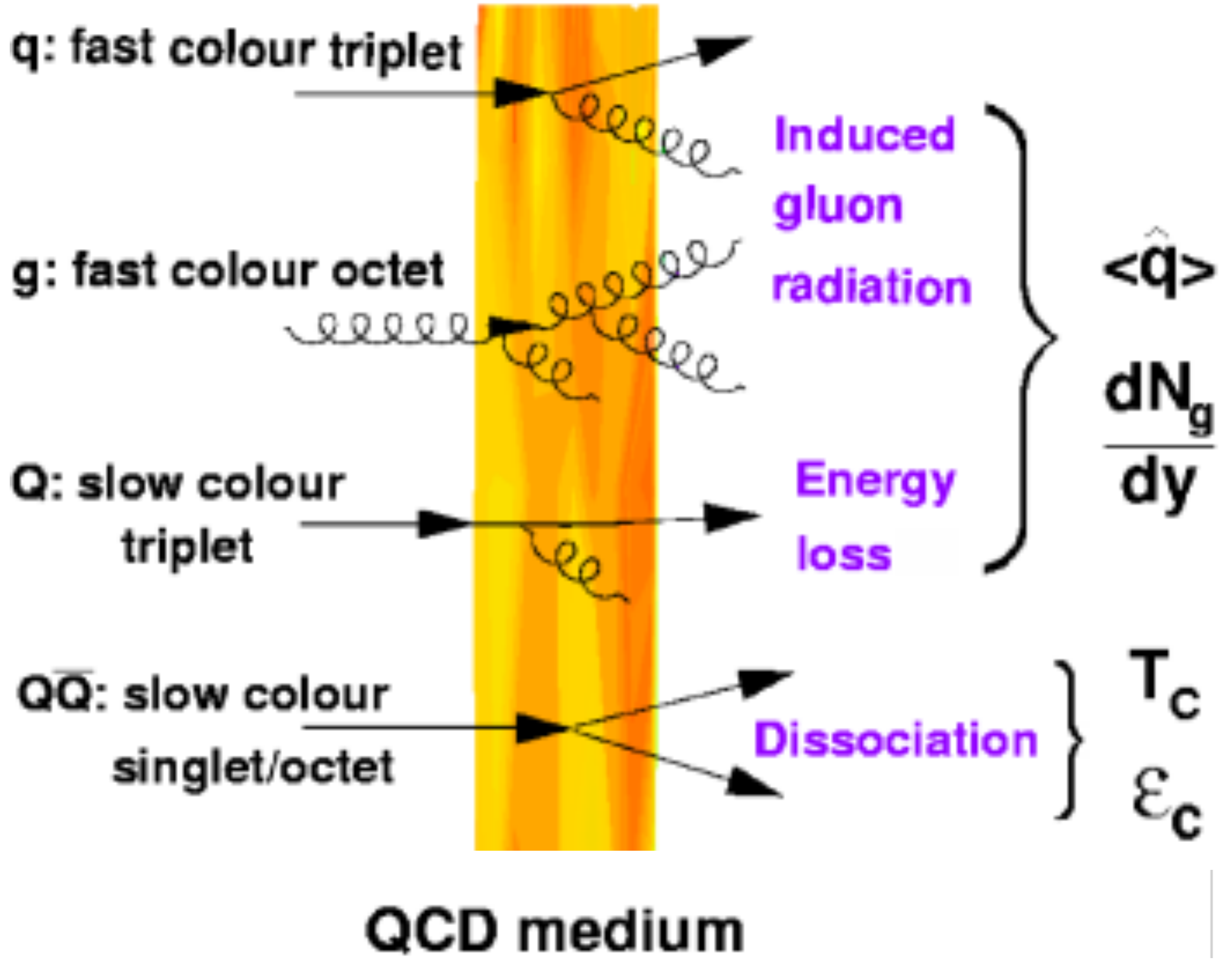

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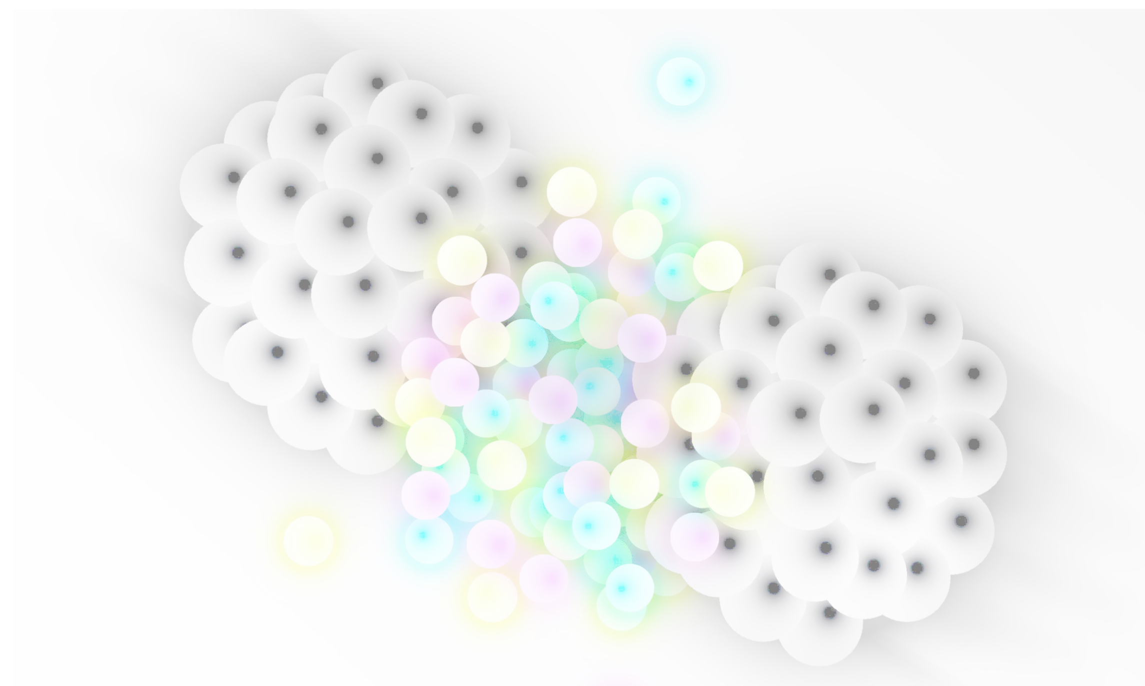

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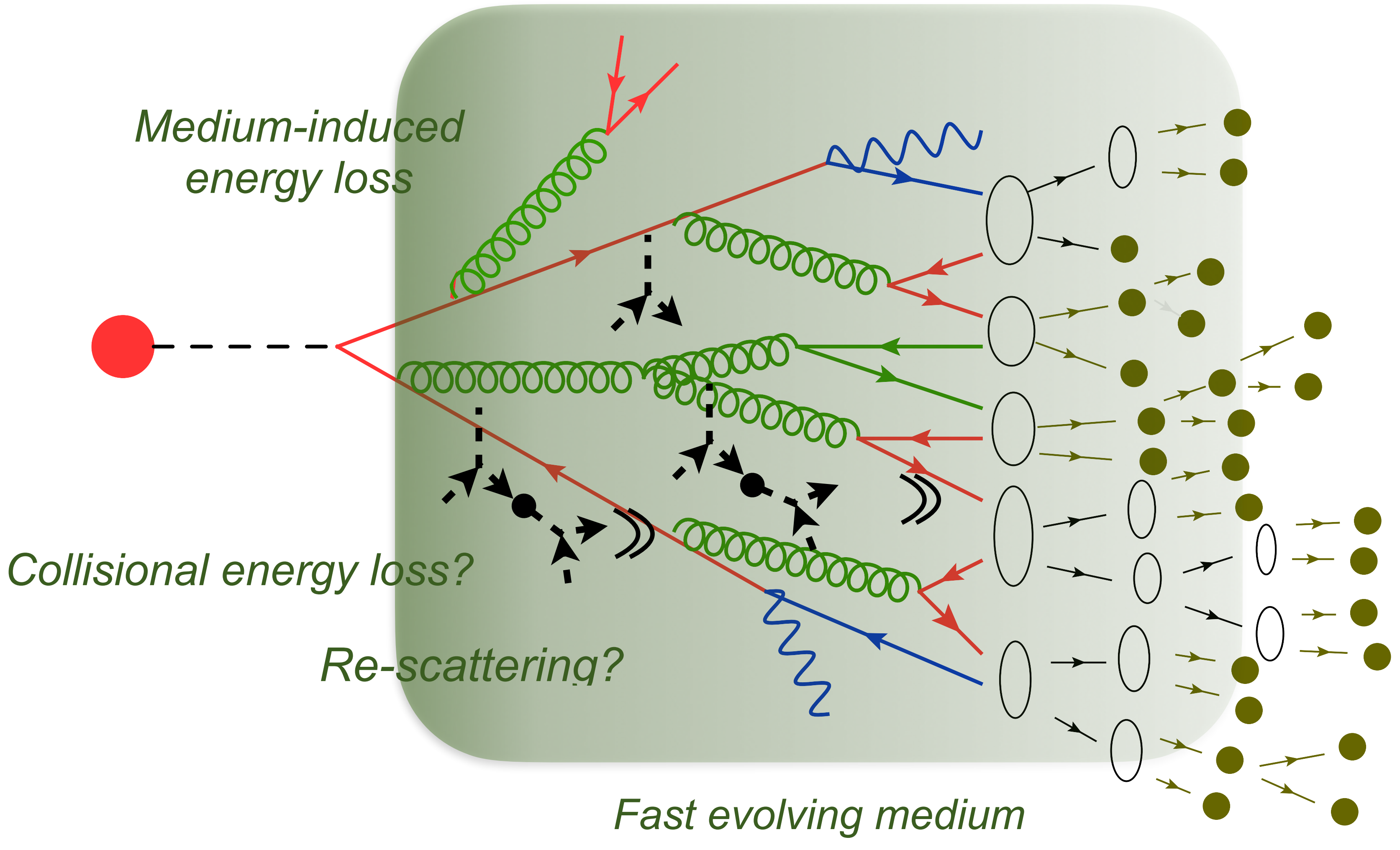
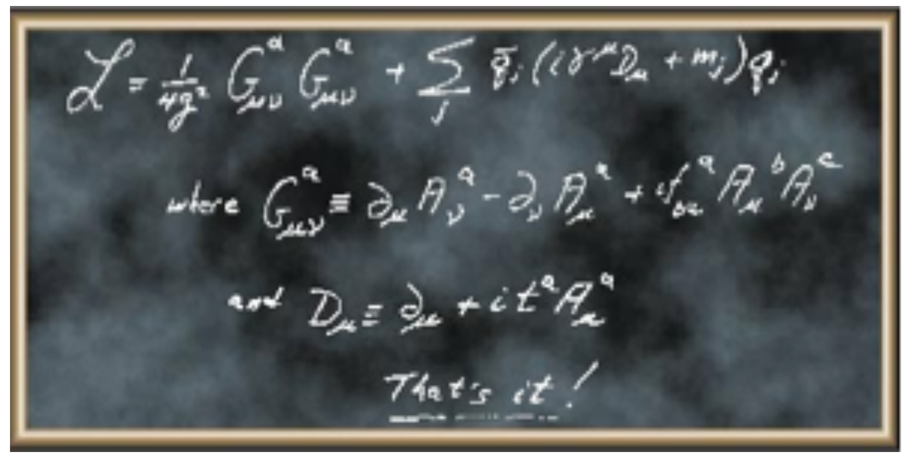
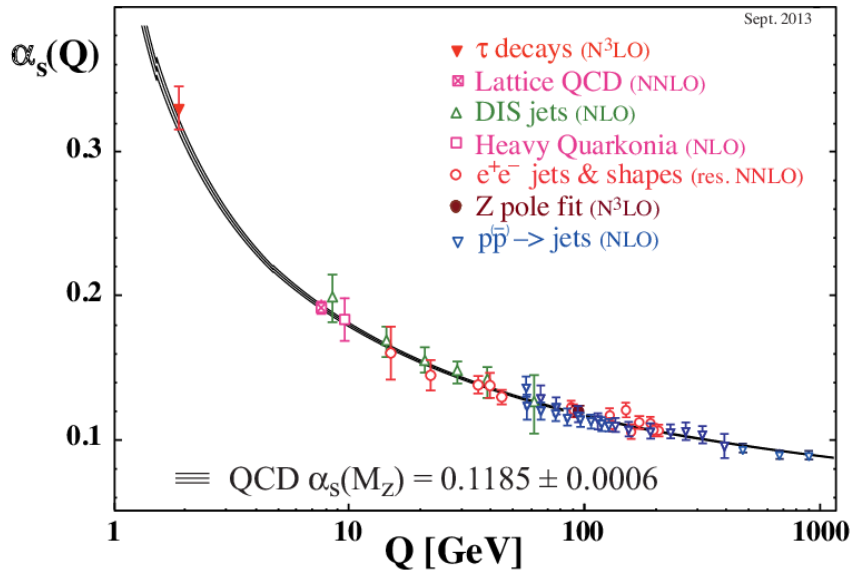
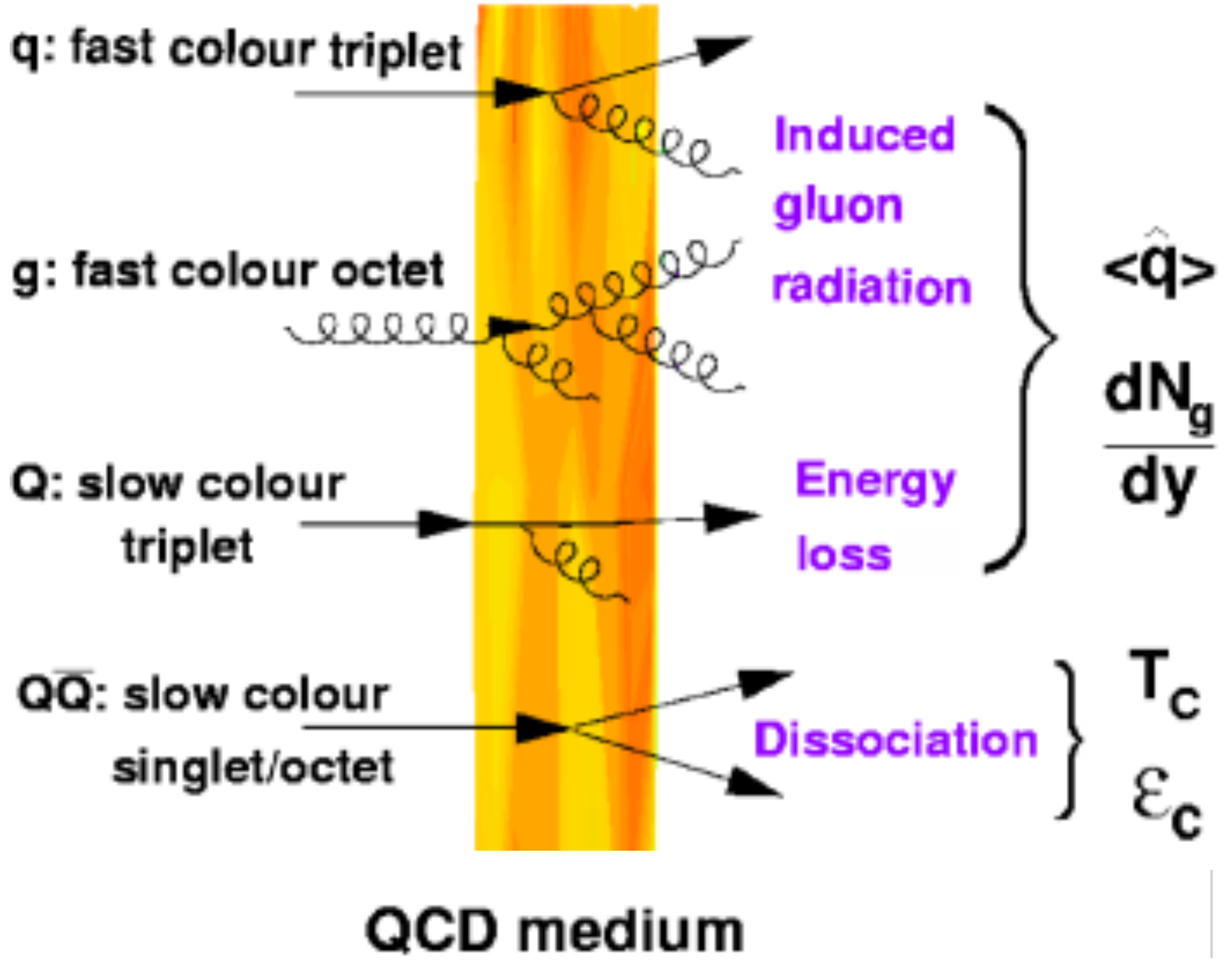






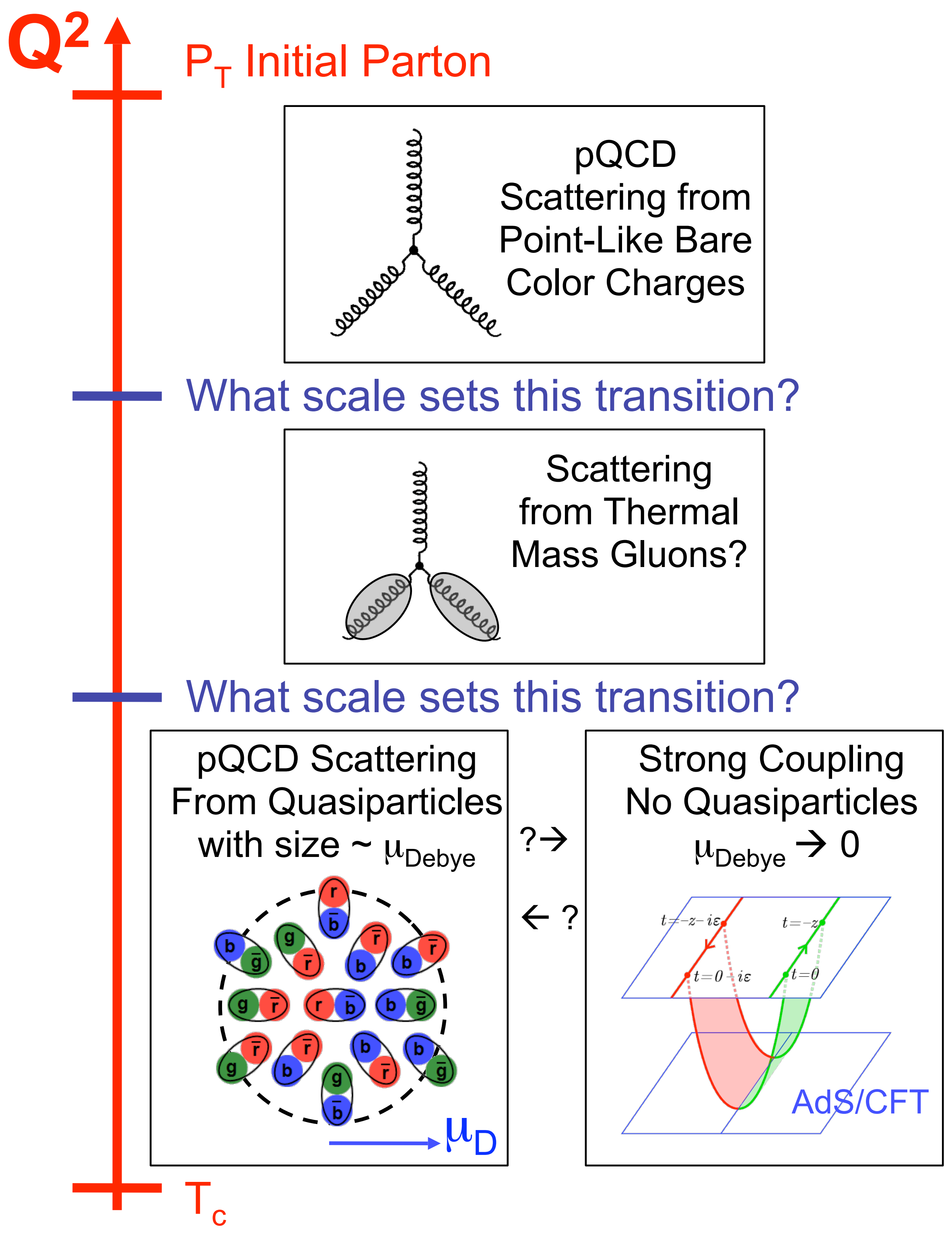


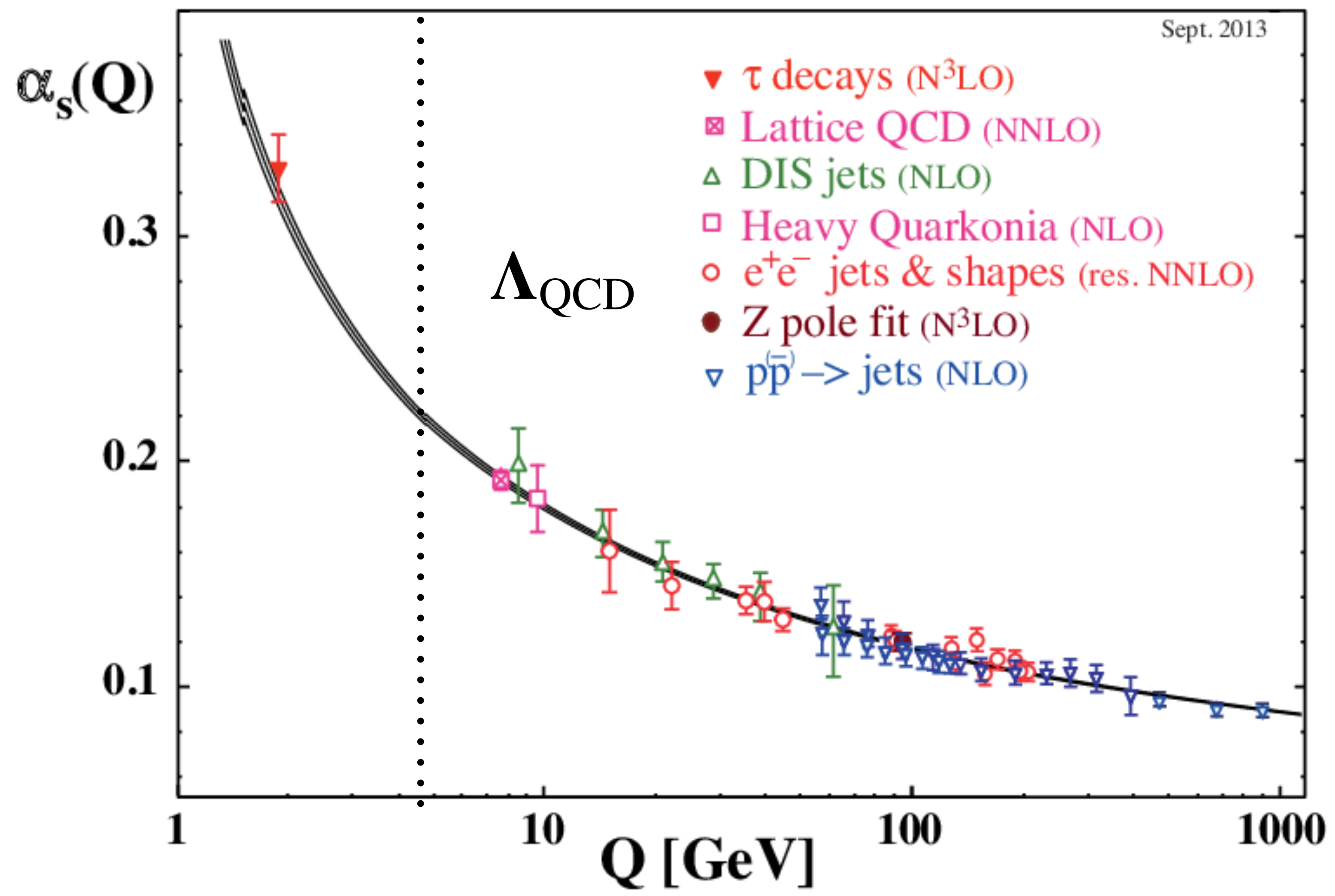
Probing the microscopic properties of the QGP

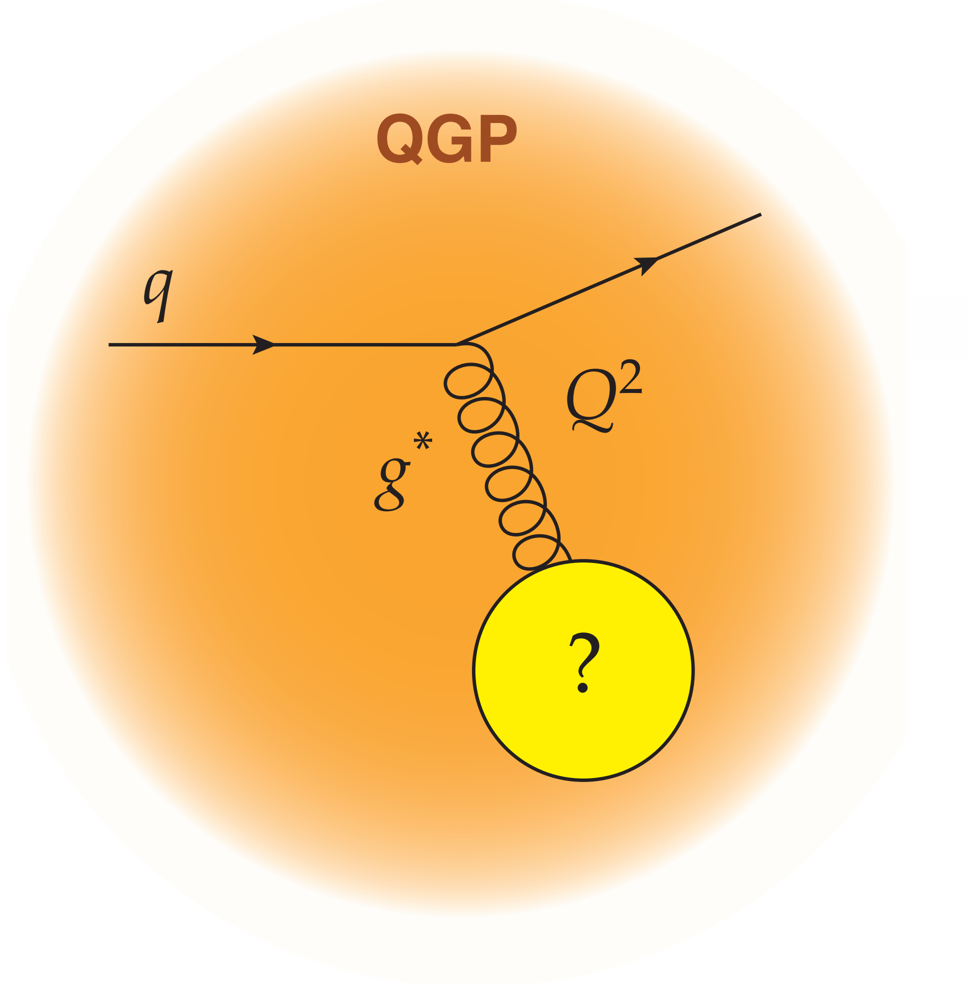
Testing limits of pQCD

And more on Hard Probes

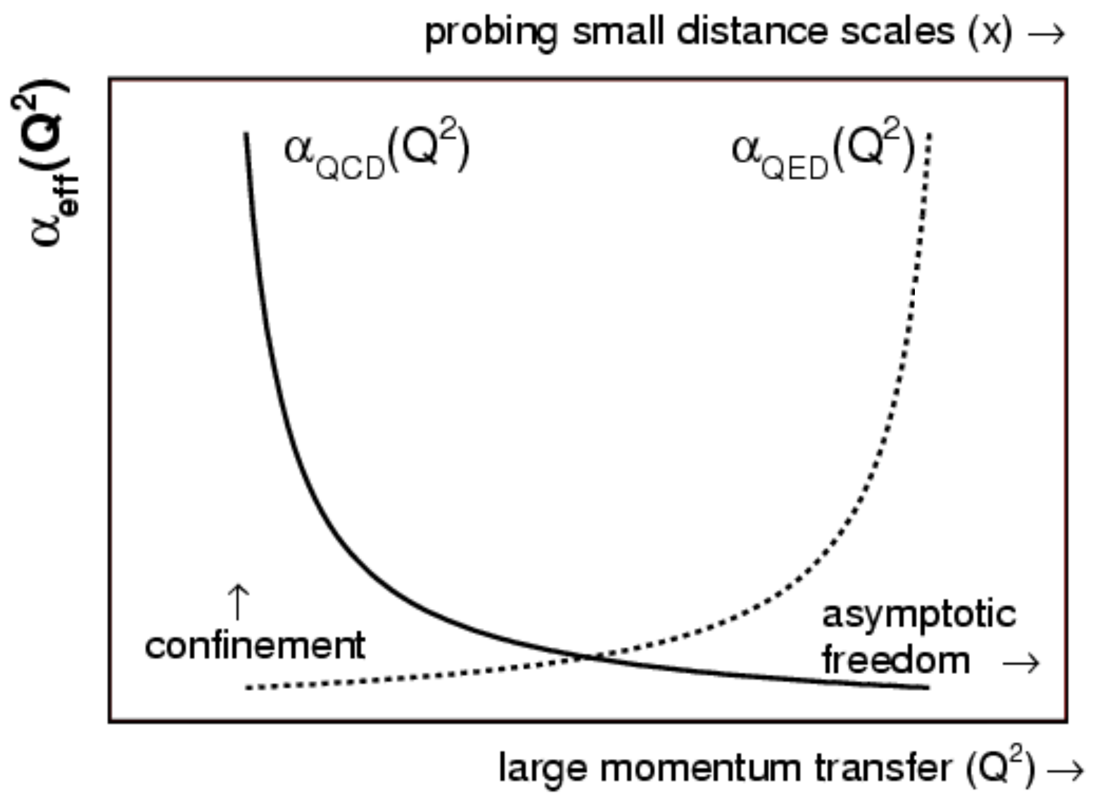
- Huge area! Not enough time to cover everything…
    - Lots of new opportunities to test frontiers of QCD and unveil QGP characteristics

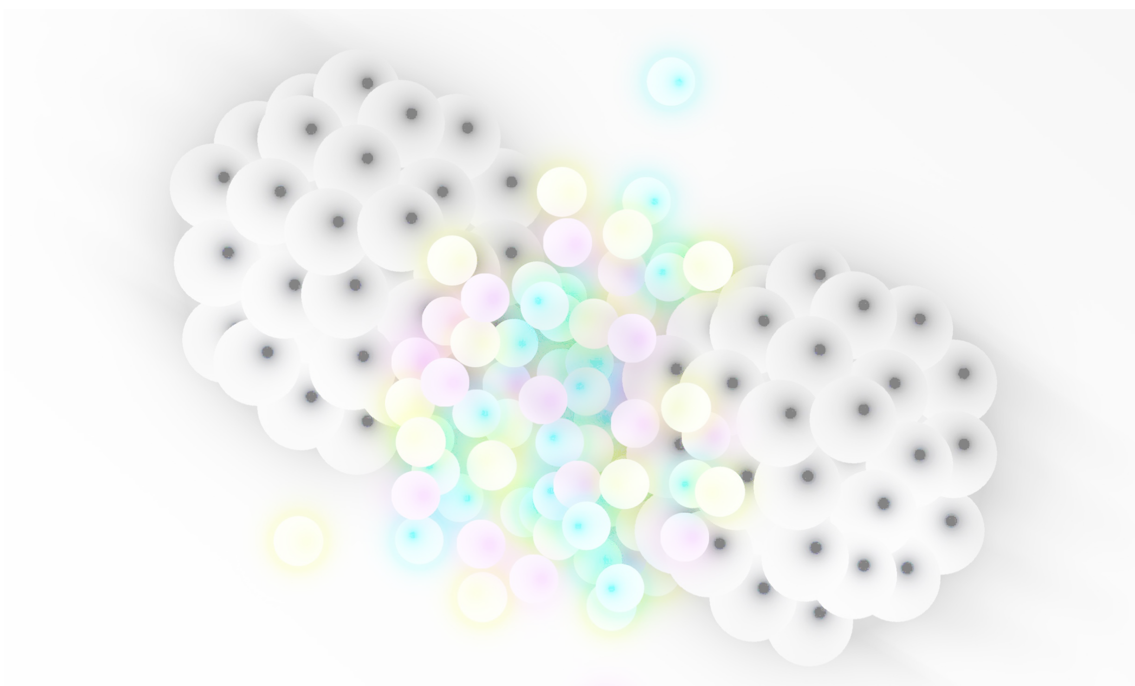






Summary





- Quantum Chromodynamics (QCD):
  - Building blocks: quarks and gluons
  - Gluon also carry "colour charge"
  - Two limits: perturbative vs non-perturbative

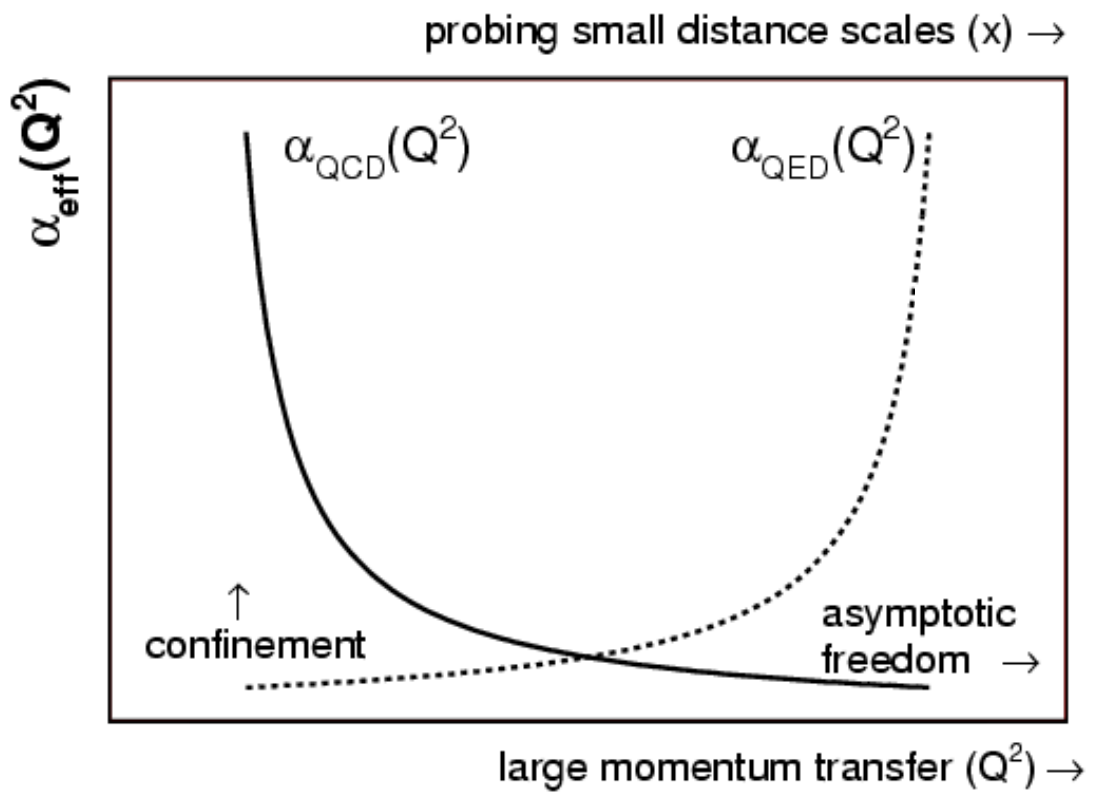
More on Friday! [T. Peña]

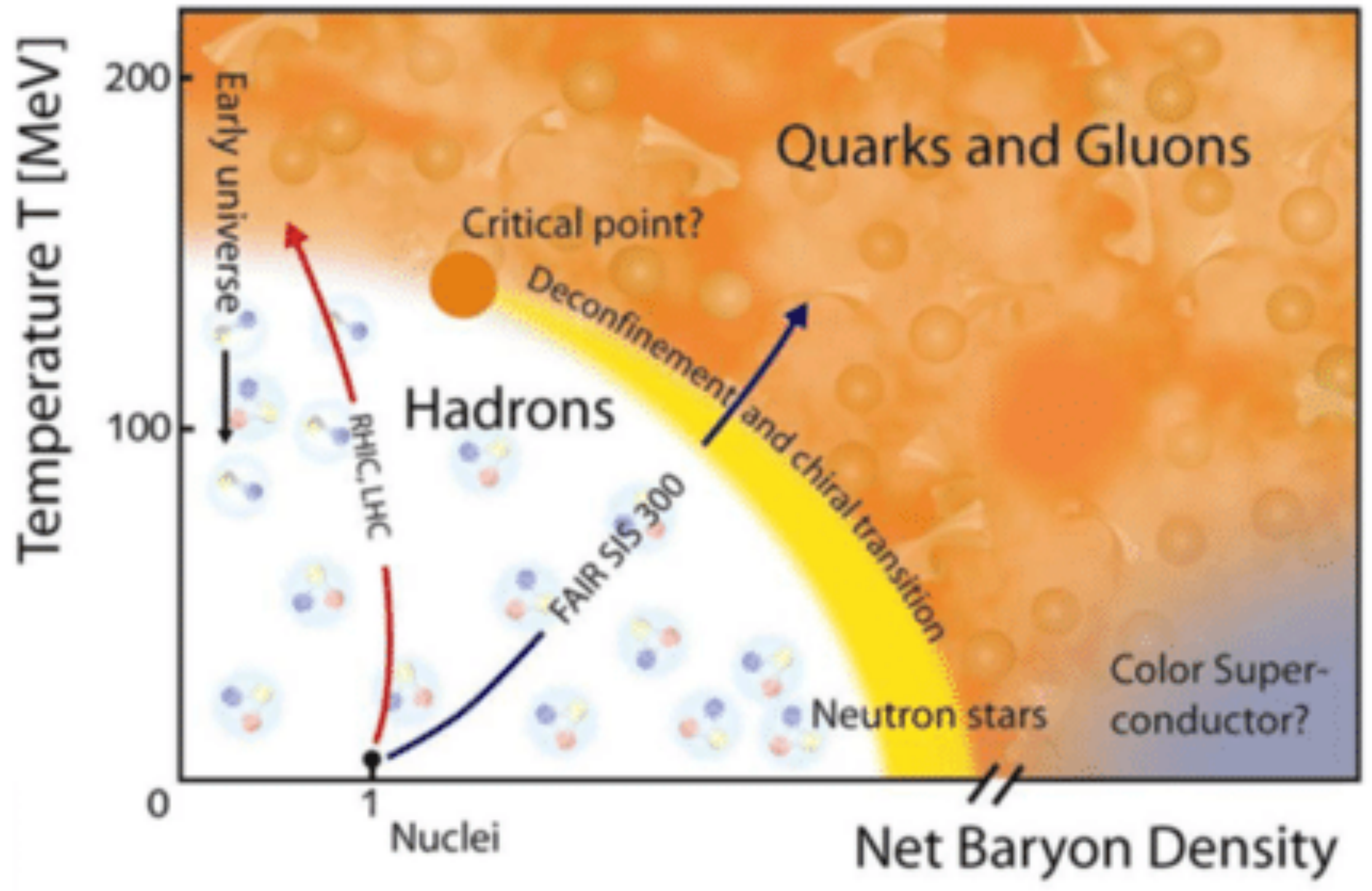
Summary

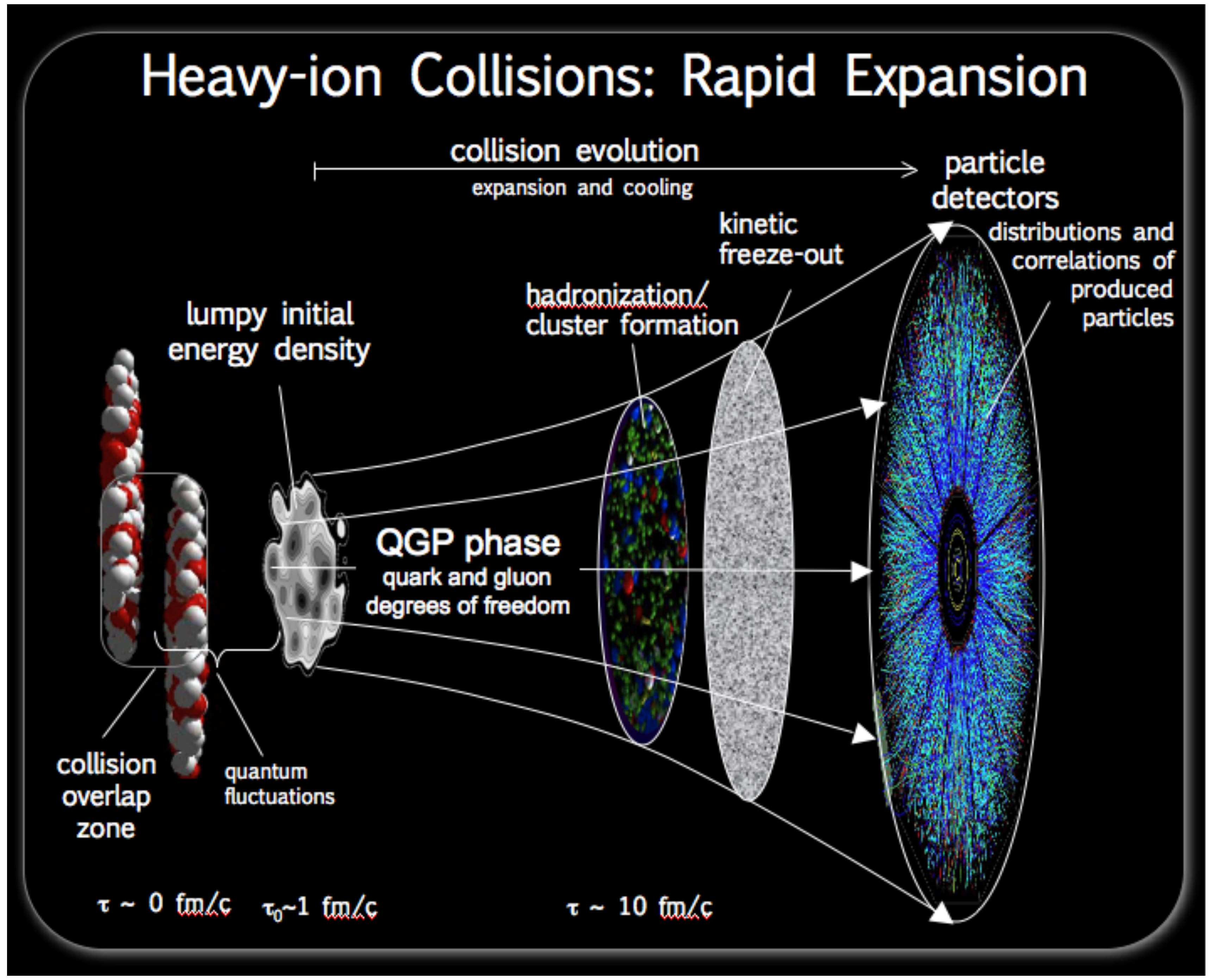
- Quantum Chromodynamics (QCD):
  - Building blocks: quarks and gluons
  - Gluon also carry “colour charge”
  - Two limits: perturbative vs non-perturbative

More on Friday! [T. Peña]

- Heavy-Ions:
  - Unique opportunity to study the Quark-Gluon Plasma
    - New state of QCD matter
    - Test theoretical description of the interaction from QCD first principles;





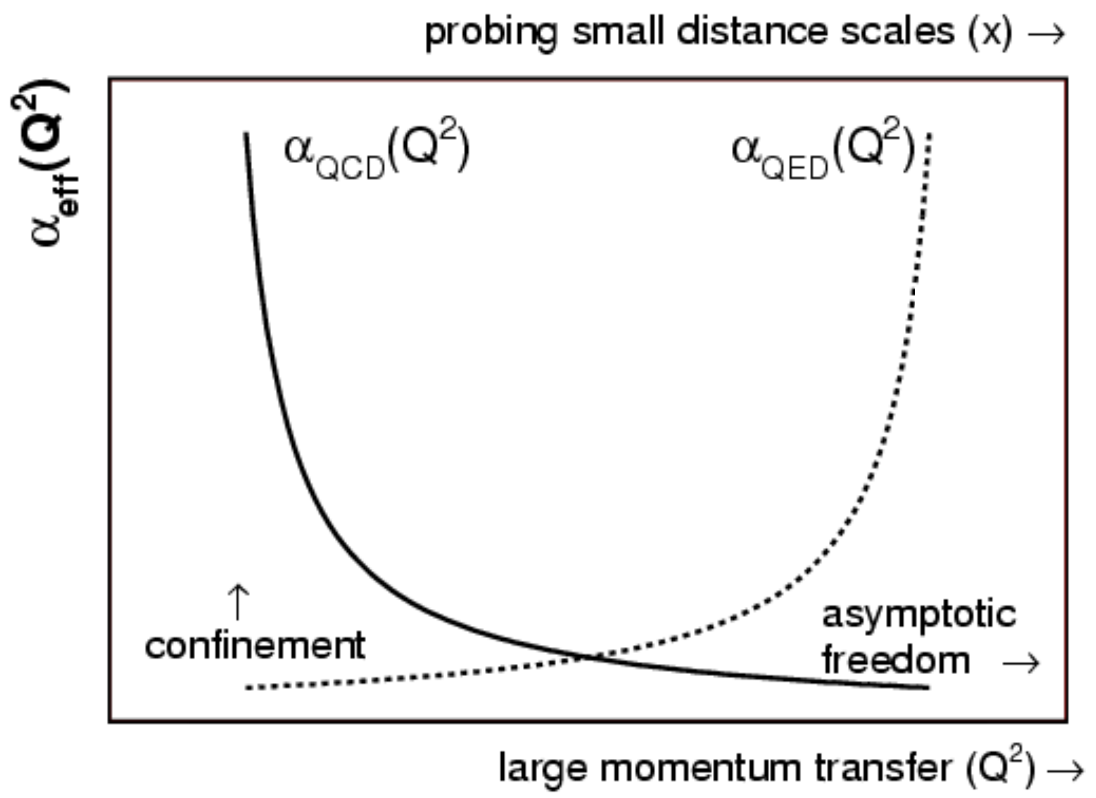


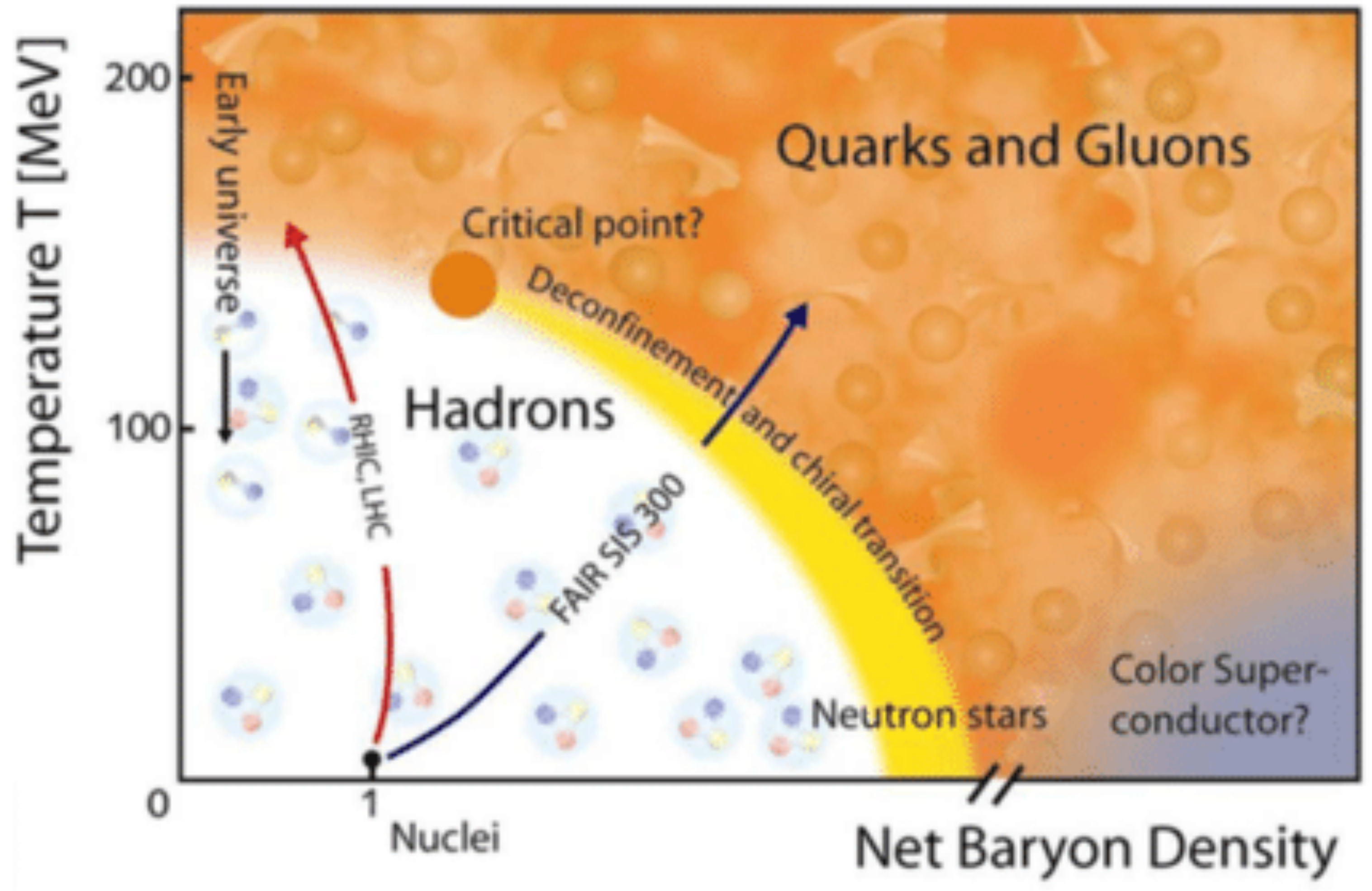
Summary

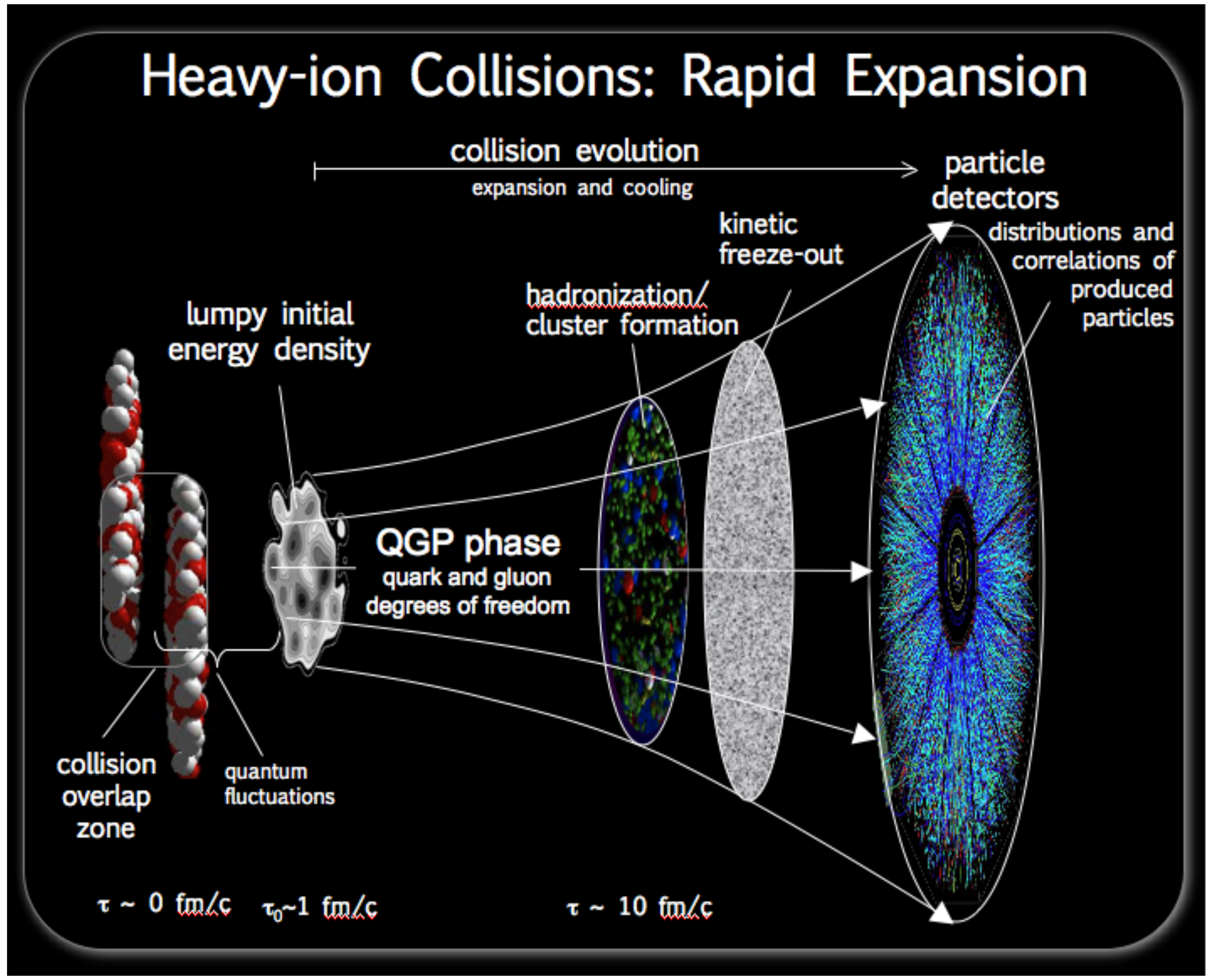
- Quantum Chromodynamics (QCD):
  - Building blocks: quarks and gluons
  - Gluon also carry “colour charge”
  - Two limits: perturbative vs non-perturbative

More on Friday! [T. Peña]

- Heavy-Ions:
  - Unique opportunity to study the Quark-Gluon Plasma
    - New state of QCD matter
    - Test theoretical description of the interaction from QCD first principles;







Questions?