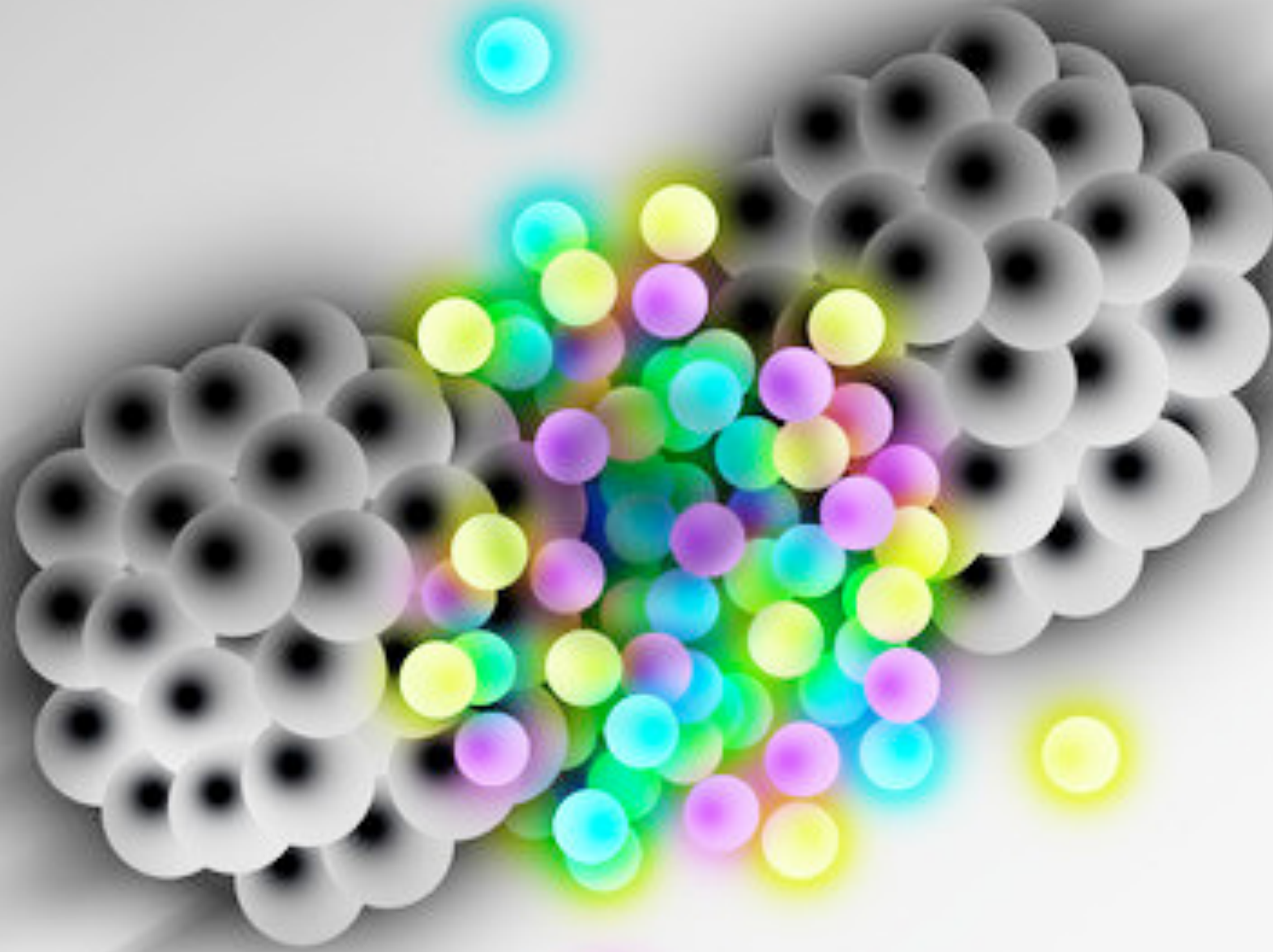


QCD & Heavy-Ion Physics

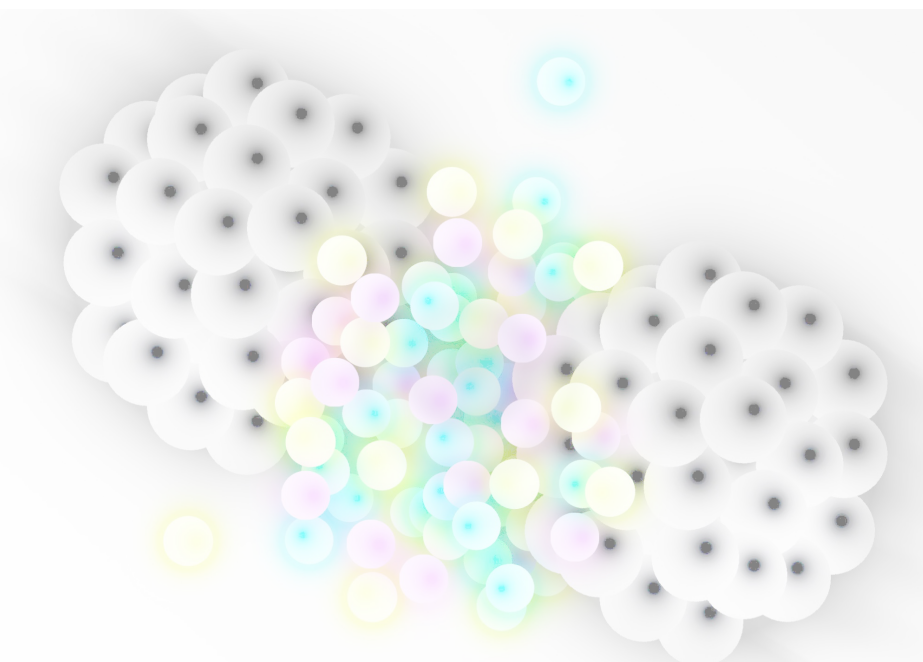


Liliana Apolinário



**TÉCNICO
LISBOA**

Standard Model: Recap



- Gauge Bosons (“Force carriers”)

Standard Model of Elementary Particles

			three generations of matter (fermions)			interactions / force carriers (bosons)	
			I	II	III		
mass			$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge			$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin			$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
			u up	c charm	t top	g gluon	H higgs
						0	
			$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
			$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
			d down	s strange	b bottom	γ photon	
			-1	-1	-1	0	
			$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
			e electron	μ muon	τ tau	Z Z boson	
			0	0	0	± 1	
			$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
			ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

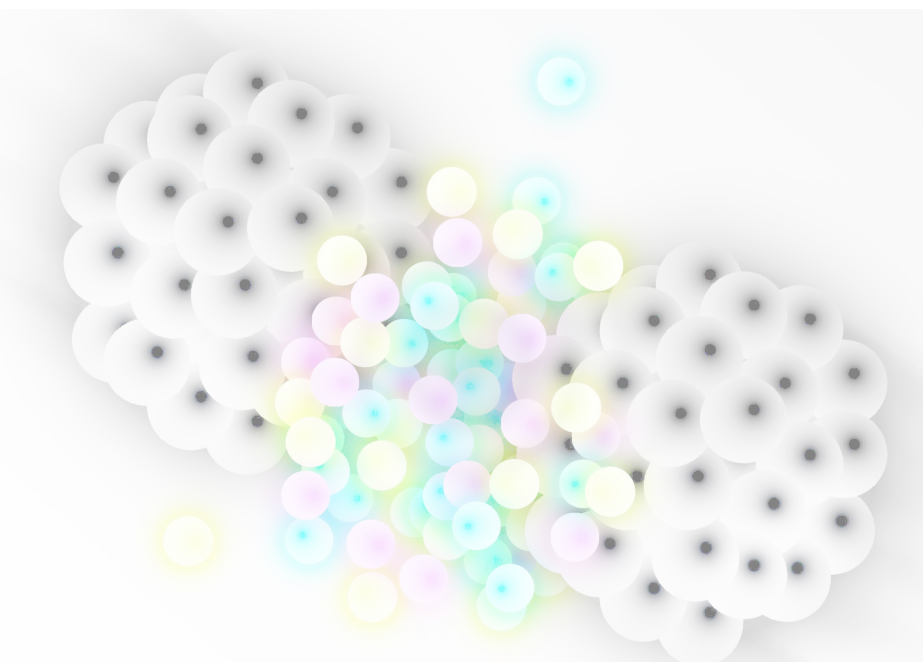
QUARKS

LEPTONS

GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS

Standard Model: Recap



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

Standard Model of Elementary Particles

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	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

QUARKS (left side of the quark section)

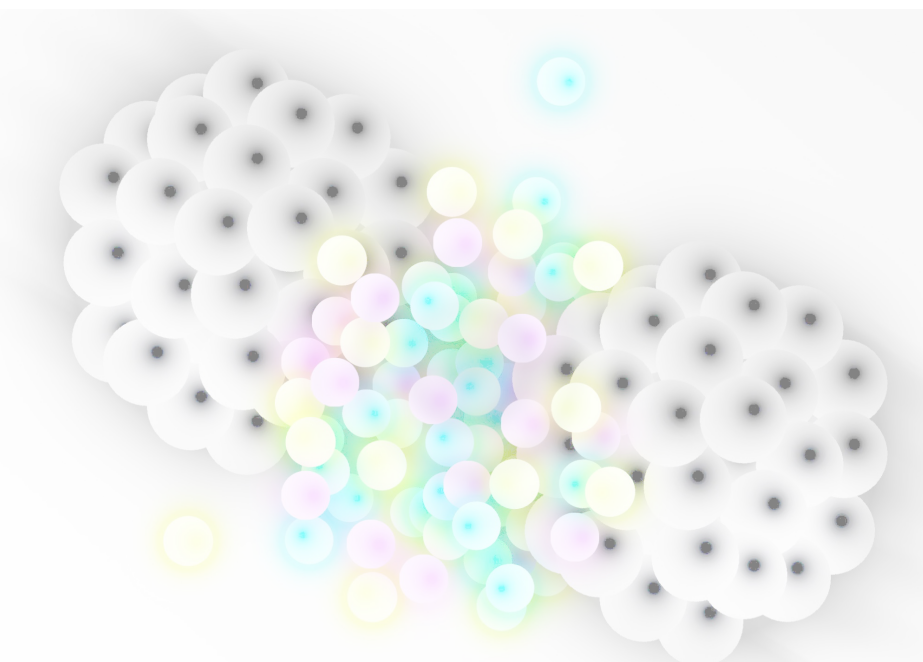
LEPTONS (left side of the lepton section)

GAUGE BOSONS VECTOR BOSONS (bottom left of the boson section)

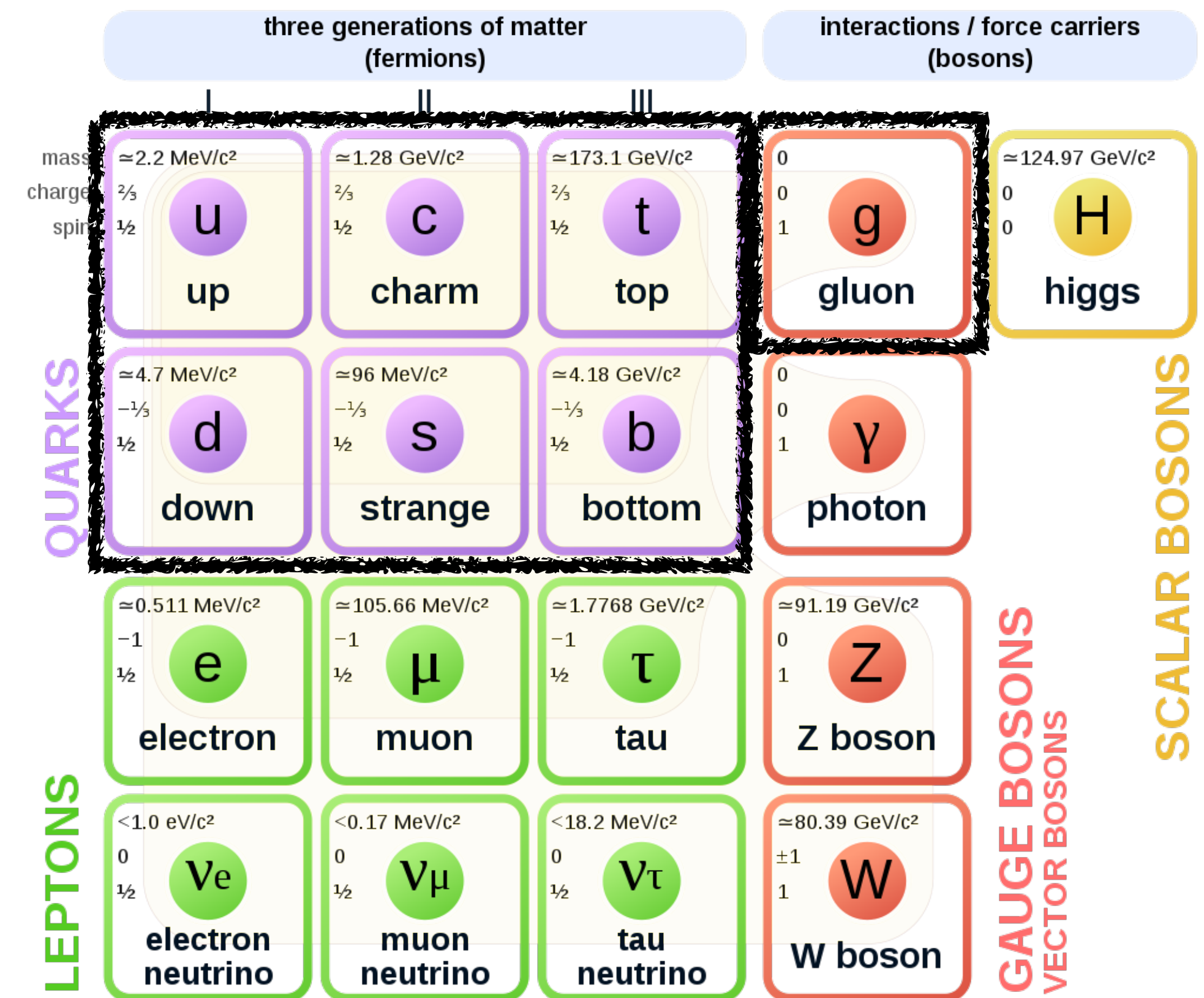
SCALAR BOSONS (bottom right of the boson section)

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)

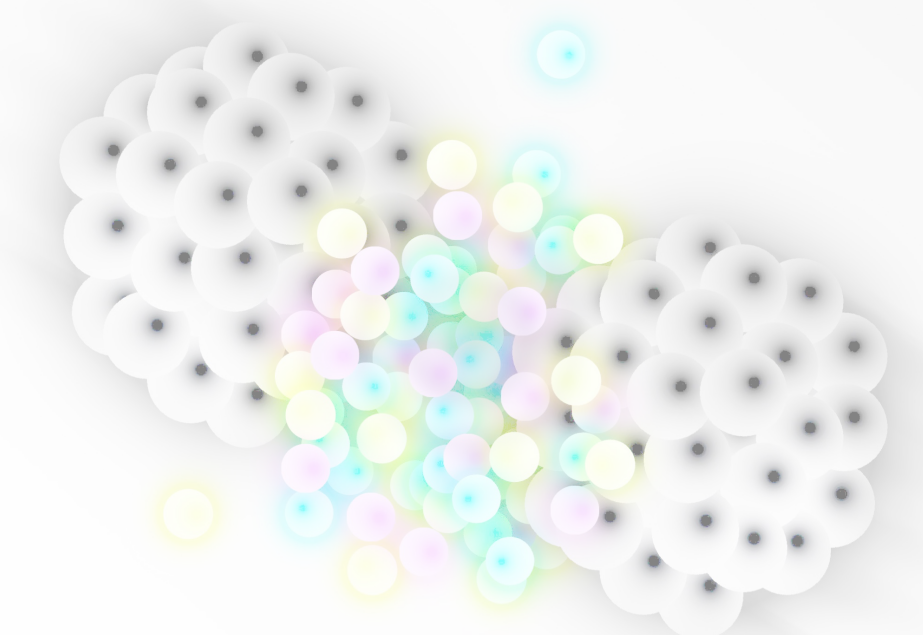
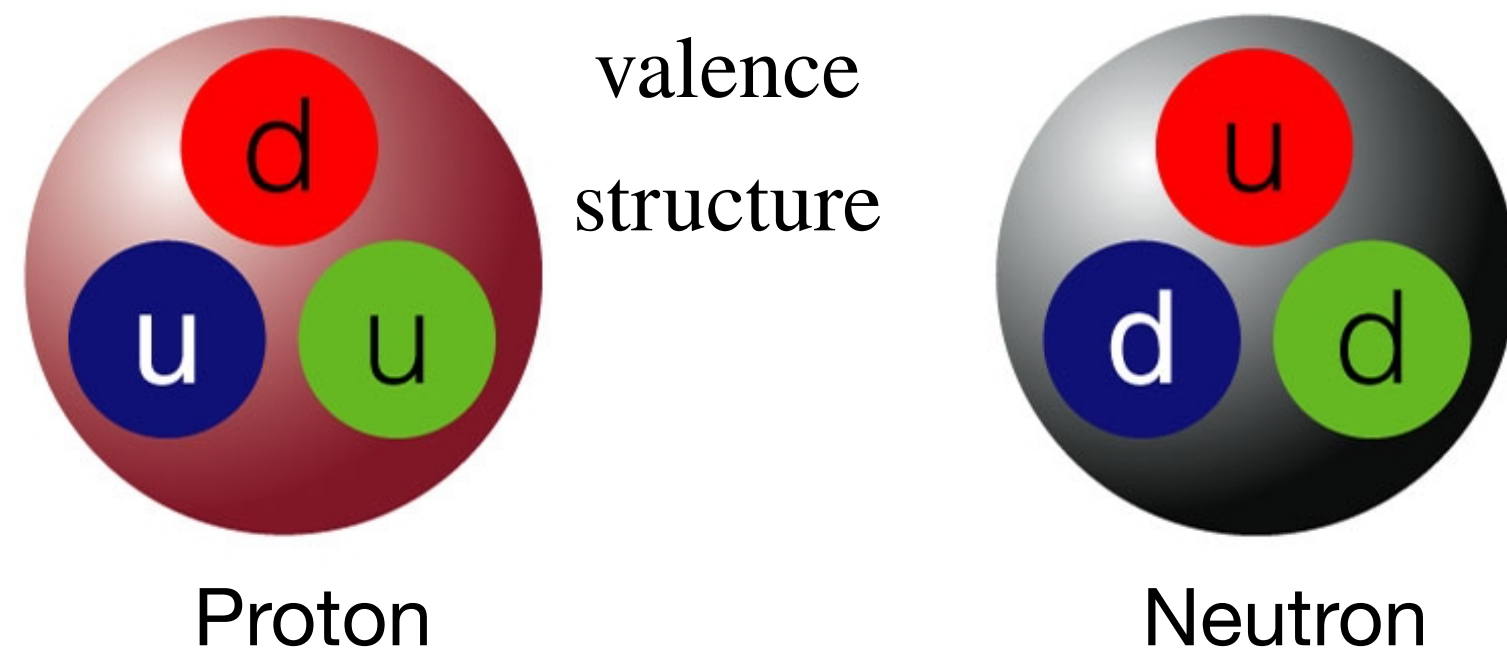


Standard Model of Elementary Particles



Standard Model: Recap

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



Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
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	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
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	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	e electron	μ muon	τ tau	Z Z boson	
	$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

QUARKS (left side of the table)

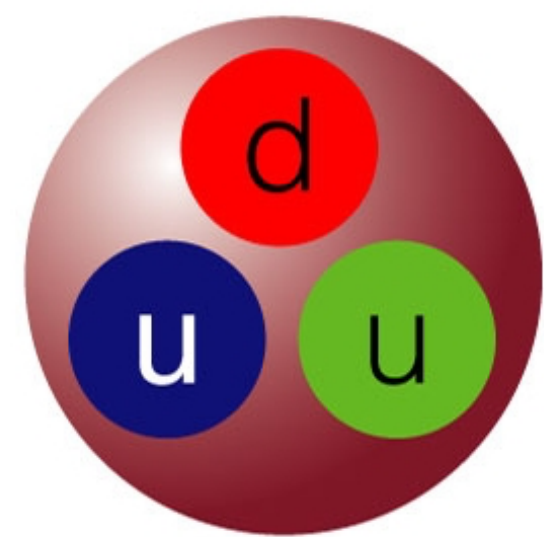
LEPTONS (left side of the table)

GAUGE BOSONS VECTOR BOSONS (bottom right of the table)

SCALAR BOSONS (right side of the table)

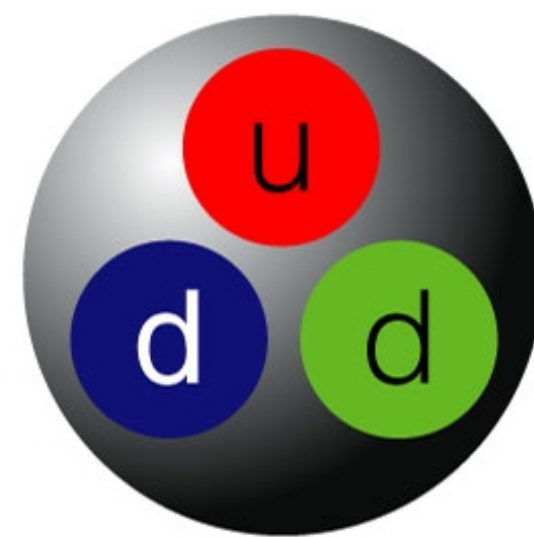
Standard Model: Recap

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valence structure

Proton

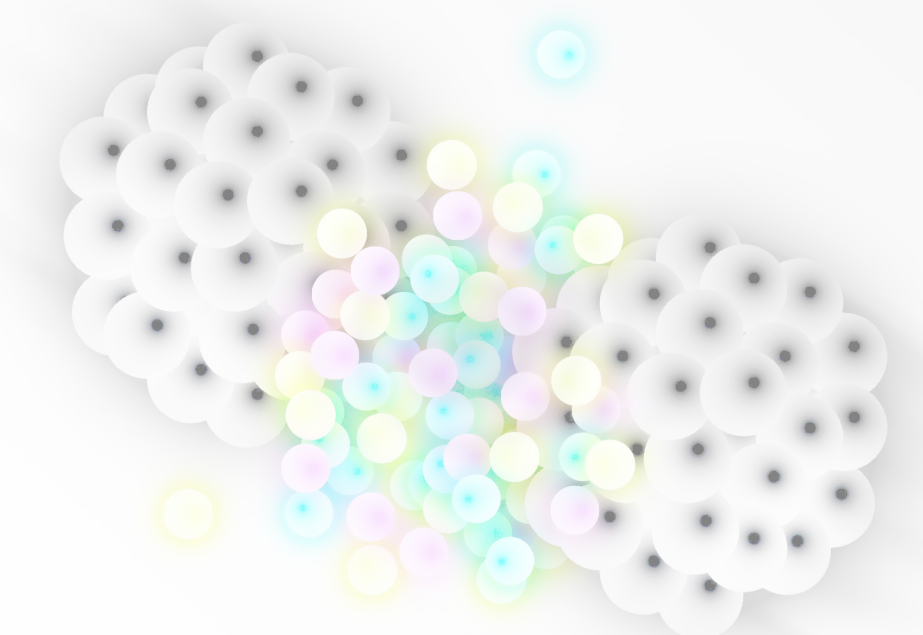


Neutron

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

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

$\sim 1\%$ mass



Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
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	u up	c charm	t top	g gluon	H higgs
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	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

QUARKS (left side of the table)

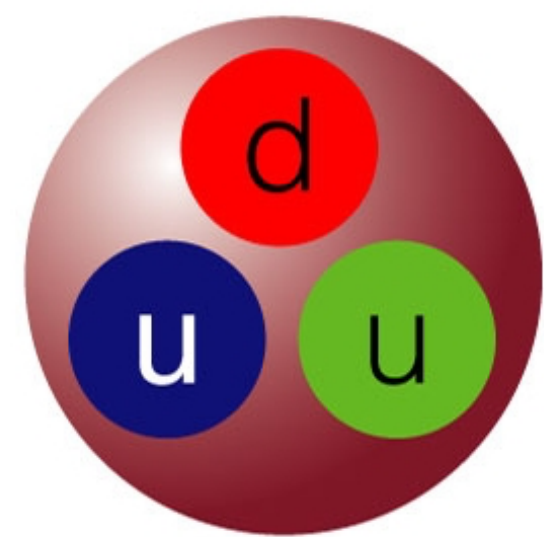
LEPTONS (left side of the table)

GAUGE BOSONS VECTOR BOSONS (bottom right)

SCALAR BOSONS (right side of the table)

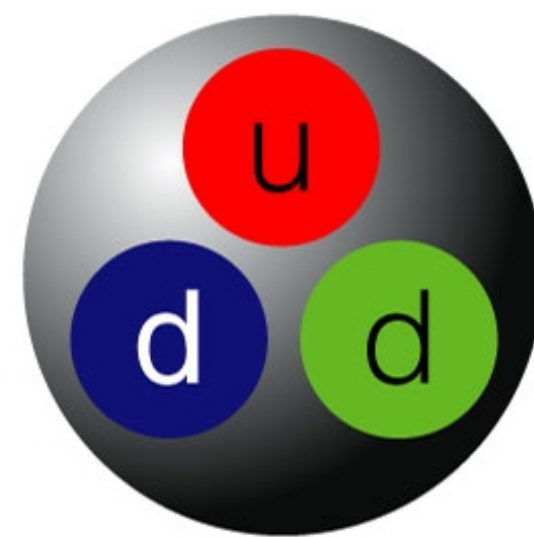
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valence structure

Proton



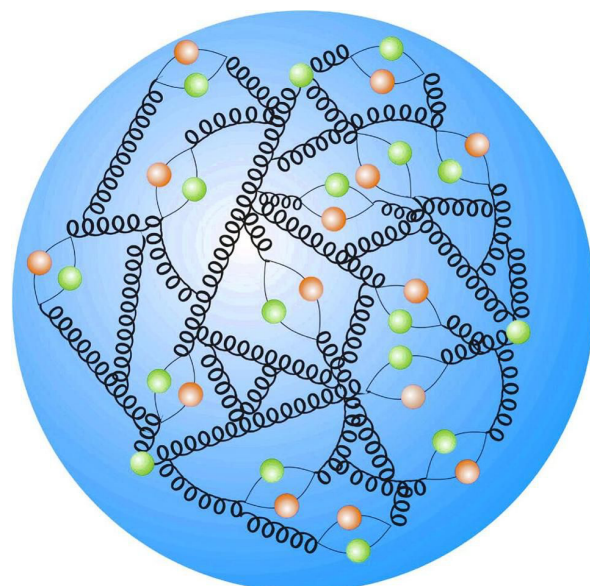
Neutron

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

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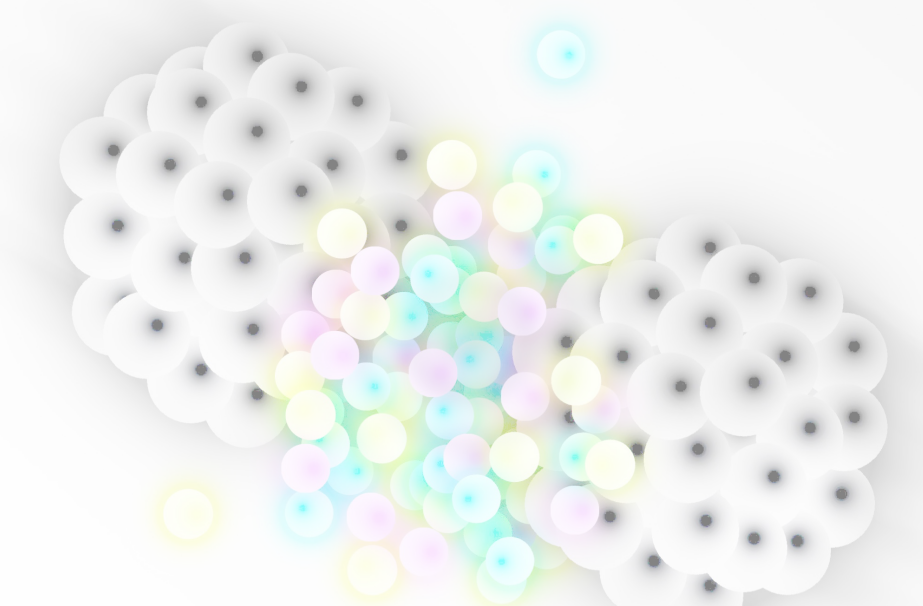
$\sim 1\%$ mass

(more realistic) proton structure



valence + sea (quarks and gluons)

100% mass



Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
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	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

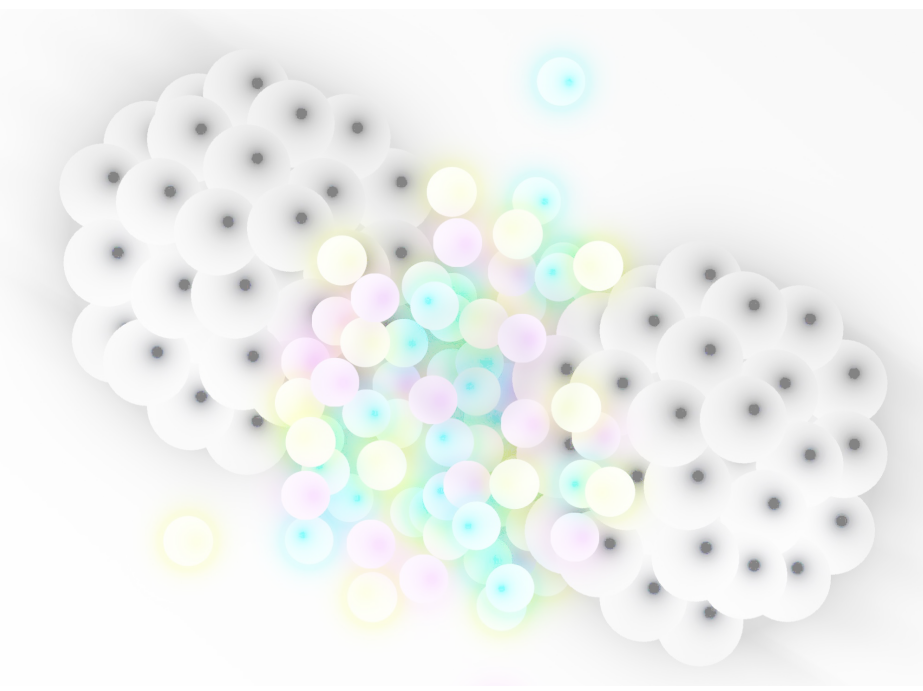
QUARKS

LEPTONS

GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS

QED vs QCD



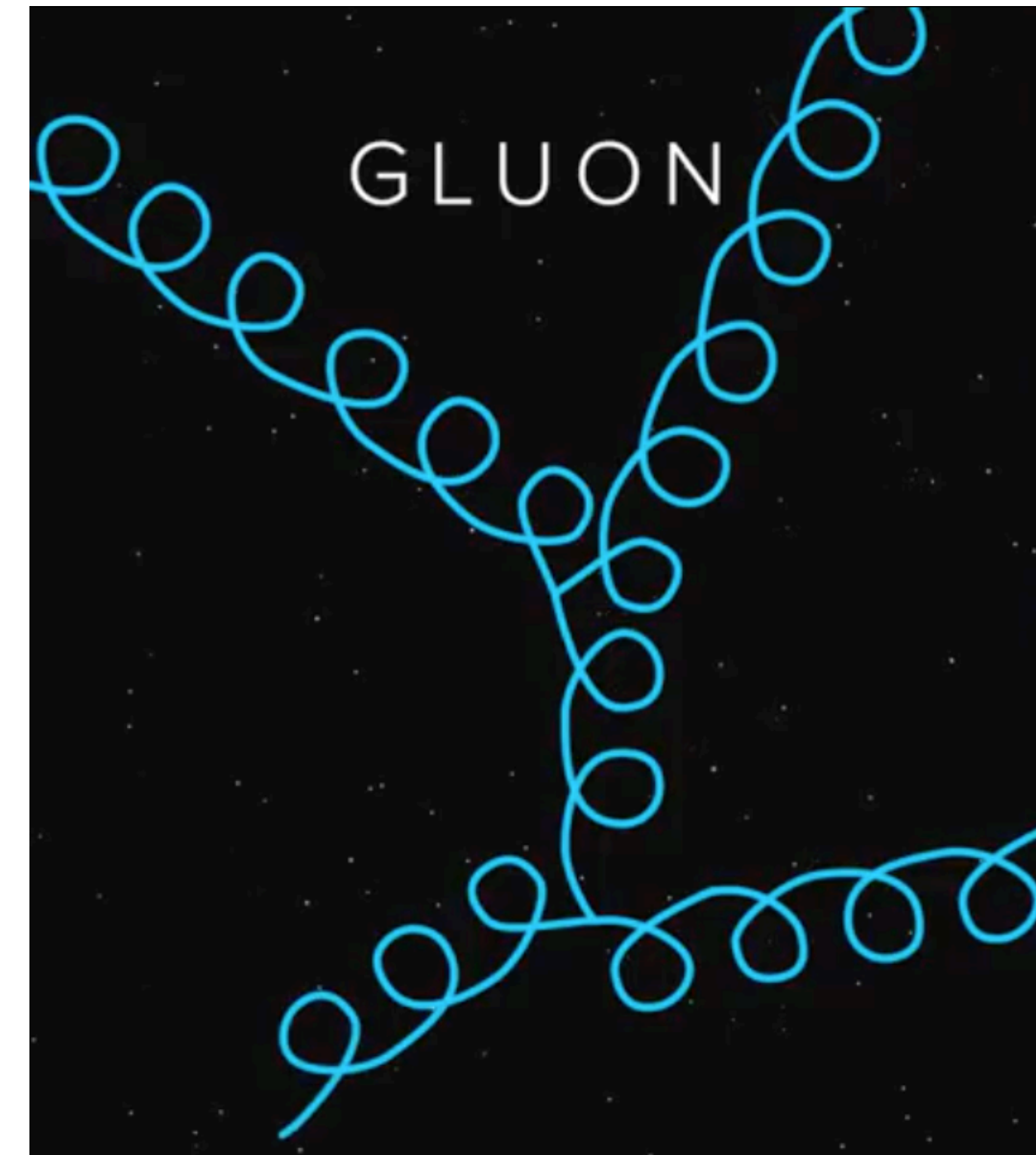
- Quantum Electrodynamics

Photons do not have electric charge

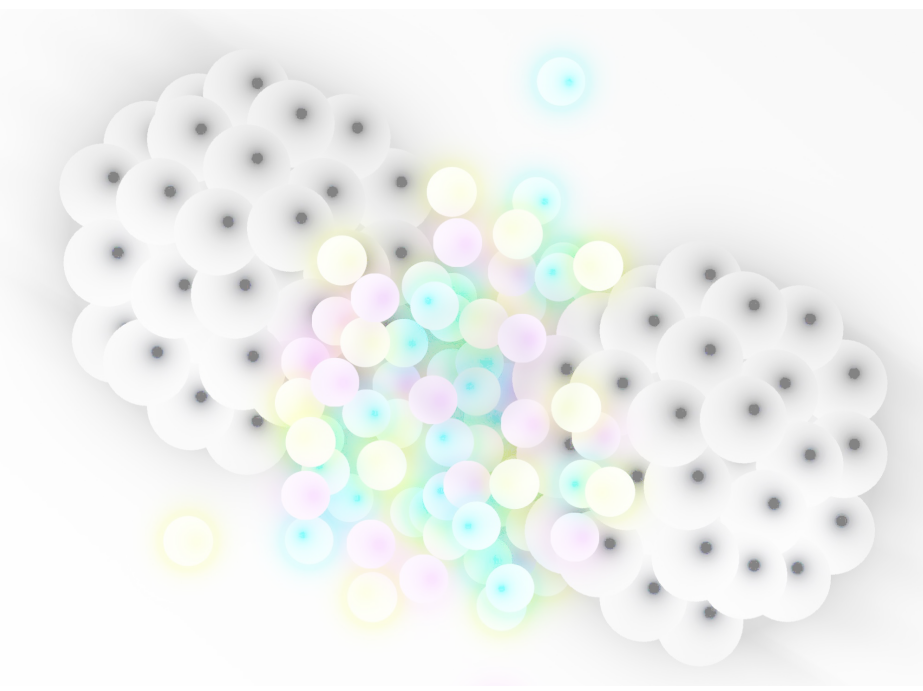


- Quantum Chromodynamics

Gluons are colourful



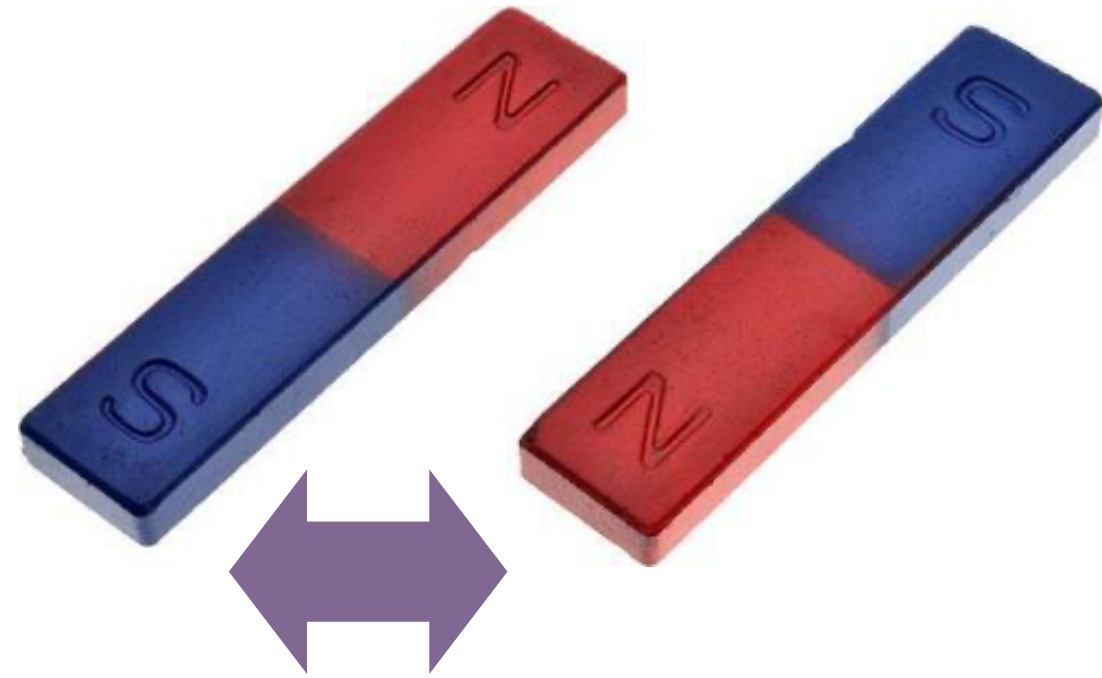
QED vs QCD



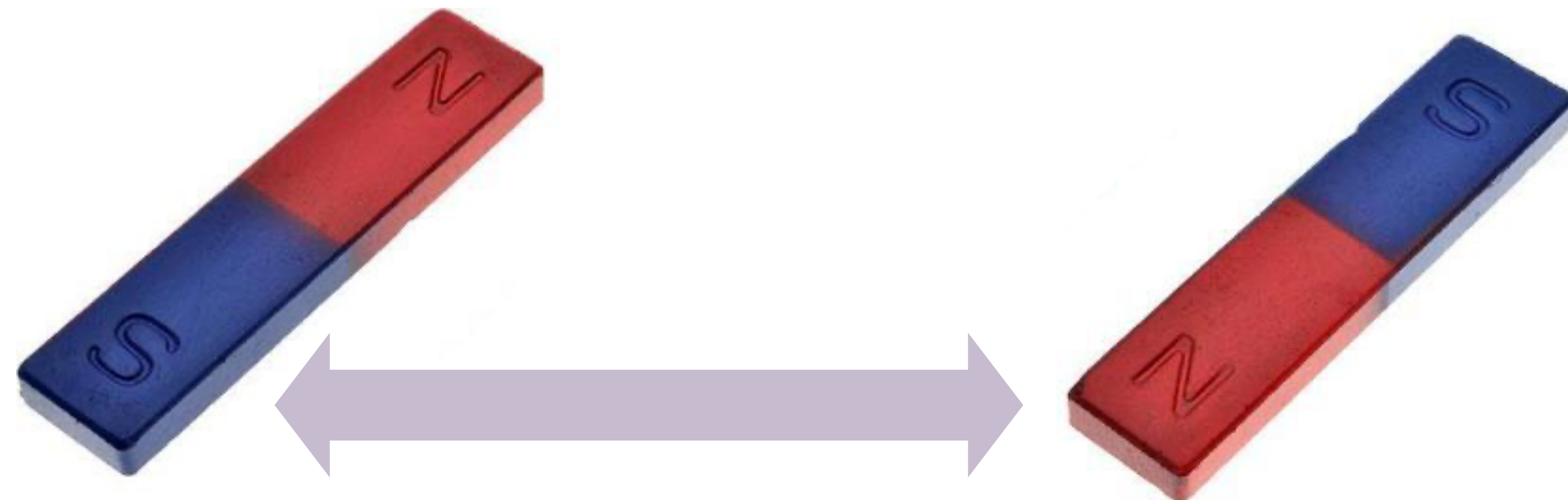
- Quantum Electrodynamics

Photons do not have electric charge

Larger attraction



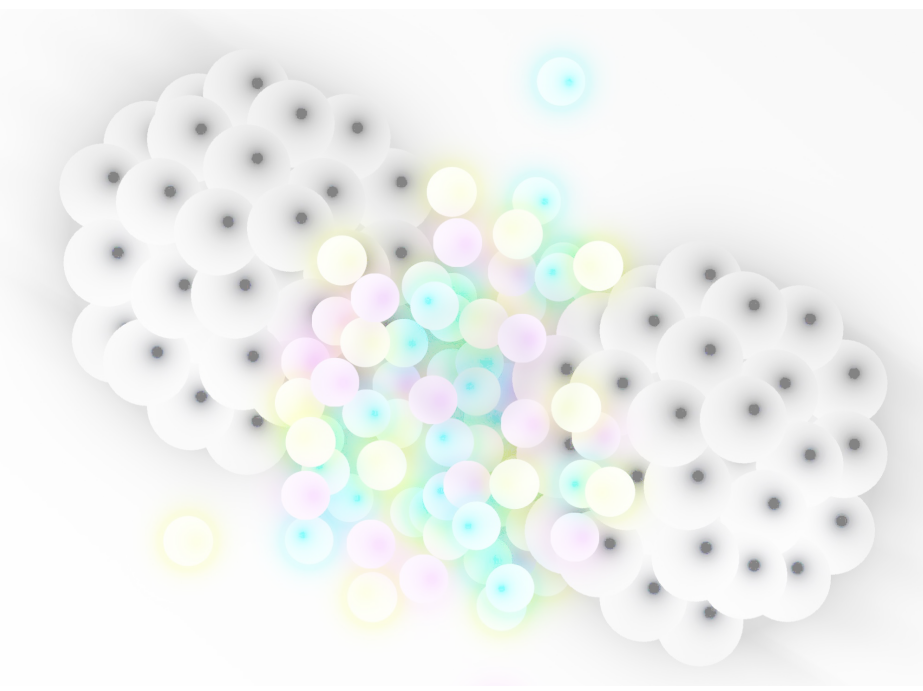
Smaller attraction



- Quantum Chromodynamics

Gluons are colourful

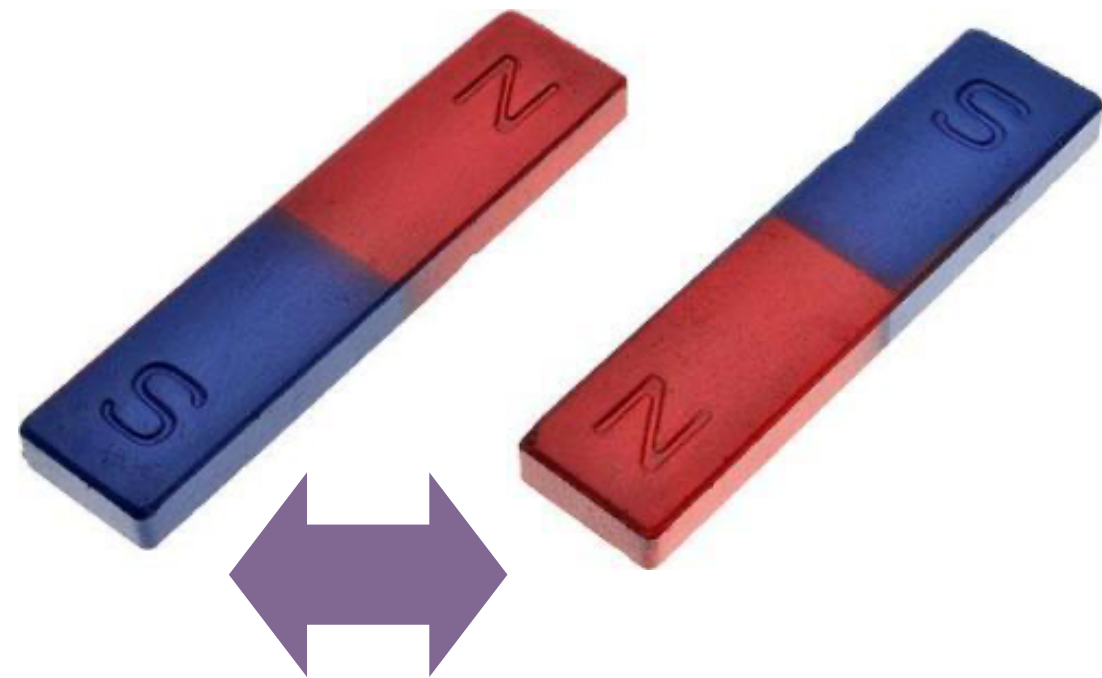
QED vs QCD



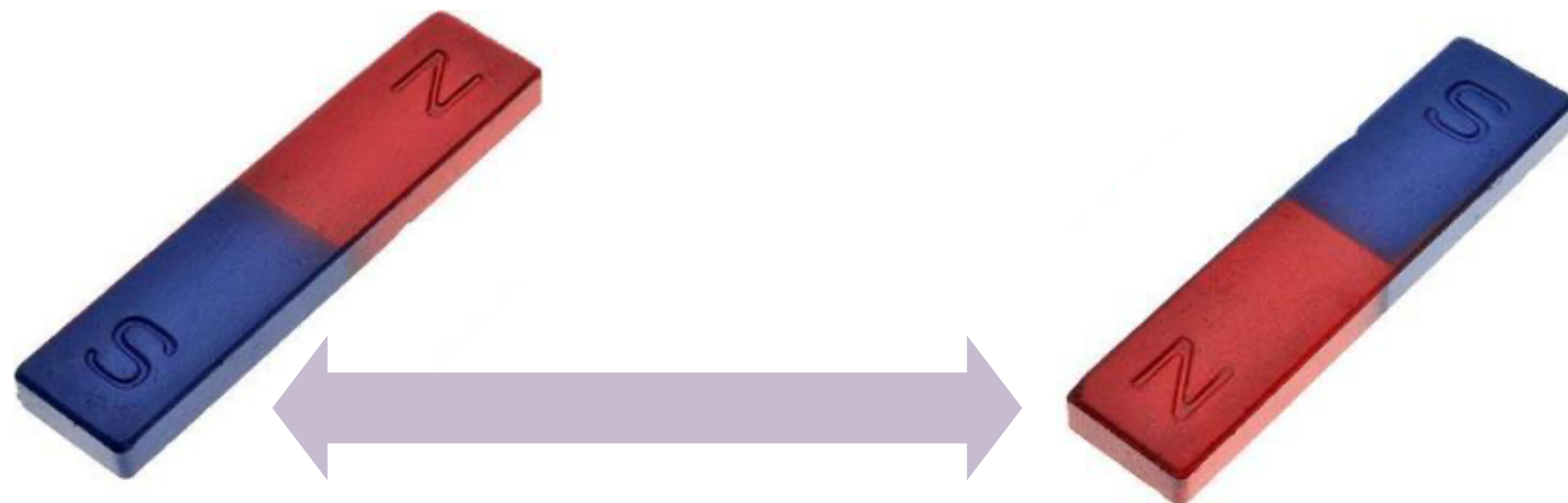
- Quantum Electrodynamics

Photons do not have electric charge

Larger attraction



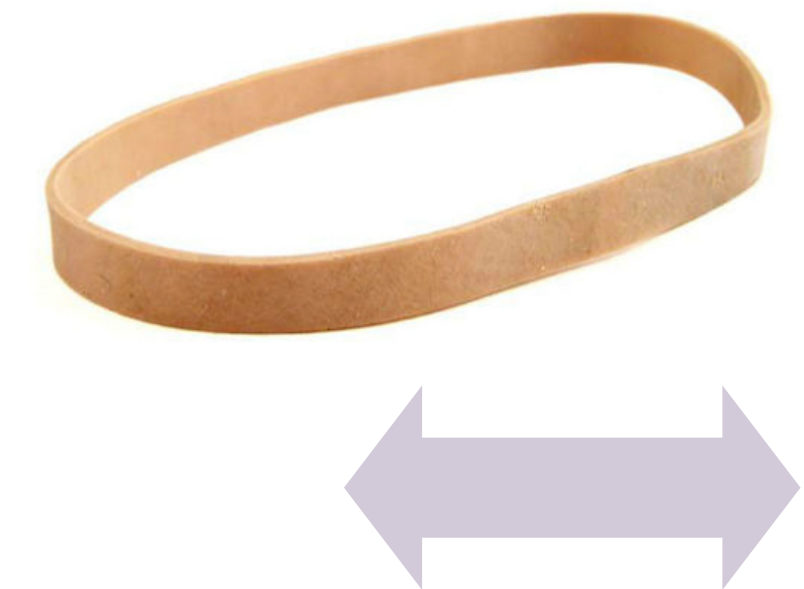
Smaller attraction



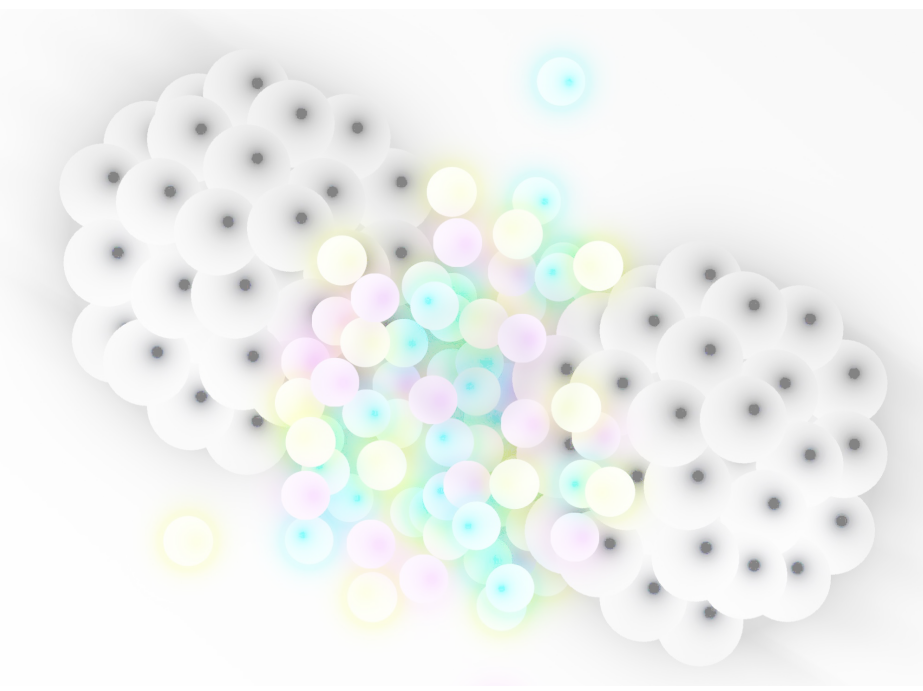
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Gluons are colourful

Smaller attraction



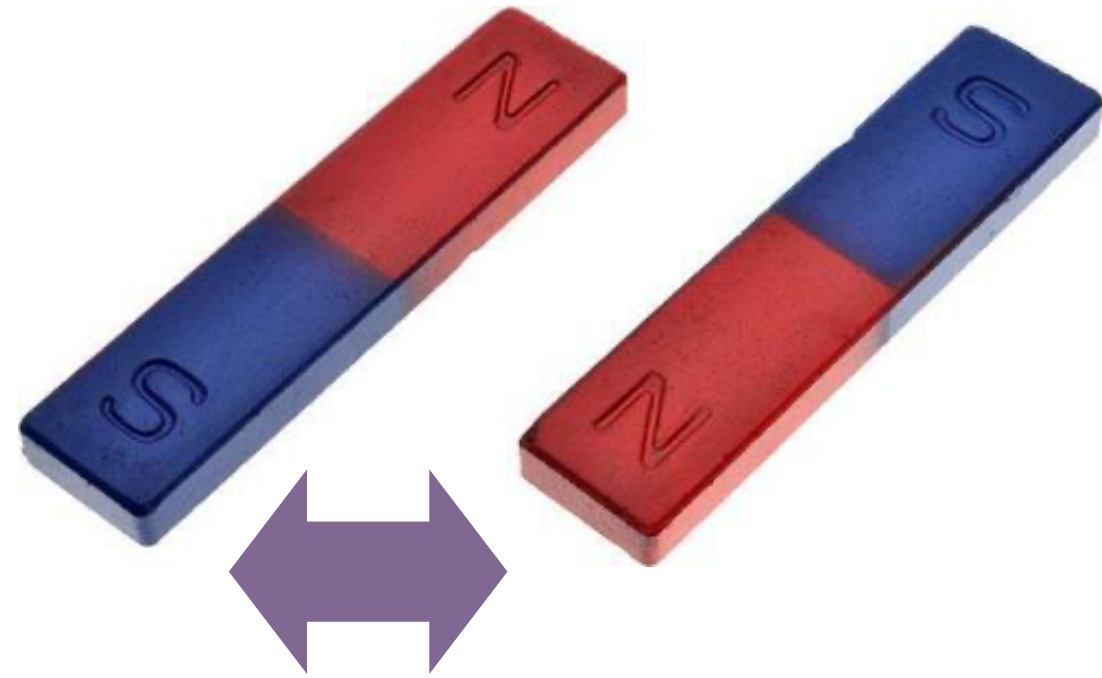
QED vs QCD



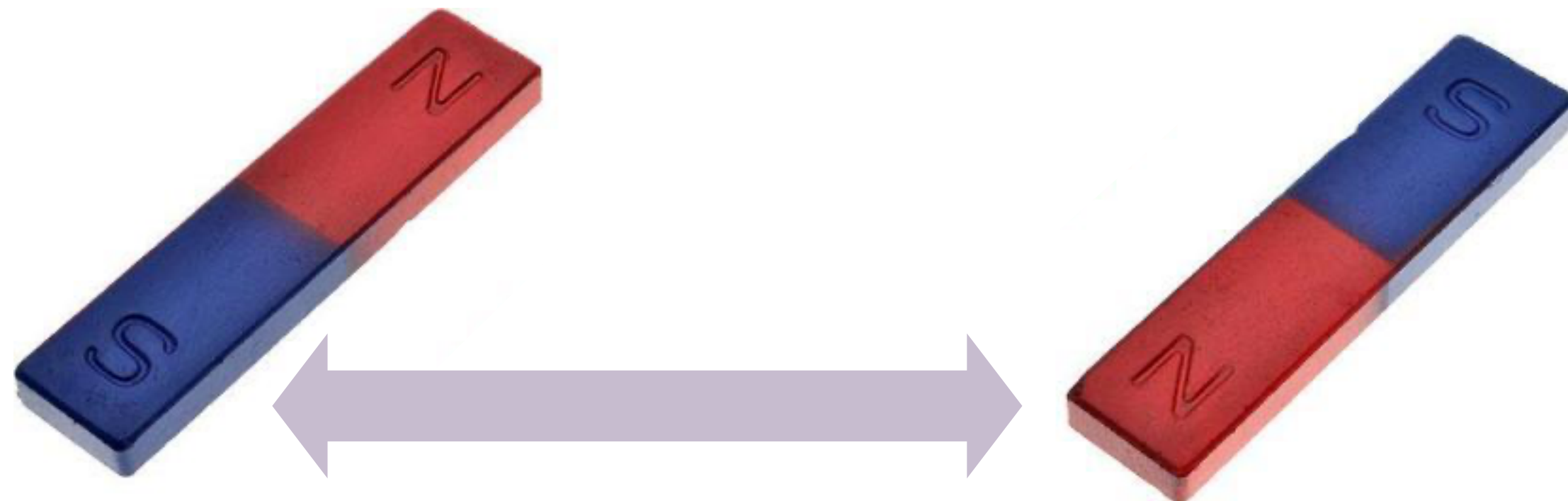
- Quantum Electrodynamics

Photons do not have electric charge

Larger attraction



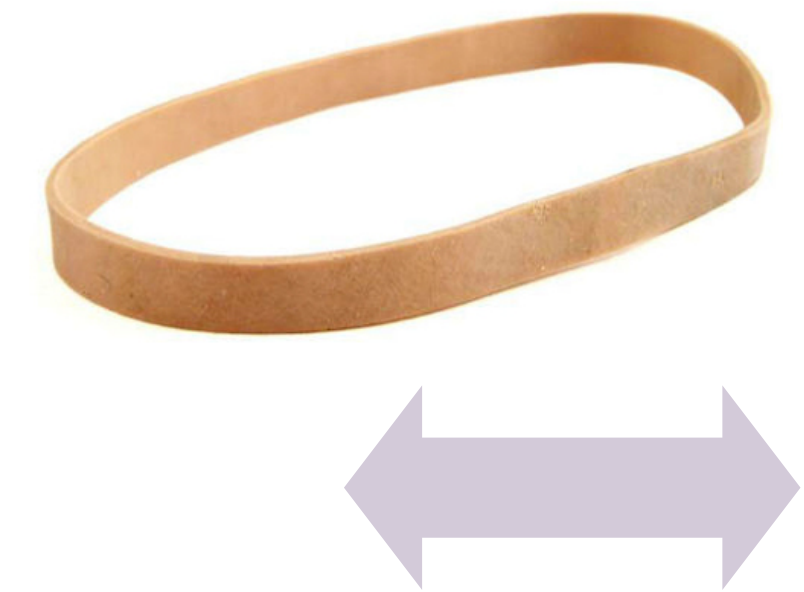
Smaller attraction



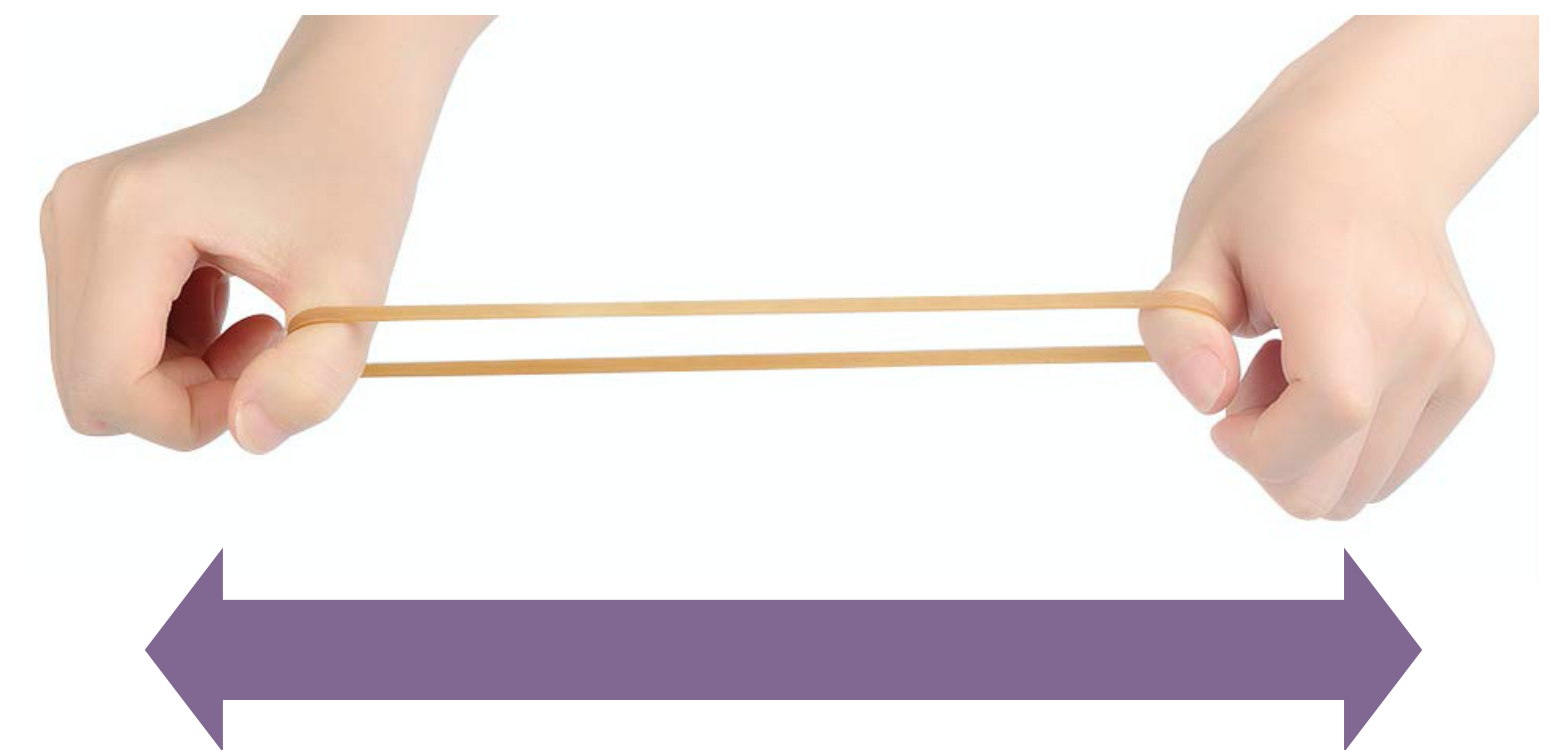
- Quantum Chromodynamics = Strong Force

Gluons are colourful

Smaller attraction

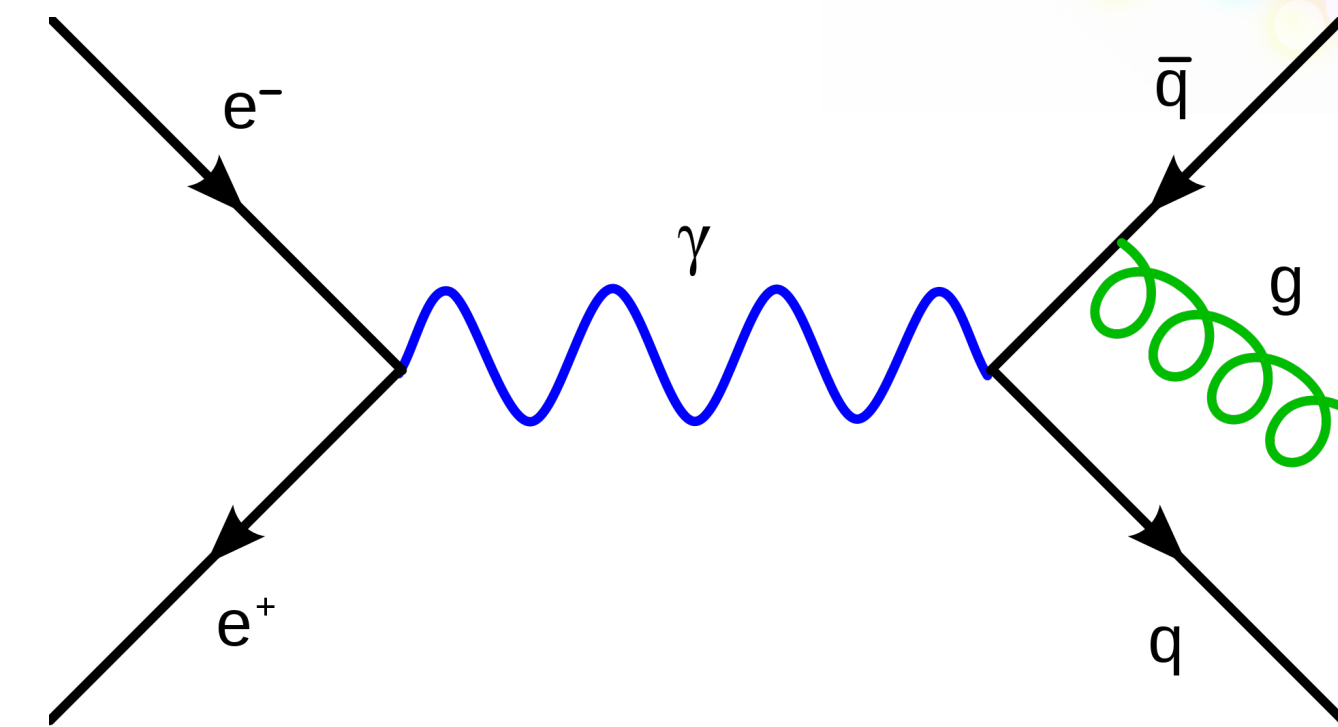
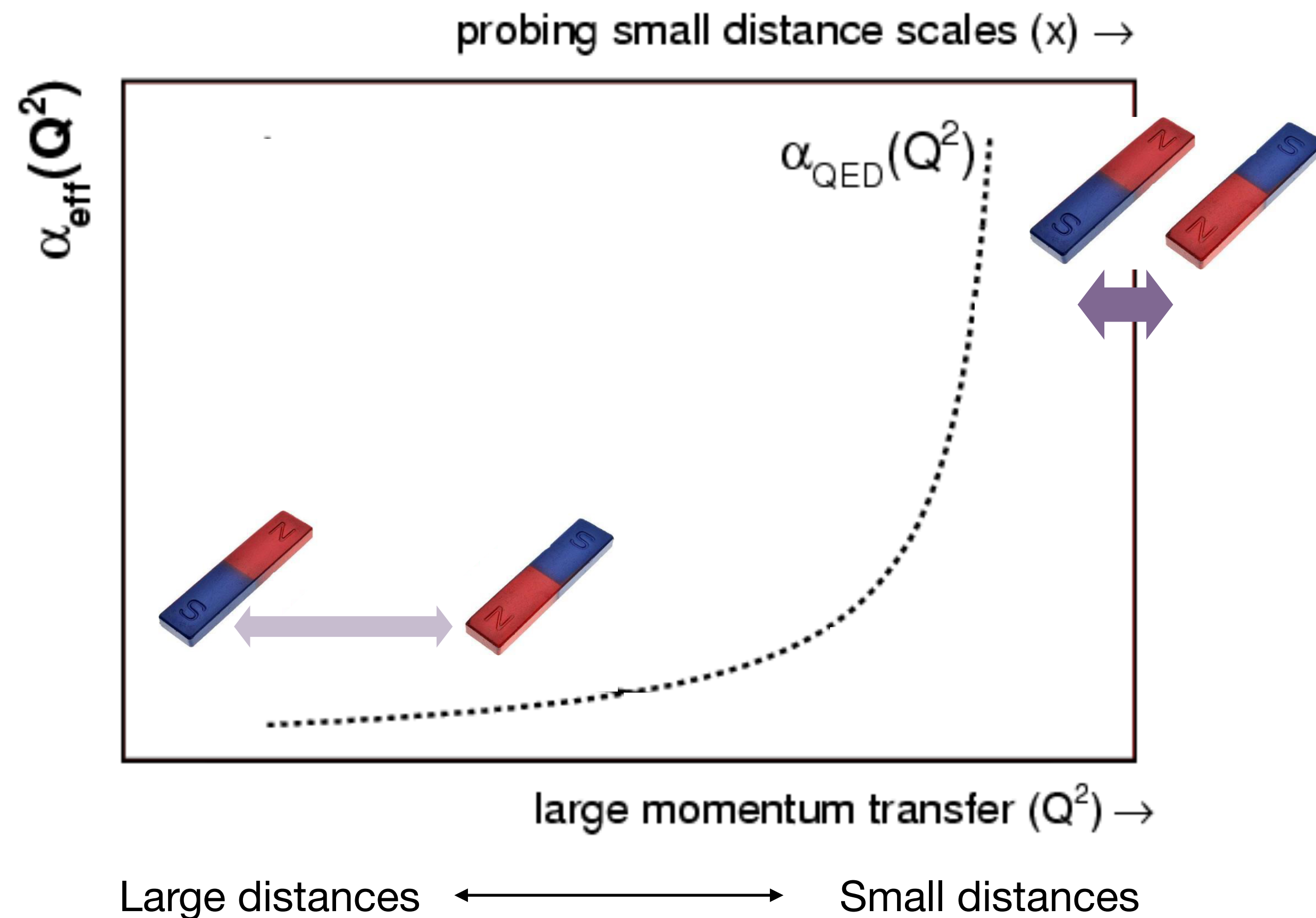


Larger attraction



Coupling Constant

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



Standard Model of Elementary Particles

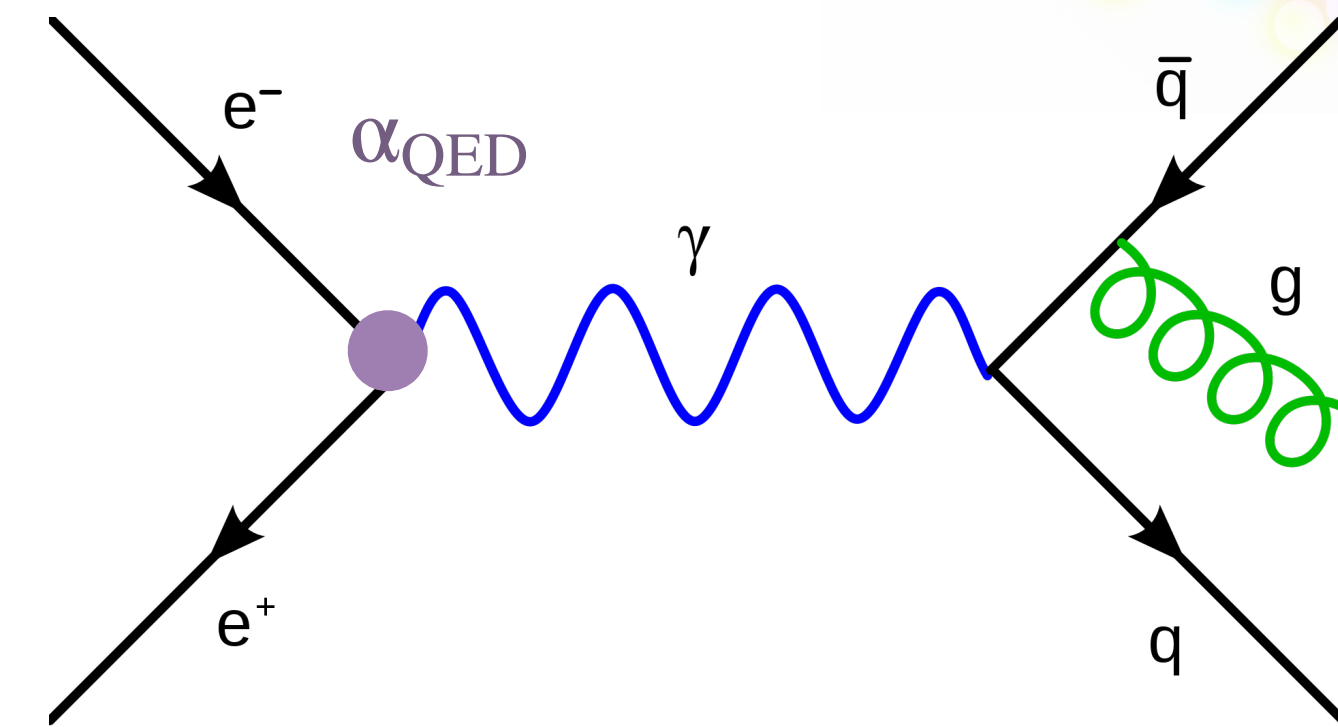
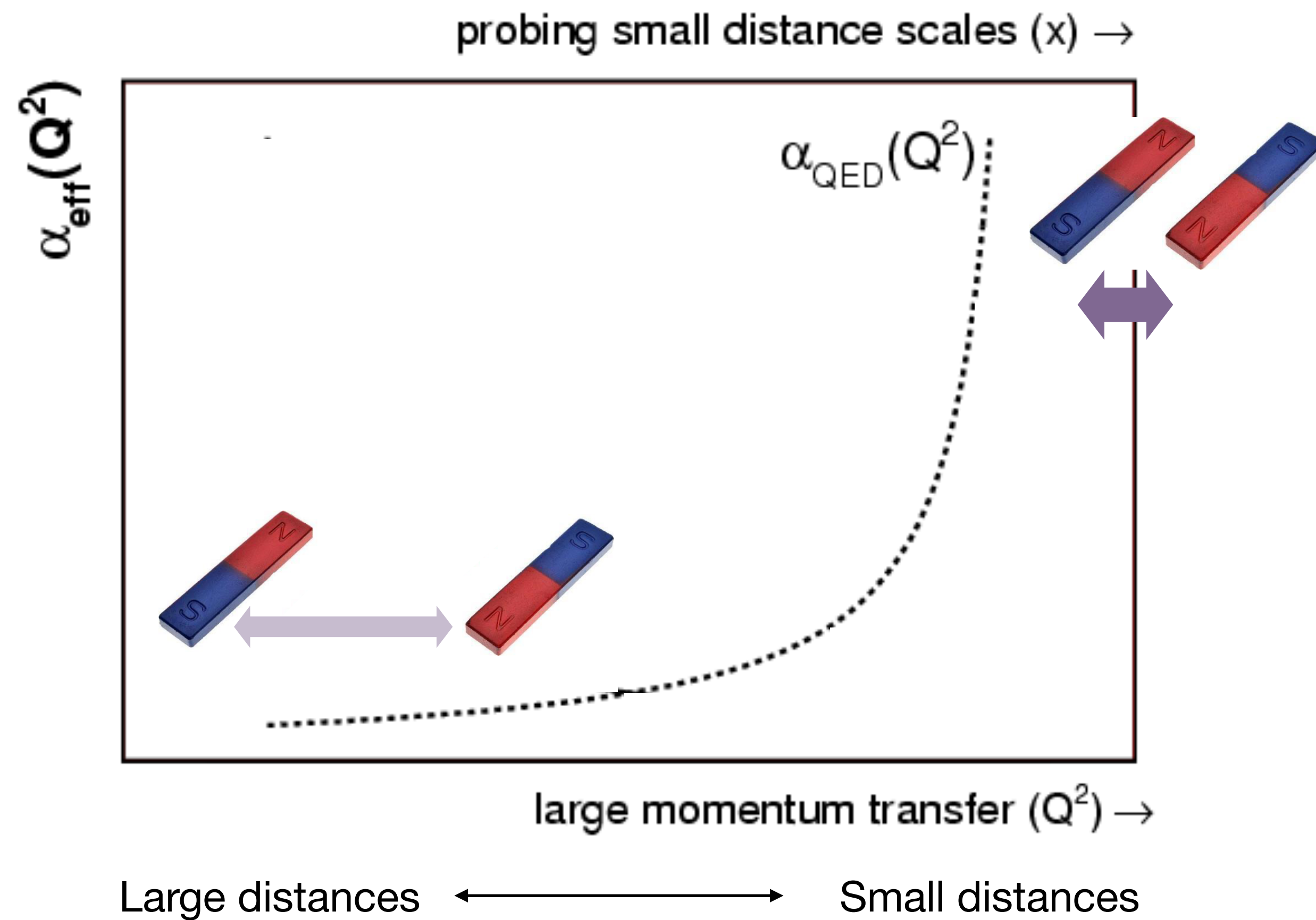
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QUARKS	u up	c charm	t top	g gluon	H higgs
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	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
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GAUGE BOSONS VECTOR BOSONS

SCALAR BOSONS

Coupling Constant

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



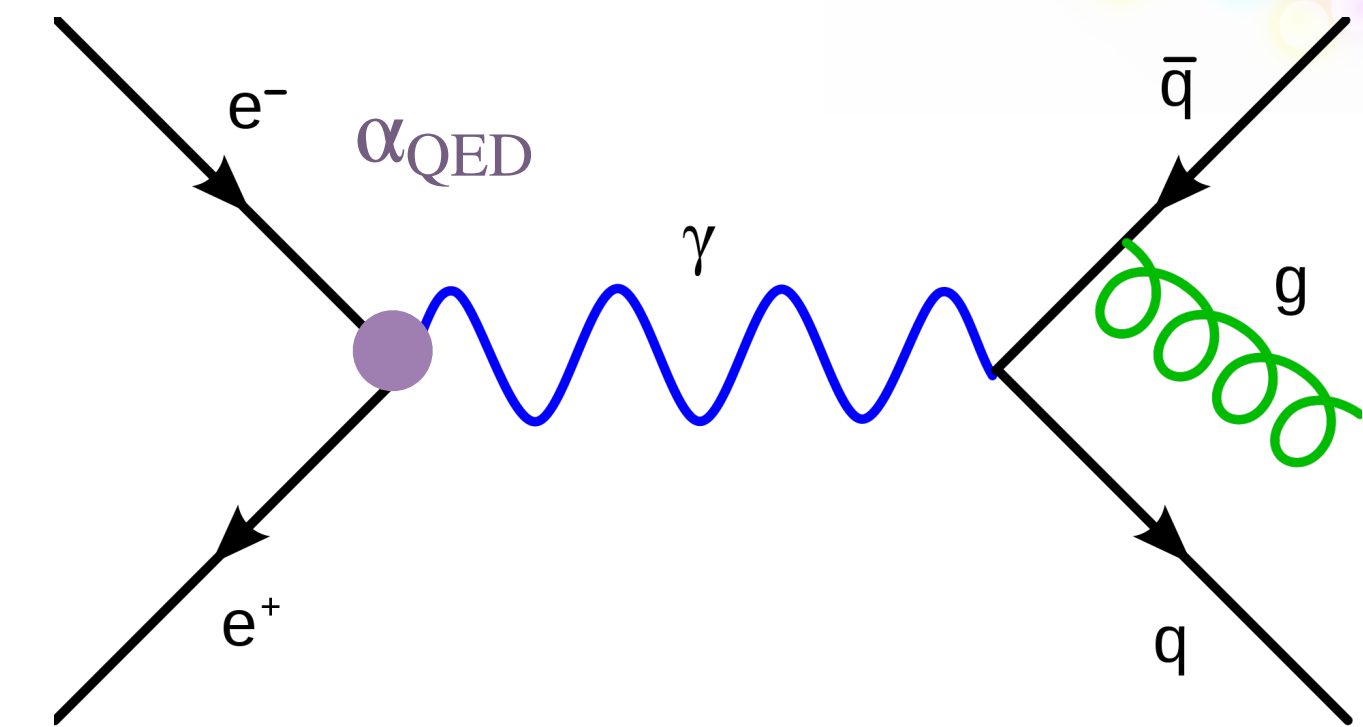
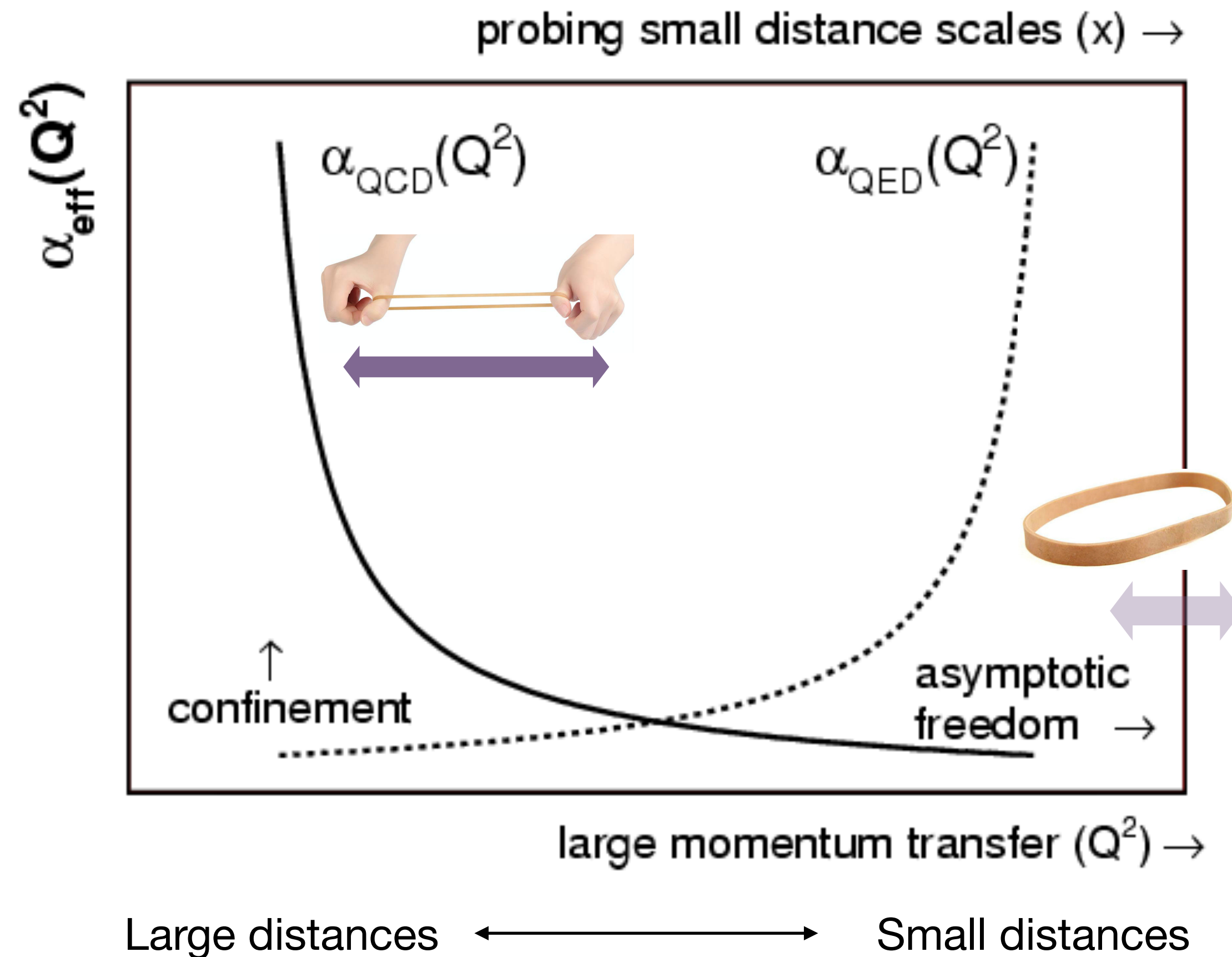
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GAUGE BOSONS VECTOR BOSONS **SCALAR BOSONS**

Coupling Constant

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



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	d down	s strange	b bottom	γ photon	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
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	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	0	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	± 1	$\approx 80.39 \text{ GeV}/c^2$
	$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	1	
	0	0	0		
	W W boson				
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$		

QUARKS

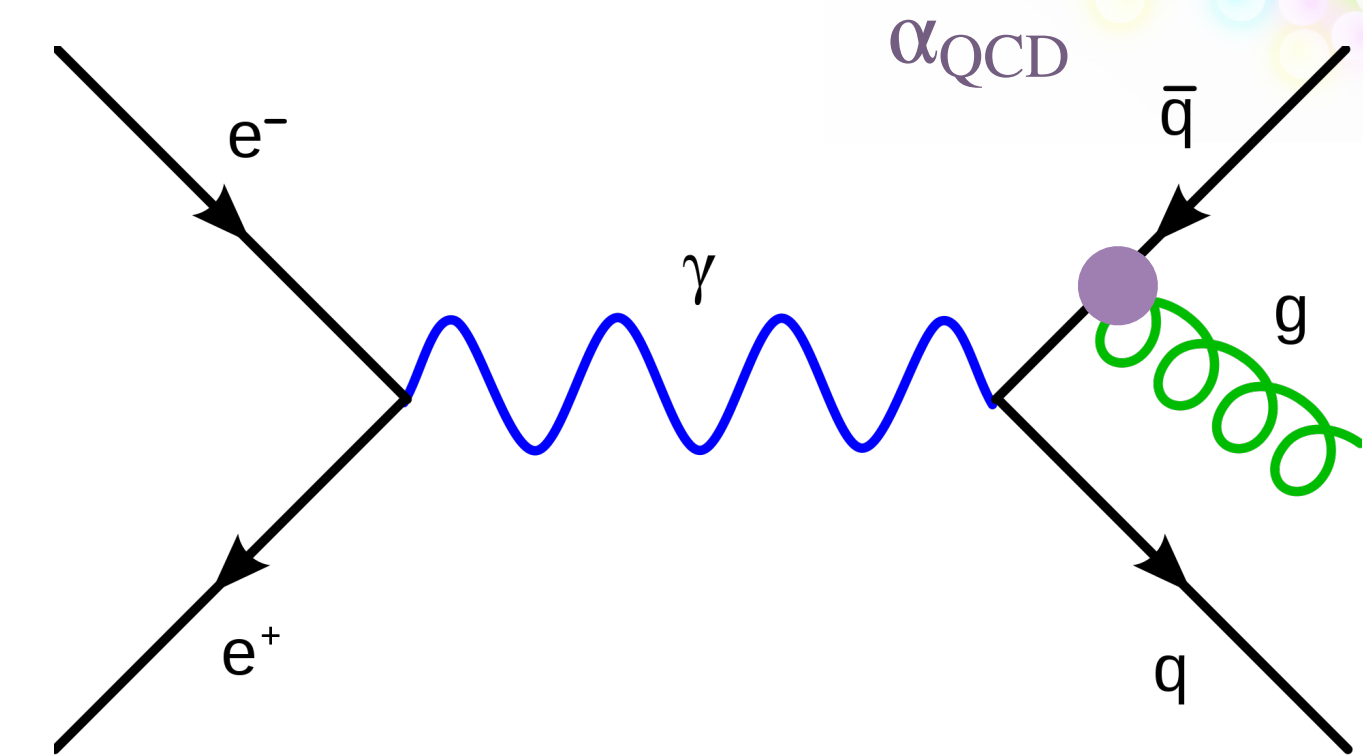
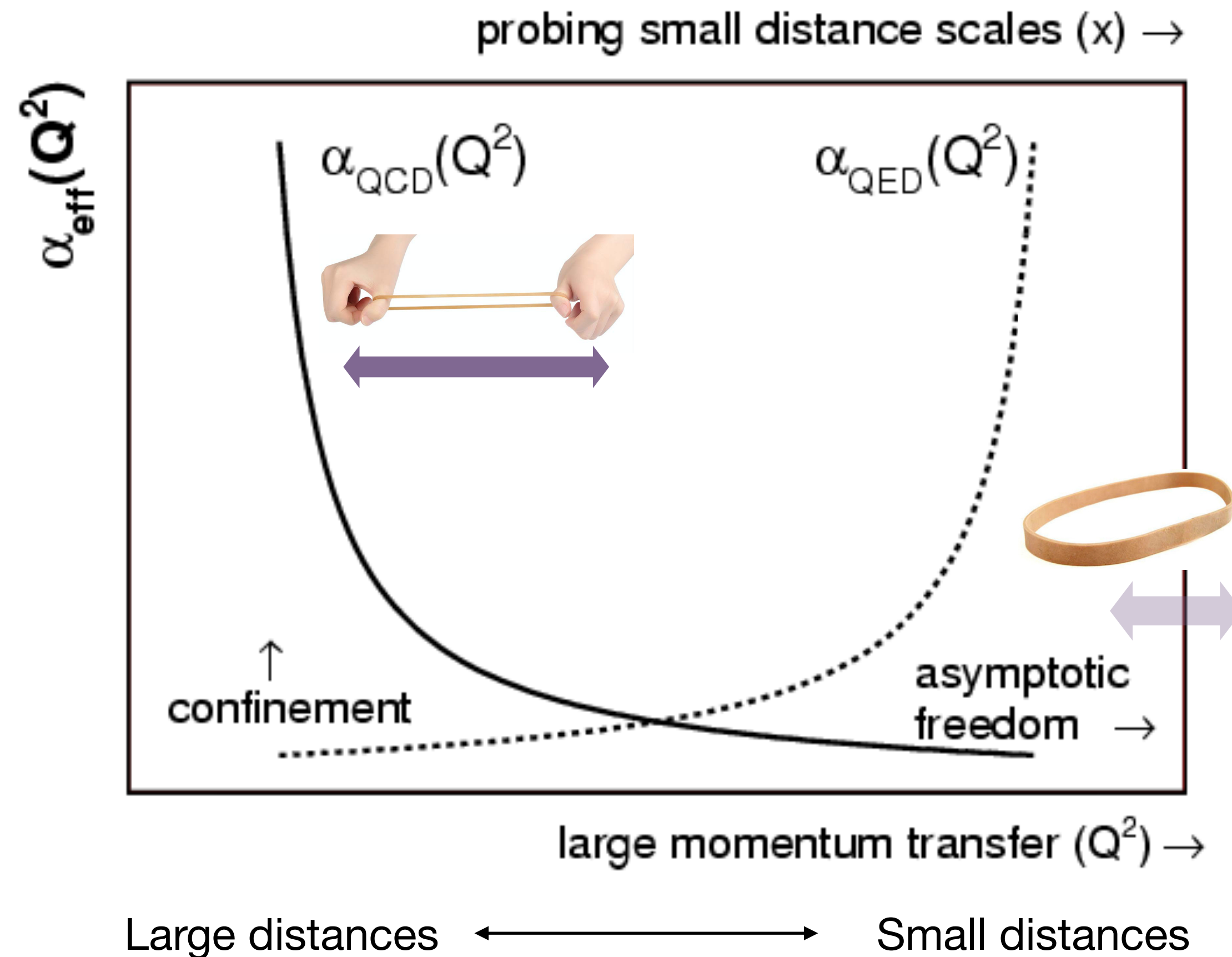
LEPTONS

GAUGE BOSONS VECTOR BOSONS

SCALAR BOSONS

Coupling Constant

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



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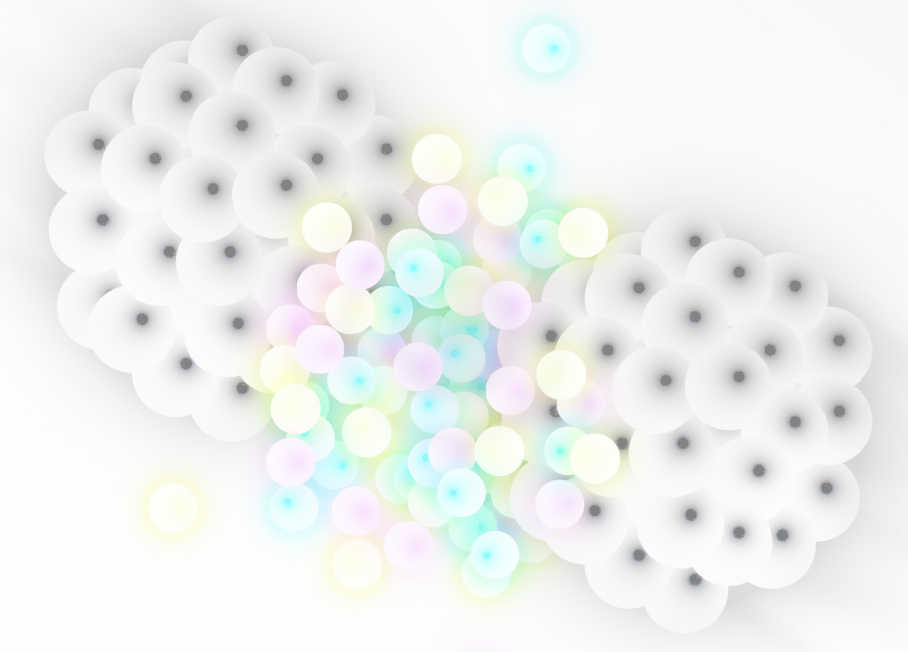
QUARKS

LEPTONS

GAUGE BOSONS VECTOR BOSONS

SCALAR BOSONS

Quantum Chromodynamics



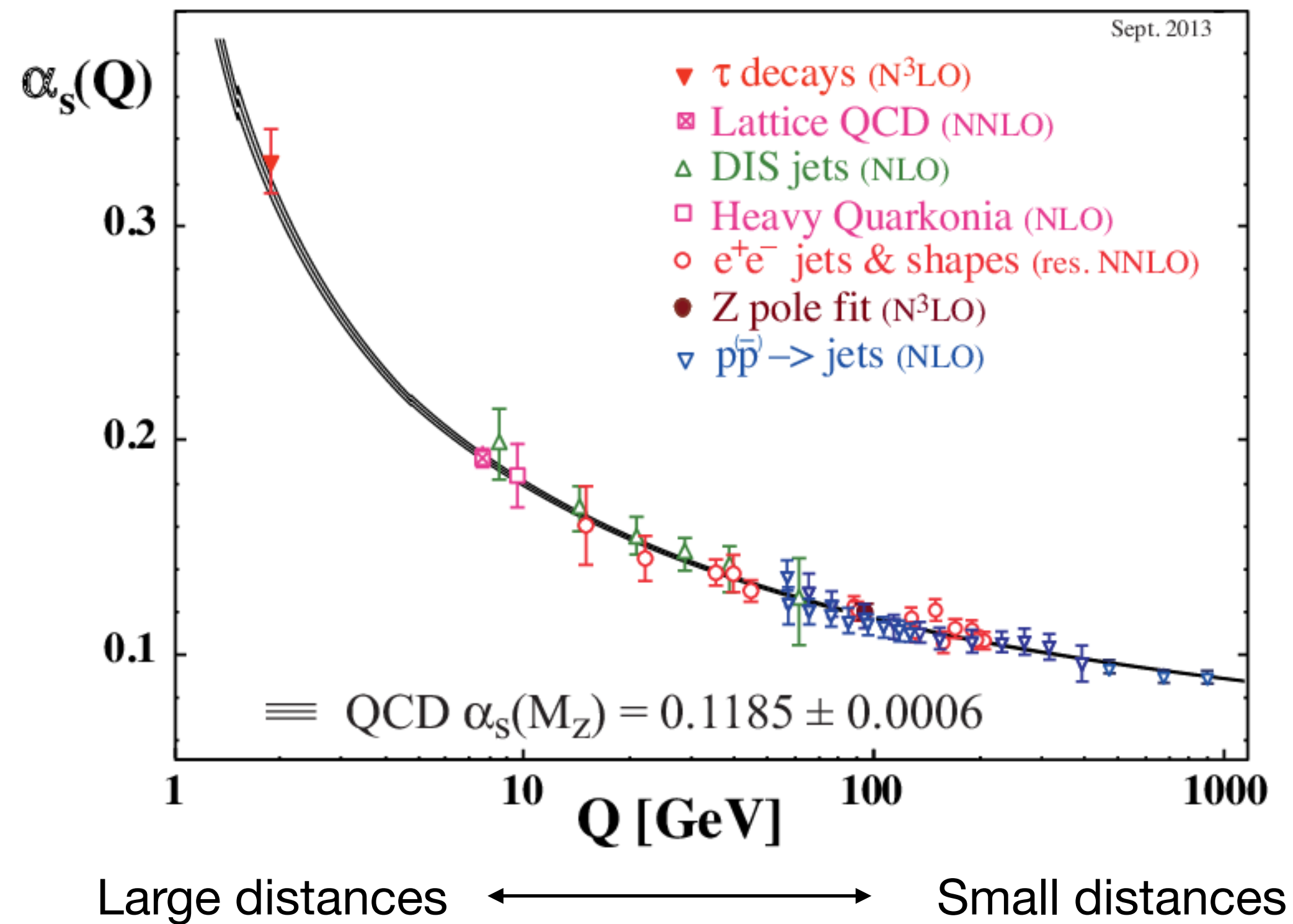
- Interaction strength given by α_{QED} and α_{QCD}

$$\mathcal{L} = \frac{1}{4g^2} G_{\mu\nu}^a G_{\mu\nu}^a + \sum_f \bar{\psi}_f (i\gamma^\mu \partial_\mu + m_f) \psi_f$$

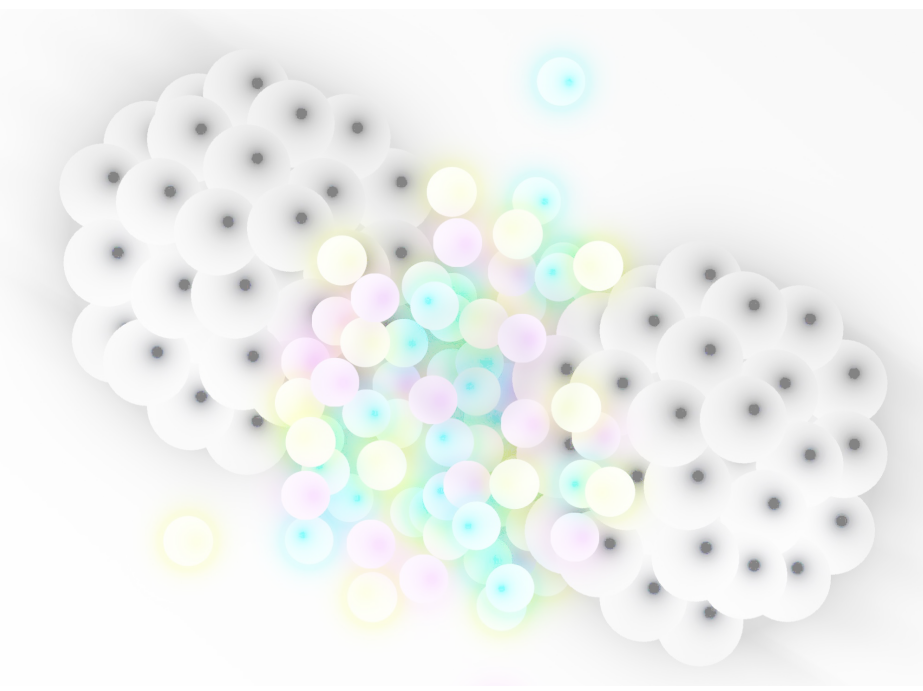
where $G_{\mu\nu}^a \equiv \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + gf_{abc} A_\mu^b A_\nu^c$

and $D_\mu = \partial_\mu + it^a A_\mu^a$

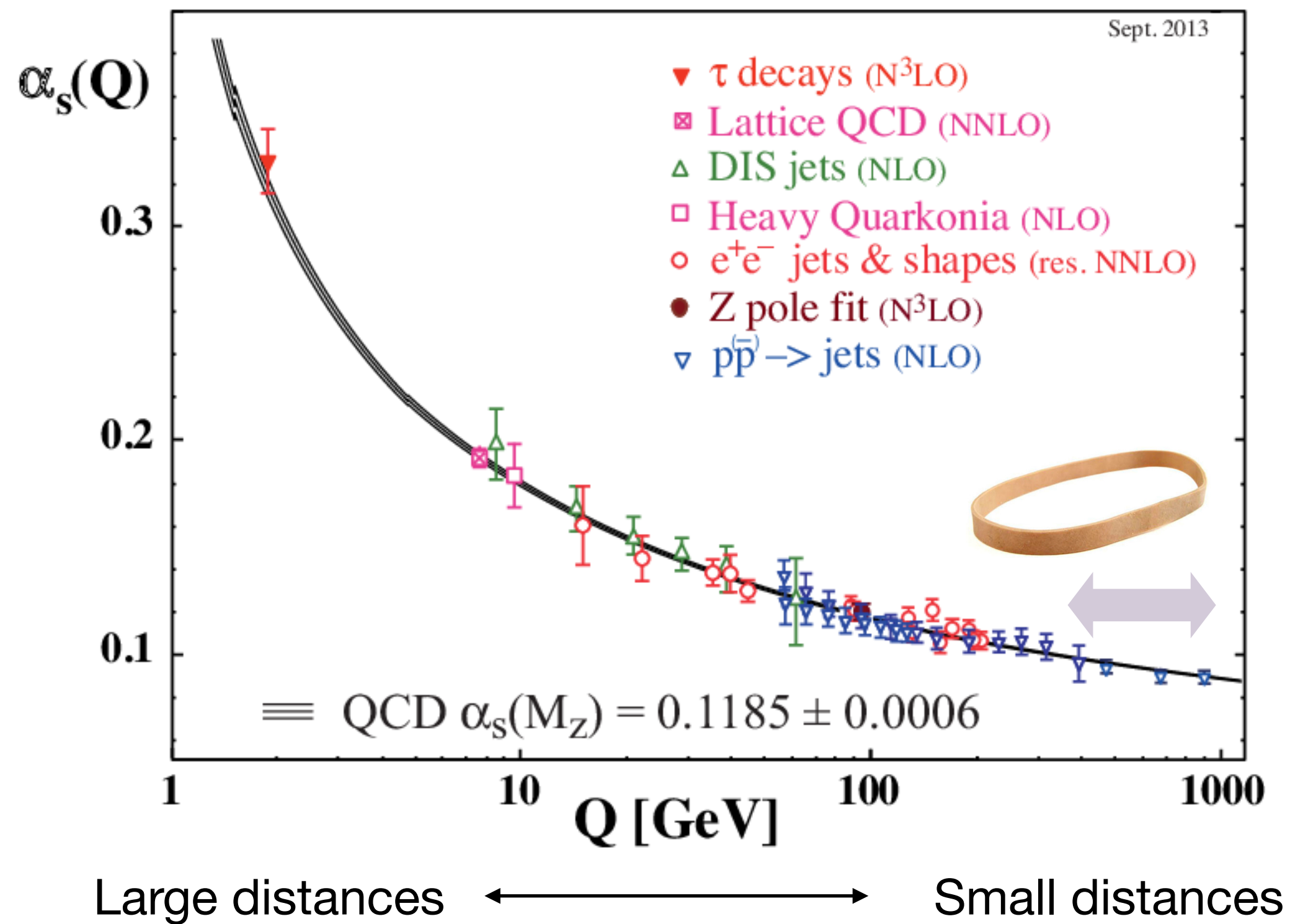
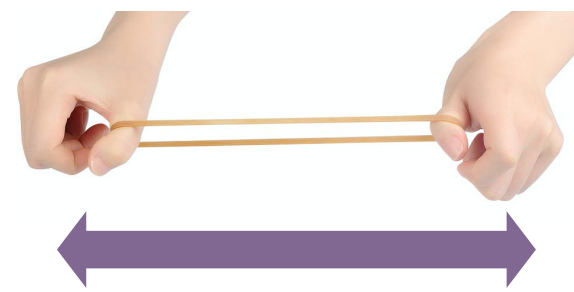
That's it!



Quantum Chromodynamics



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



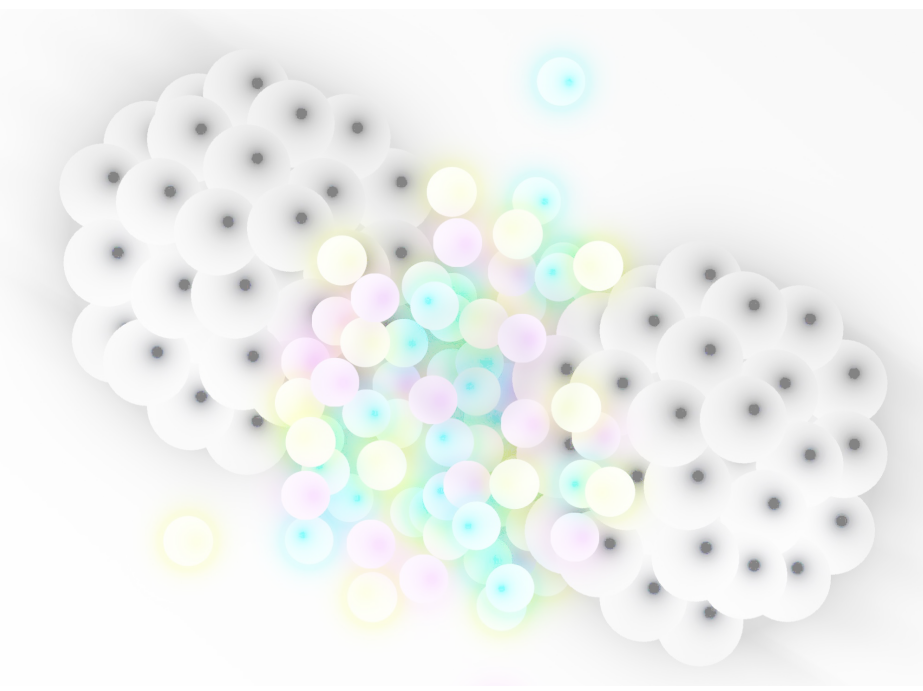
$$\mathcal{L} = \frac{1}{4g^2} G_{\mu\nu}^a G_{\mu\nu}^a + \sum_f \bar{\psi}_f (i\gamma^\mu \partial_\mu + m_f) \psi_f$$

where $G_{\mu\nu}^a \equiv \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + gf_{abc} A_\mu^b A_\nu^c$

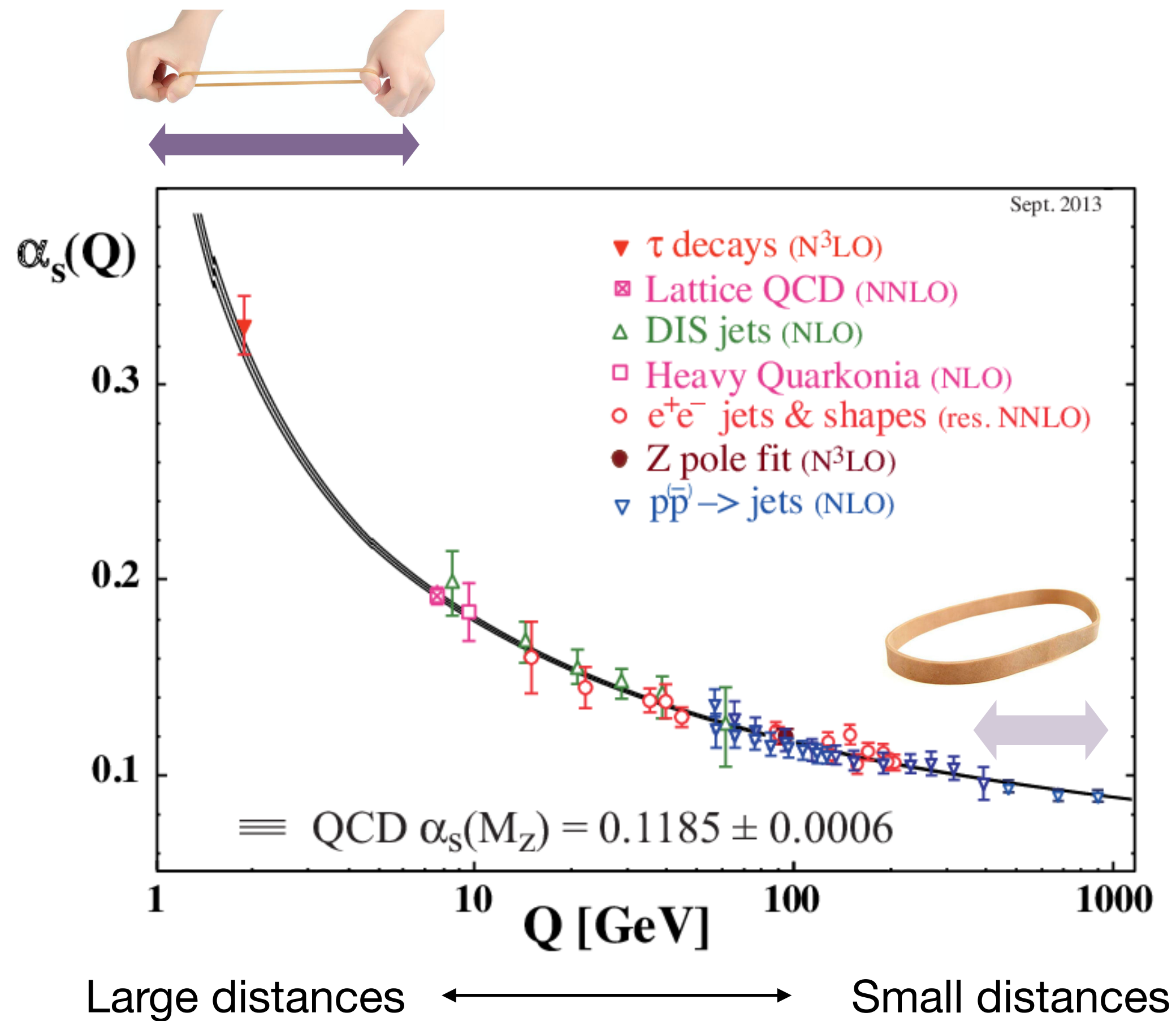
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Quantum Chromodynamics



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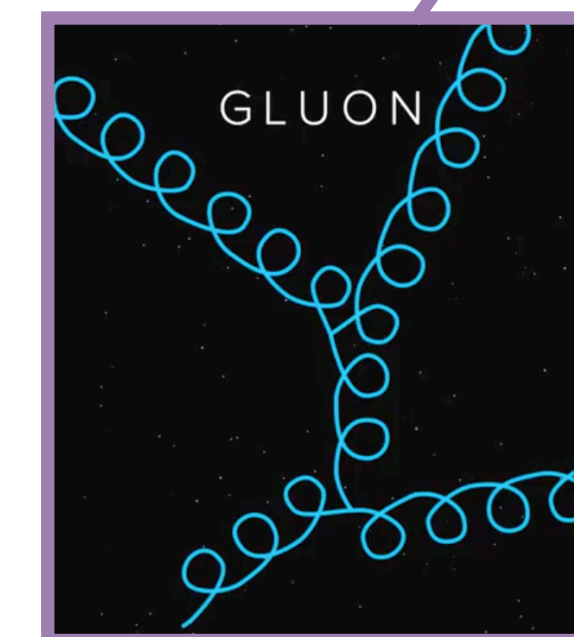


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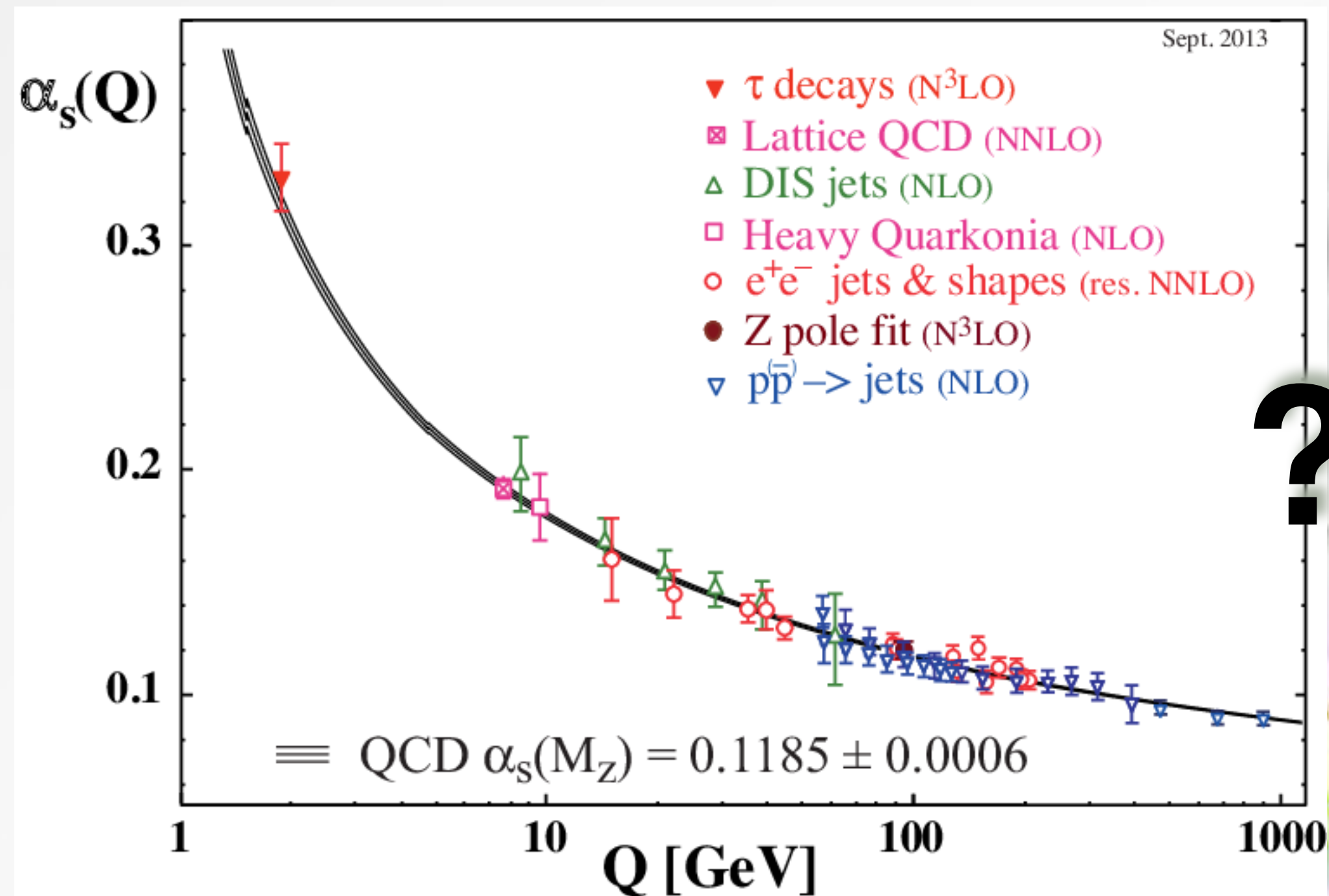
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How do we “work” with QCD?



???

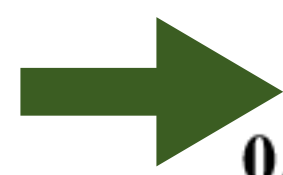
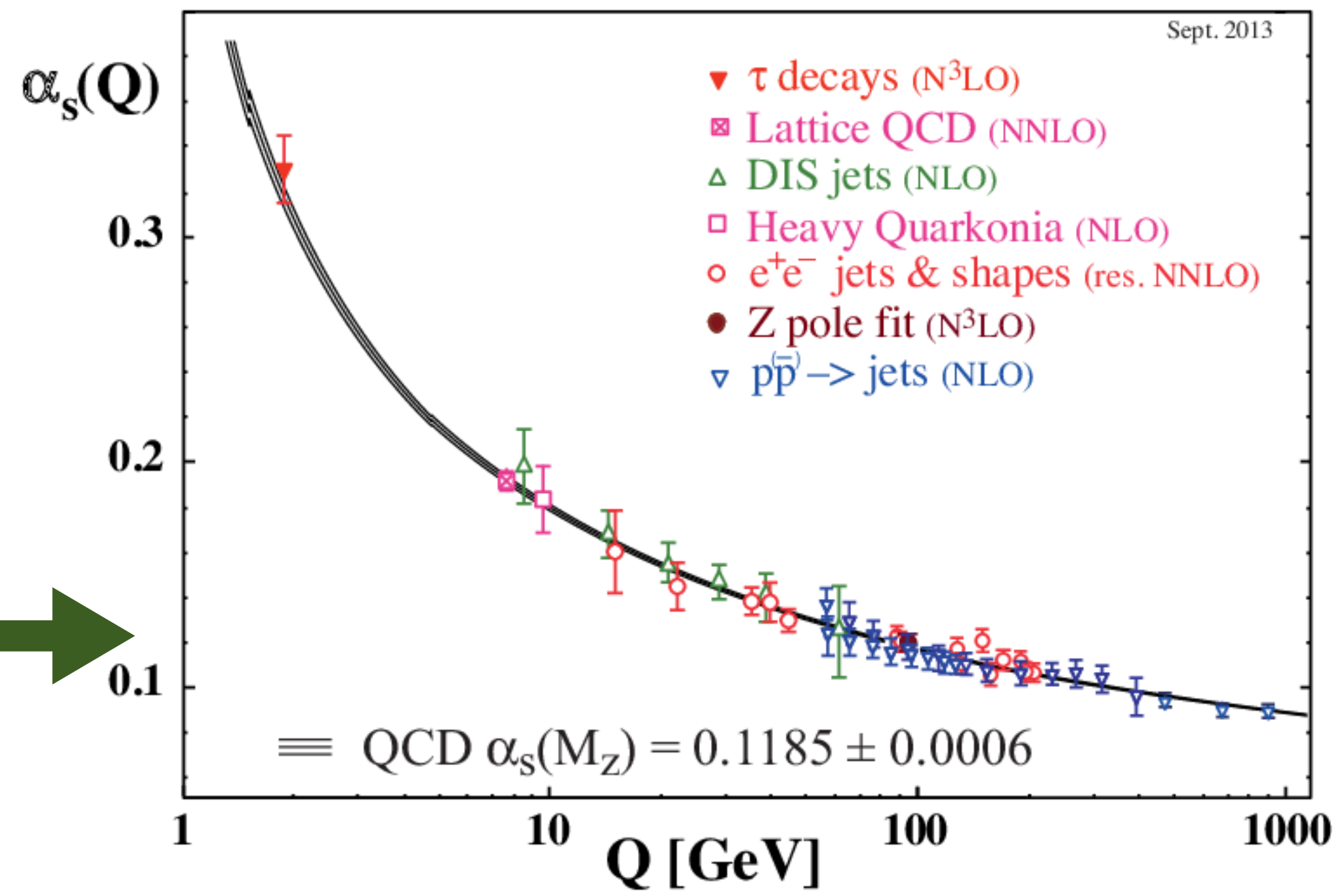
$$\mathcal{L} = \frac{1}{4g^2} G_{\mu\nu}^a G_{\mu\nu}^a + \sum_f \bar{q}_i (i\gamma^\mu D_\mu + m_j) q_i$$

where $G_{\mu\nu}^a \equiv \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + gf_{abc} A_\mu^b A_\nu^c$

and $D_\mu = \partial_\mu + it^a A_\mu^a$

That's it!

Asymptotic Freedom



Large distances ← → Small distances

$$\mathcal{L} = \frac{1}{4g^2} G_{\mu\nu}^a G_{\mu\nu}^a + \sum_f \bar{\psi}_f (i\gamma^\mu \partial_\mu + m_f) \psi_f$$

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That's it!

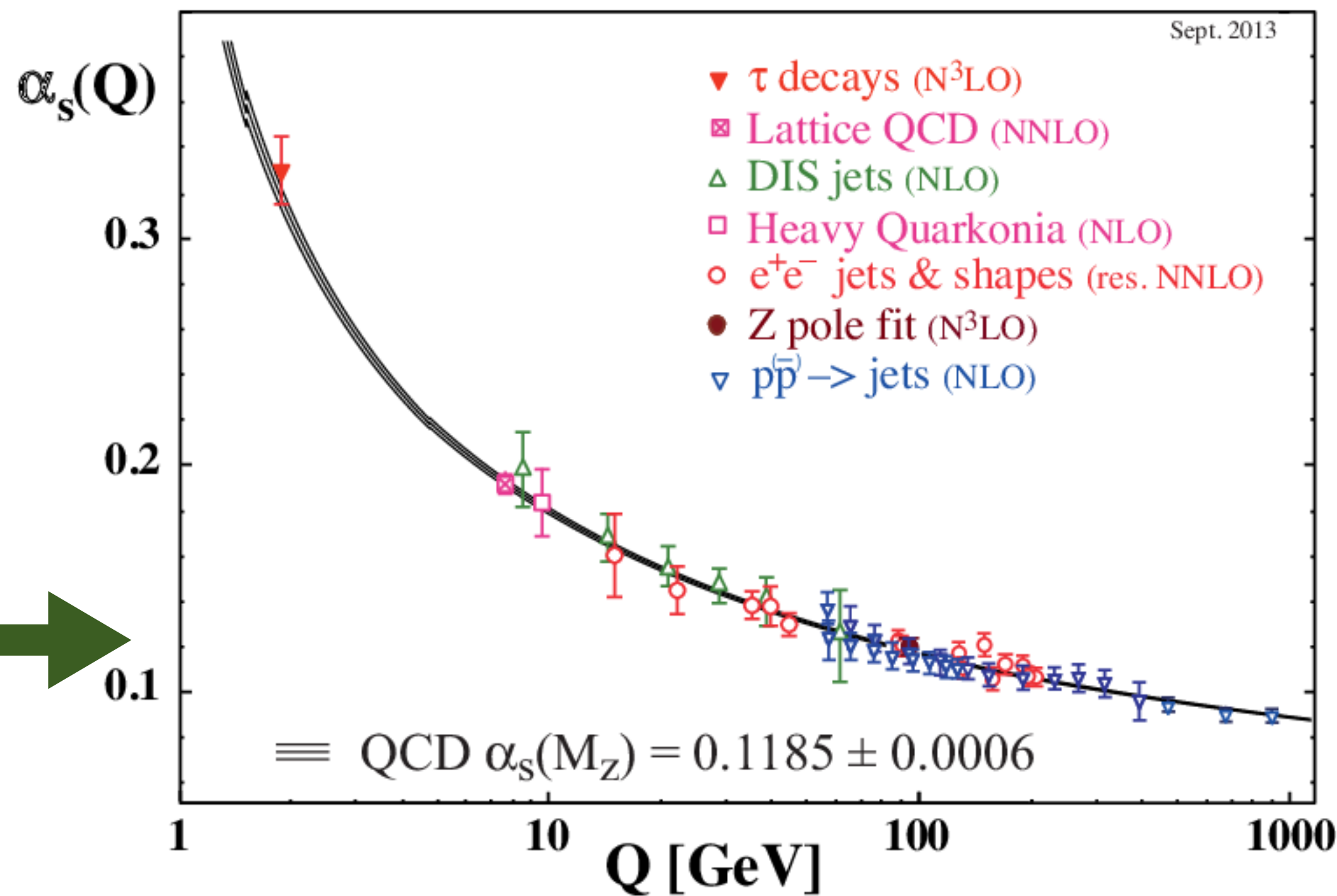
Example: Taylor Series of $f(x)$

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

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

Higher order terms can be neglected for $x \ll 1$

Asymptotic Freedom



Large distances ← → Small distances

QCD Lagrangian within perturbation theory!

→ perturbative QCD (pQCD)

$$\mathcal{L} = \frac{1}{4g^2} G_{\mu\nu}^a G_{\mu\nu}^a + \sum_f \bar{\psi}_f (i\gamma^\mu \partial_\mu + m_f) \psi_f$$

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That's it!

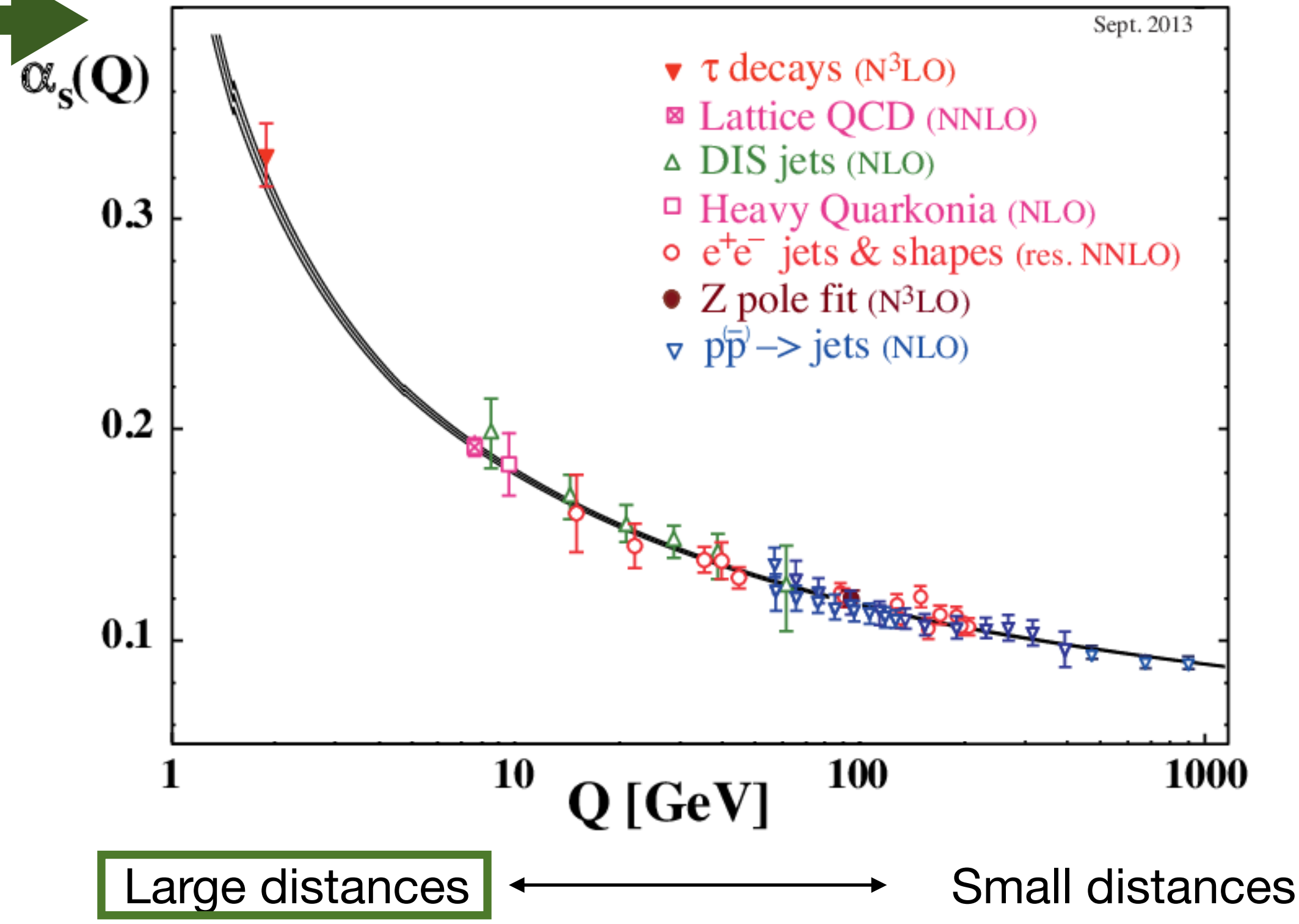
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Higher order terms can be neglected for $x \ll 1$

Confinement

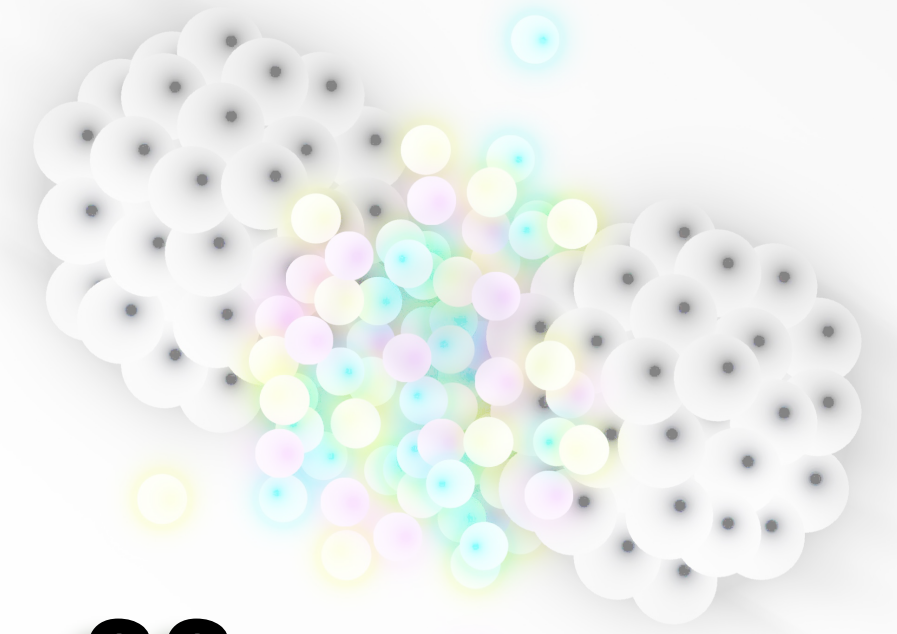


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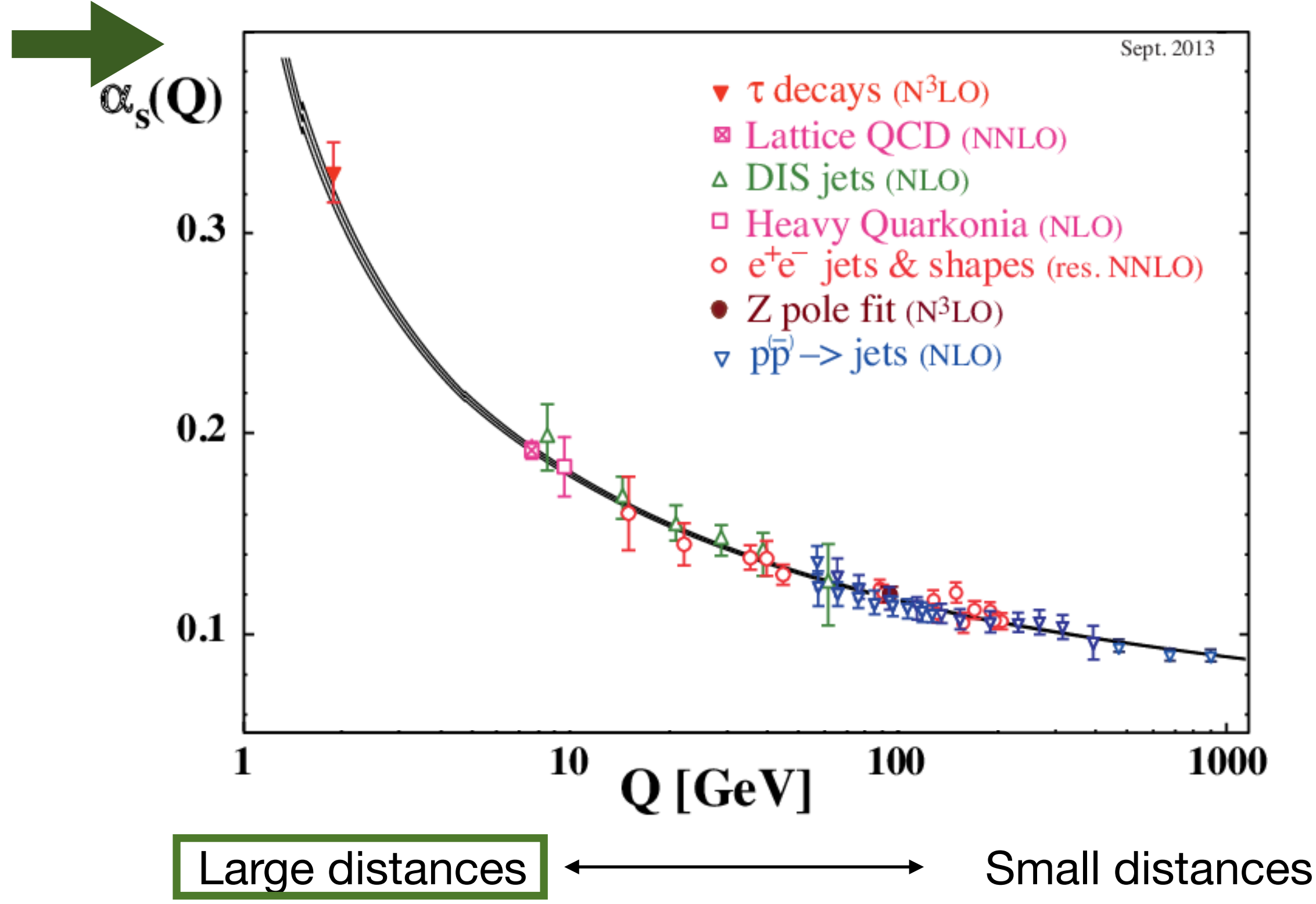
and $D_\mu \equiv \partial_\mu + it^a A_\mu^a$

That's it!



??

Confinement

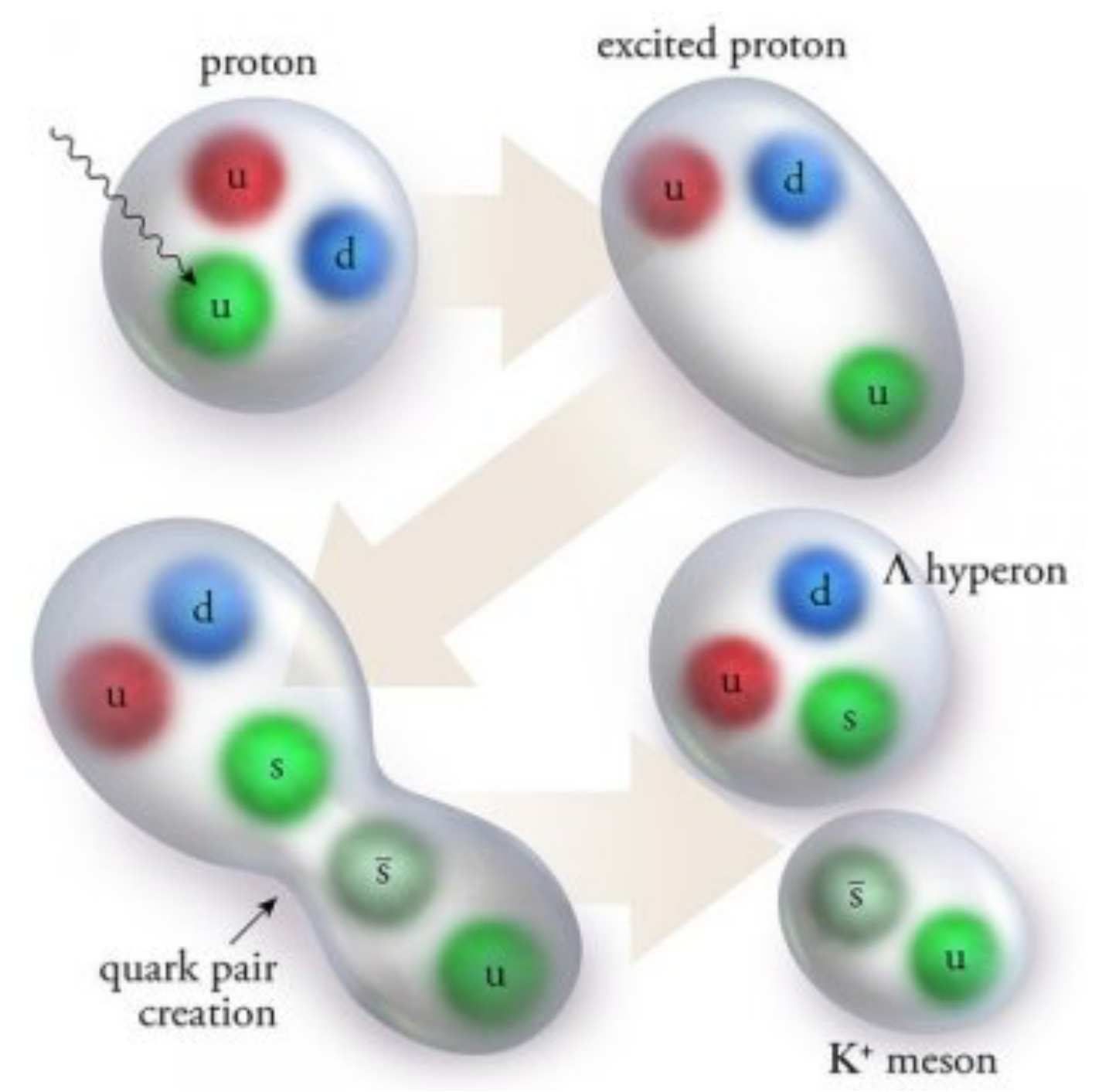
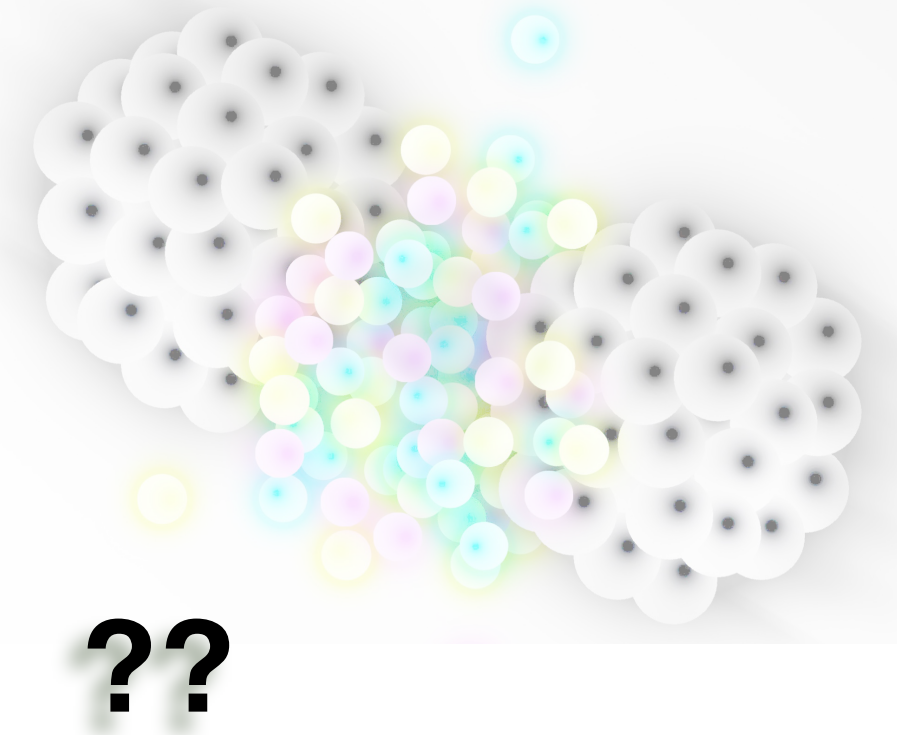


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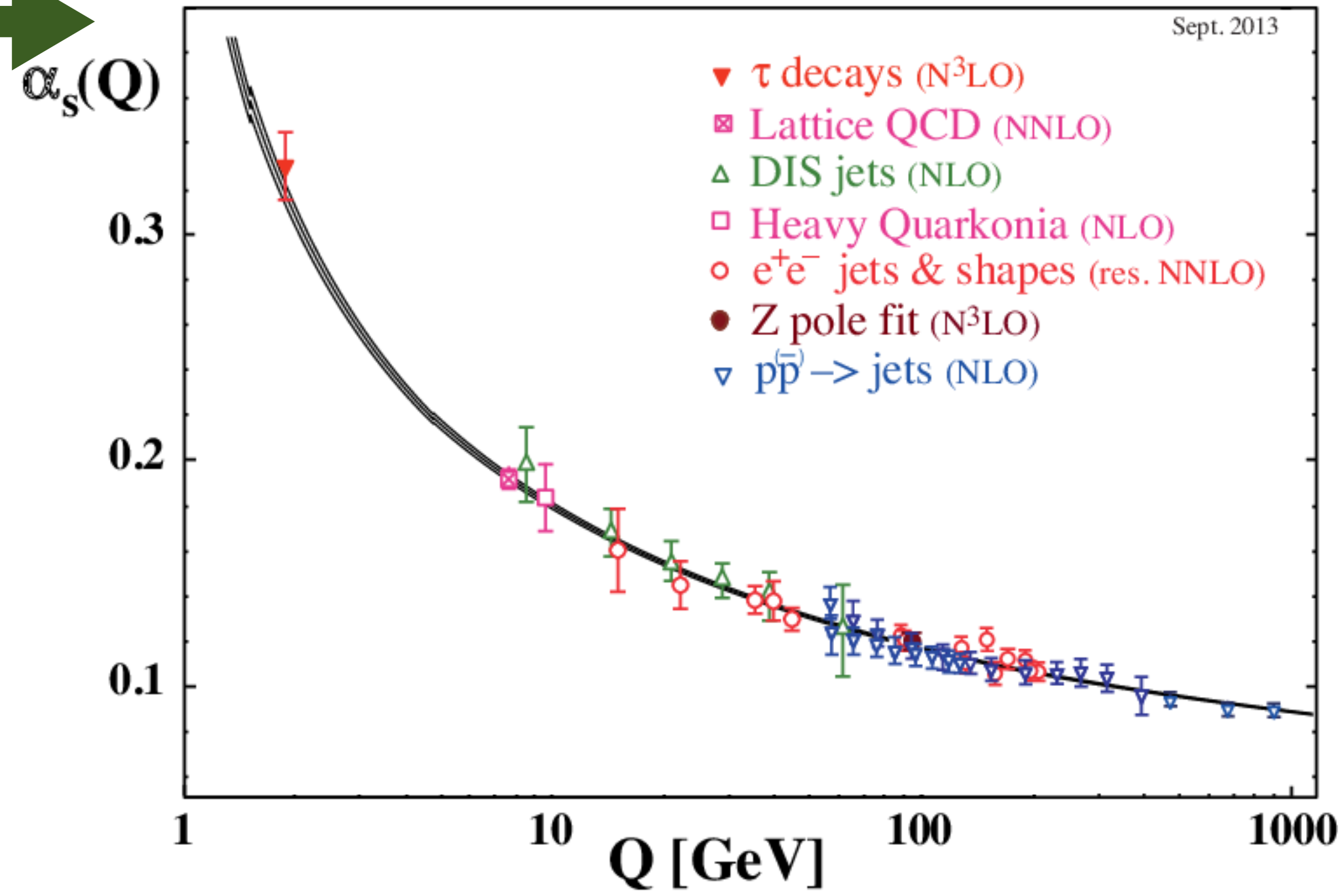
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Confinement



Large distances ← → Small distances

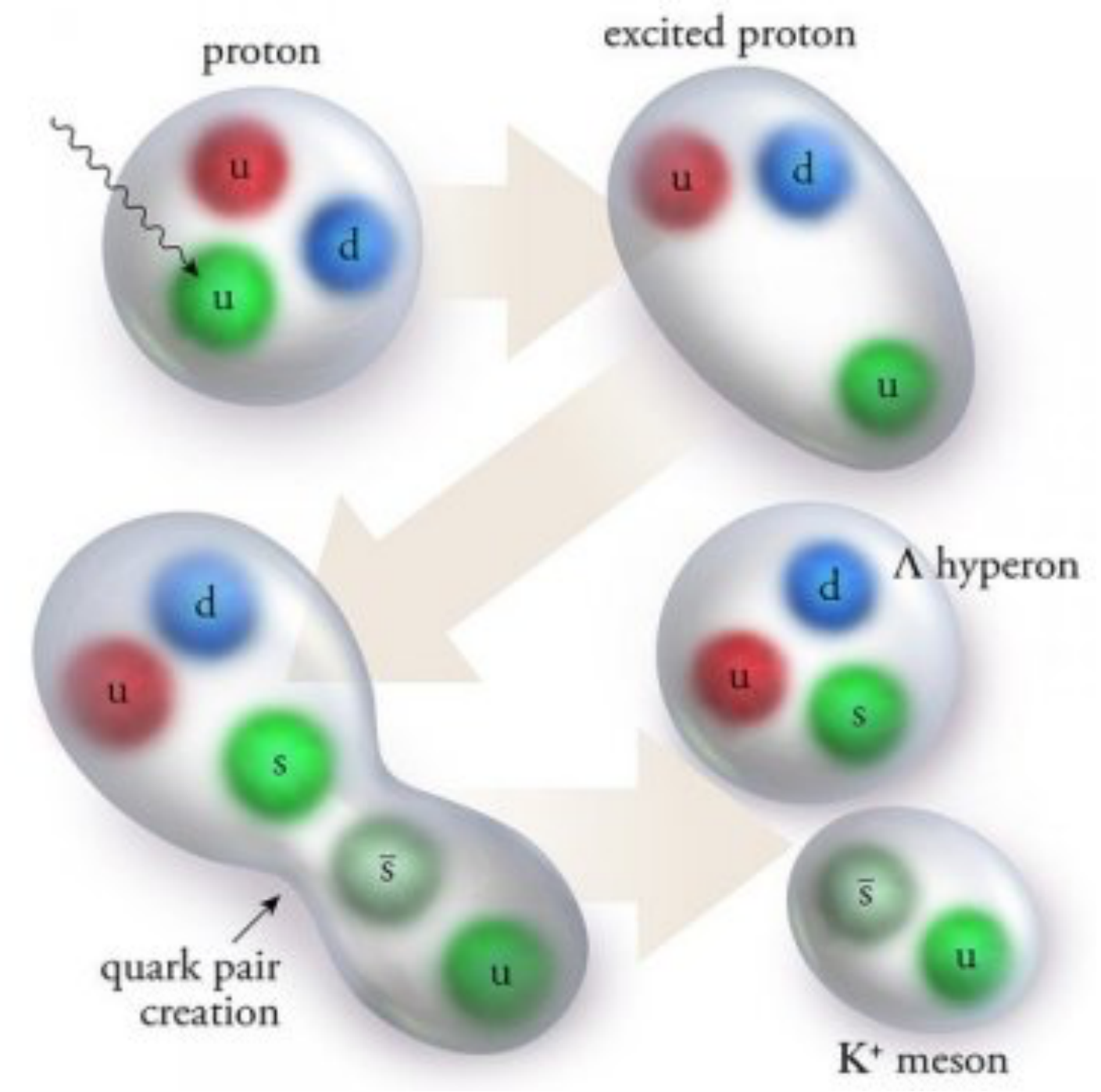
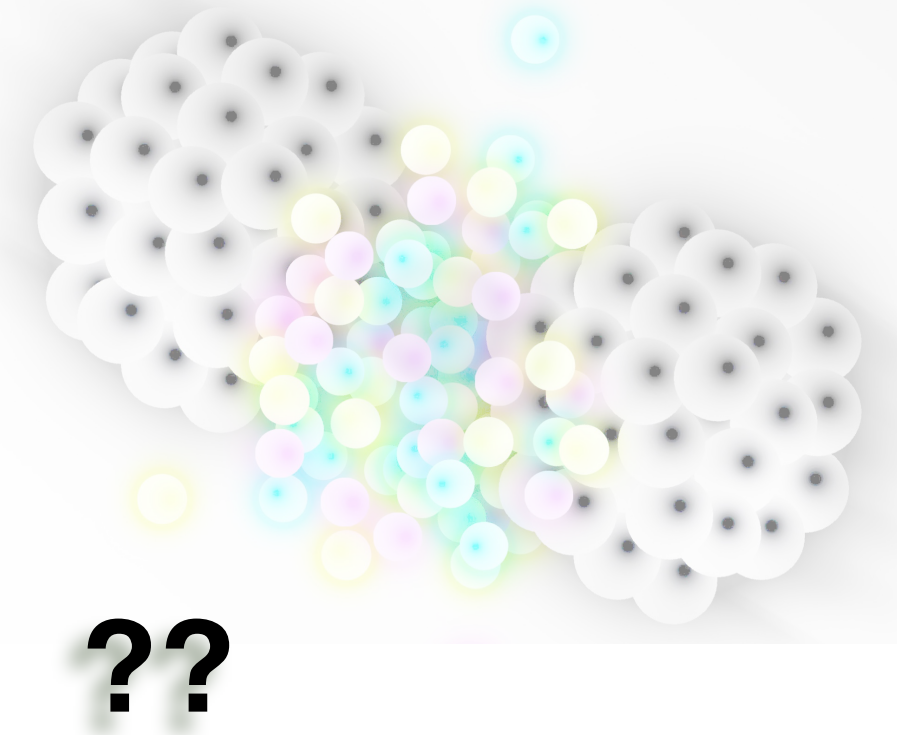
Perturbation theory not possible...
 → Non-perturbative QCD (non-pQCD)

$$\mathcal{L} = \frac{1}{4g^2} G_{\mu\nu}^a G_{\mu\nu}^a + \sum_f \bar{\psi}_f (i\gamma^\mu \partial_\mu + m_f) \psi_f$$

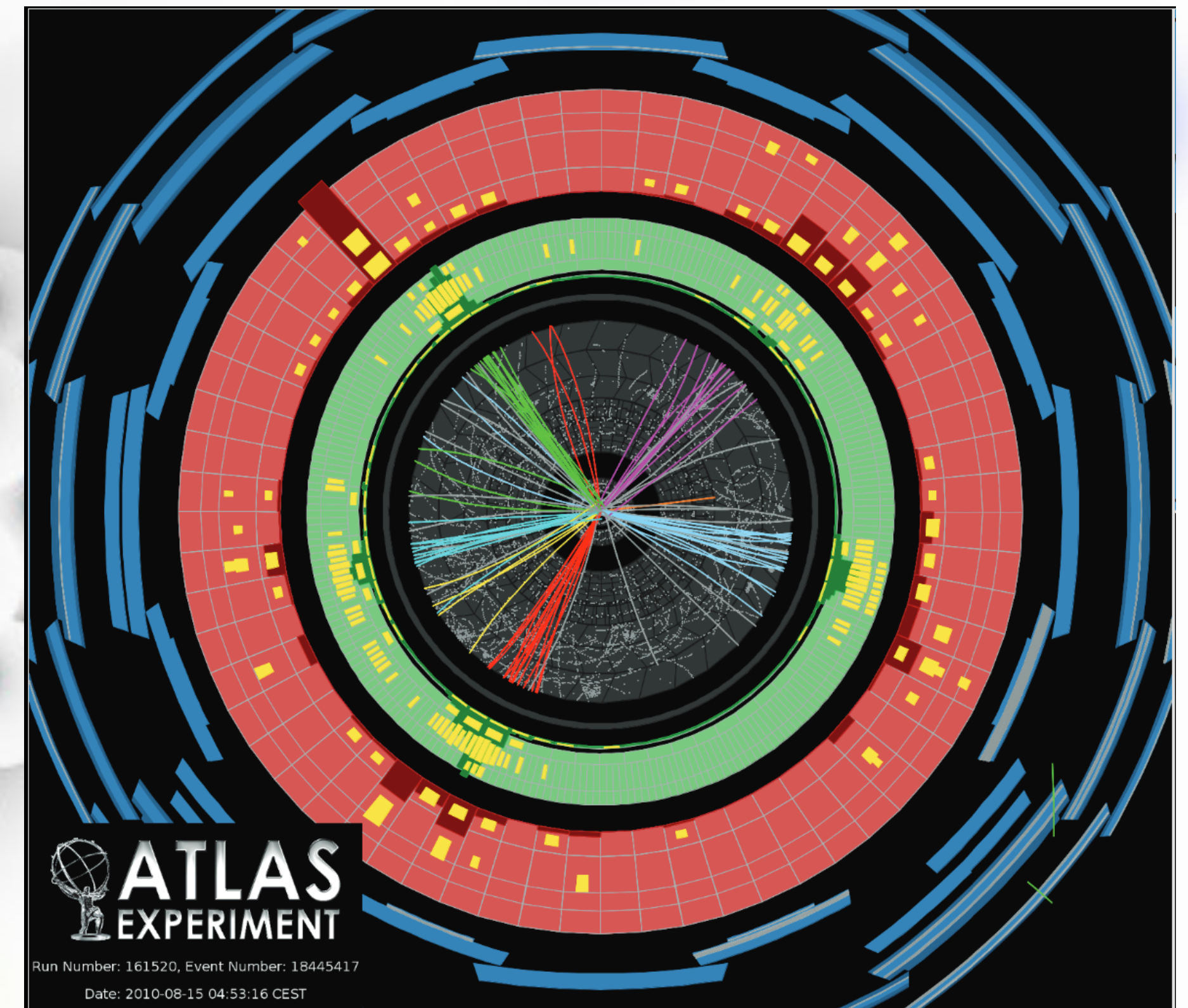
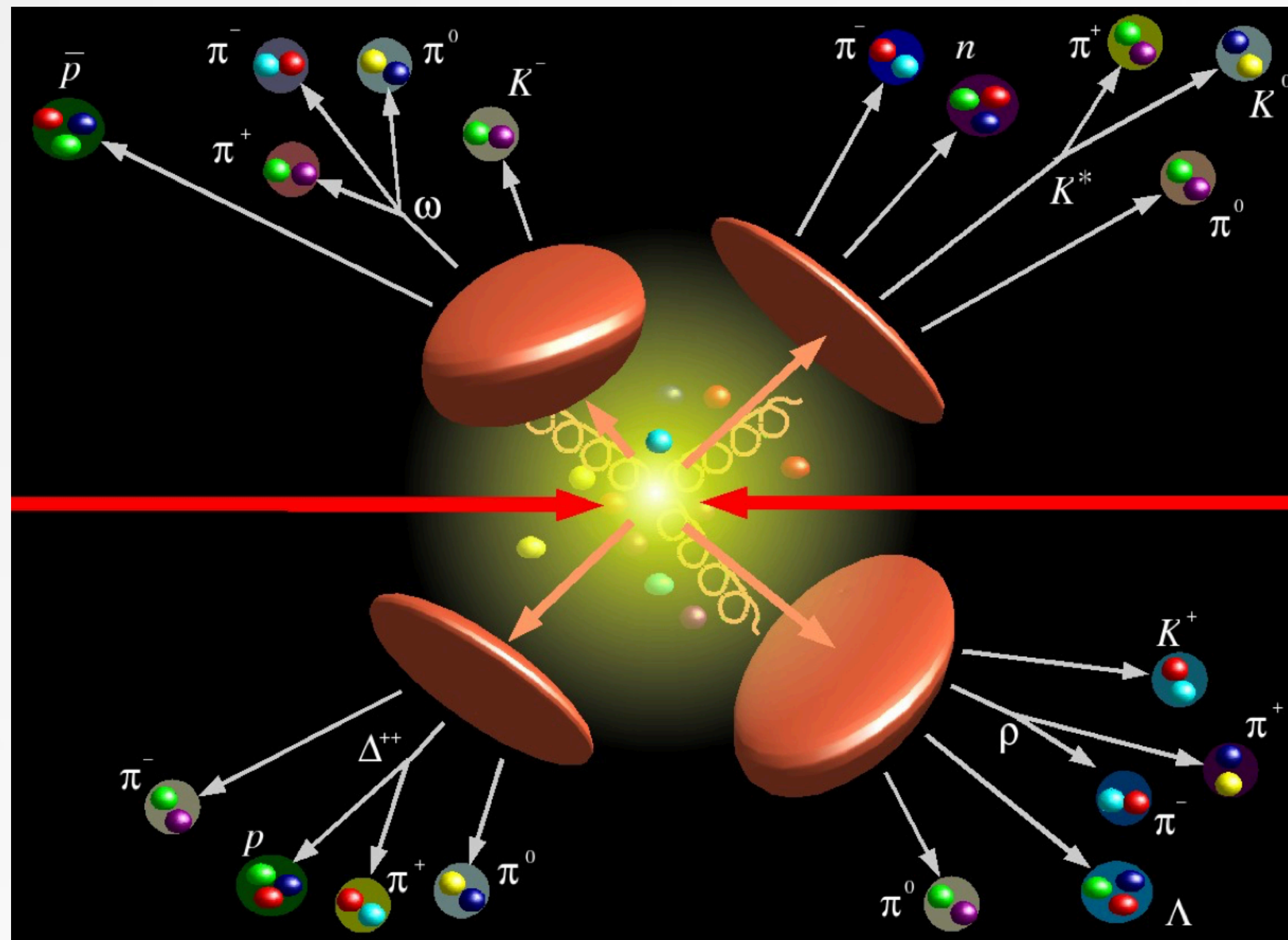
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That's it!



QCD: Two limits, same theory

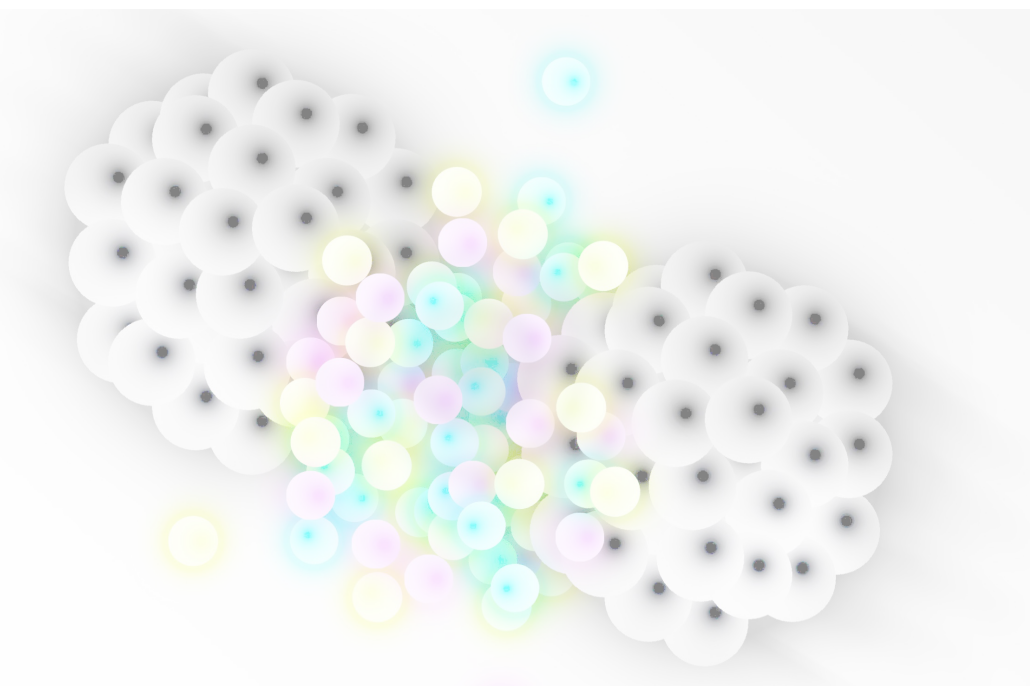


Quarks & gluons

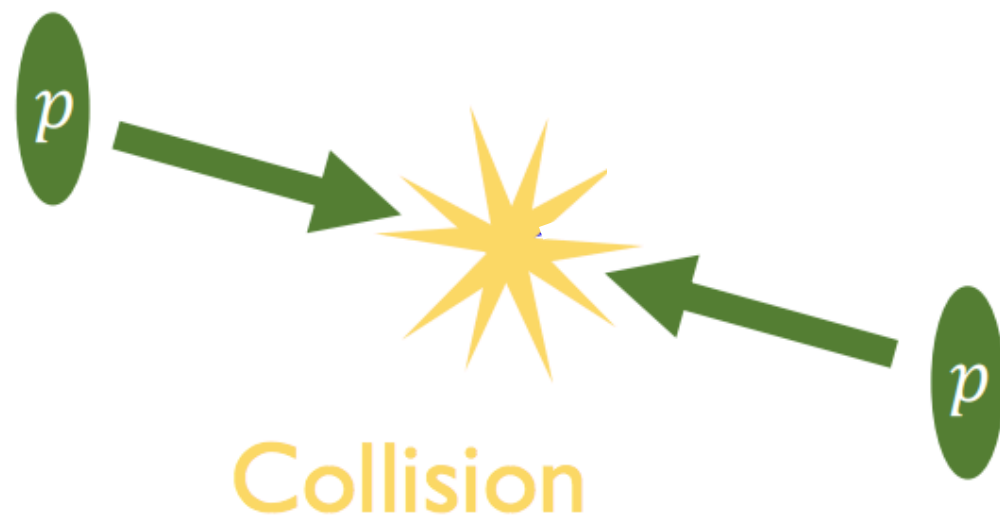
Hadrons

What we detect experimentally?

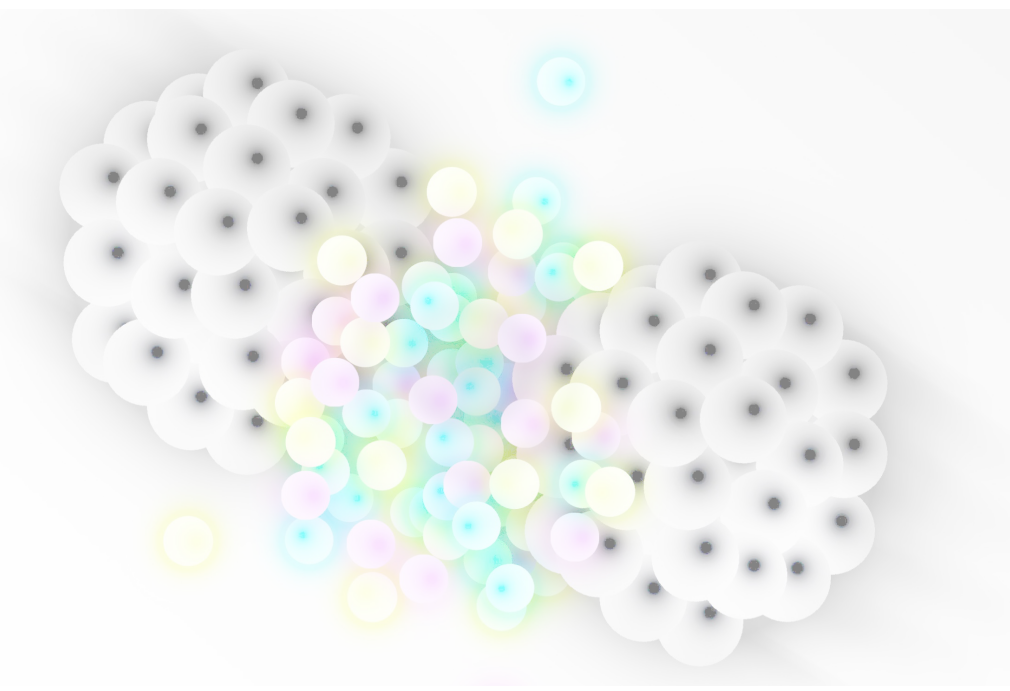
QCD Parton Shower



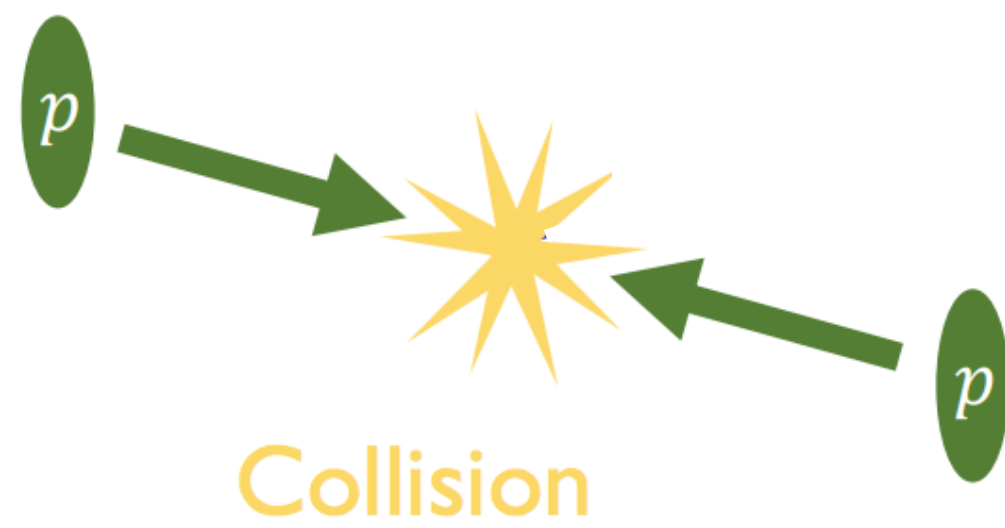
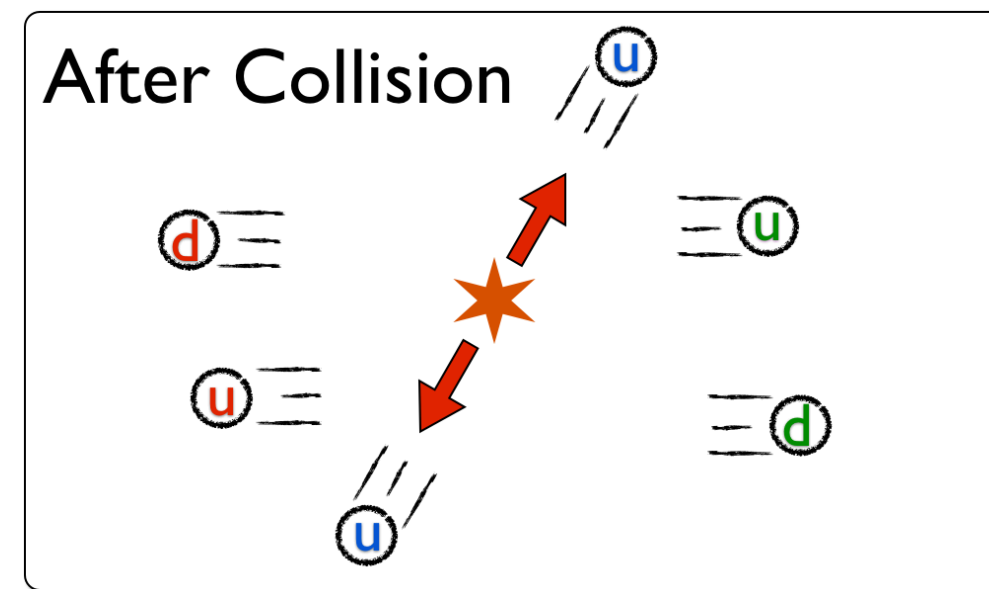
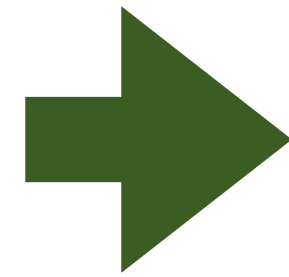
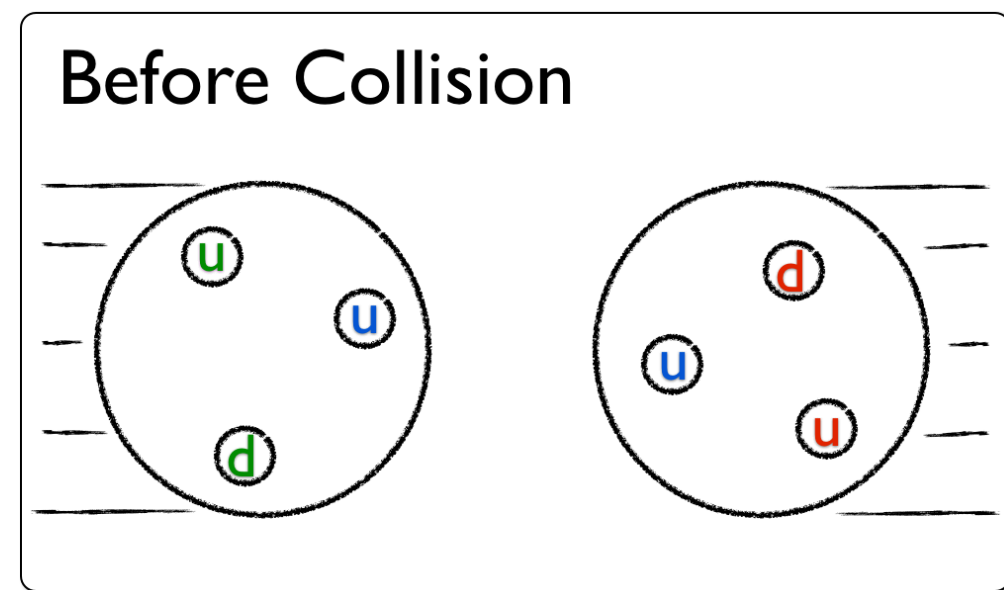
- Process with a large momentum transfer:



QCD Parton Shower

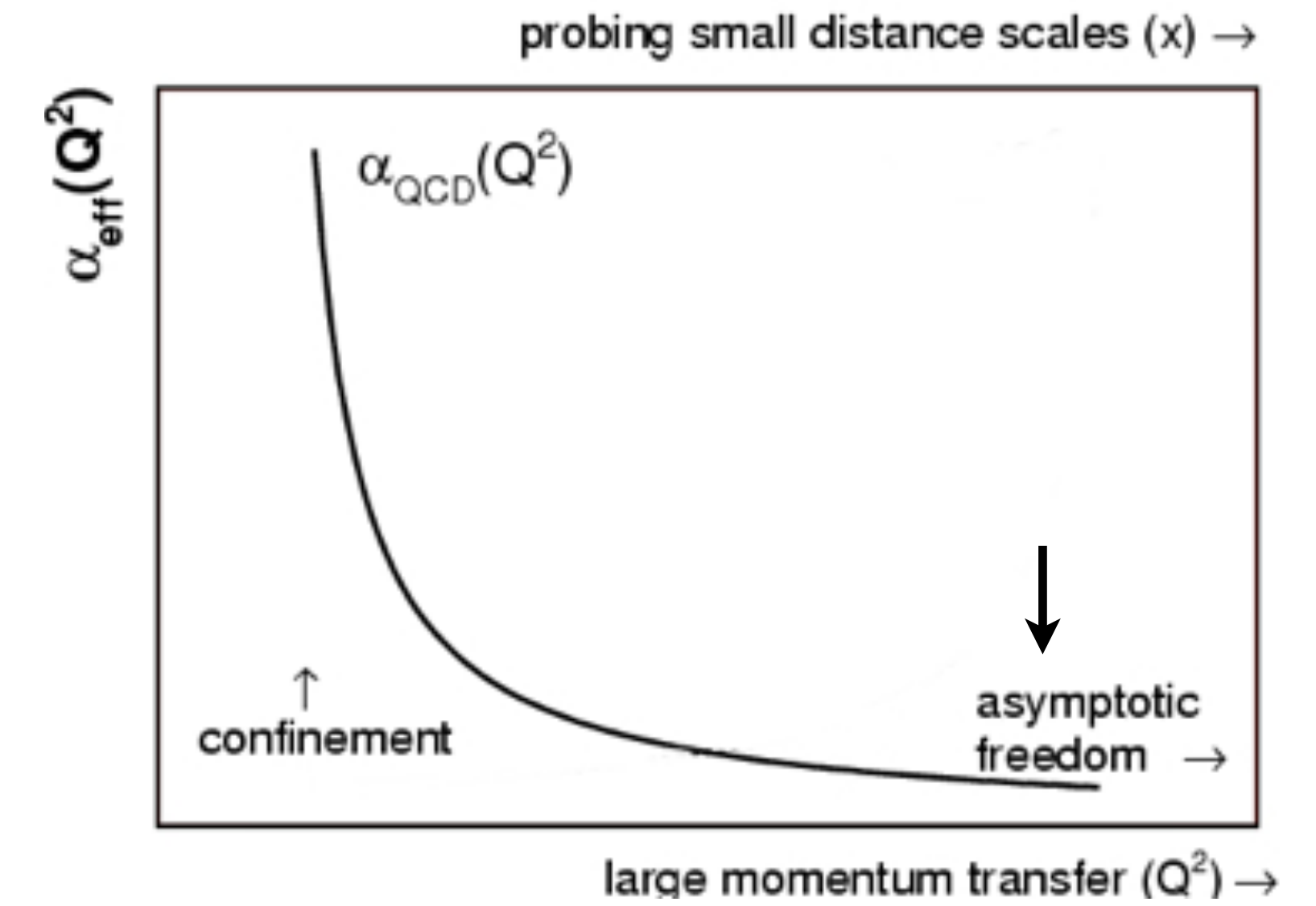
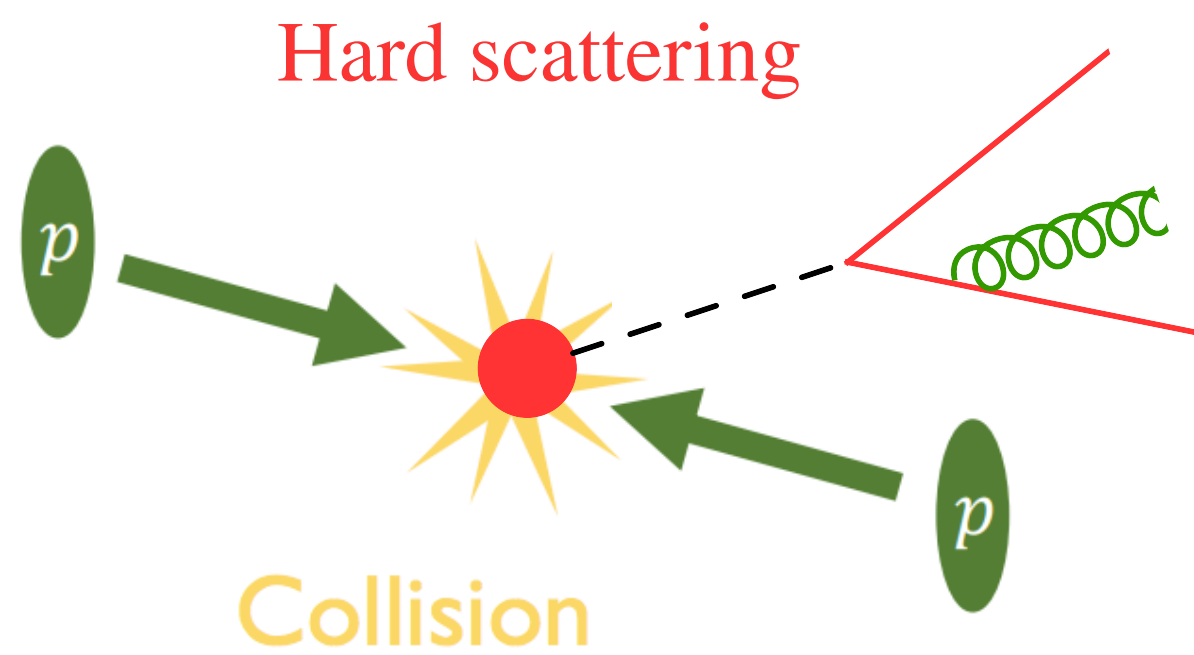
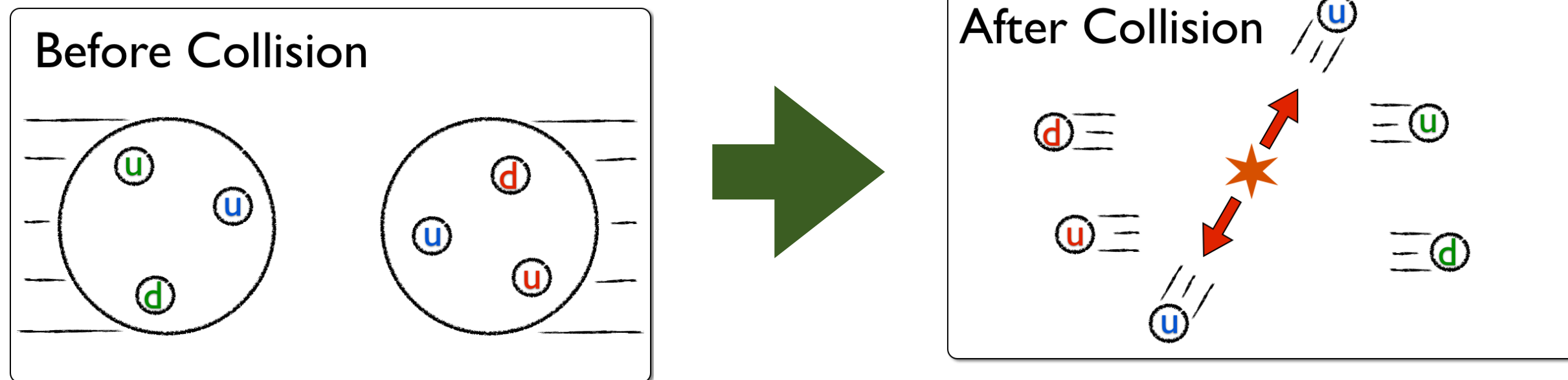


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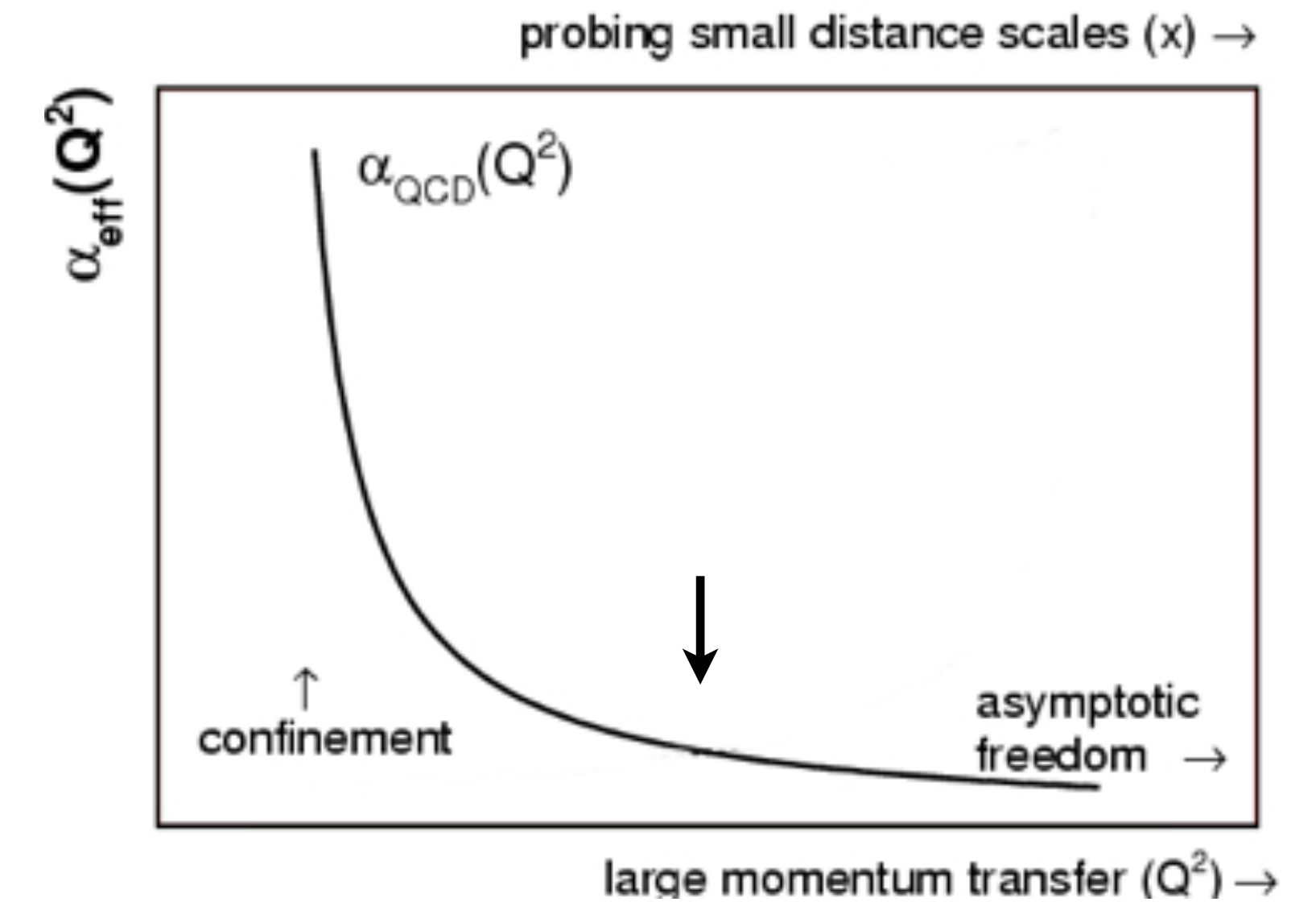
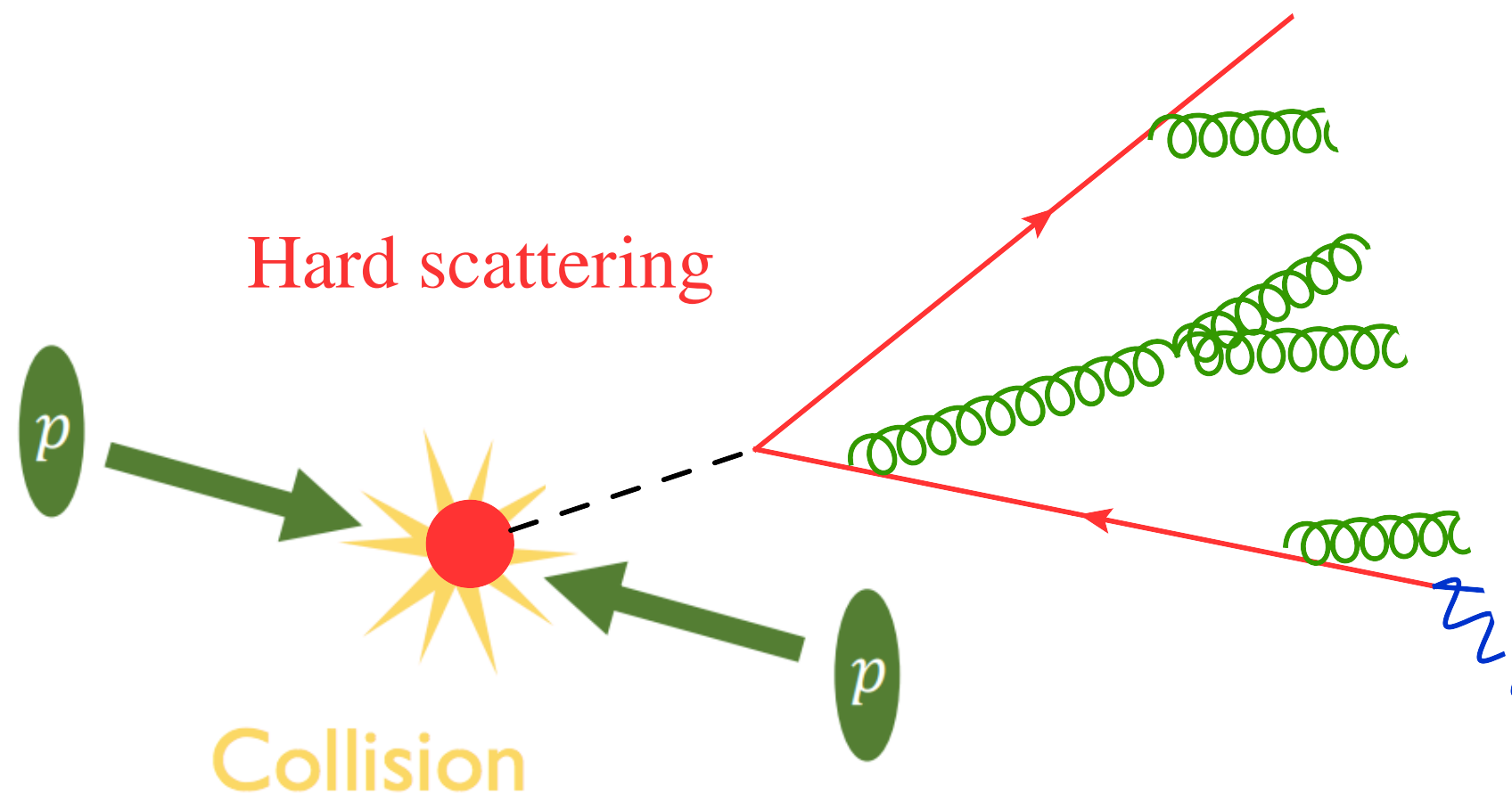
QCD Parton Shower

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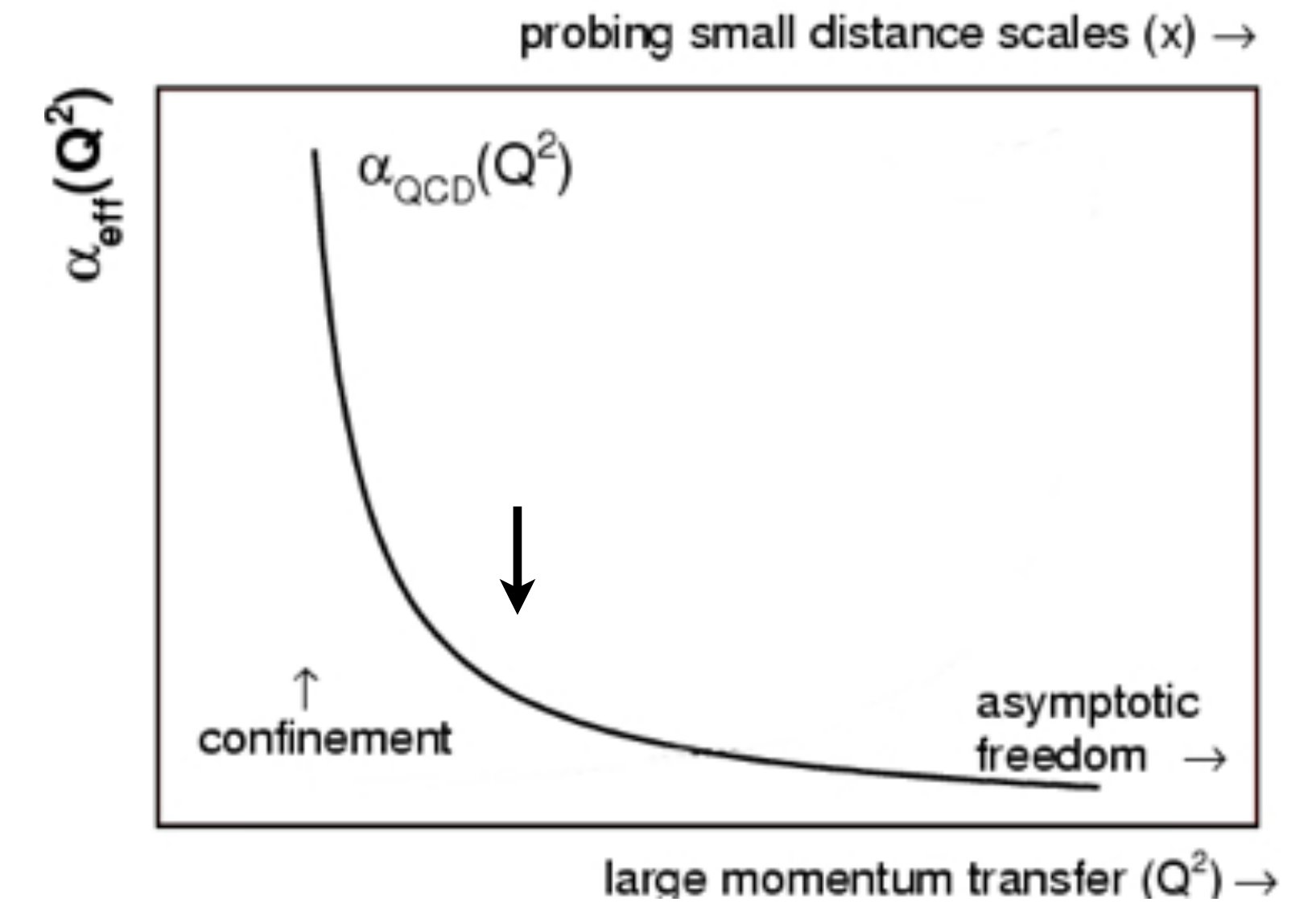
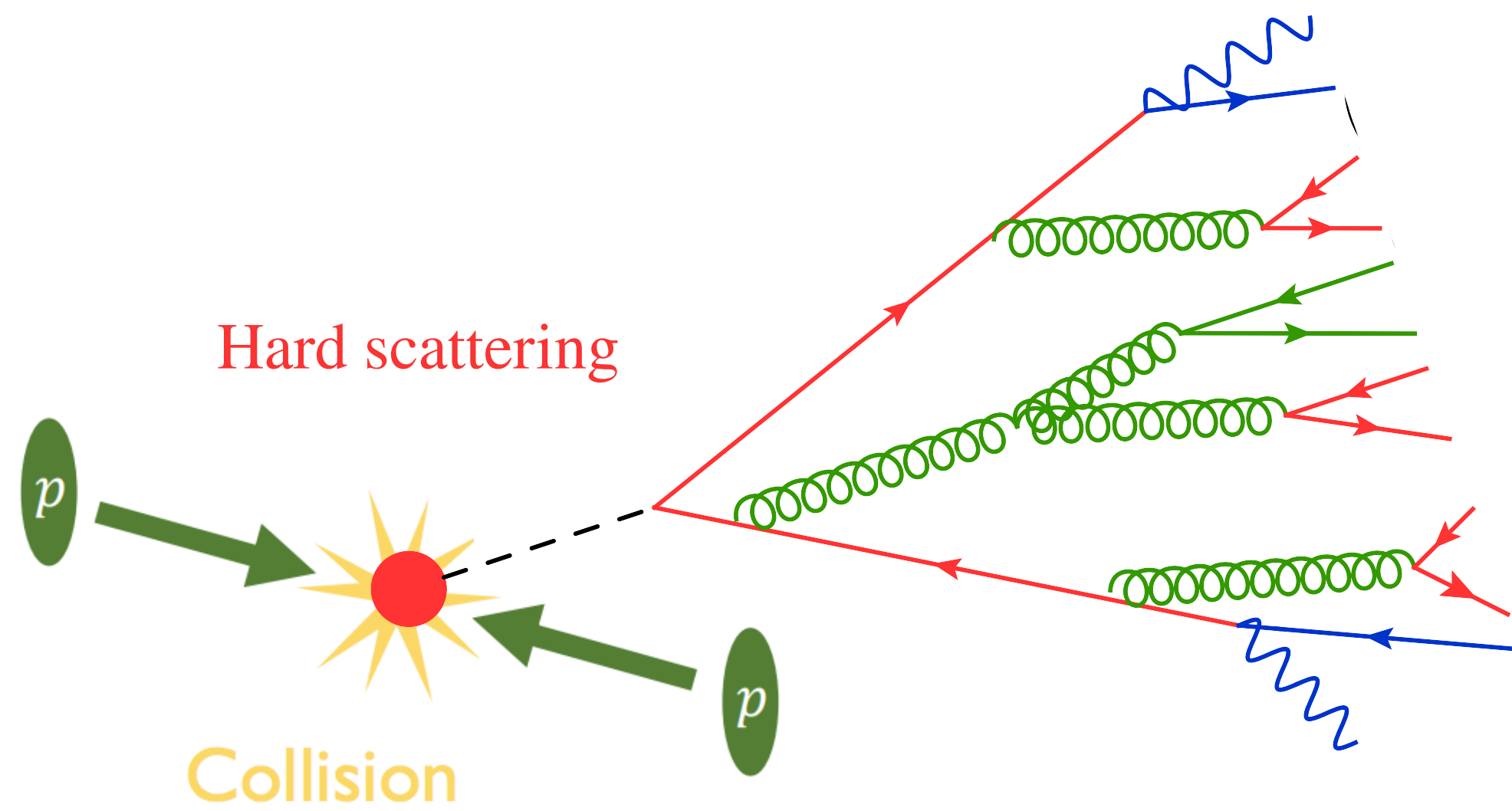
QCD Parton Shower

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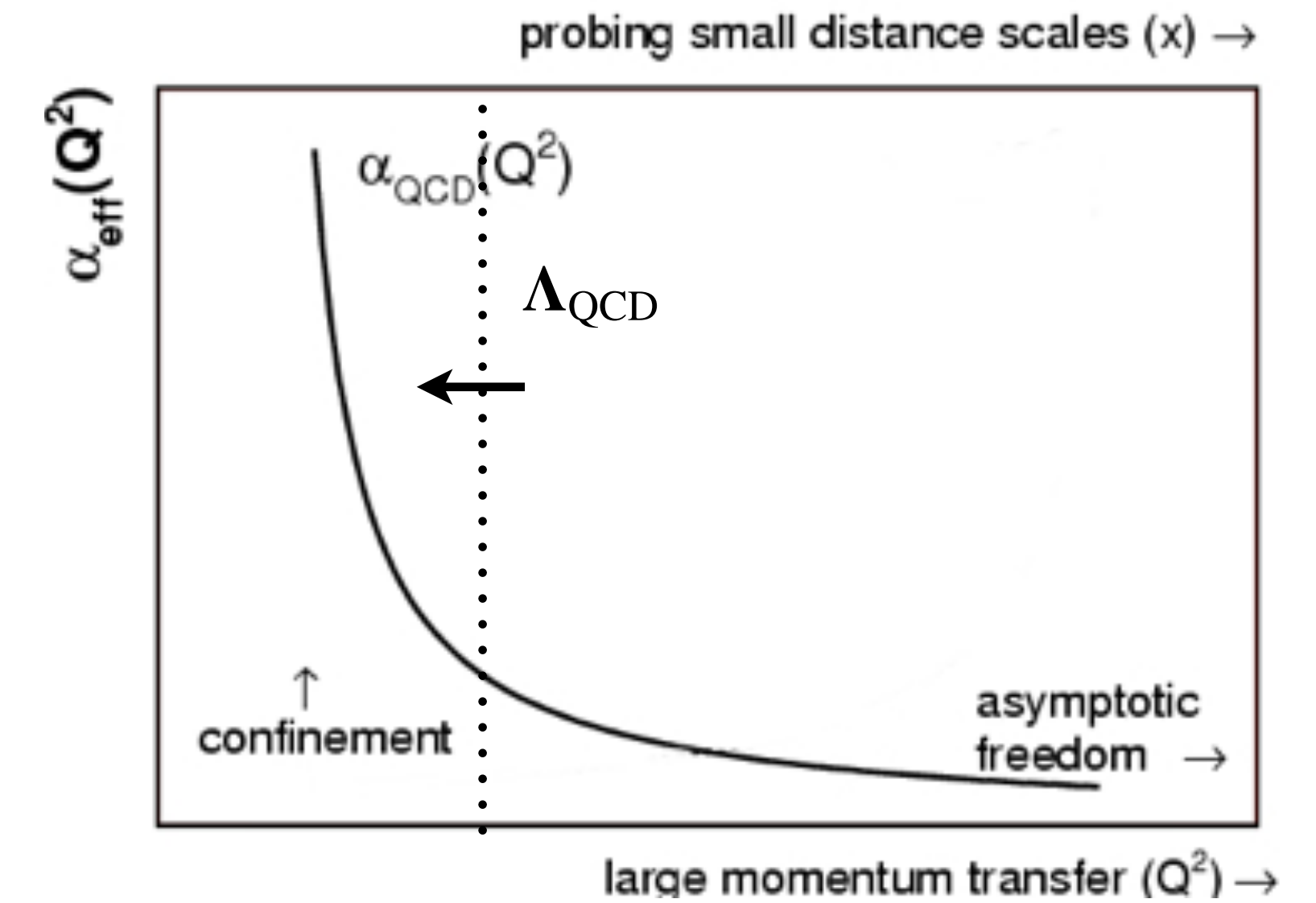
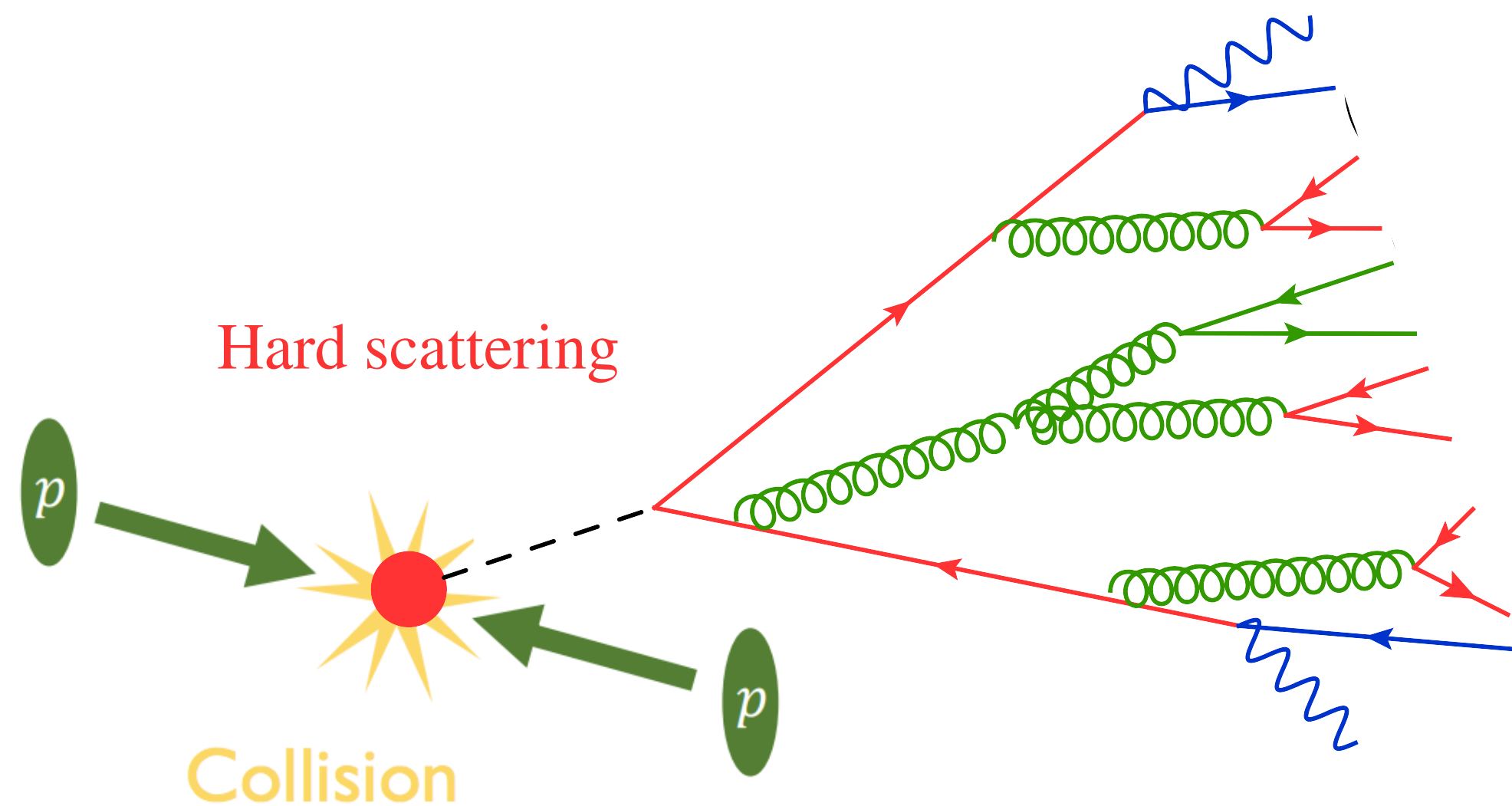
QCD Parton Shower

- Process with a large momentum transfer:



QCD Parton Shower

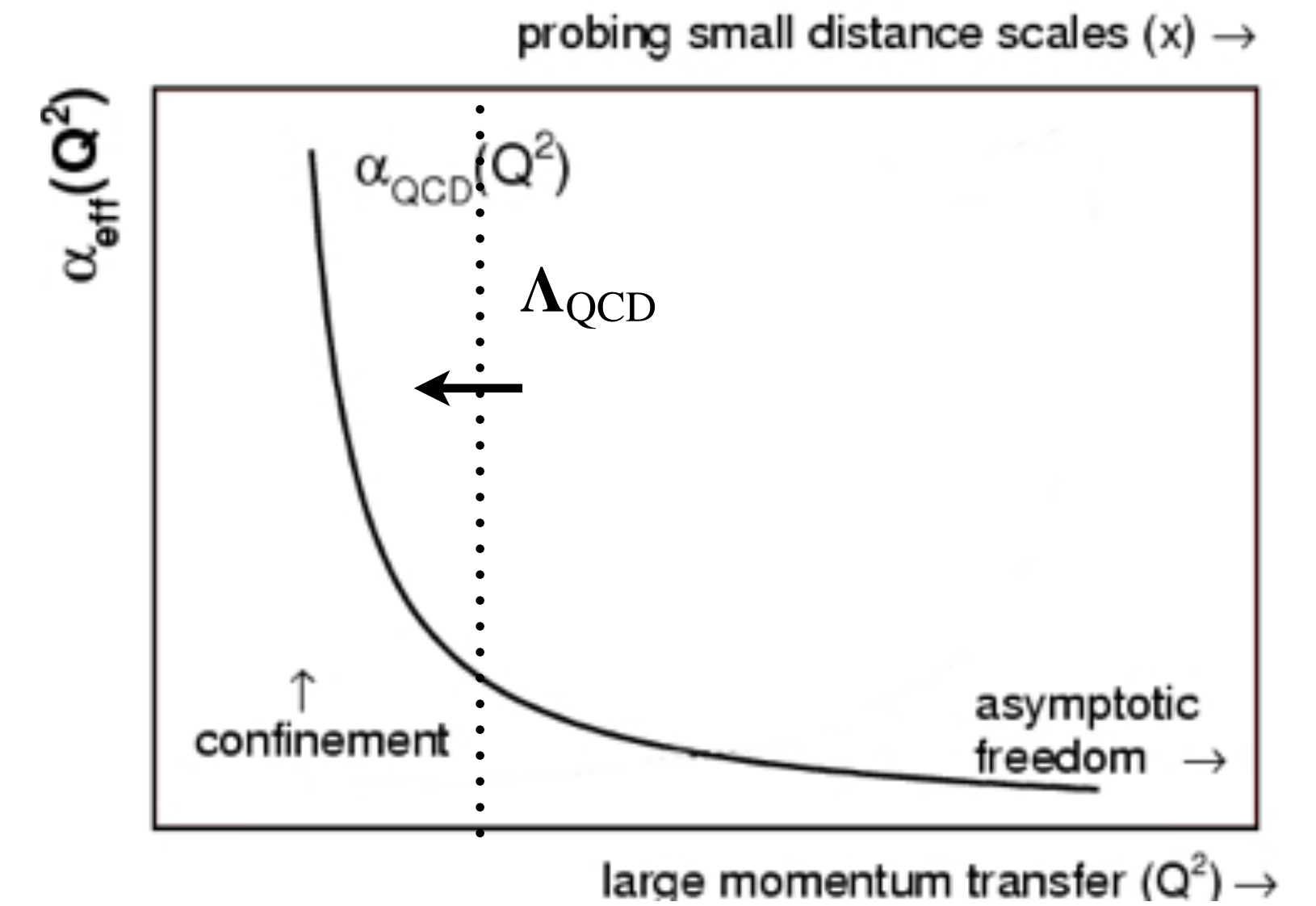
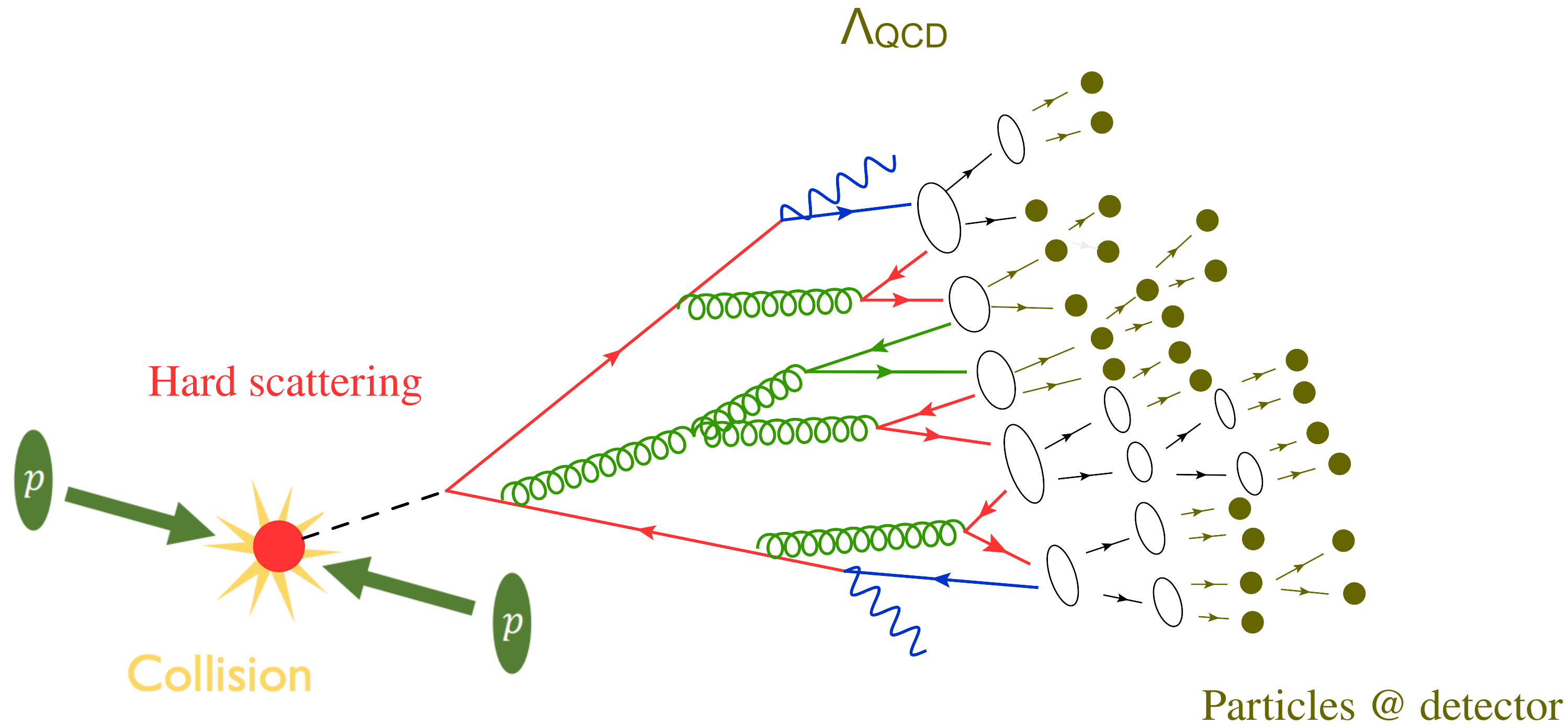
- Process with a large momentum transfer:



α_{QCD} no longer $\ll 1$

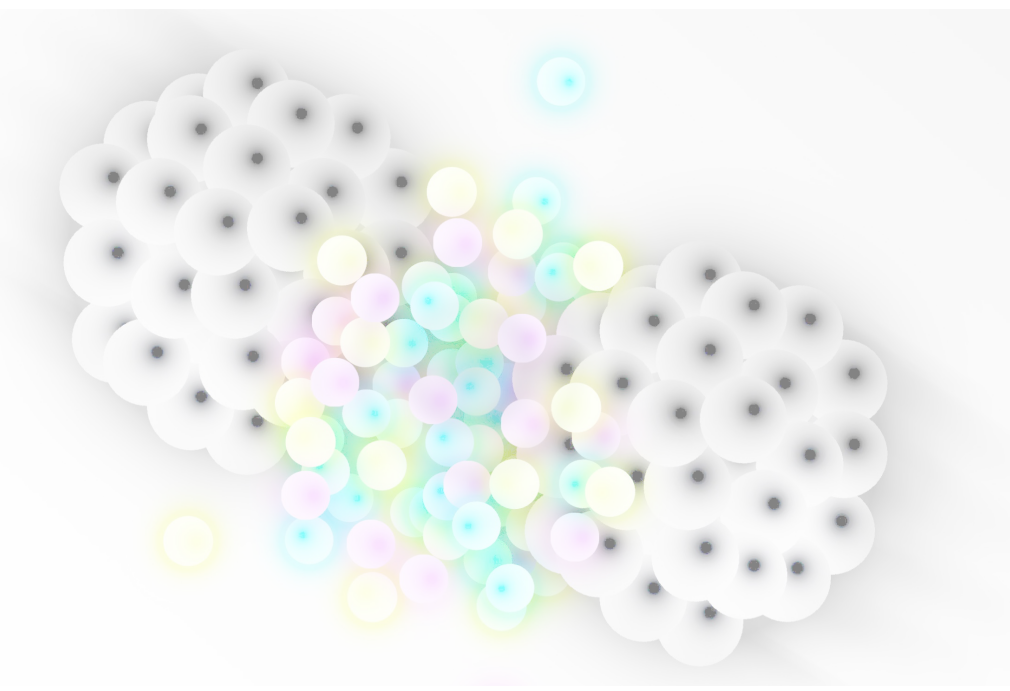
QCD Parton Shower

- Process with a large momentum transfer:

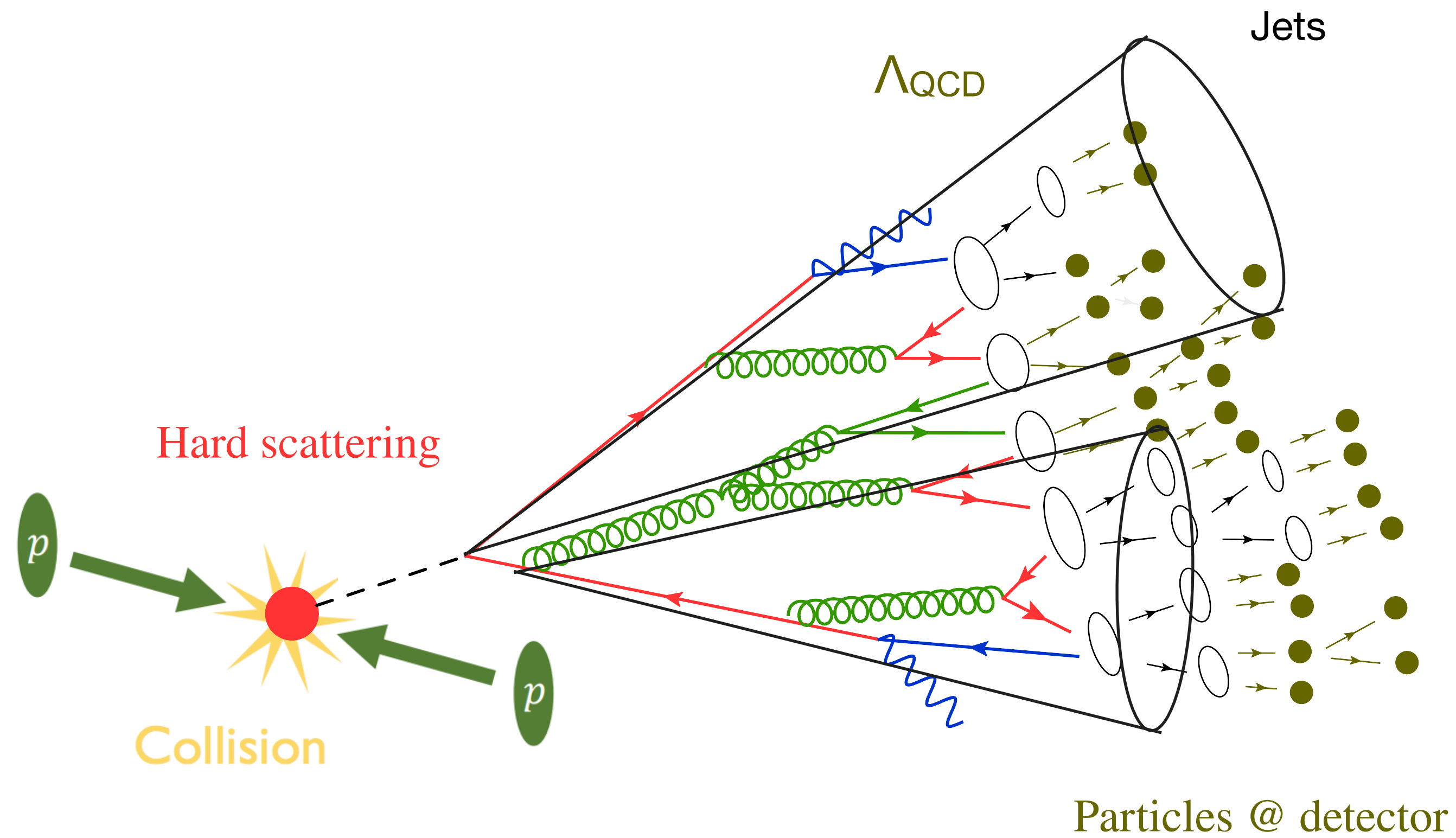


α_{QCD} no longer $\ll 1$

QCD Parton Shower

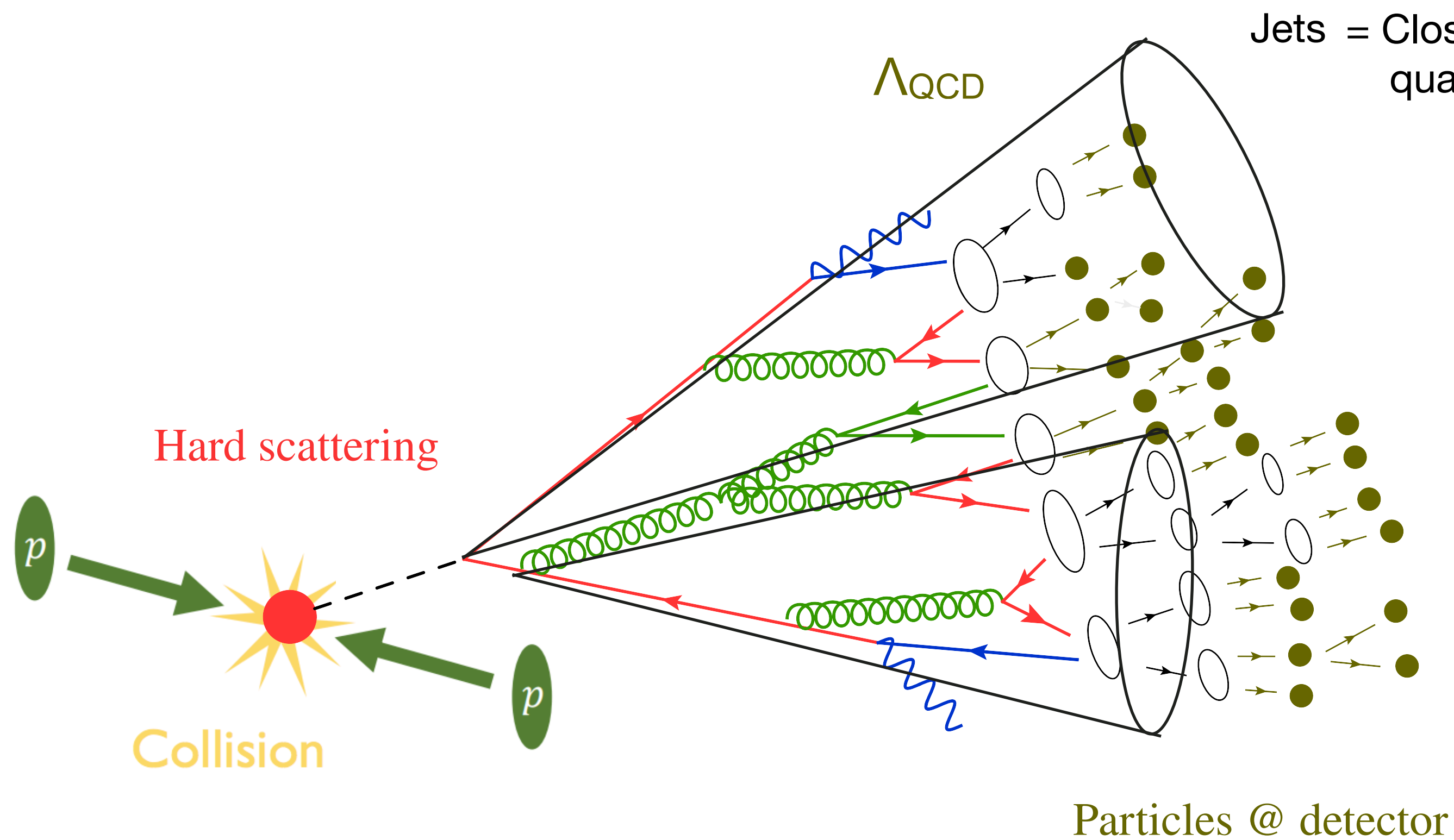


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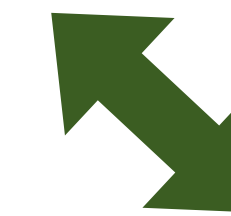
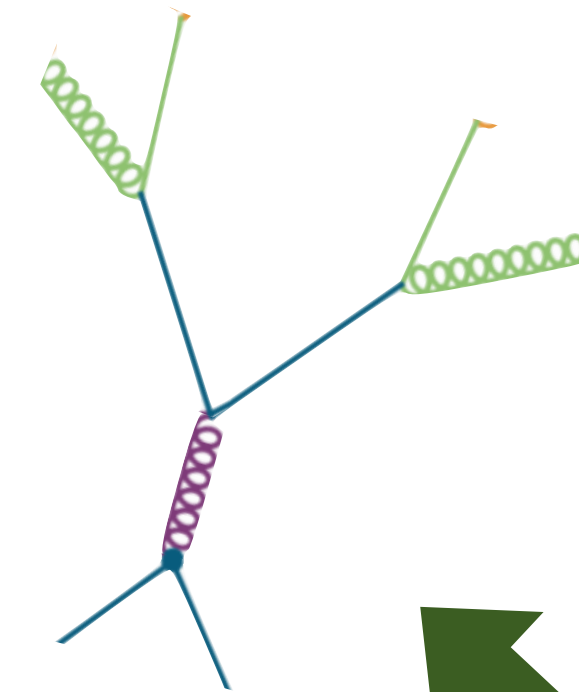
QCD Parton Shower

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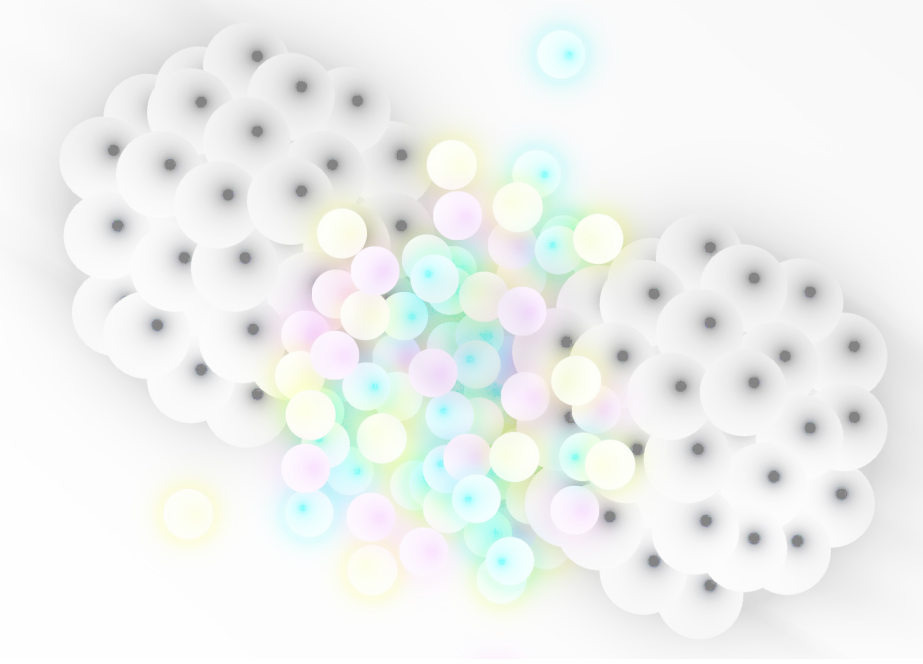
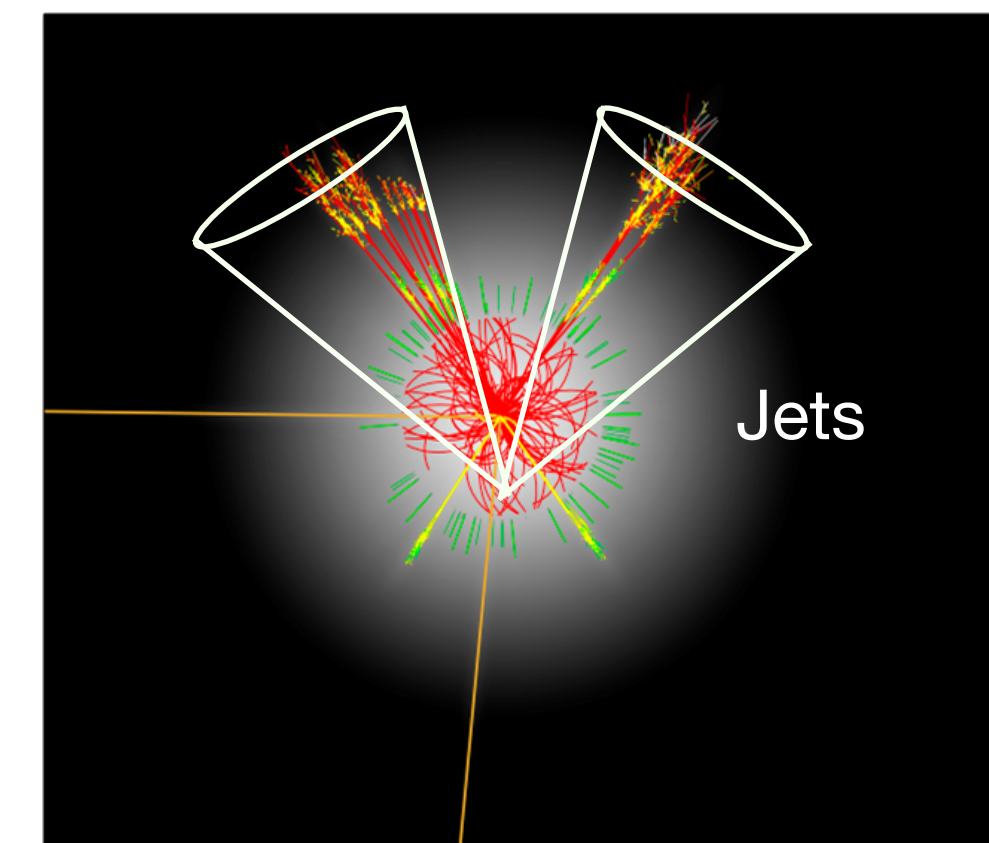


Jets = Closest proxy for quarks/gluons

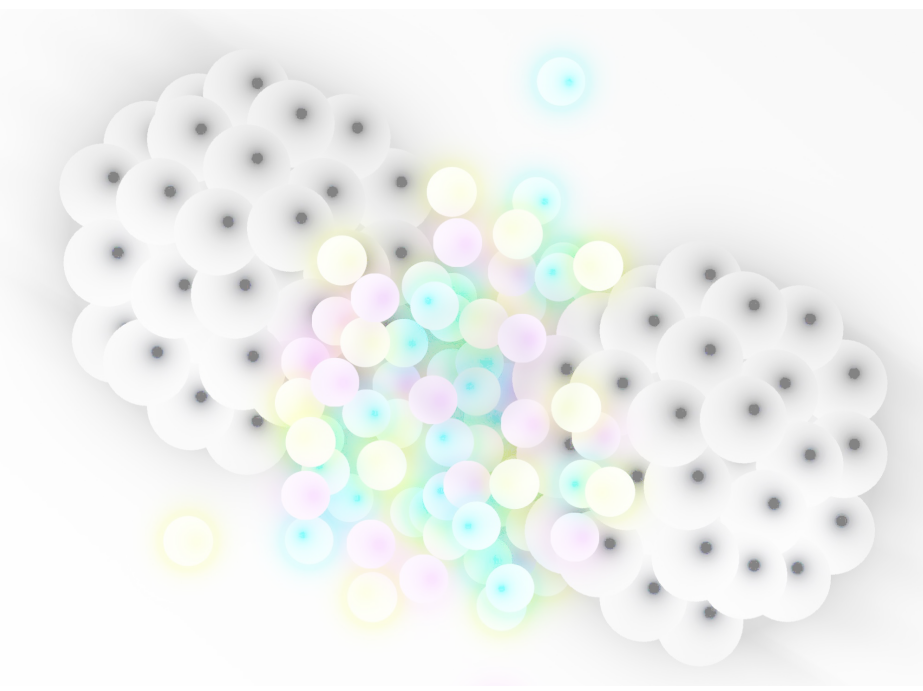
What we calculate



What we measure

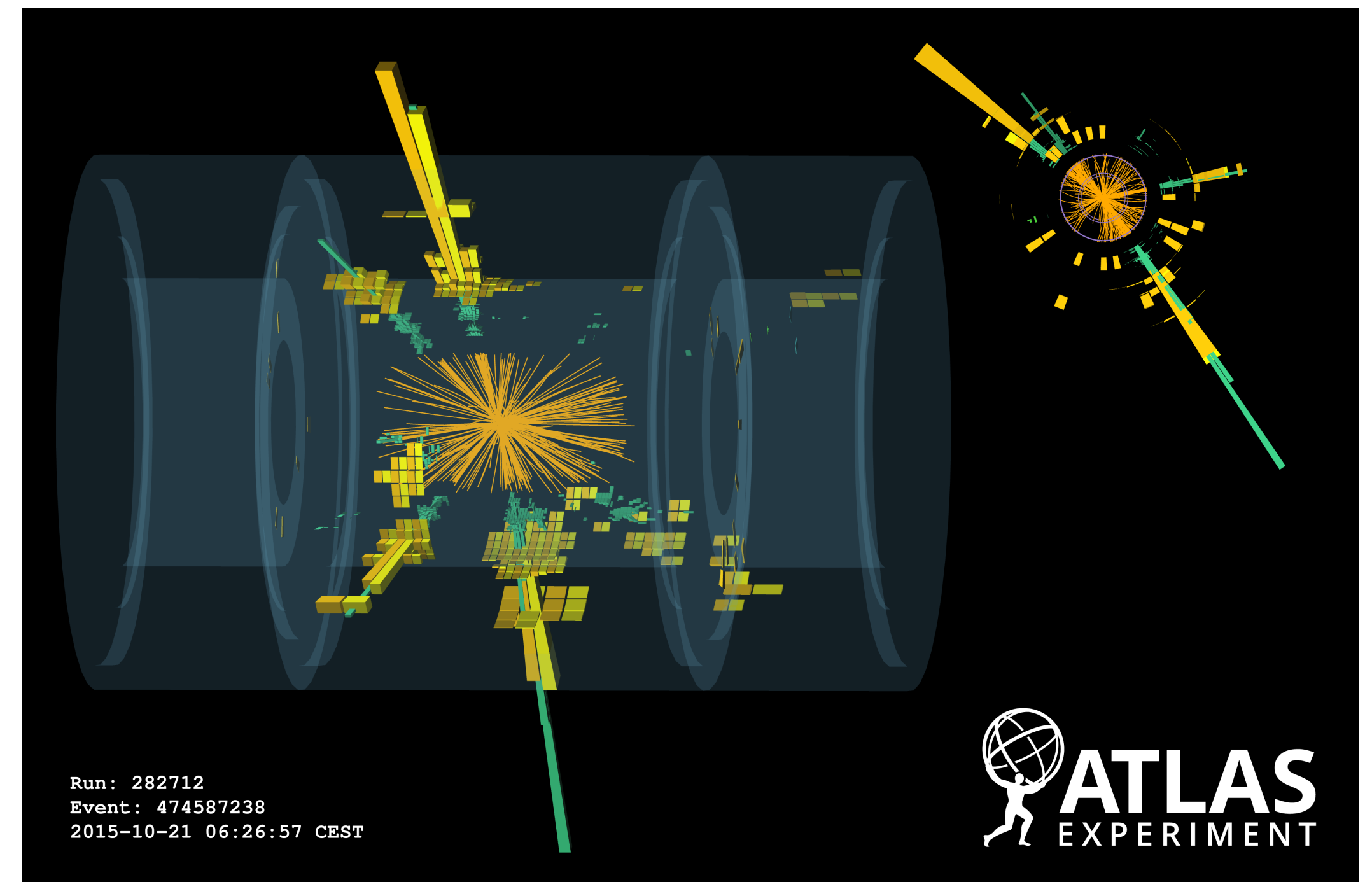
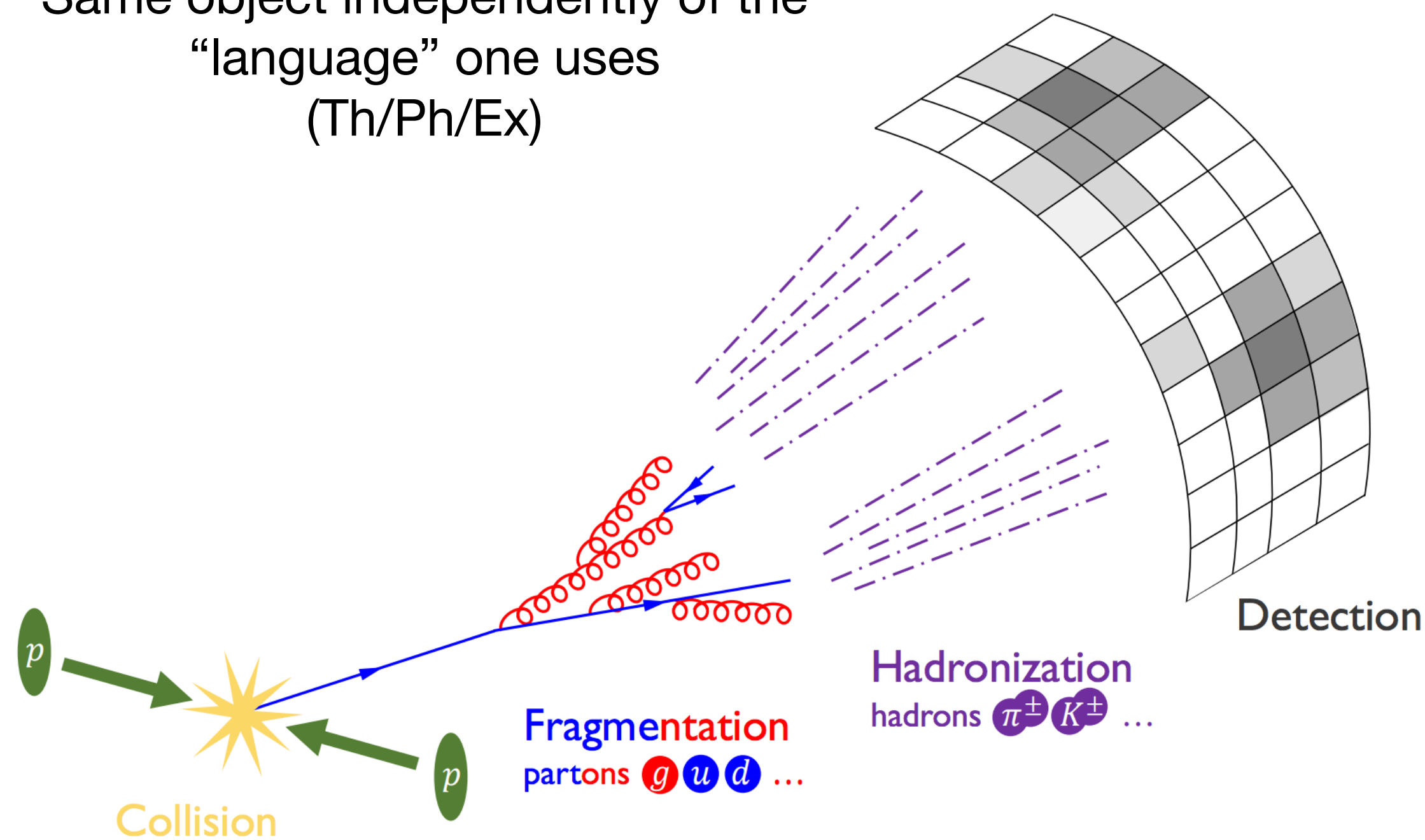


QCD Parton Shower to Jets

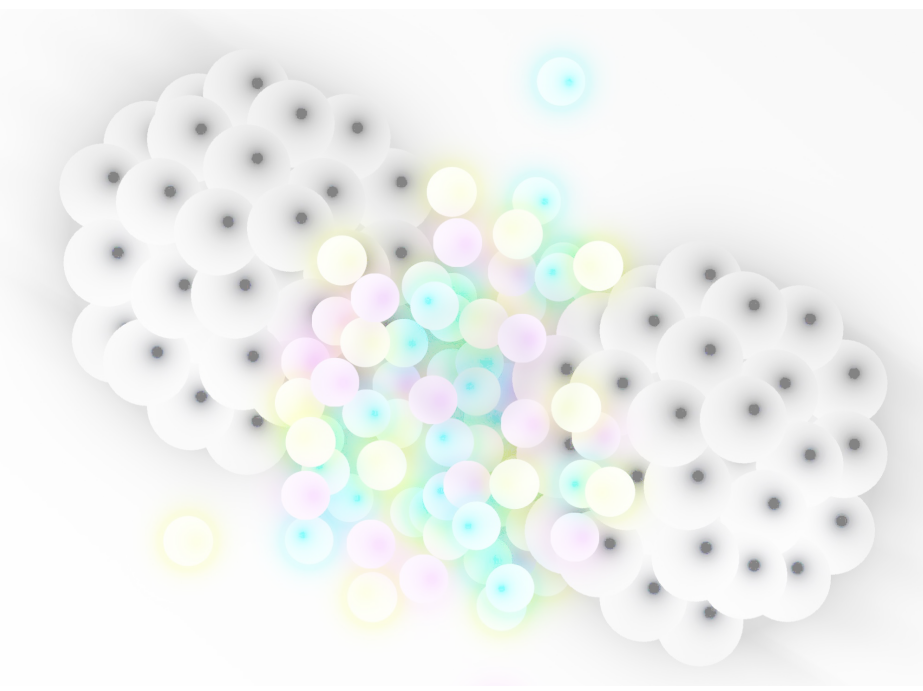


- What is a jet?
 - Spray of collimated particles that were originated by a high momentum parton (quark or gluon)

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



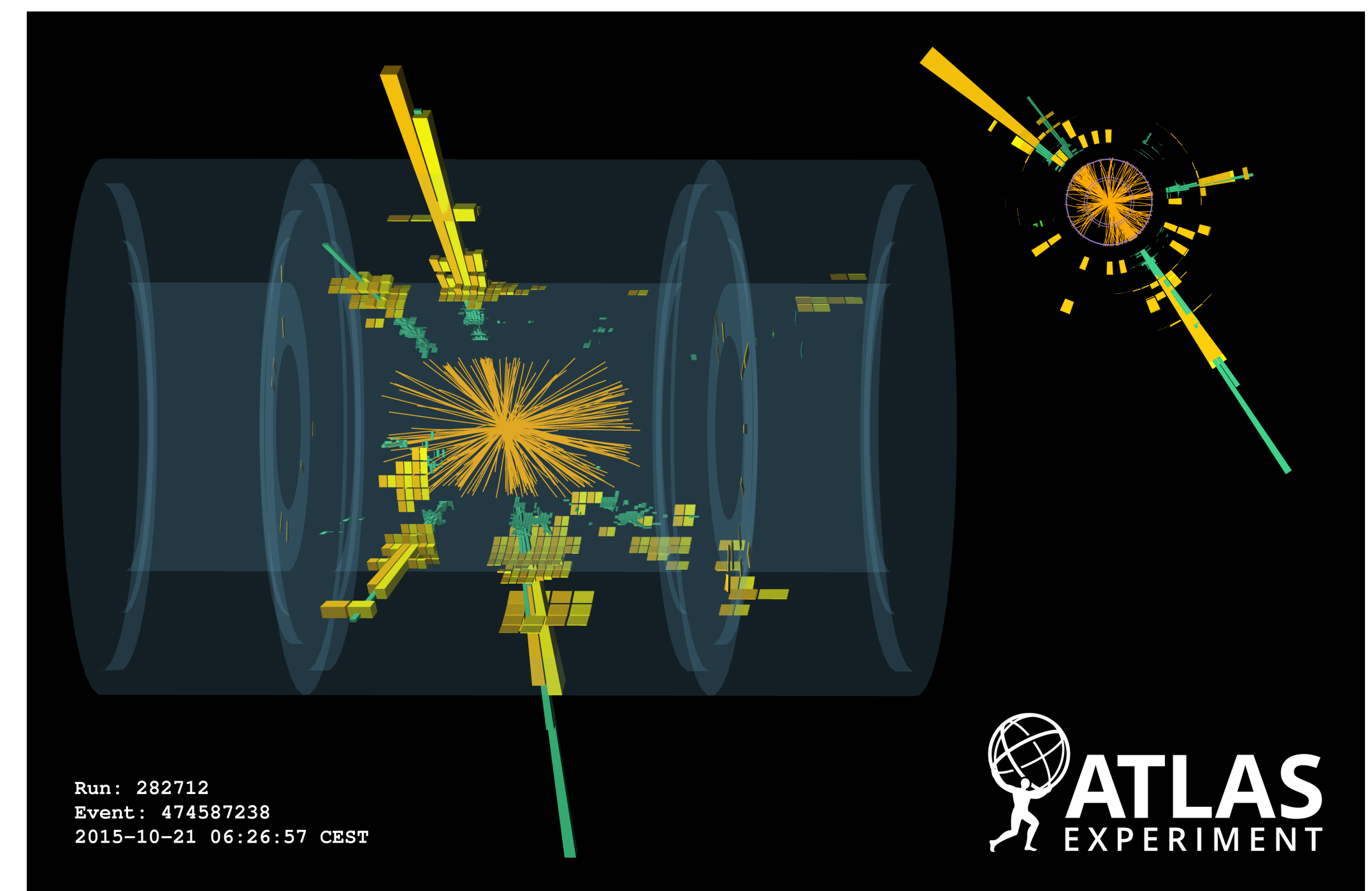
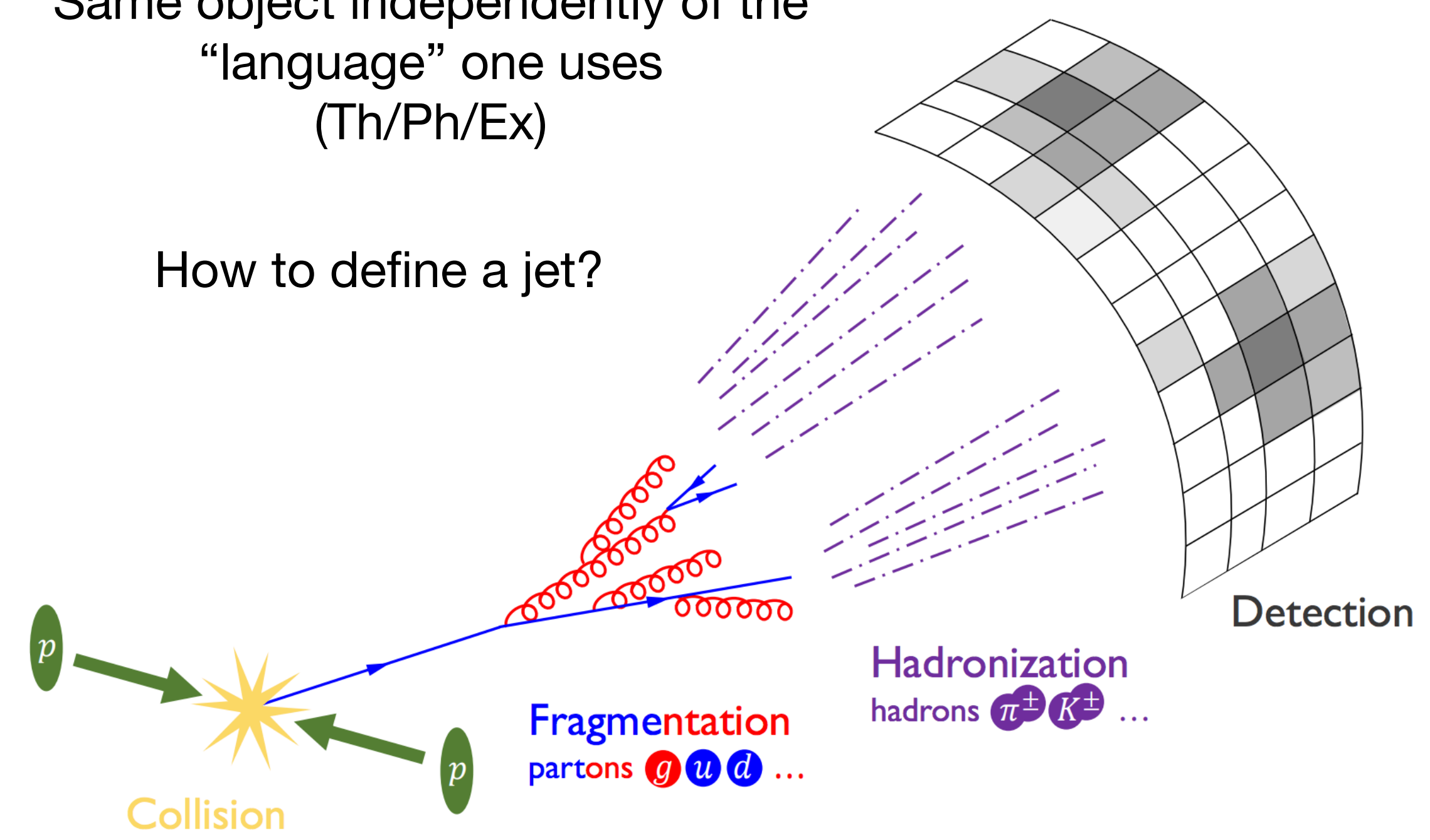
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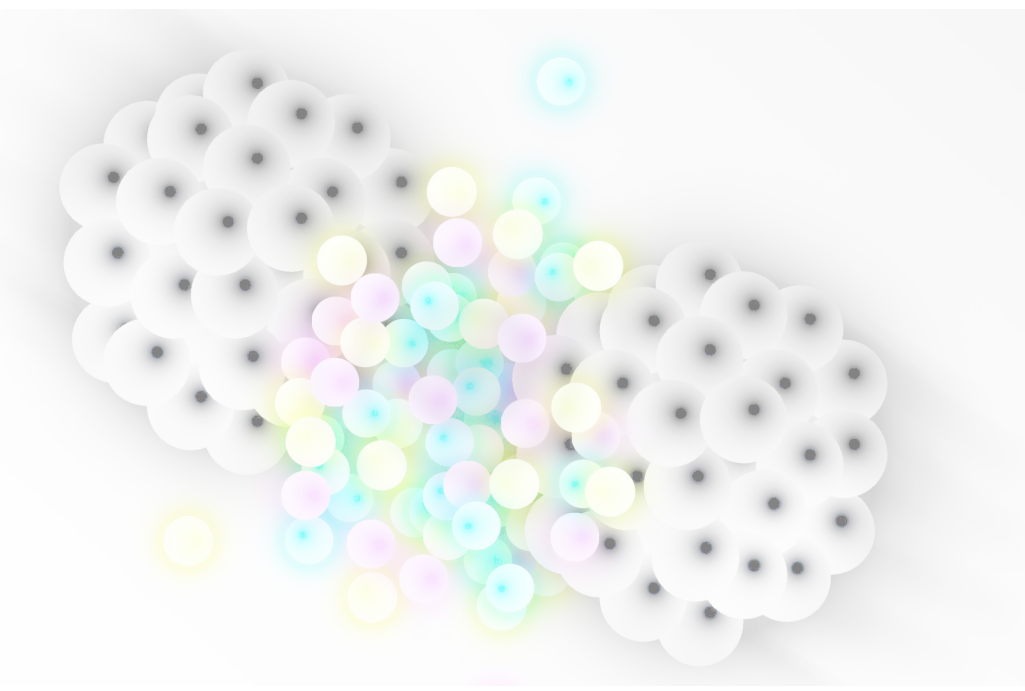
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How to define a jet?

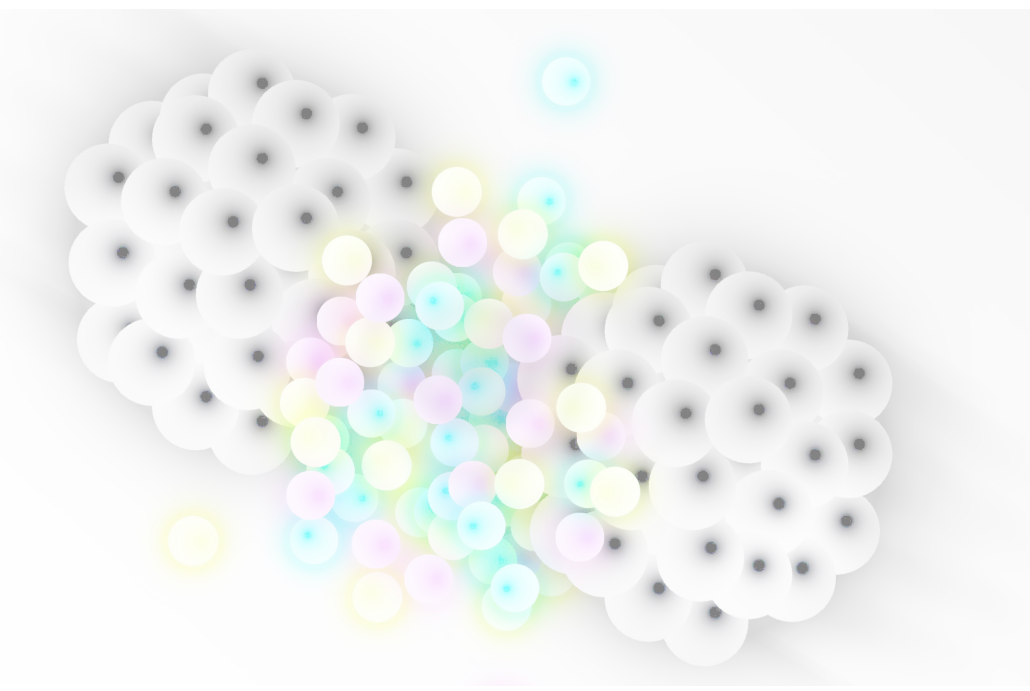


Jet algorithms



- 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

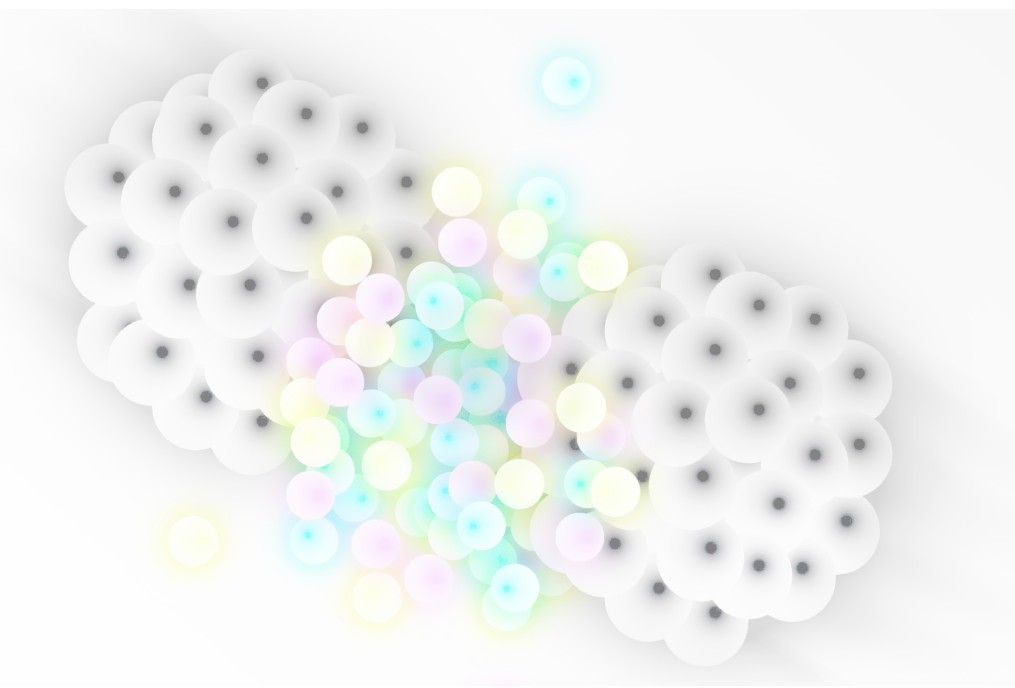
Jet algorithms



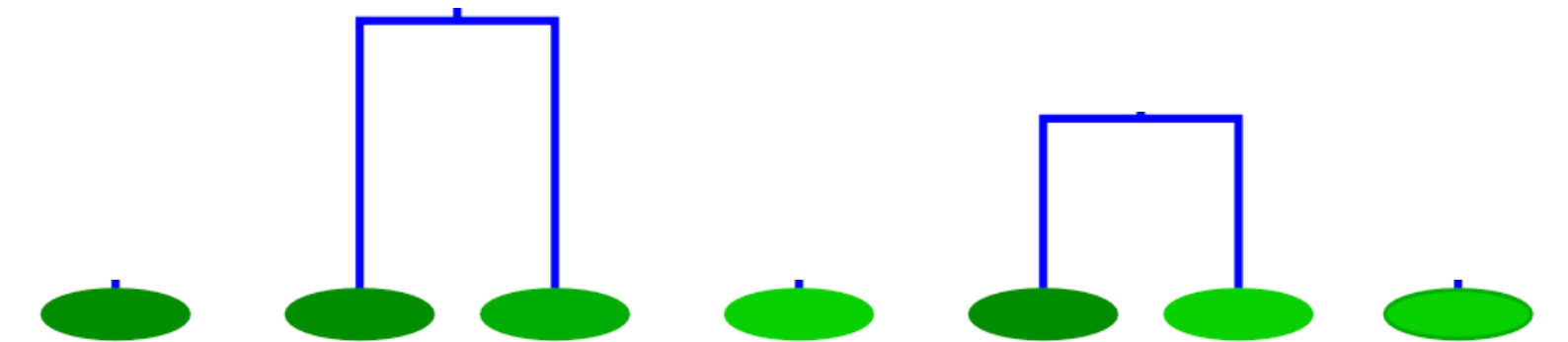
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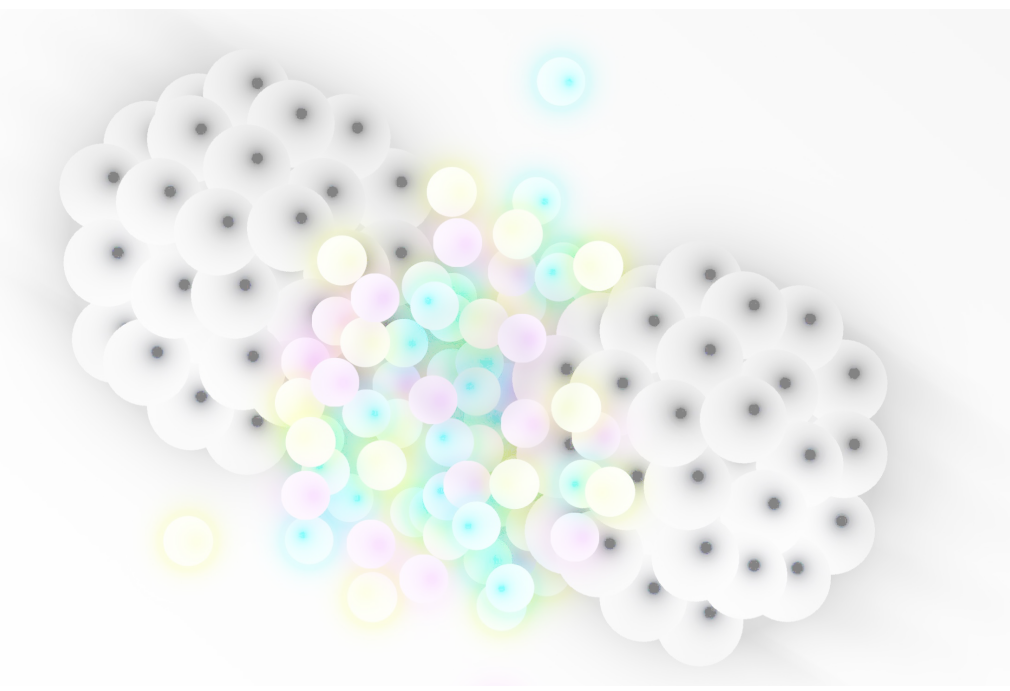
Jet algorithms



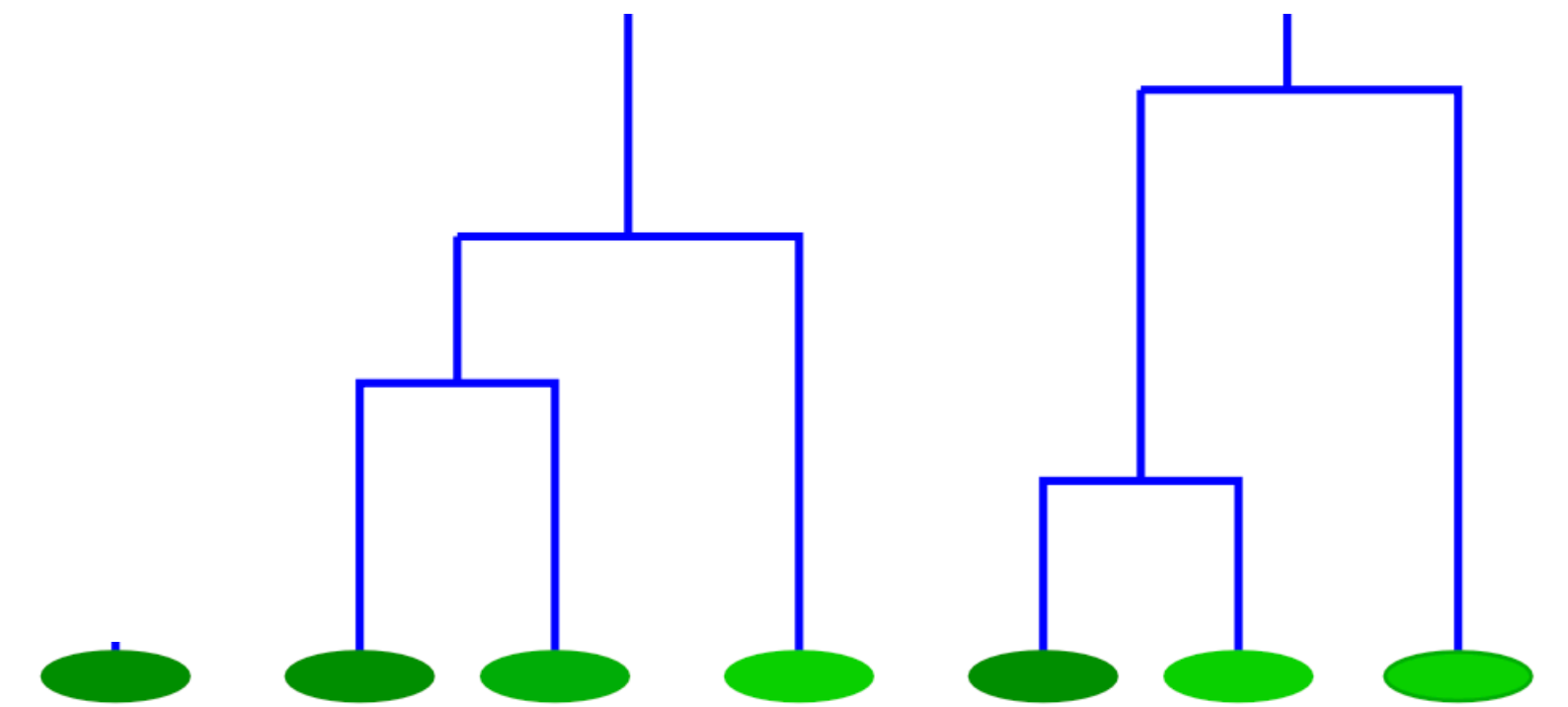
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Jet algorithms

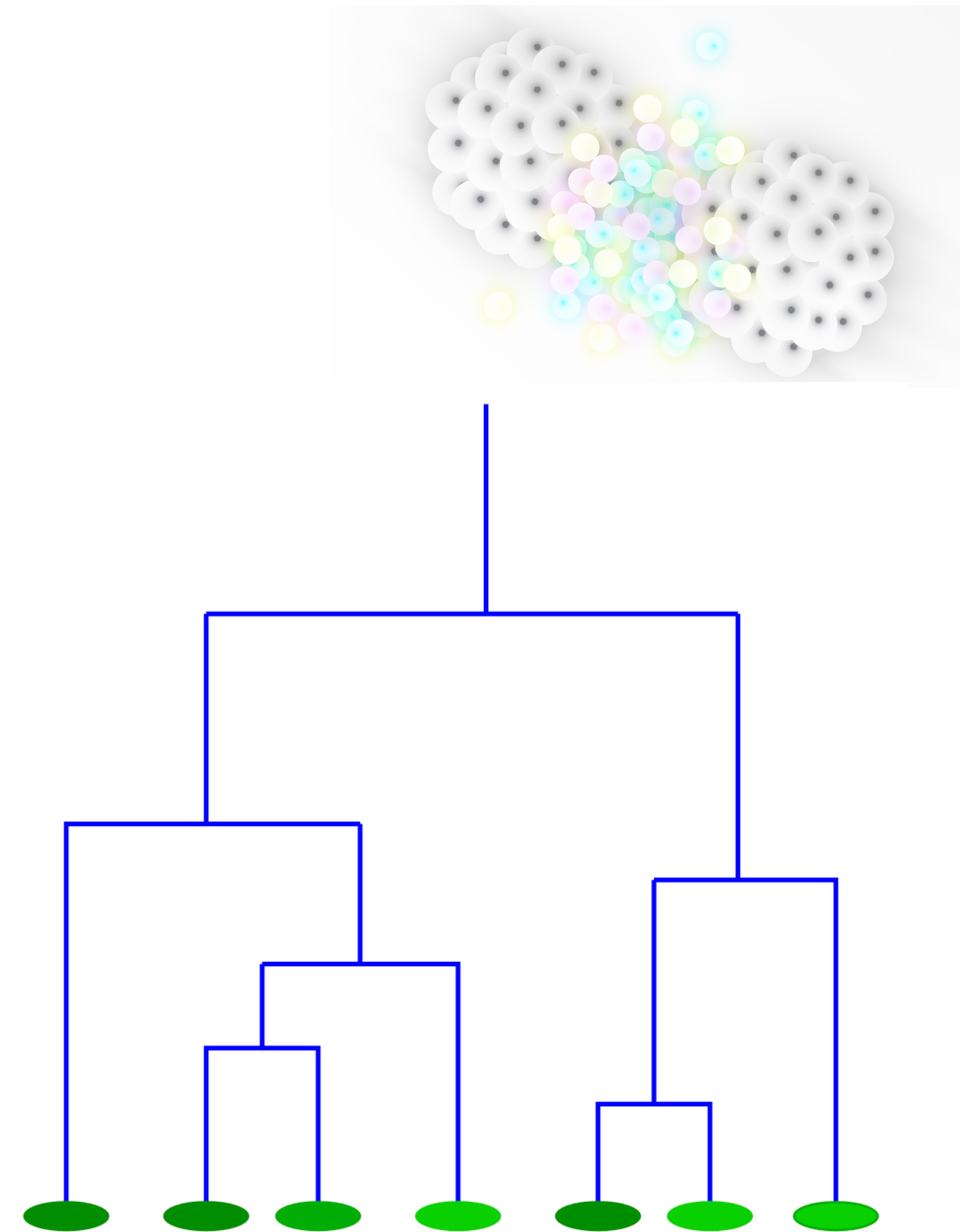


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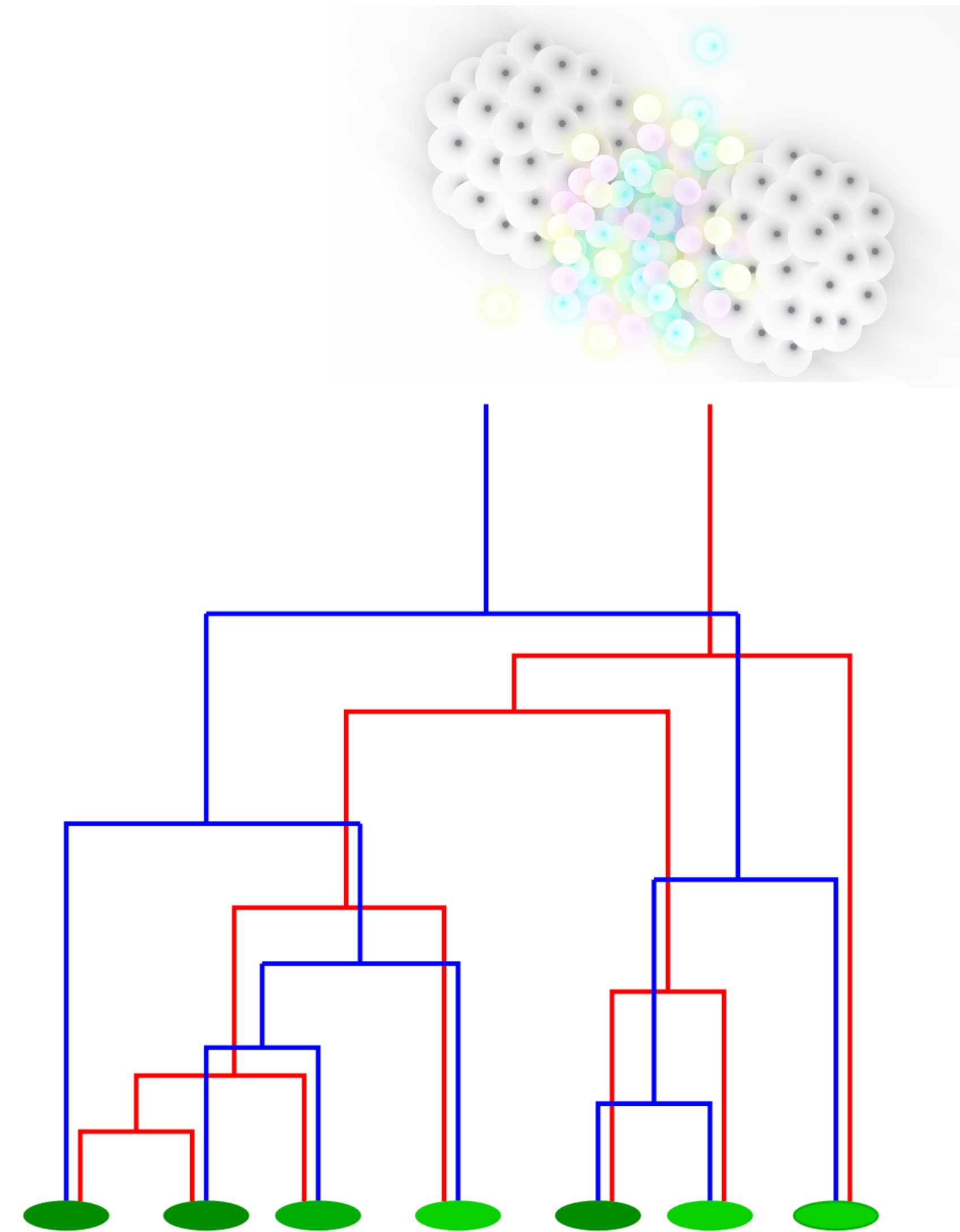
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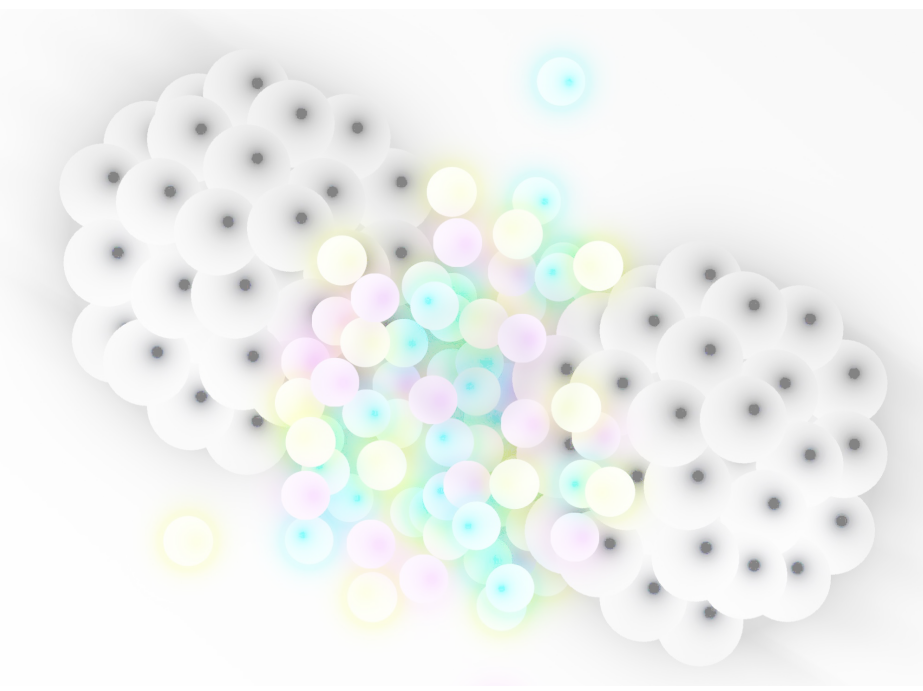


Jet algorithms

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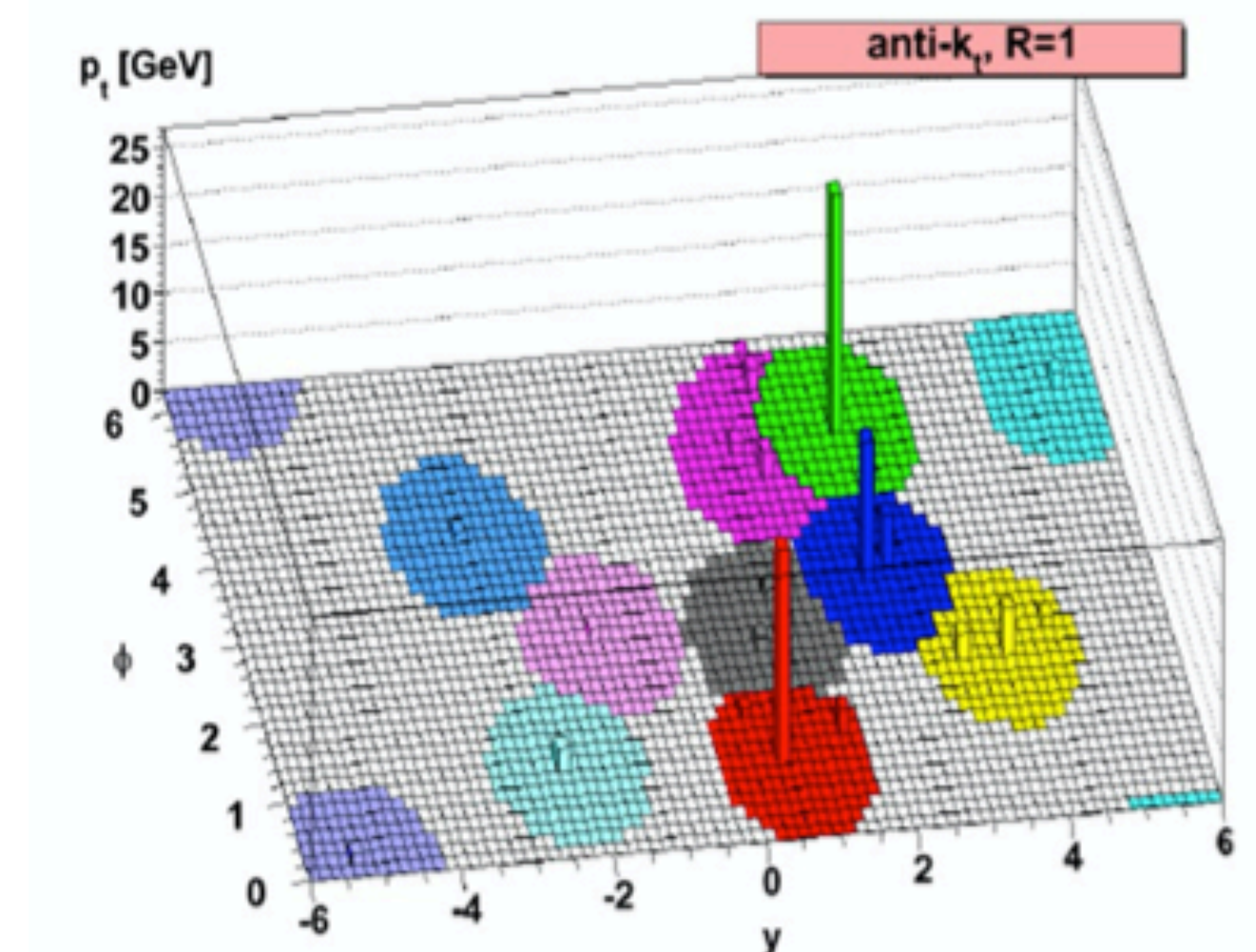
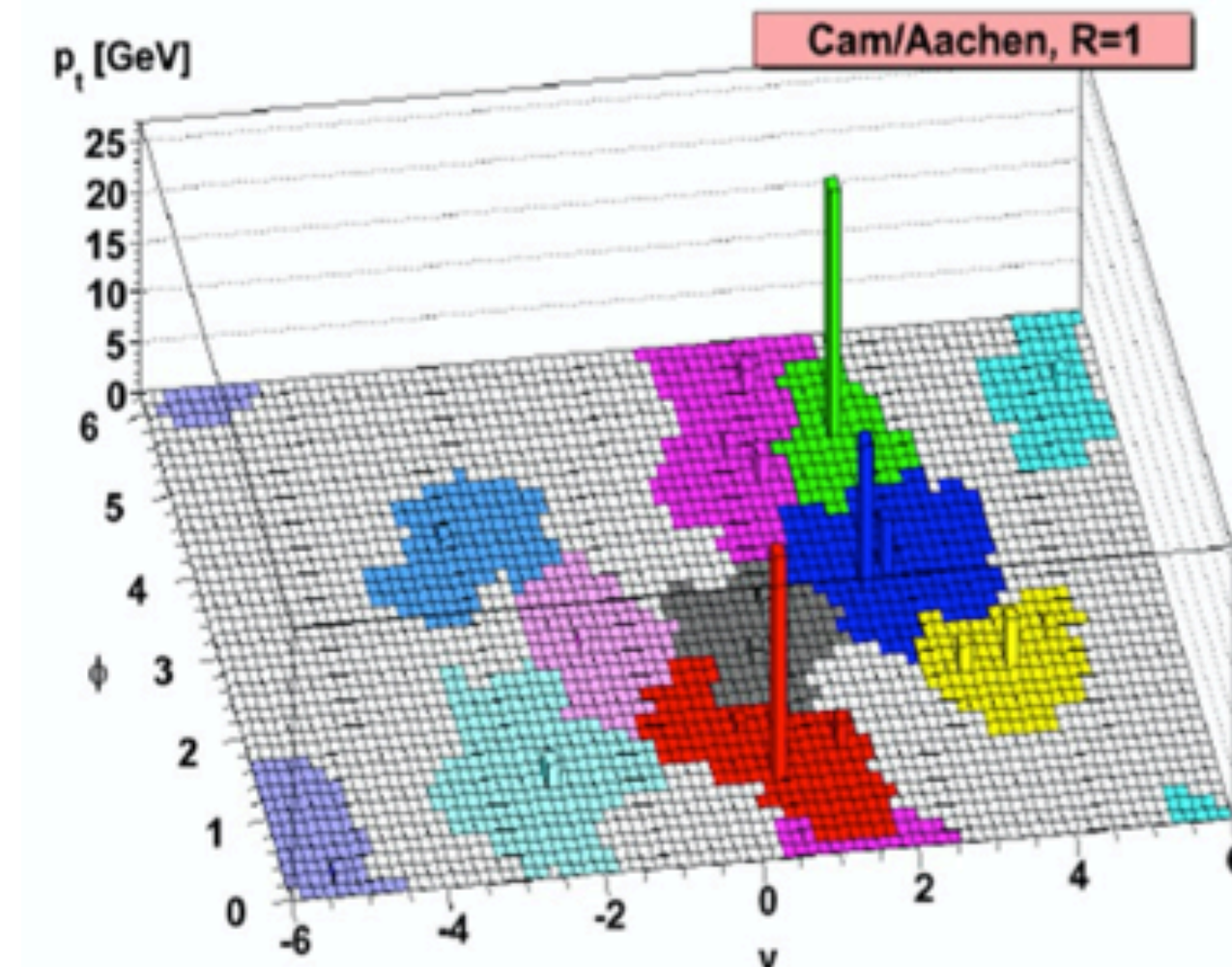
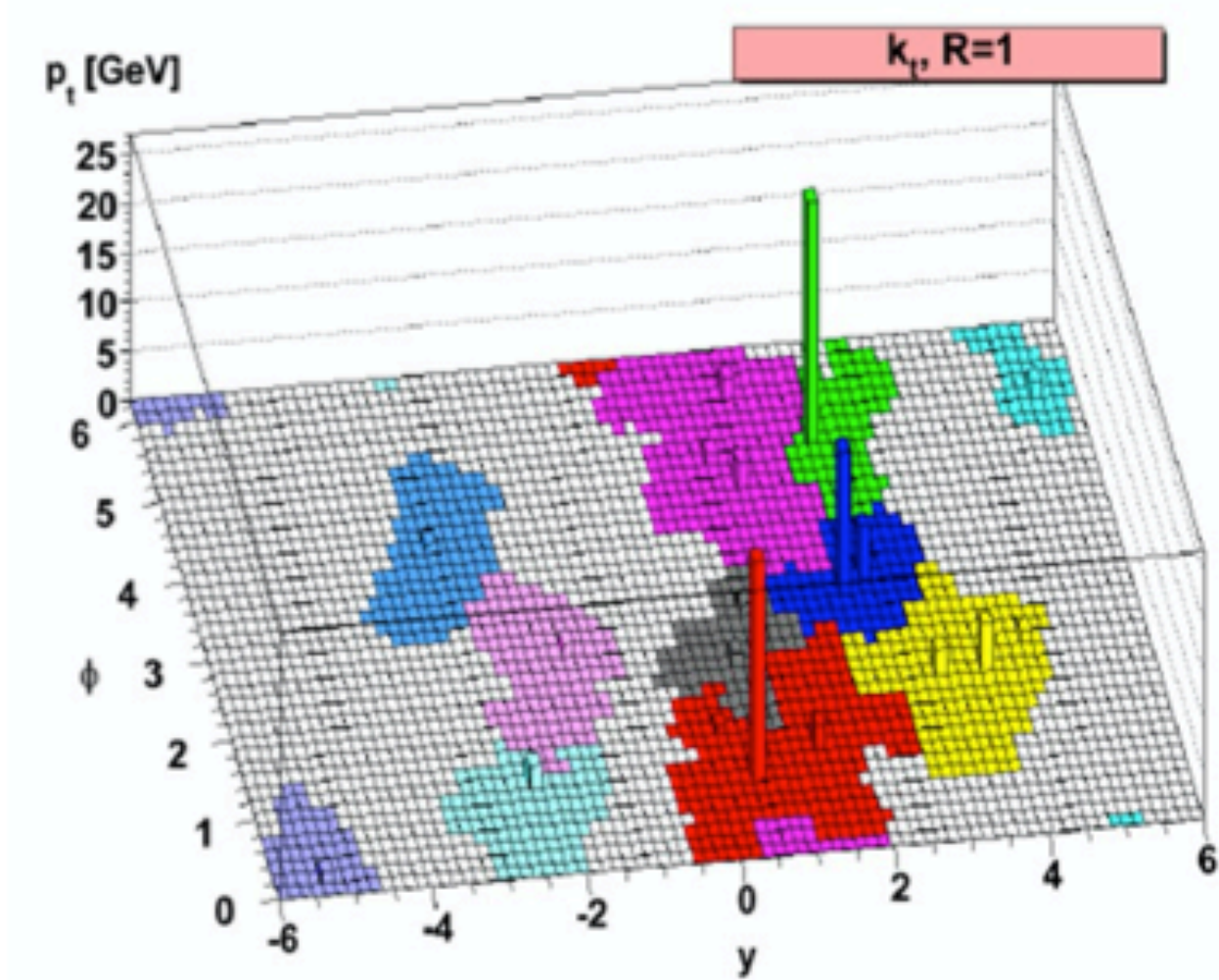


Jet algorithms

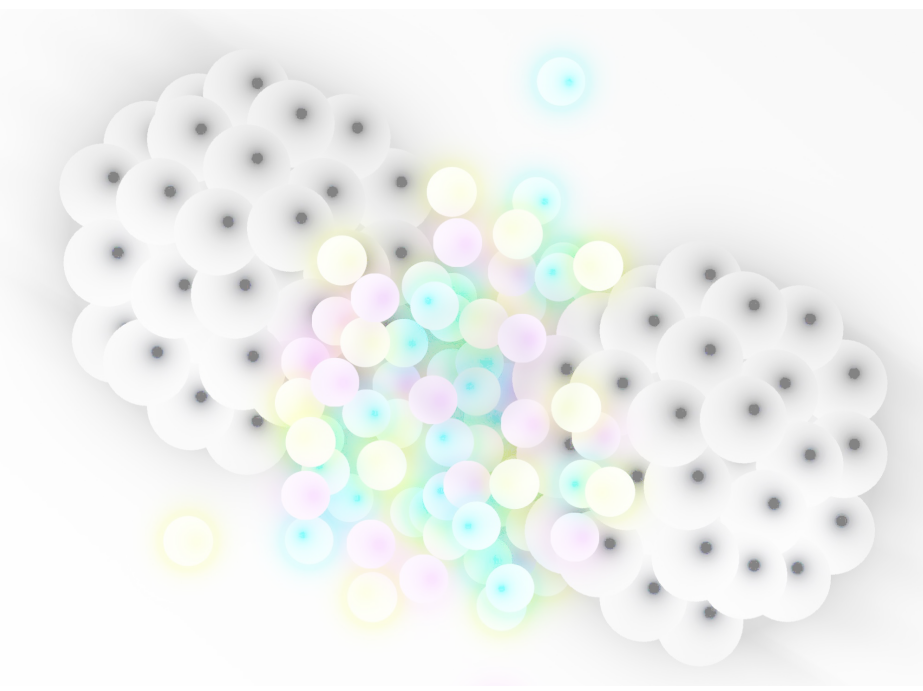


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Same event,
different jets



Jet algorithms

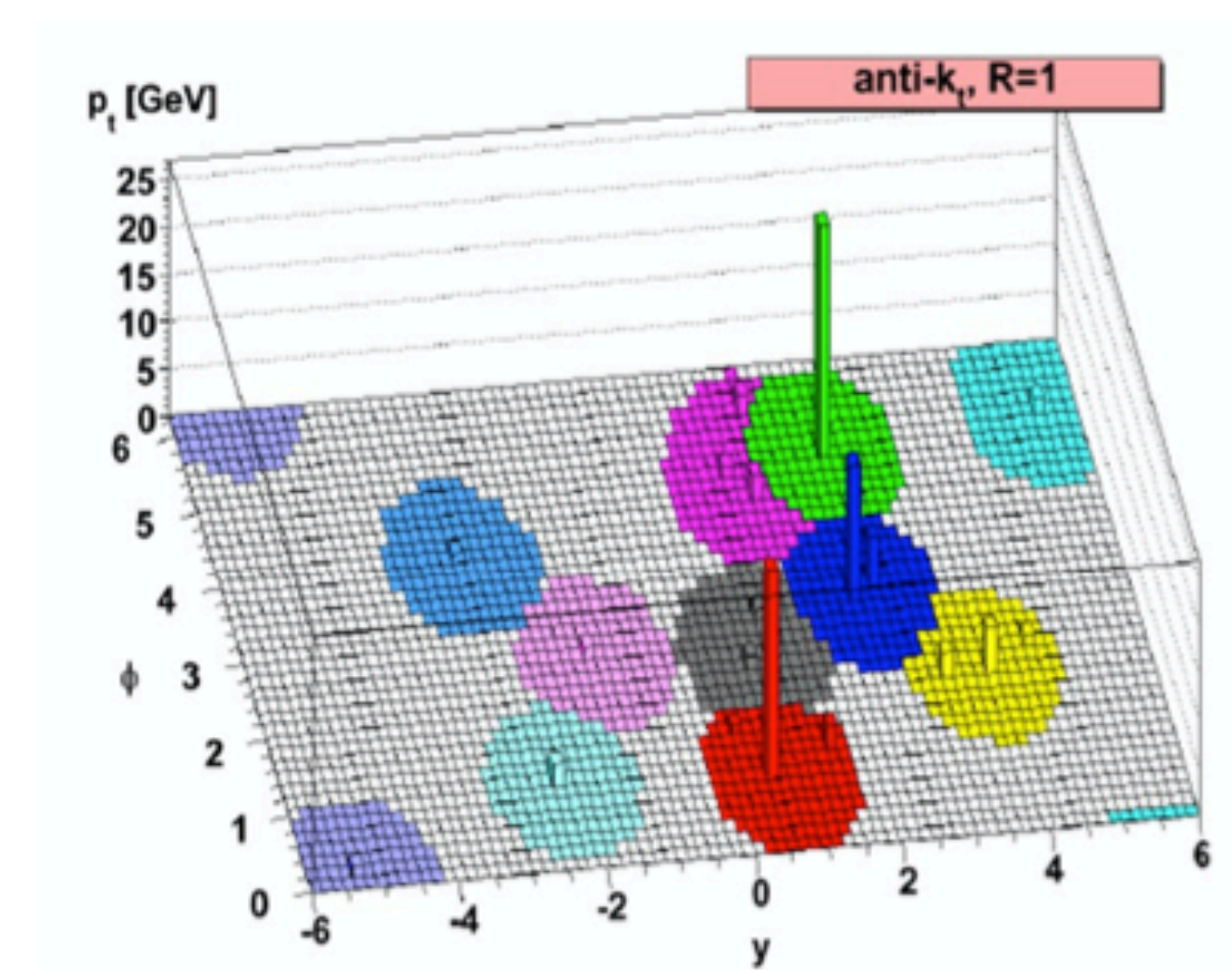
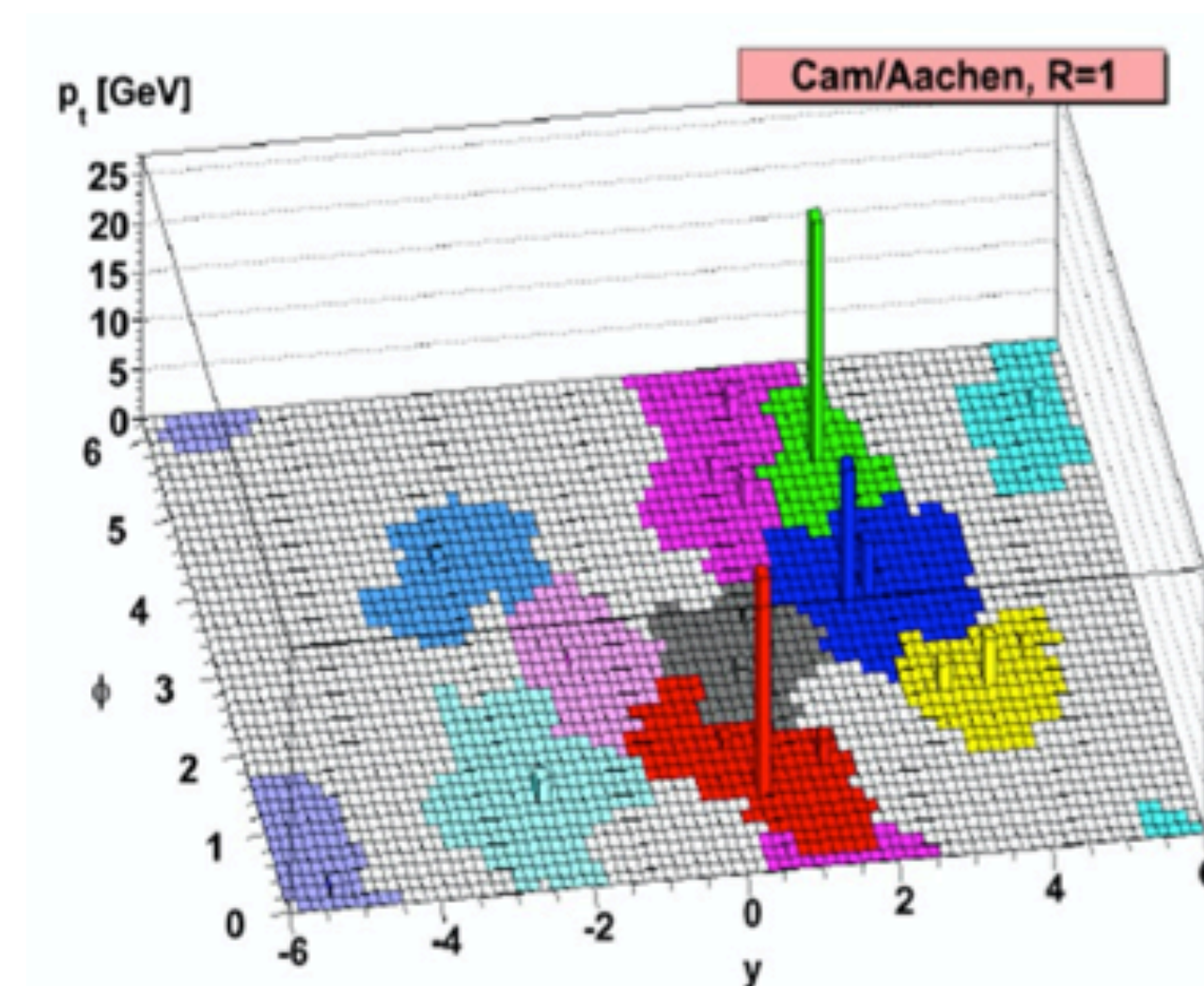
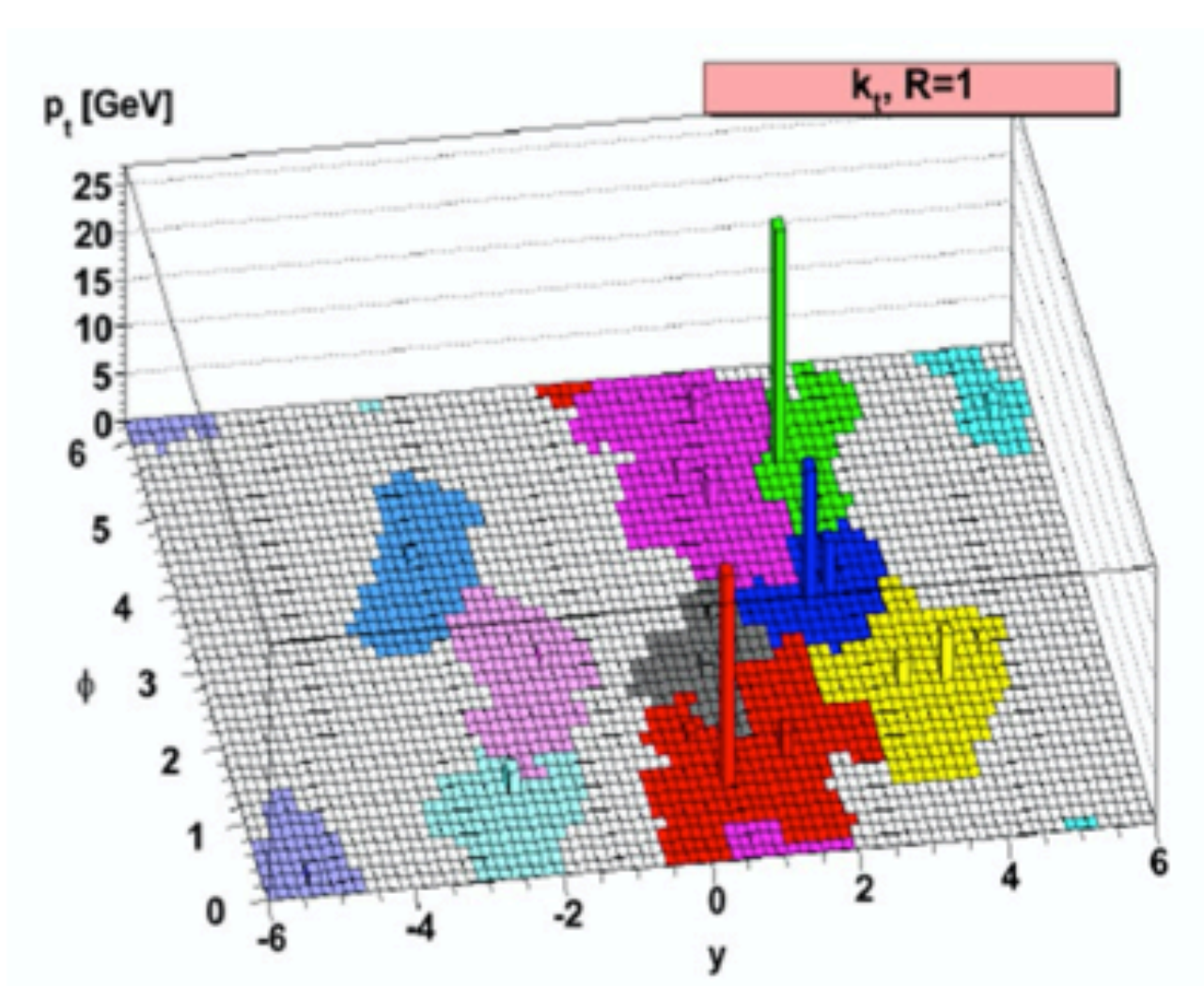


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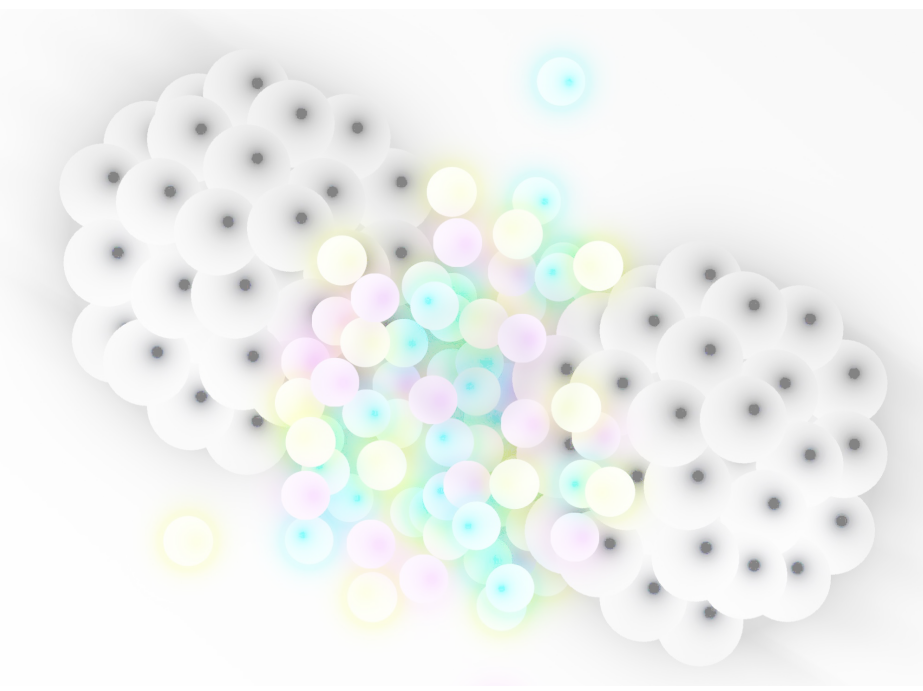
$$R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

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

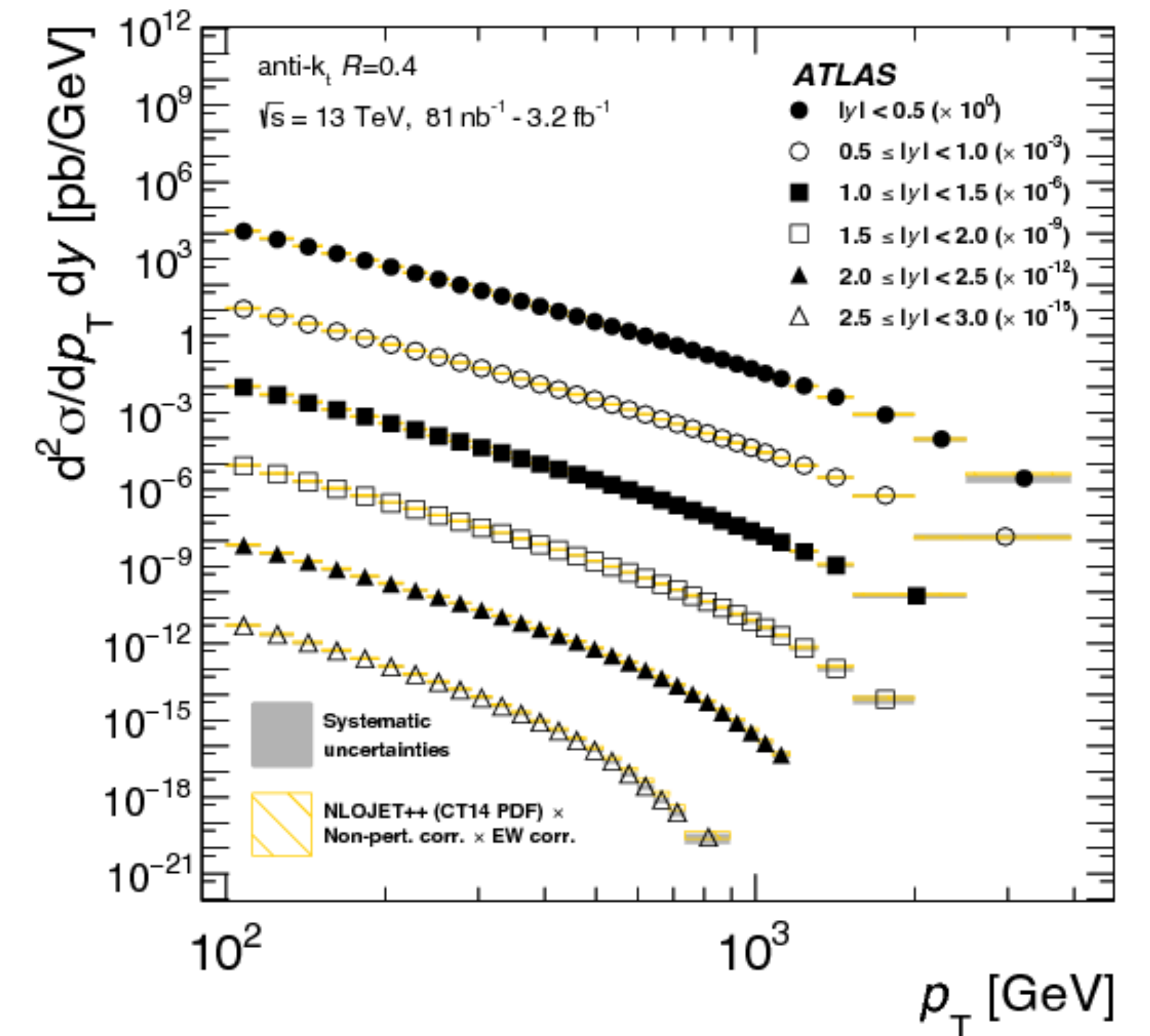
Same event,
different jets



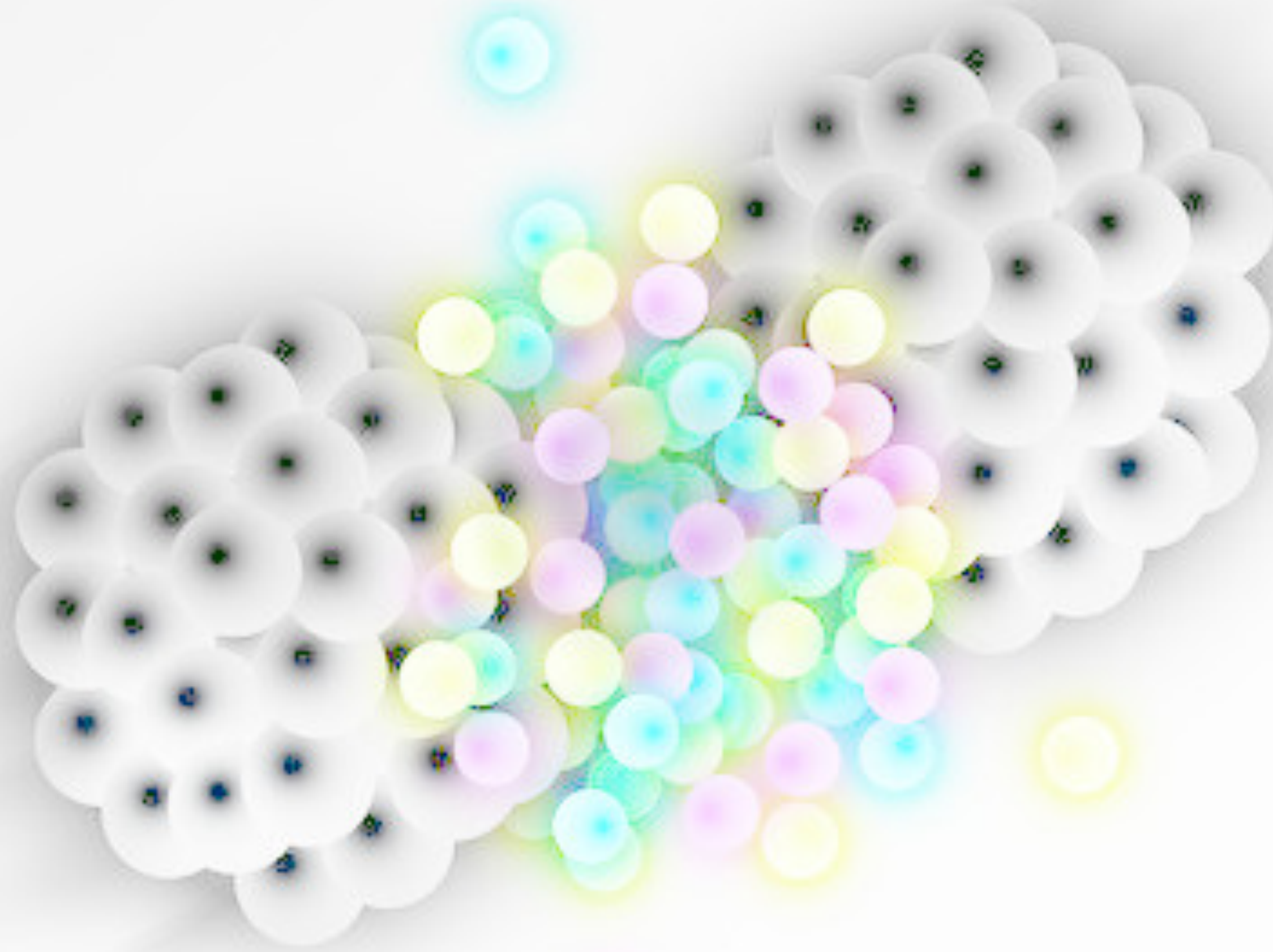
An example of QCD success



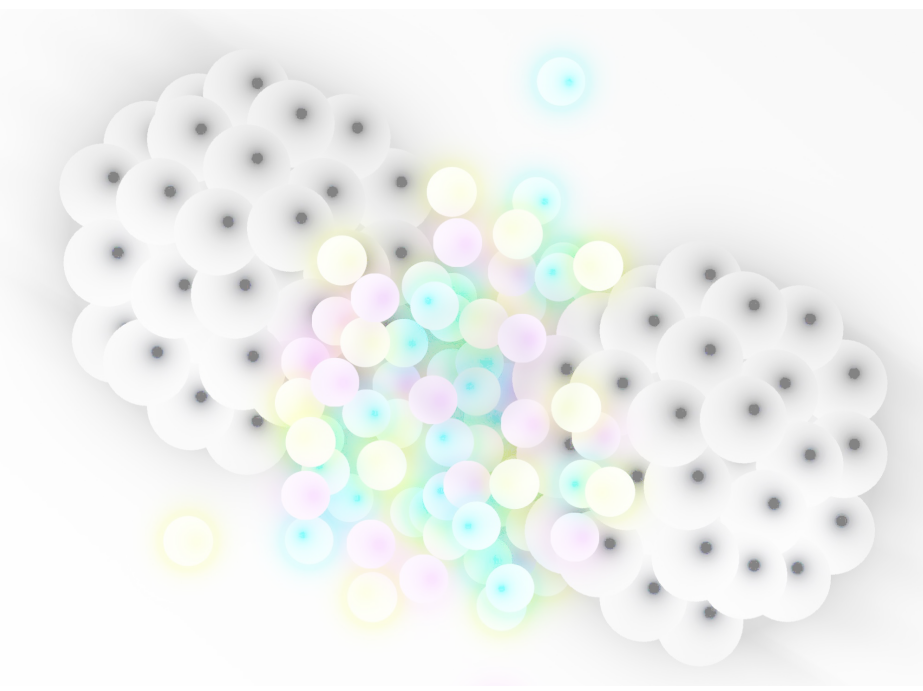
- Jets in pp collisions: excellent phenomenological tool!
 - Theoretical understanding from first principles
 - Accurate theoretical description of jet production in 10 orders of magnitude in cross-section!
 - Well controlled experimentally
 - Used in a multitude of phenomenological studies (top quark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



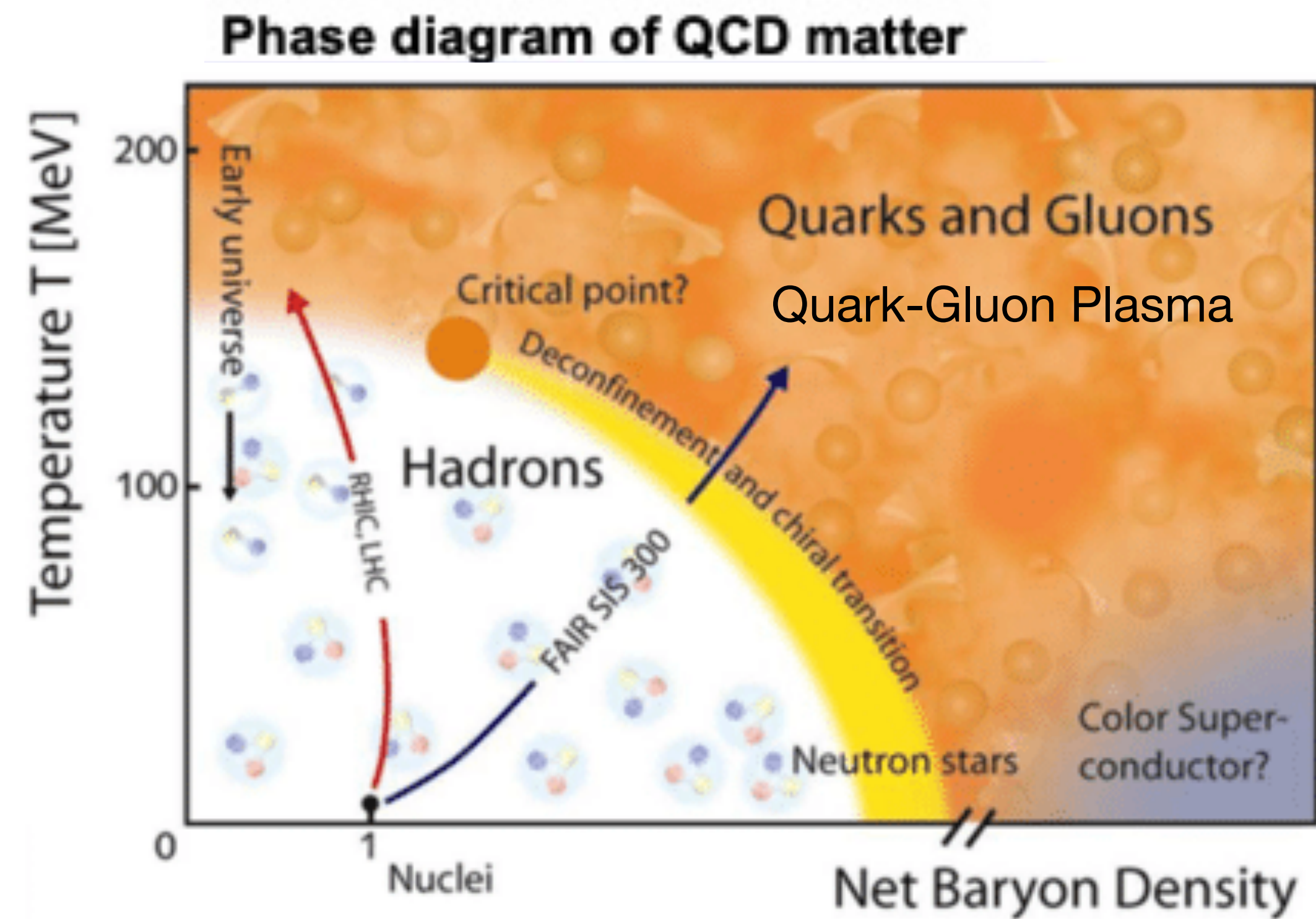
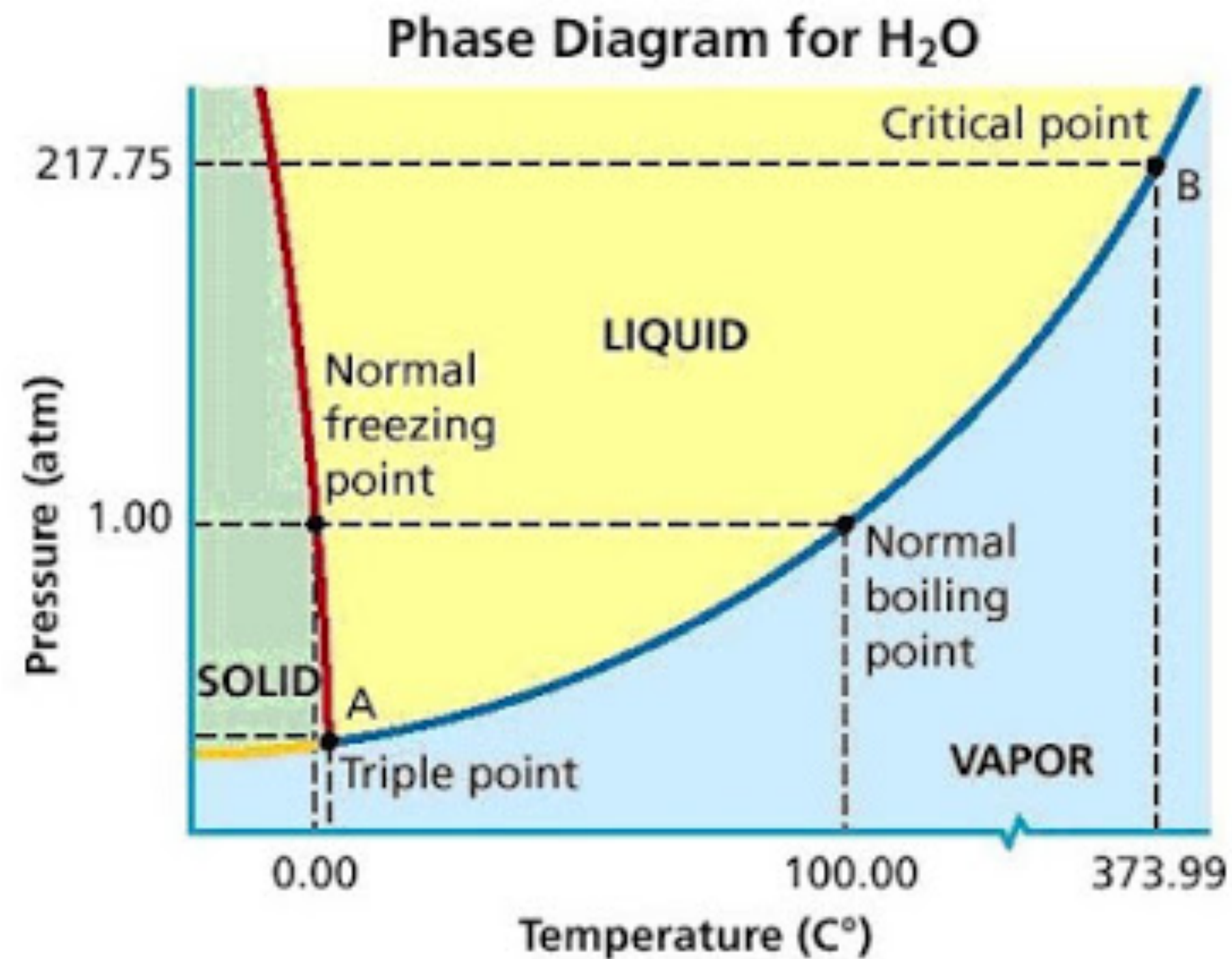
**Is QCD limited to a collection of
small particles?**



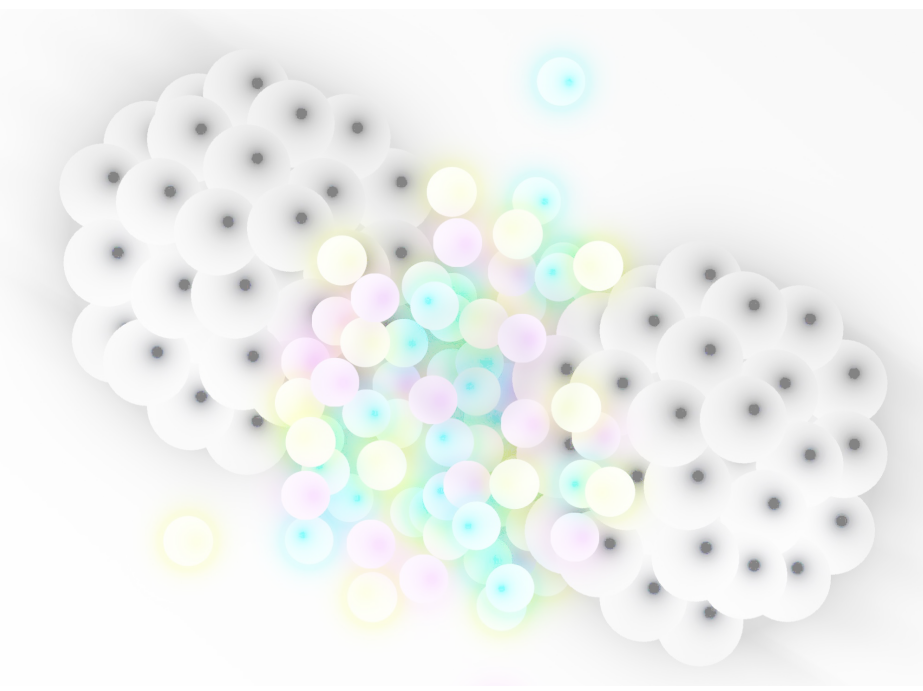
From dilute QCD to dense QCD



- QCD matter has a rich and vast phase diagram:



From dilute QCD to dense QCD

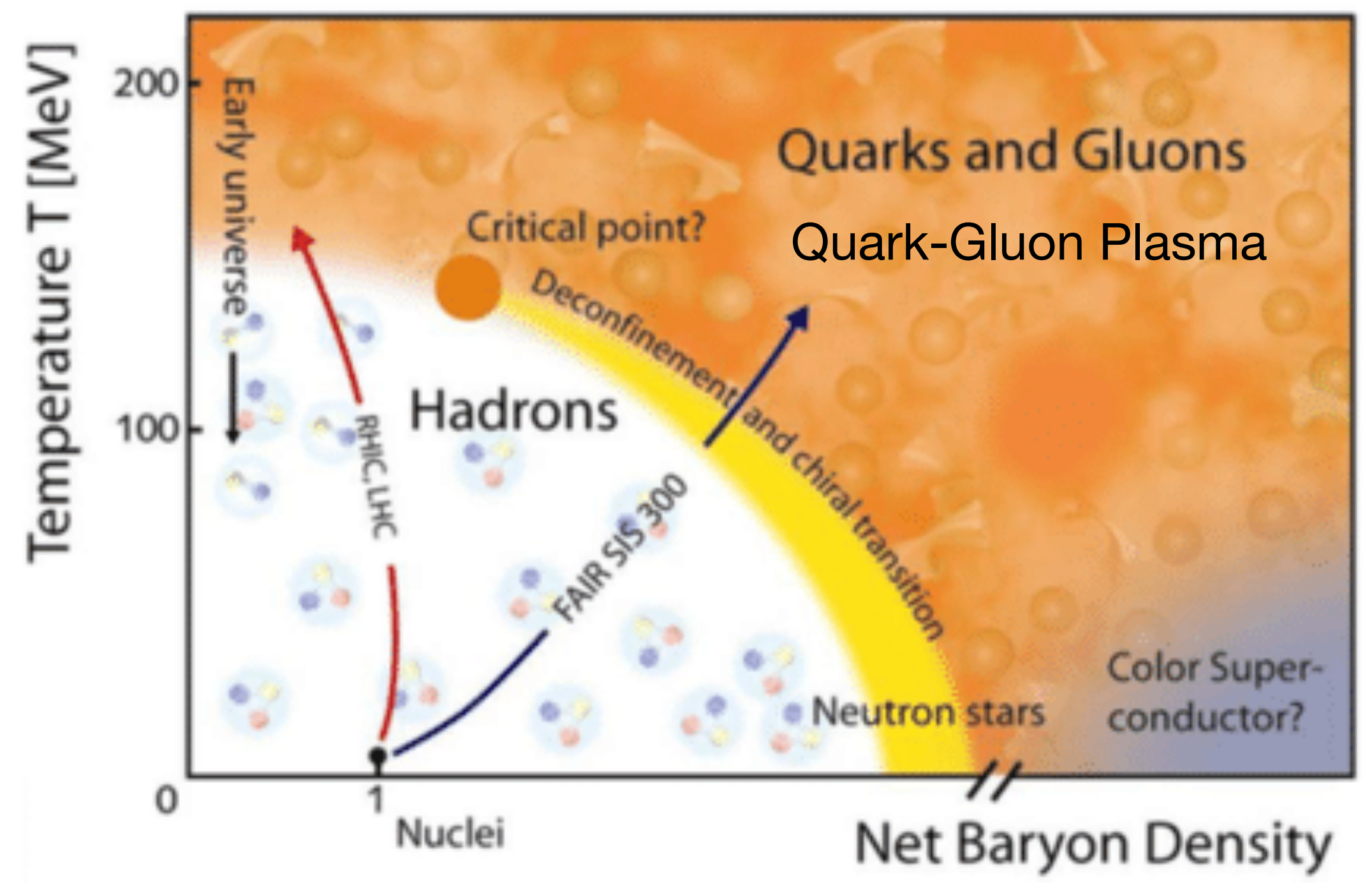


- QCD matter has a rich and vast phase diagram:

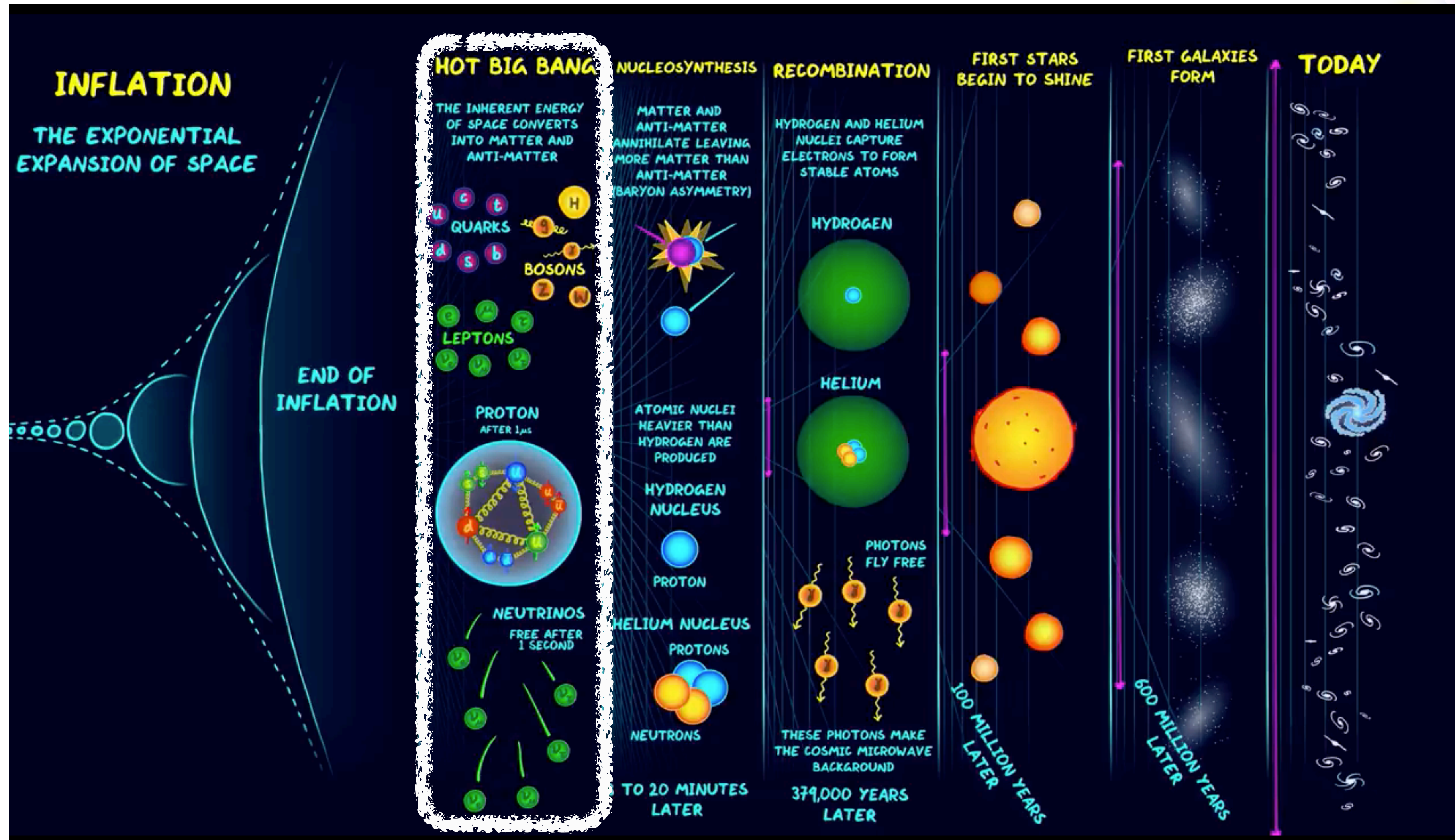
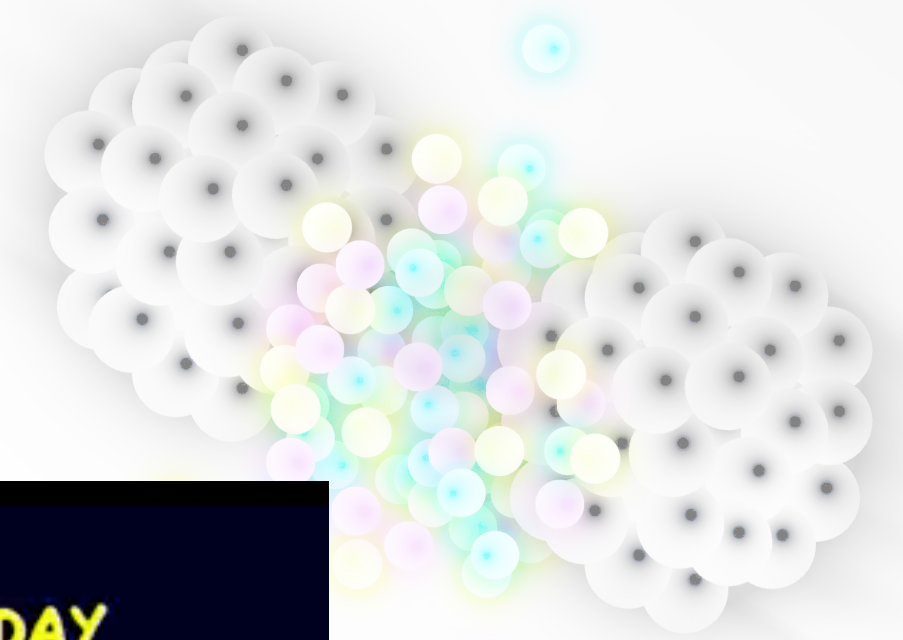
QCD theory (1973)
SU(3) Color symmetry; confinement;
asymptotic freedom, ...

QGP initial idea (1975)
“Weakly coupling quark soup”
State of matter where quarks and
gluons are asymptotically free

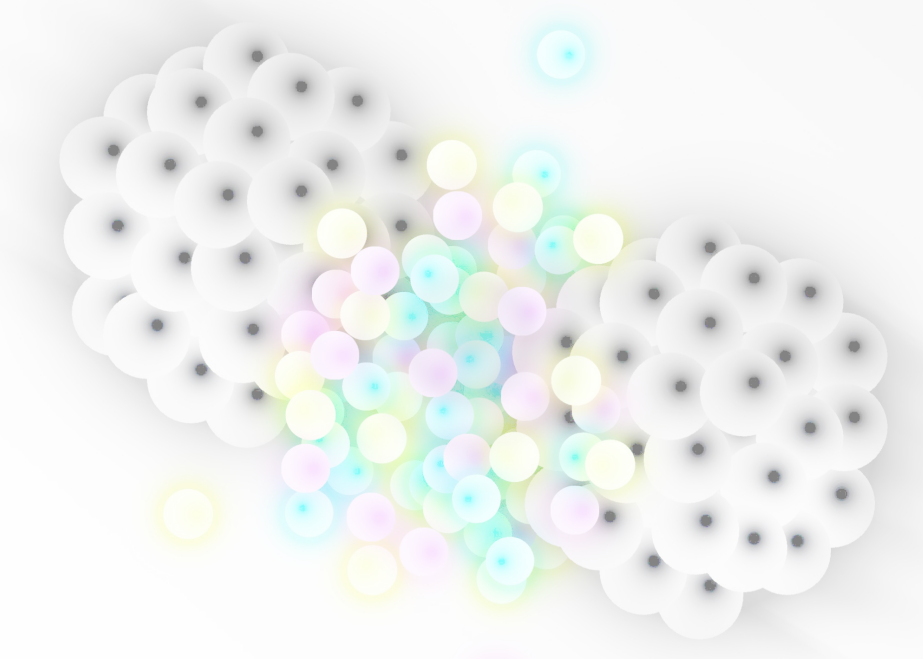
Phase diagram of QCD matter



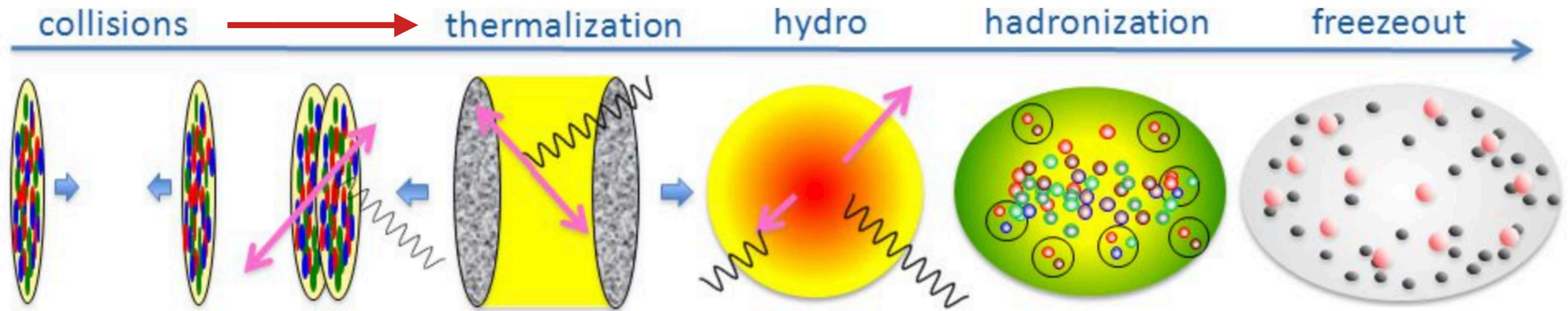
QGP @ Early Universe



QGP @ Heavy-Ion Collisions



- Heavy-Ion Collisions:



pre-equilibrium

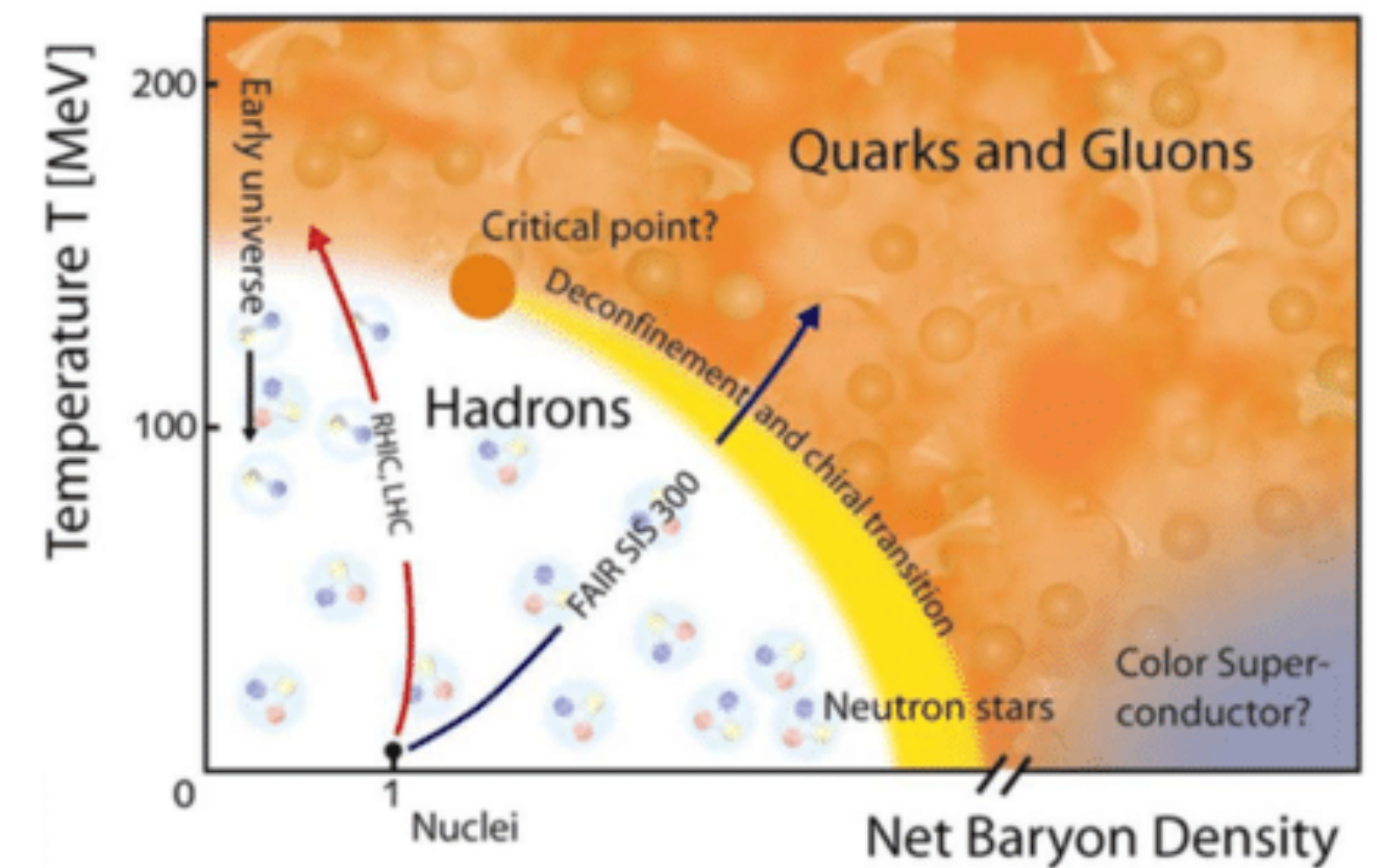
QGP and hydrodynamic expansion

FCC?:
PbPb @ 39 TeV

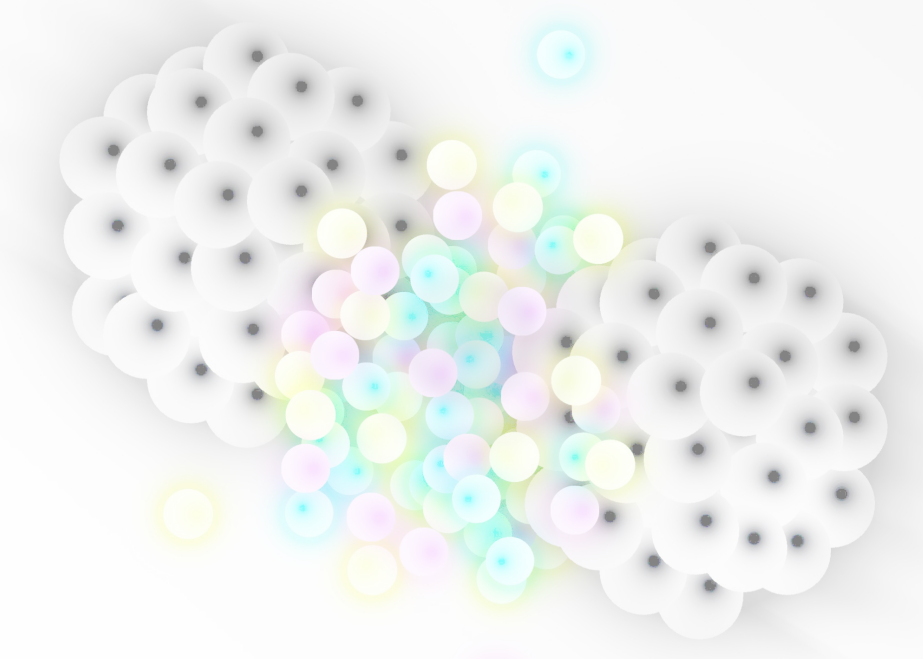
RHIC (~2000):
AuAu @ 200 GeV

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

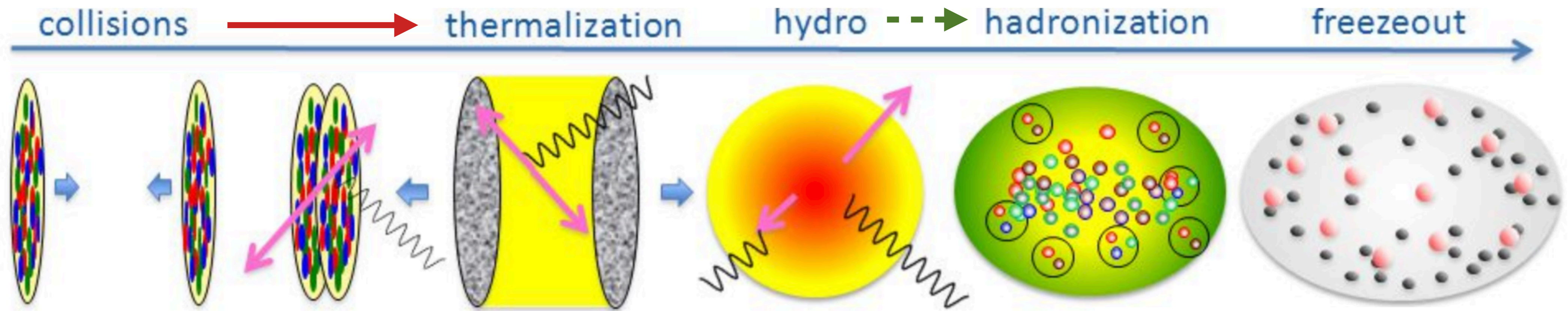
hadronic phase



QGP @ Heavy-Ion Collisions



- Heavy-Ion Collisions:



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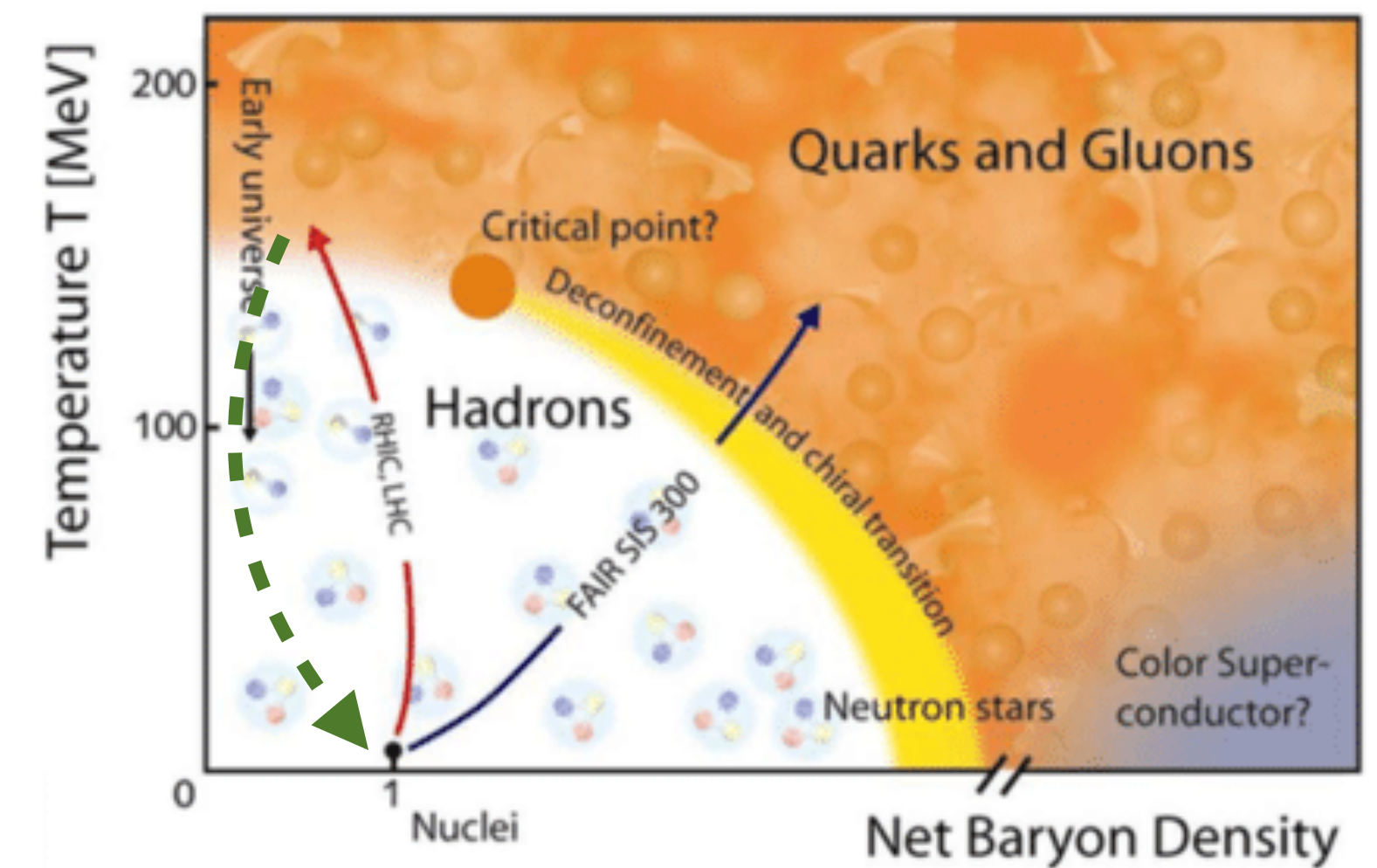
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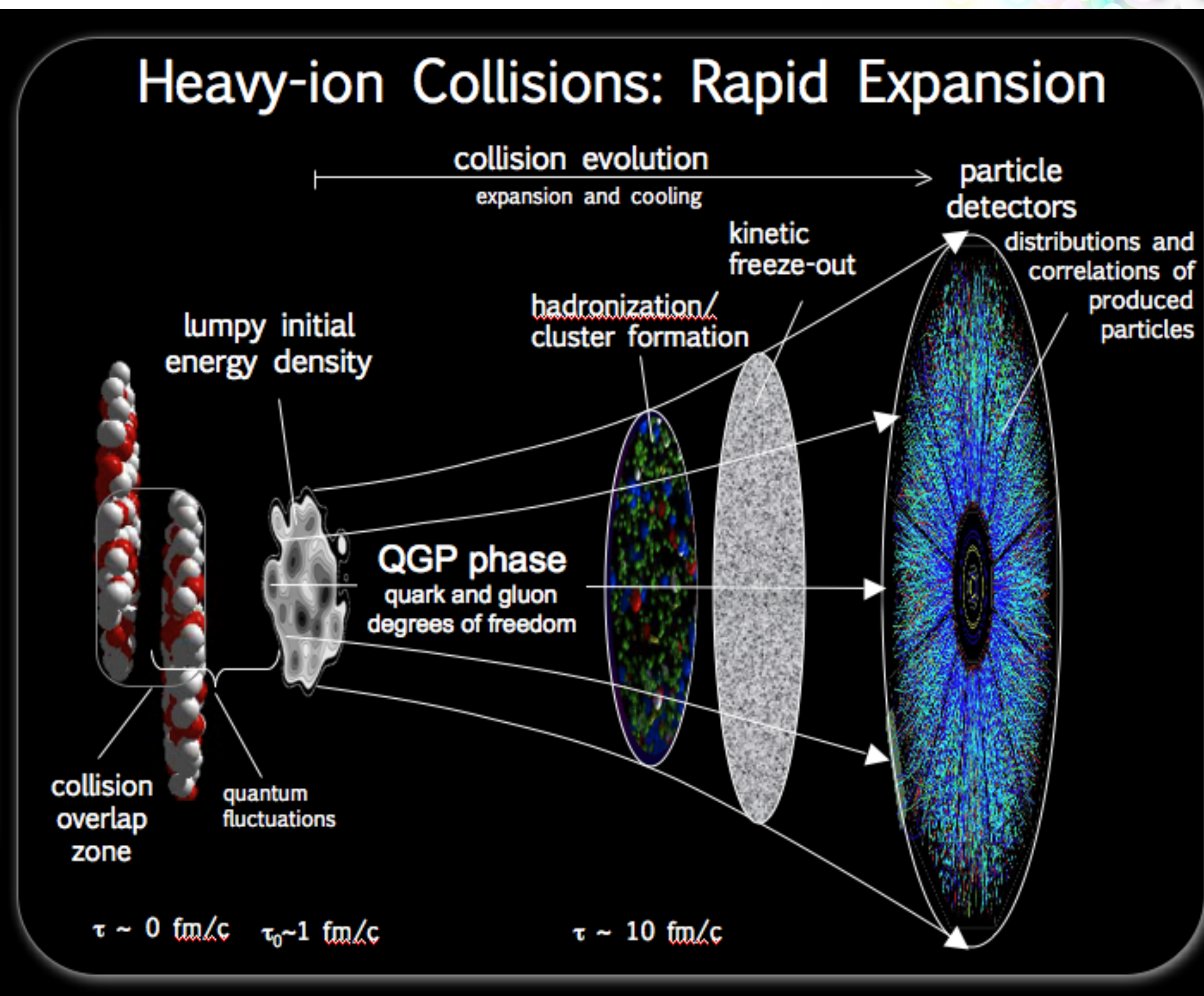
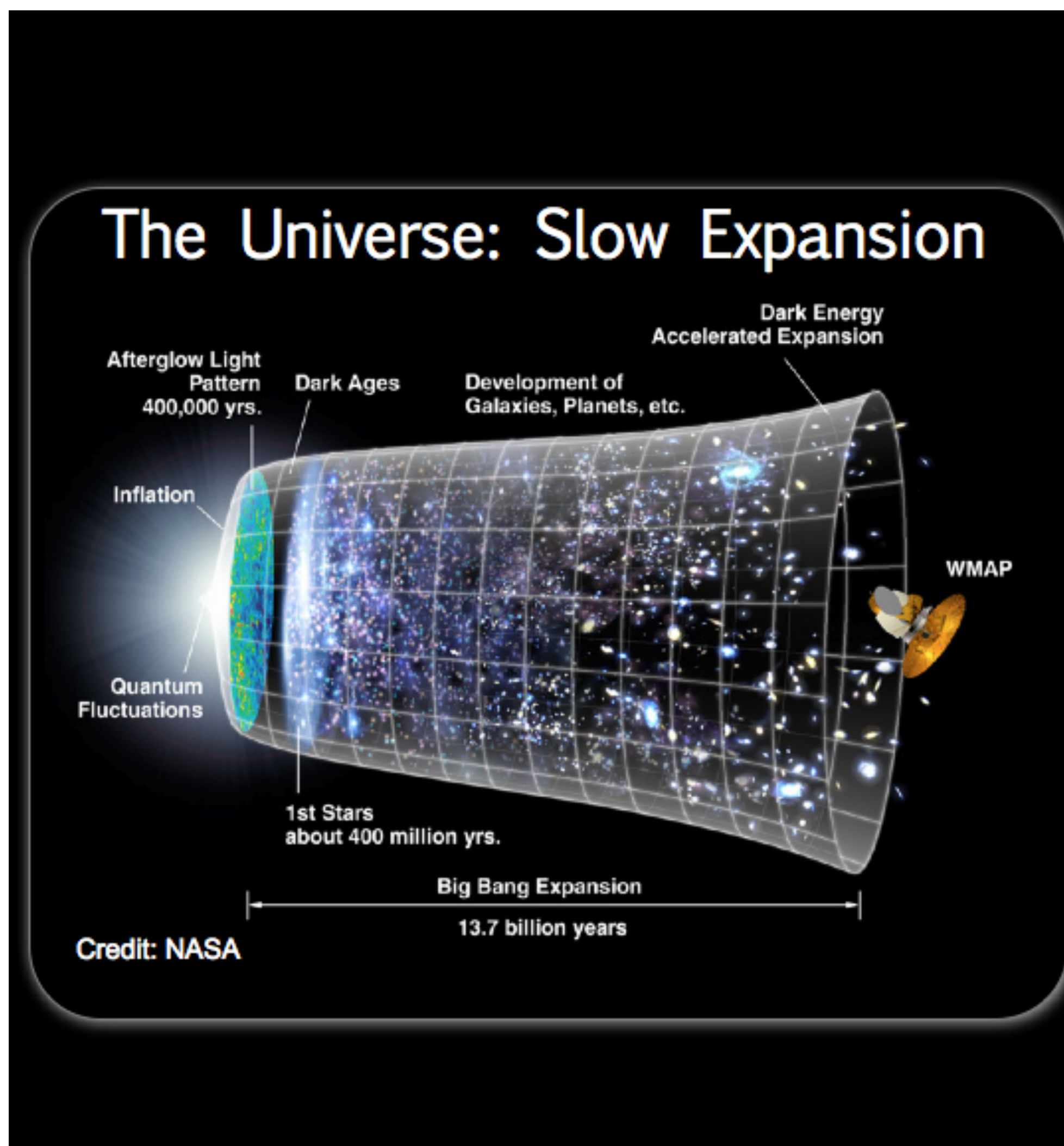
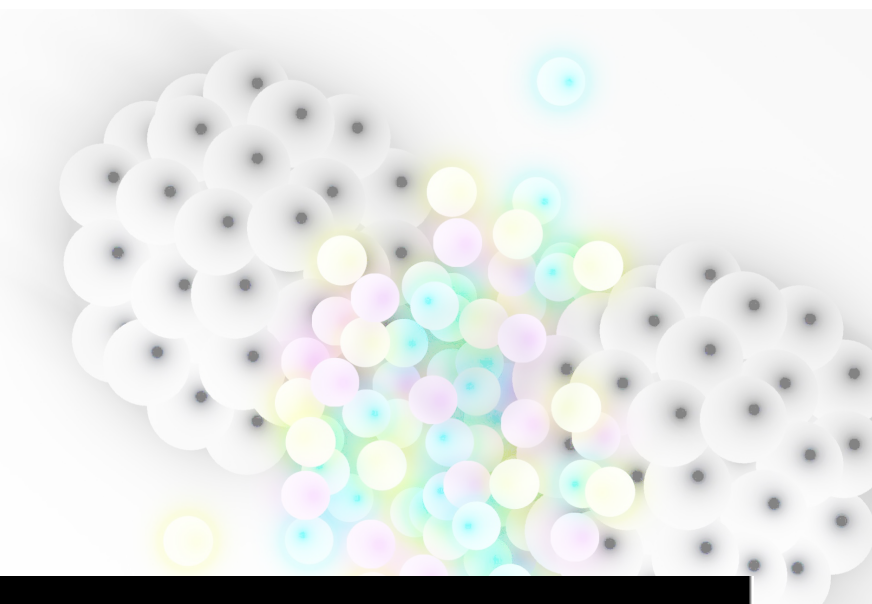
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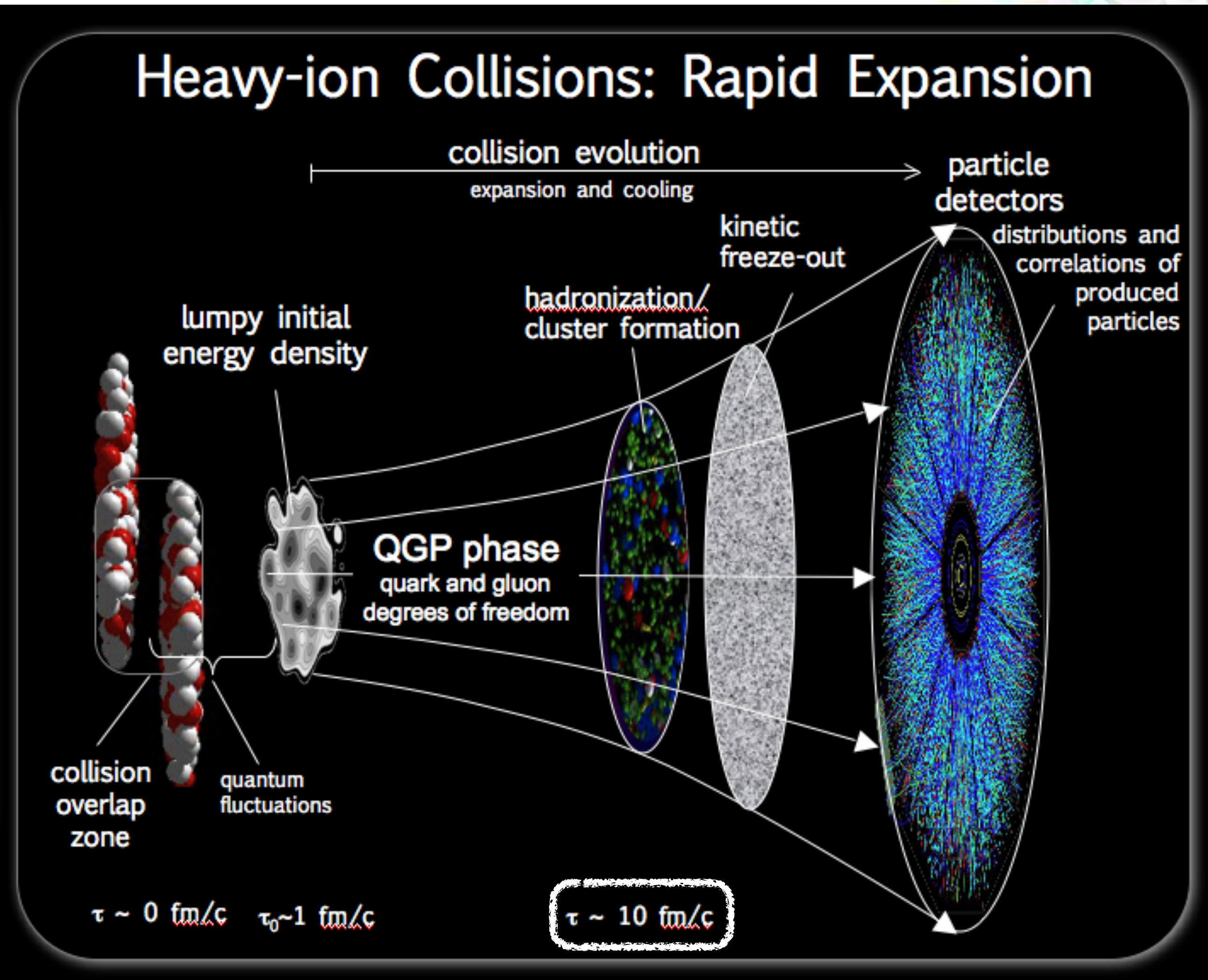
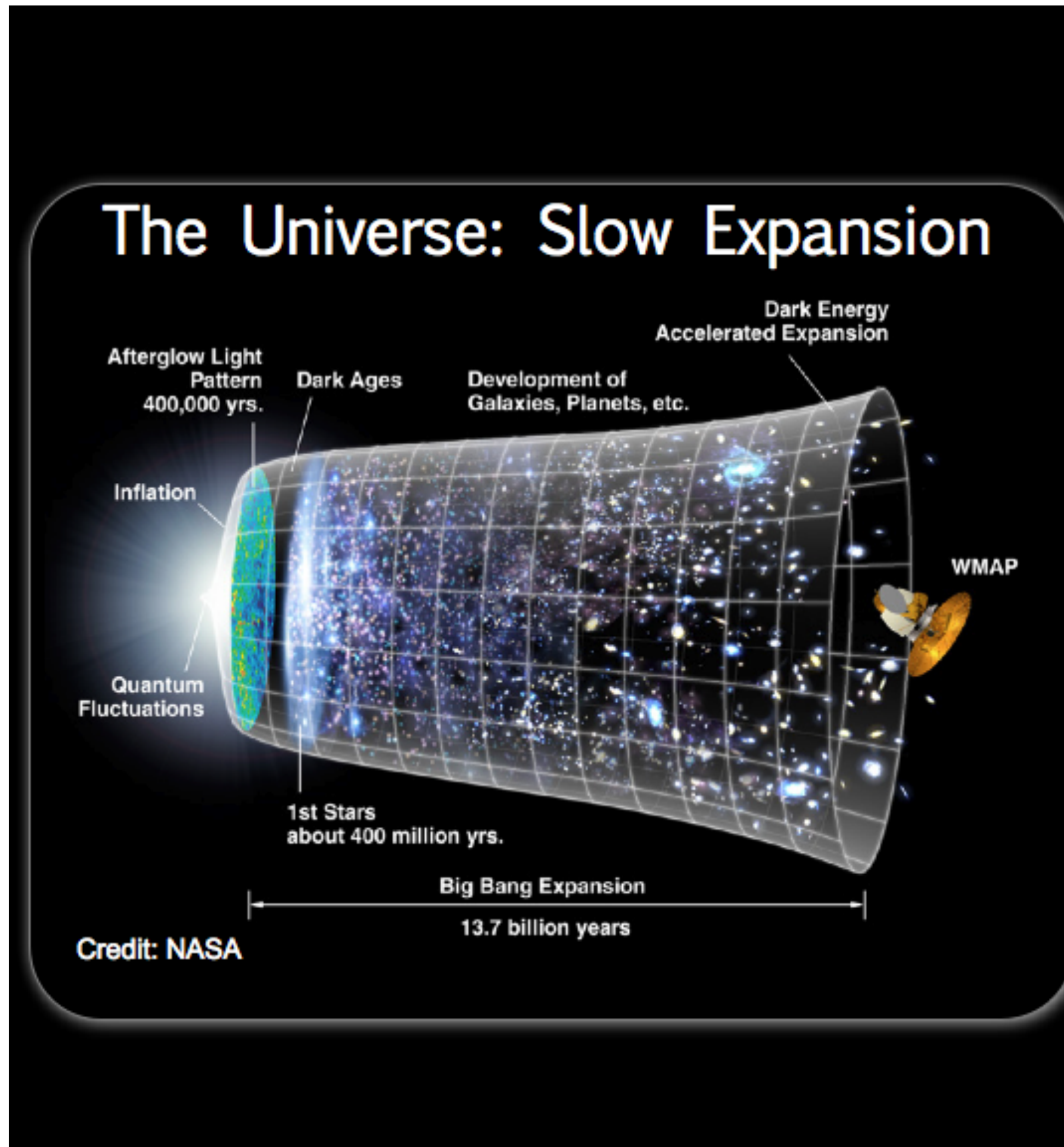
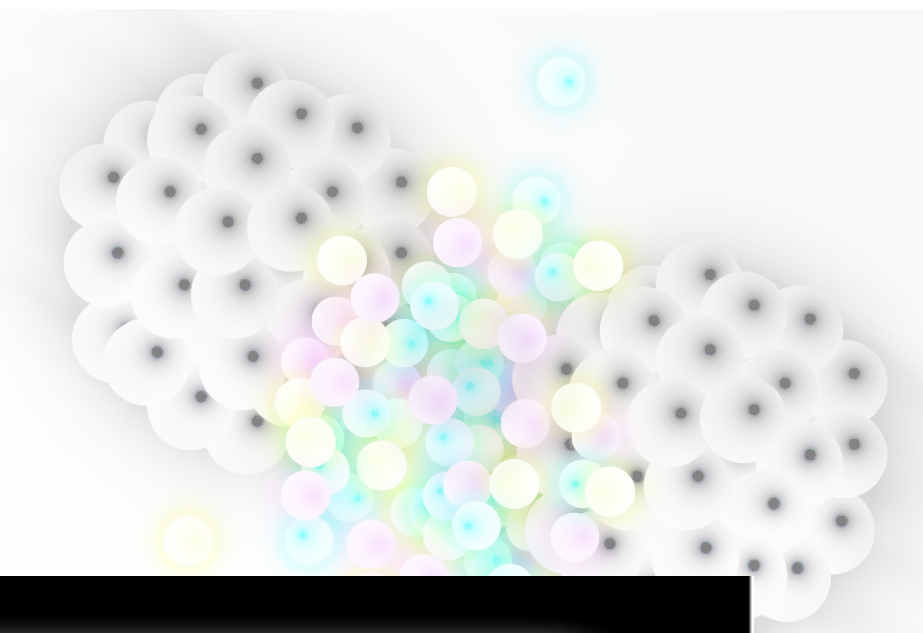
hadronic phase



“Big-Bang” vs “Mini-Bang”

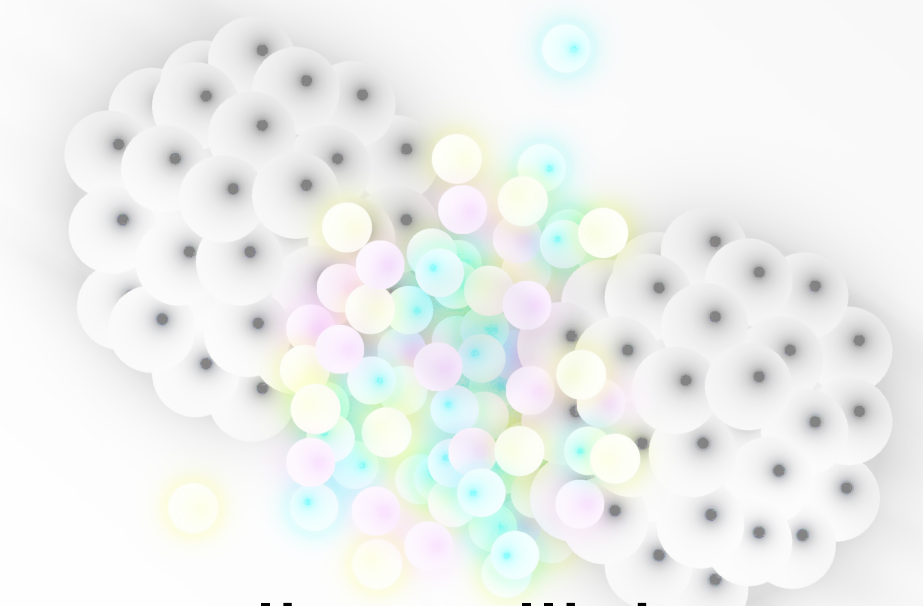
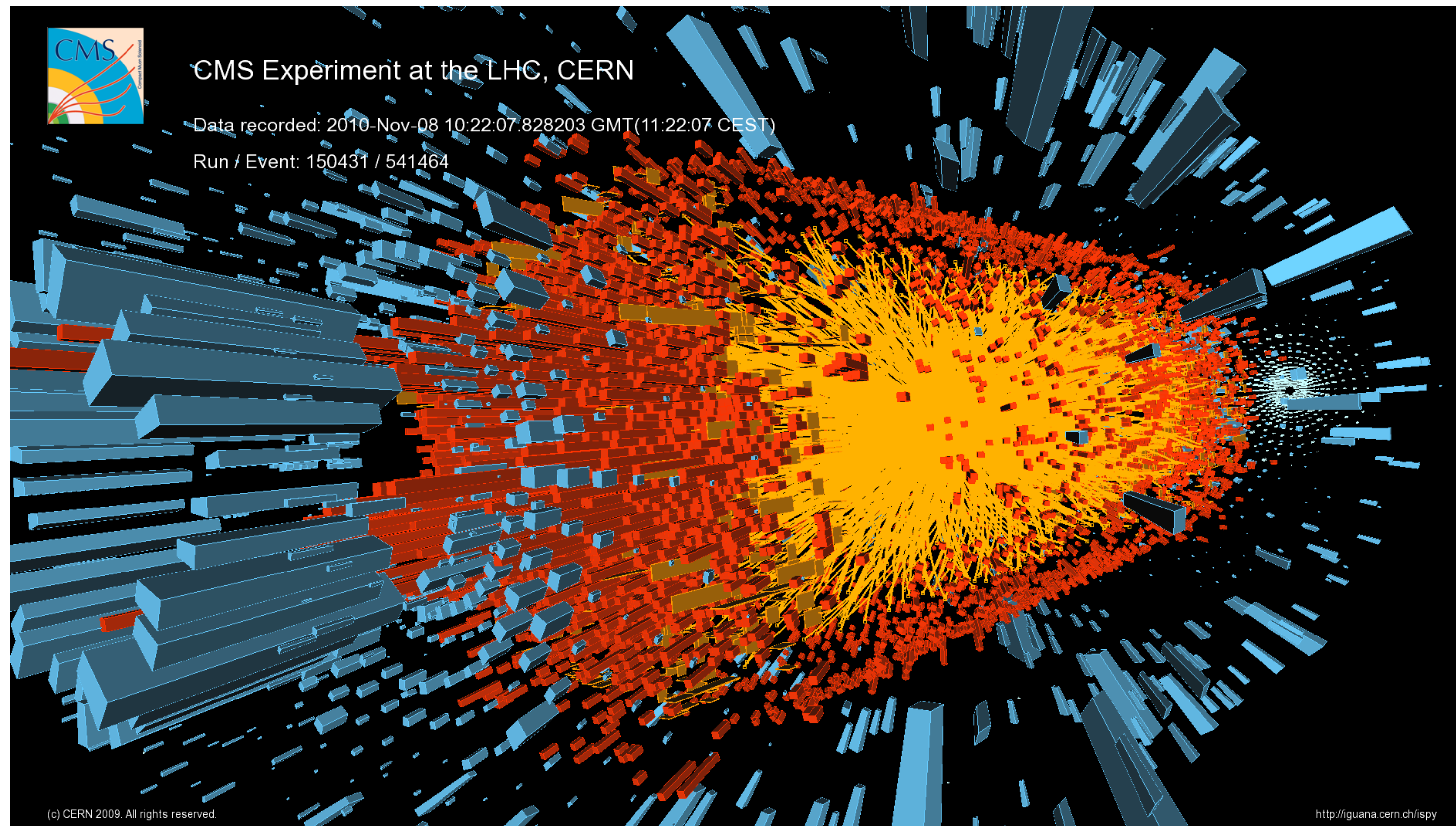


“Big-Bang” vs “Mini-Bang”



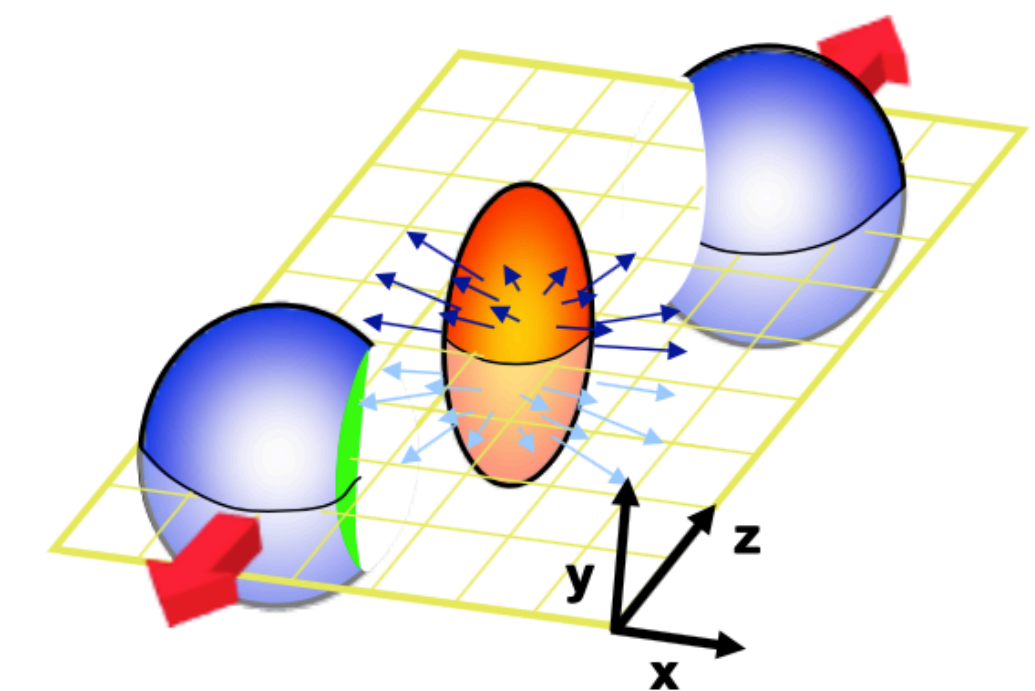
How to probe the QGP @ lab?

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

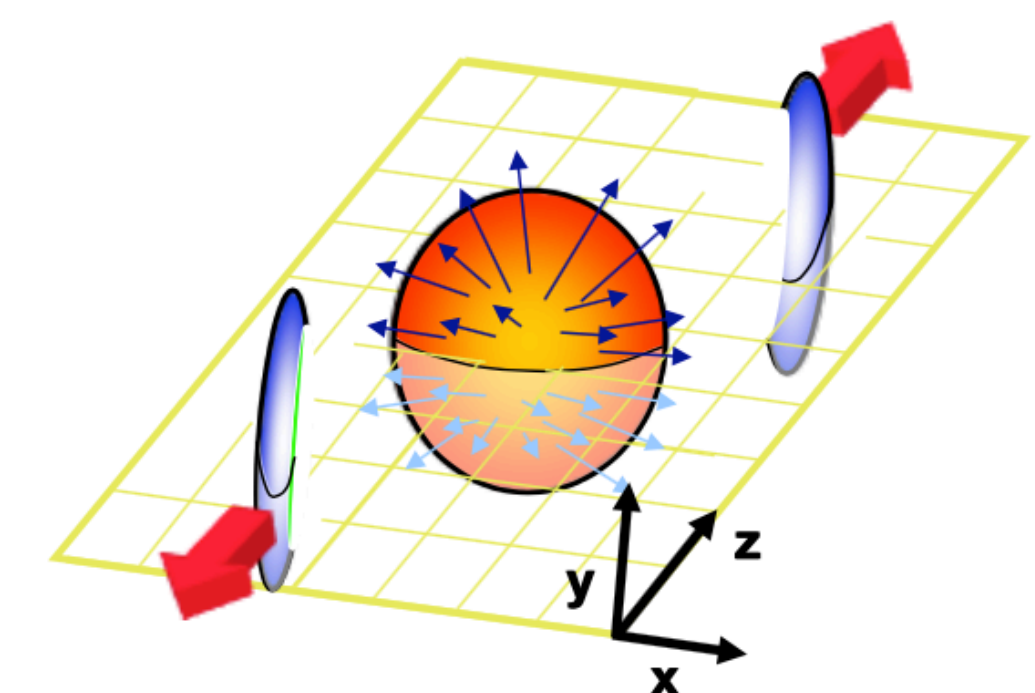


Try different centrality collisions

Peripheral Collision



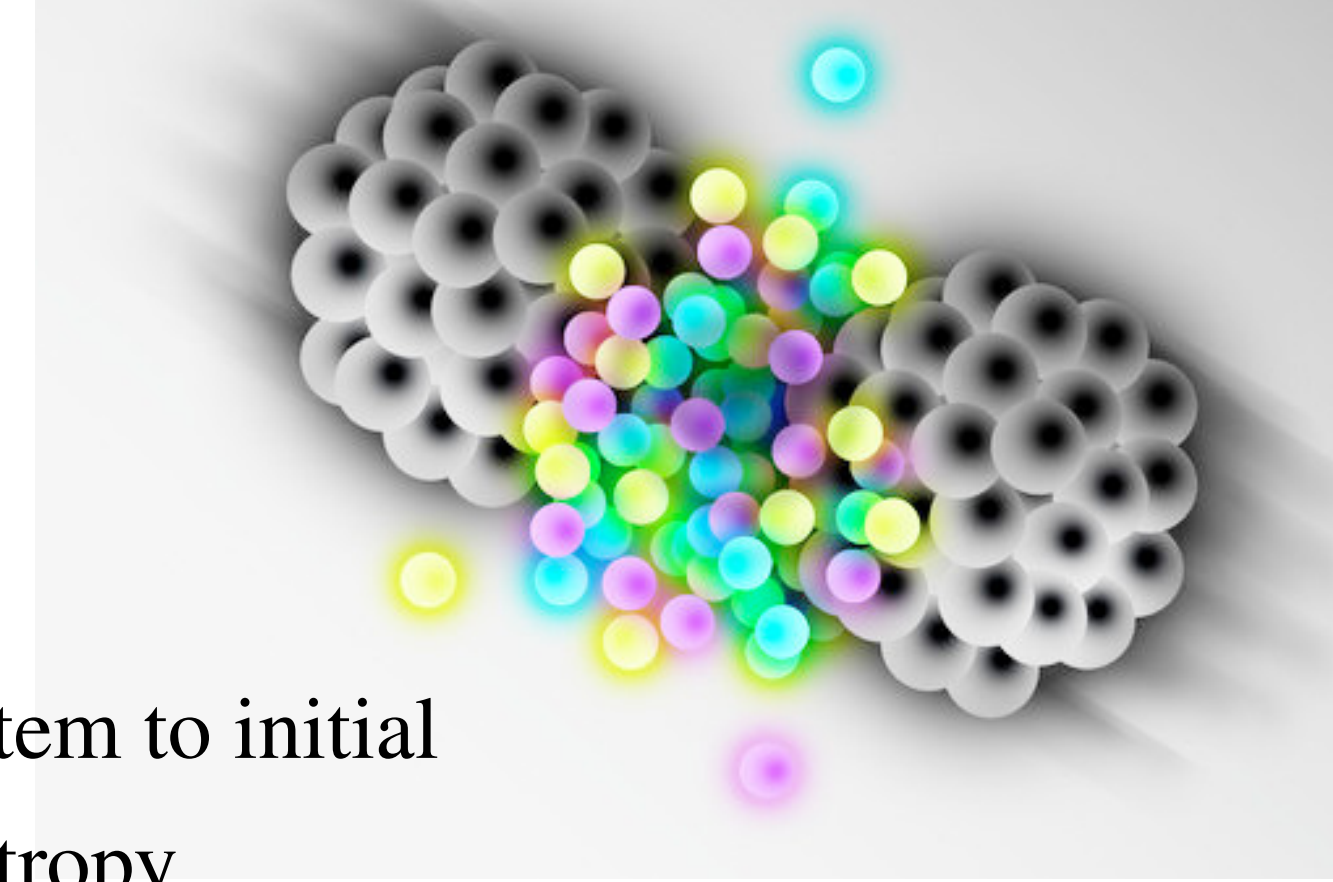
(near) Central Collision



Soft probes

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

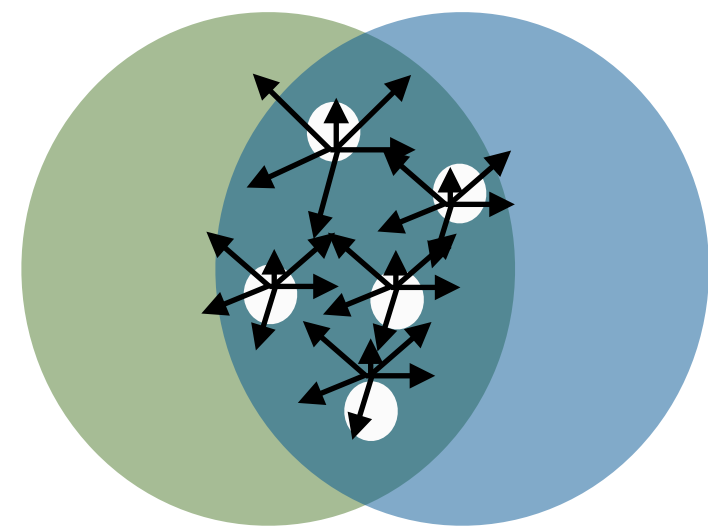
Response of the system to initial spatial anisotropy



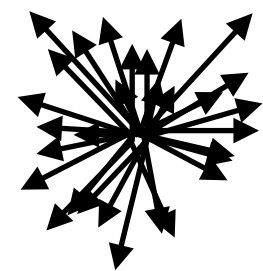
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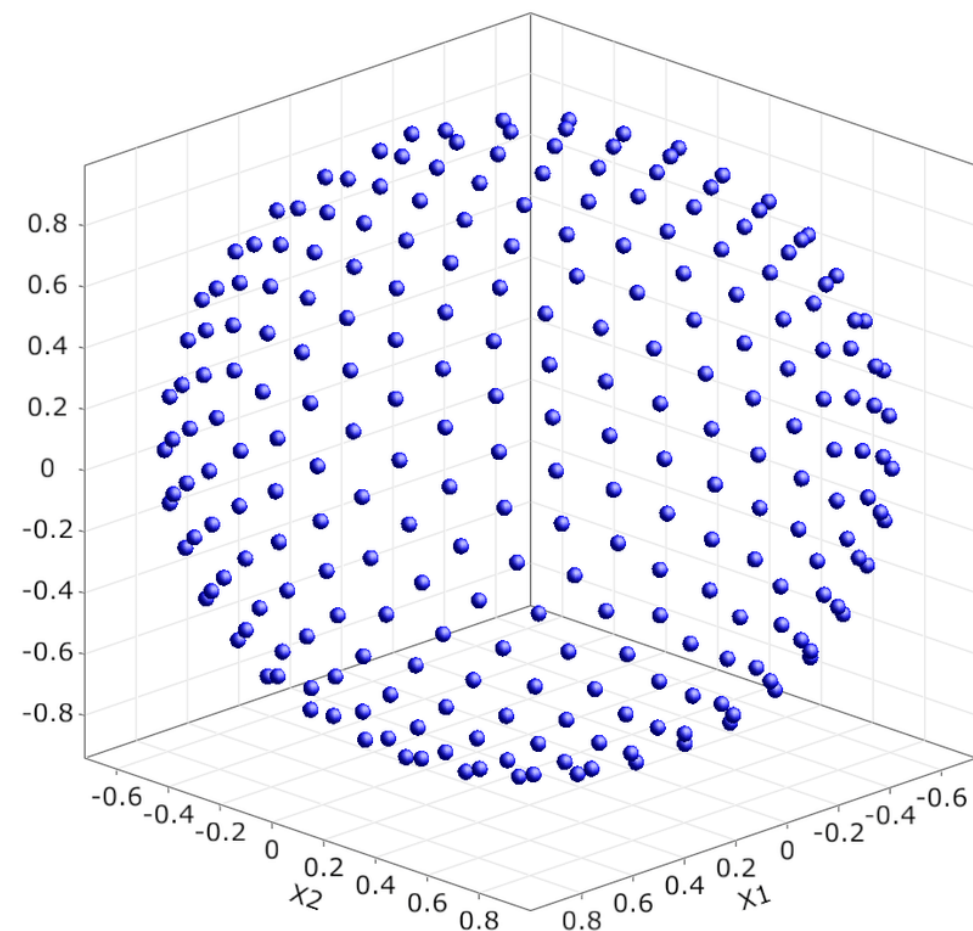
Superposition of multiple pp collisions



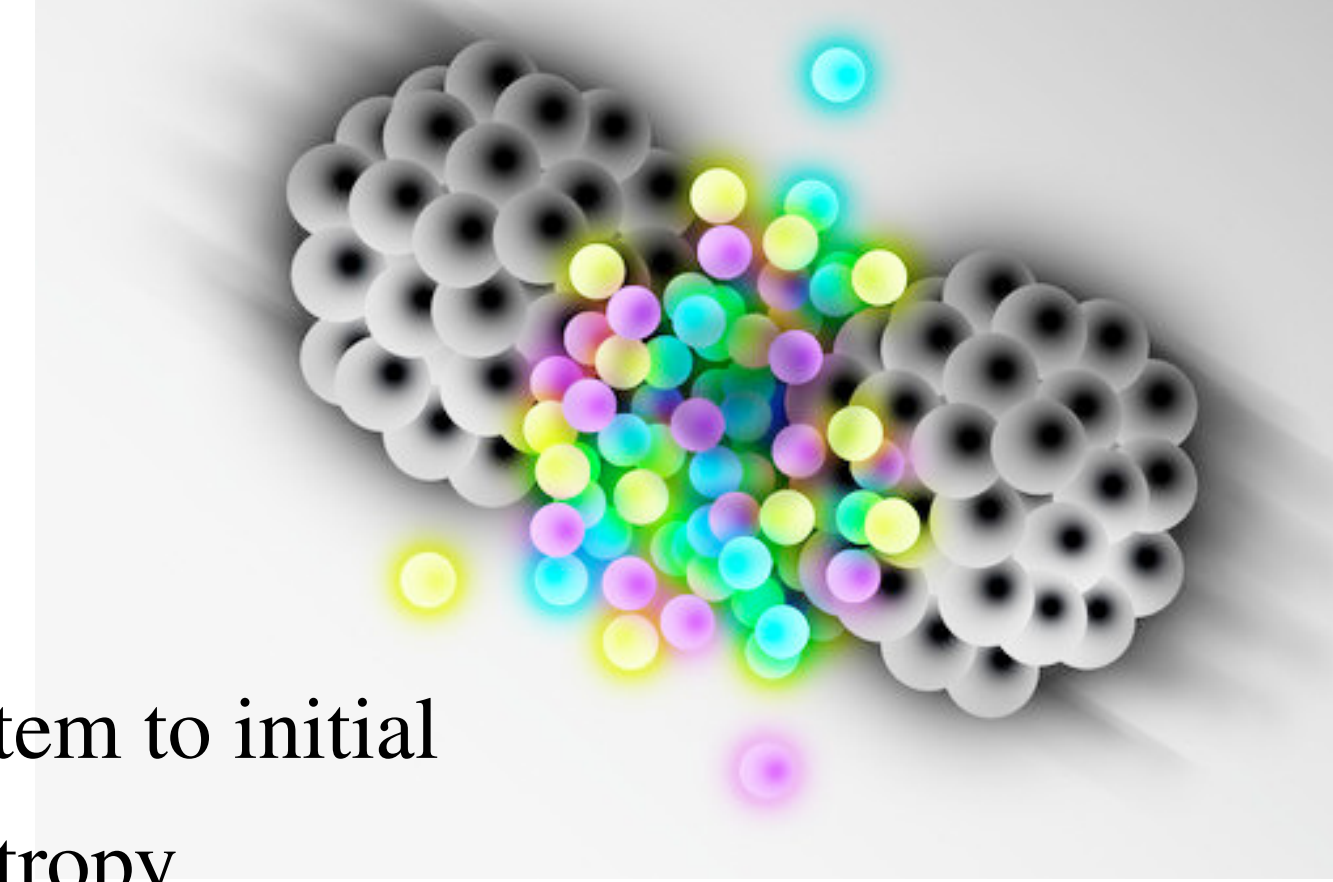
“Gas-like” behaviour?



Uniform distribution of final particles



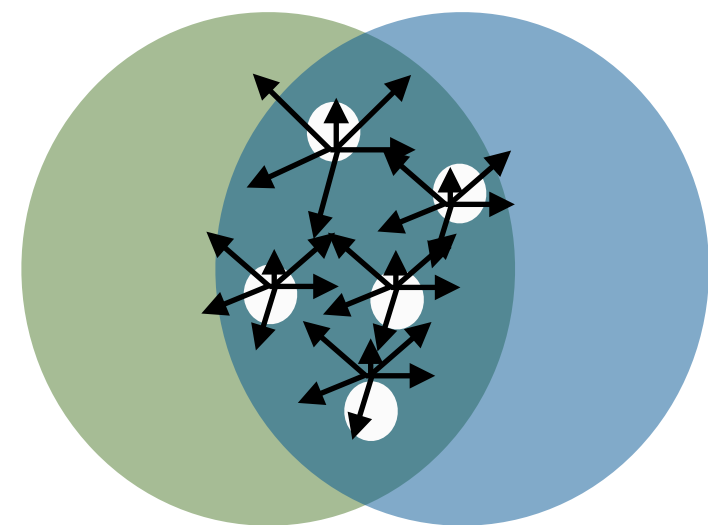
Response of the system to initial spatial anisotropy



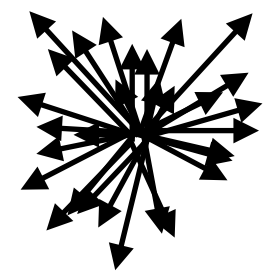
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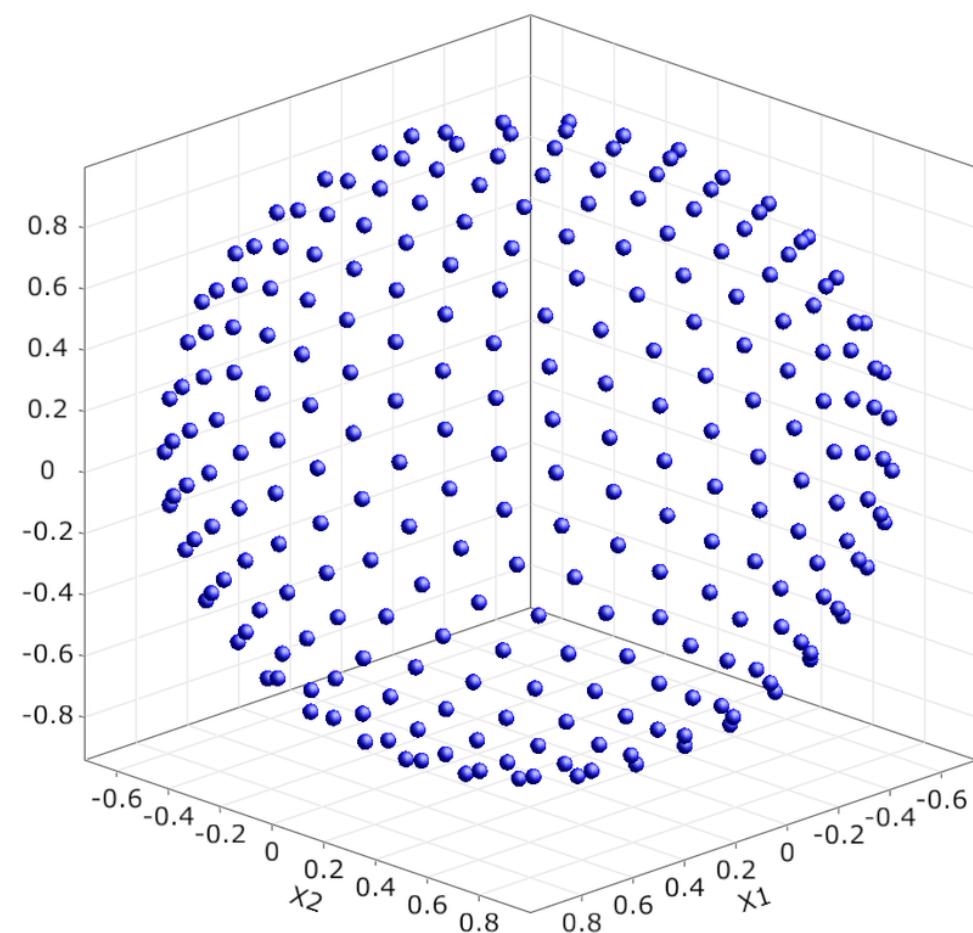
Superposition of multiple pp collisions



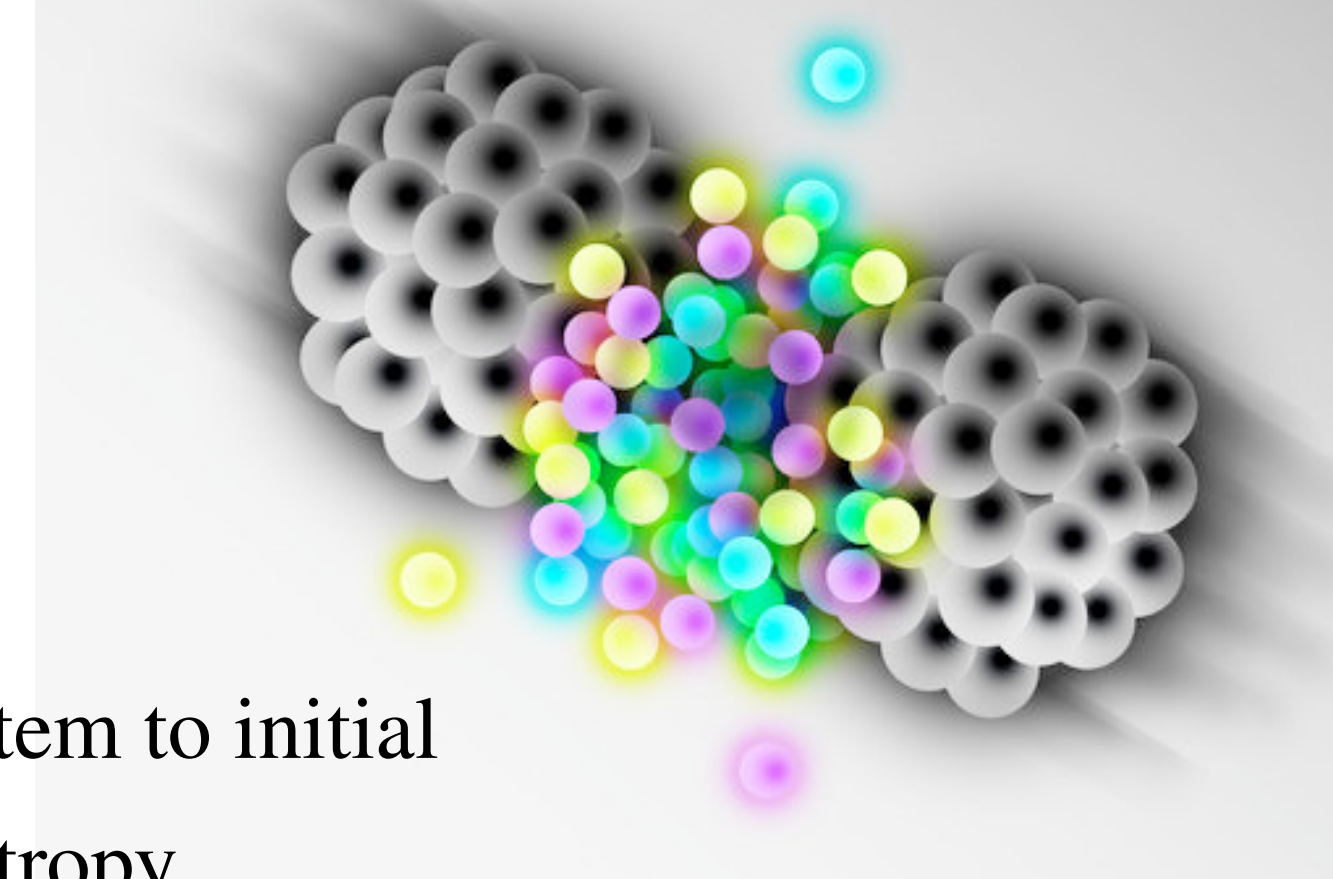
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Uniform distribution of final particles

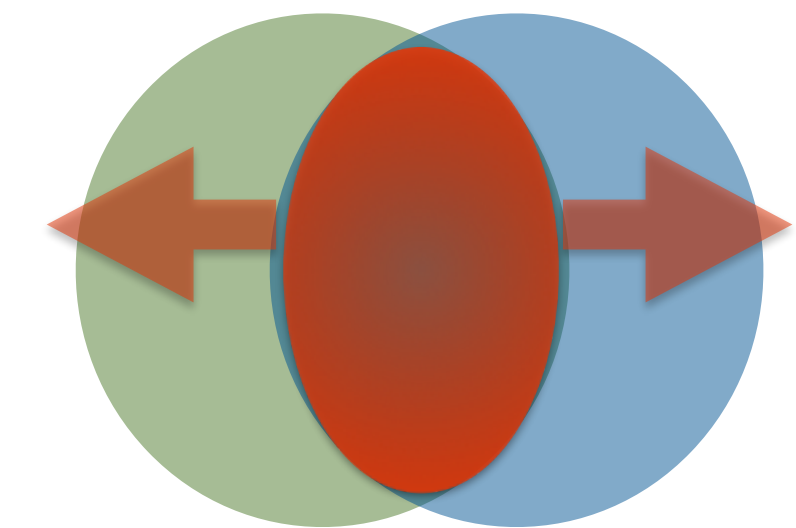


Response of the system to initial spatial anisotropy

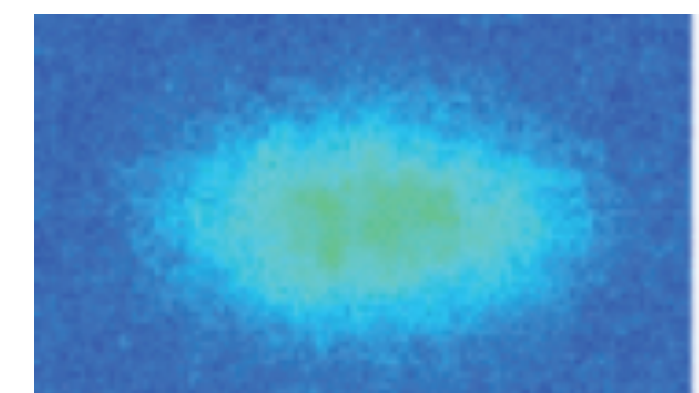
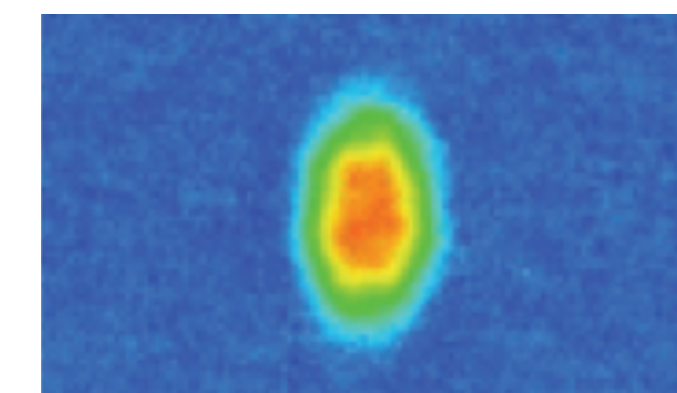
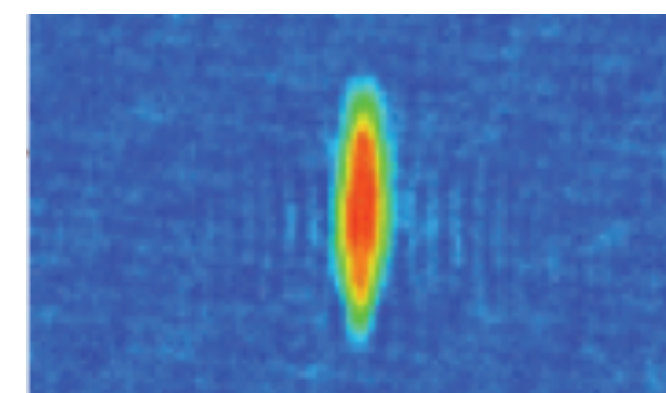


Collective bulk

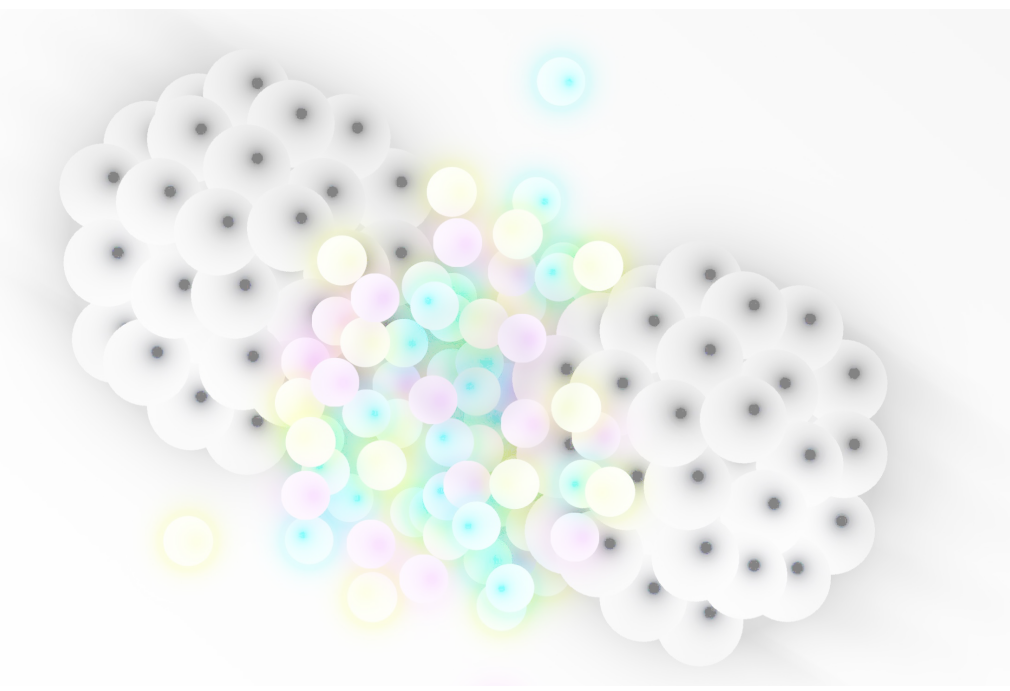
“Liquid-like” behaviour?



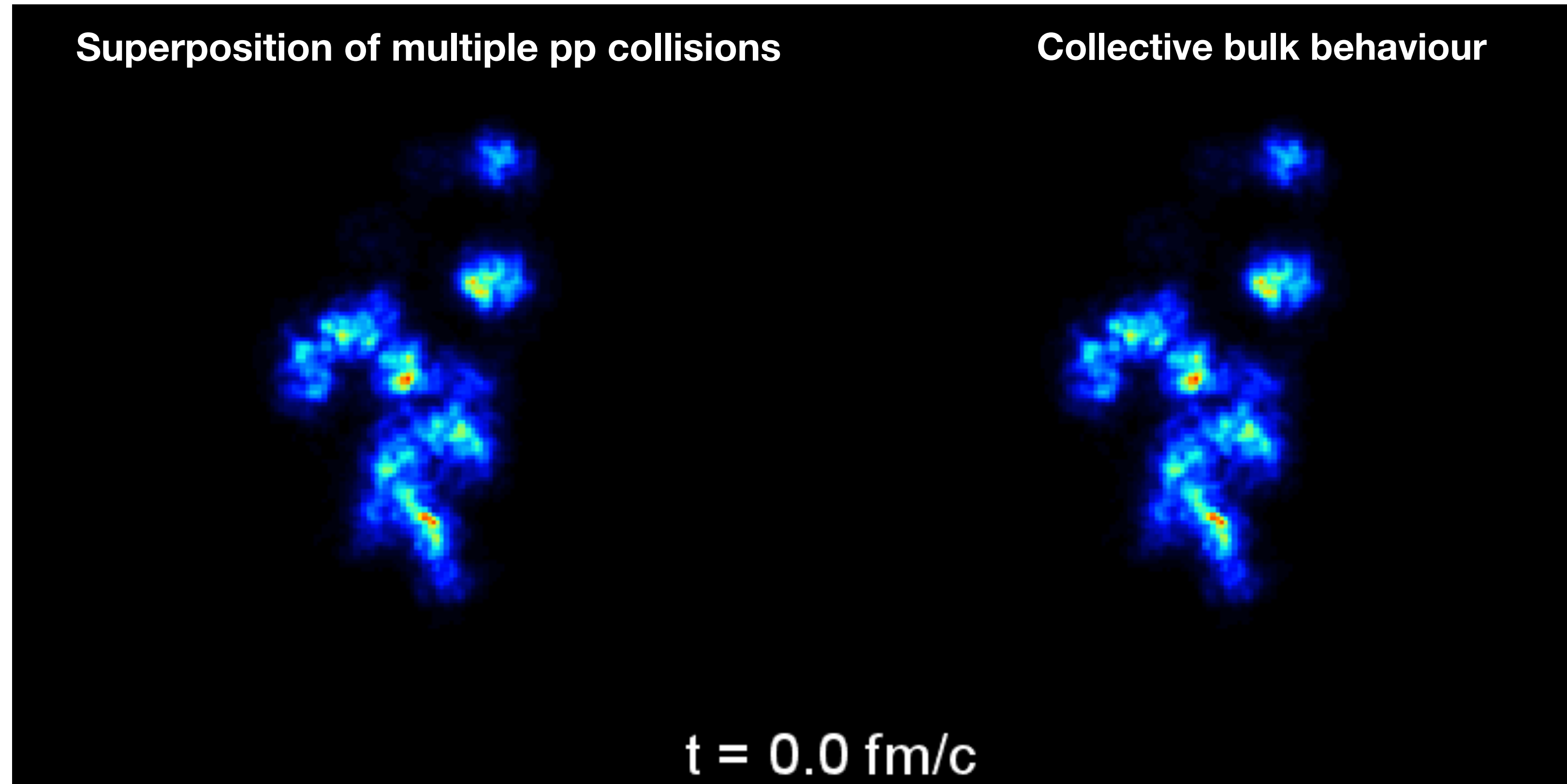
Initial anisotropies also present in the distribution of final particles



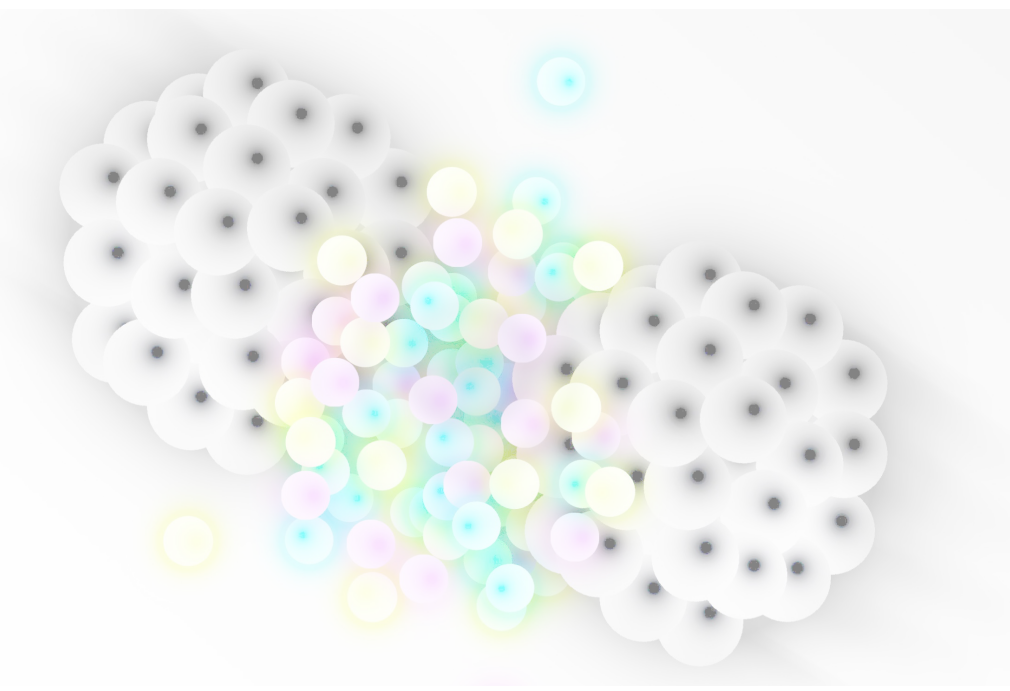
Soft probes



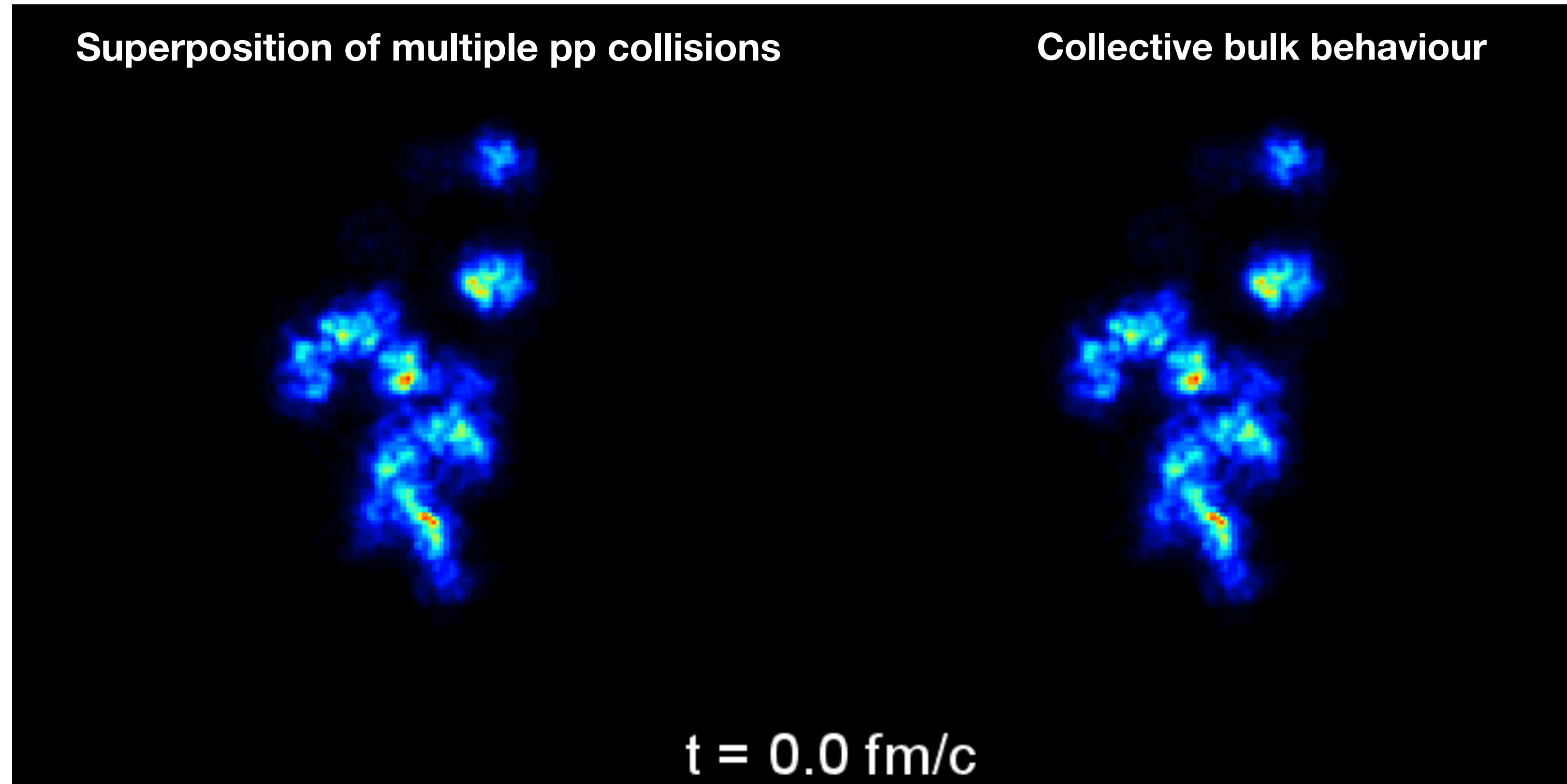
- Sensitive to macroscopic properties of the QGP:
 - Local or large scale collective behaviour?



Soft probes

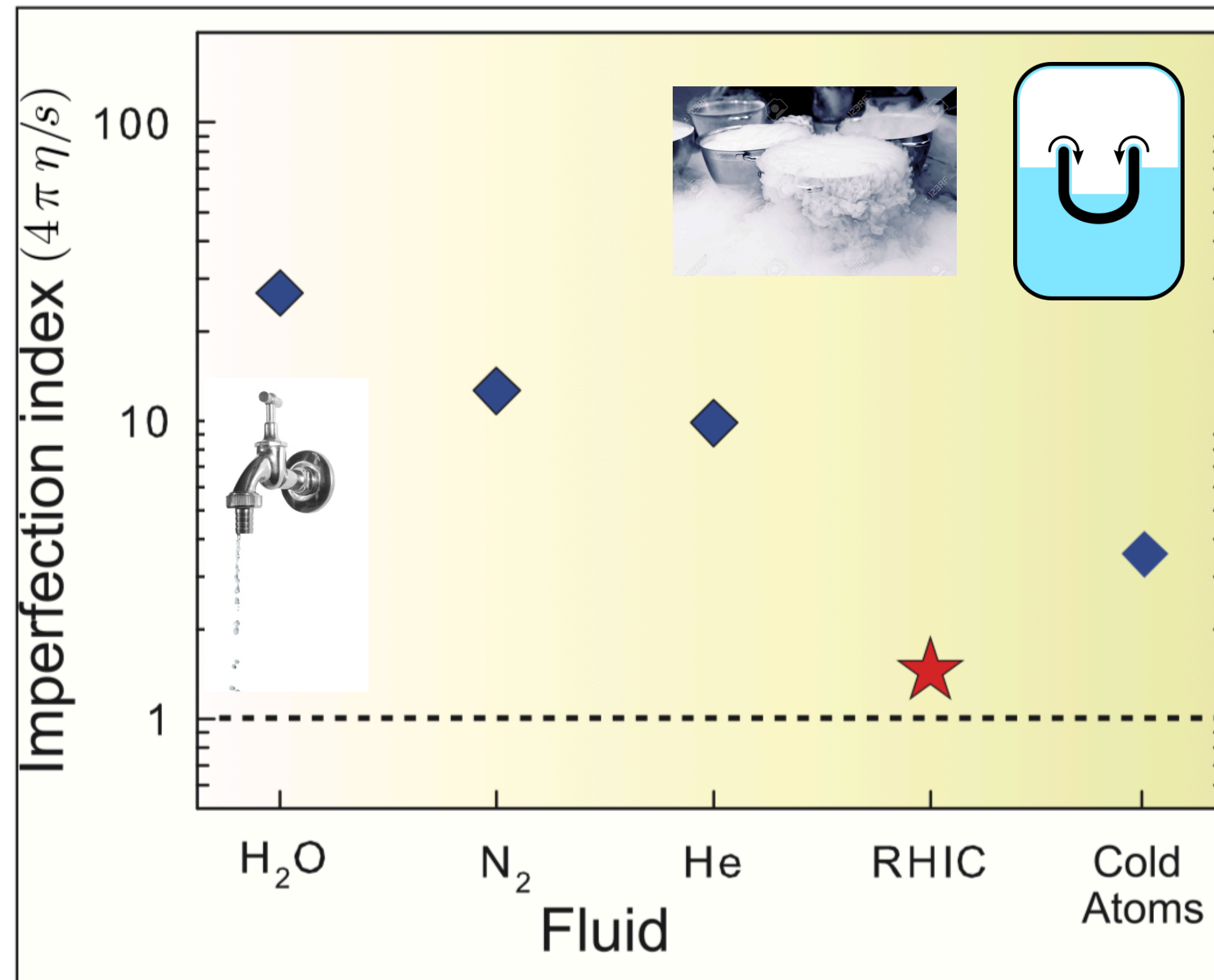


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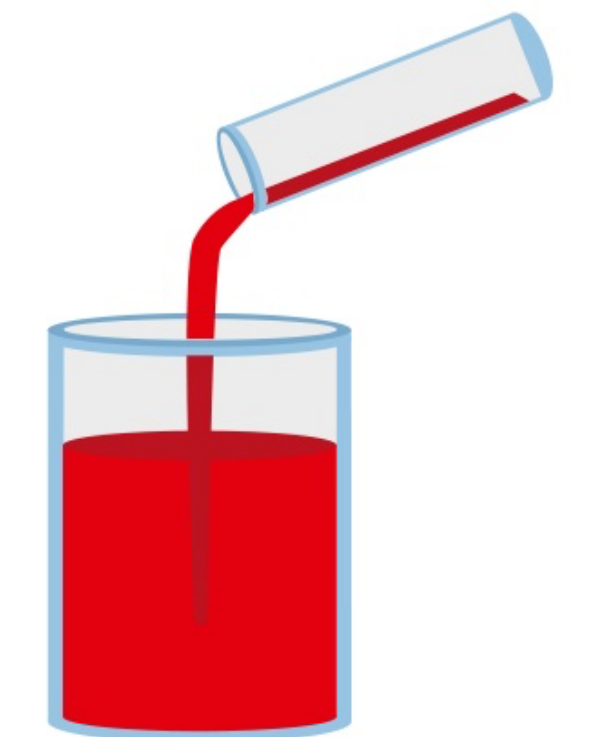


QGP: an almost perfect liquid

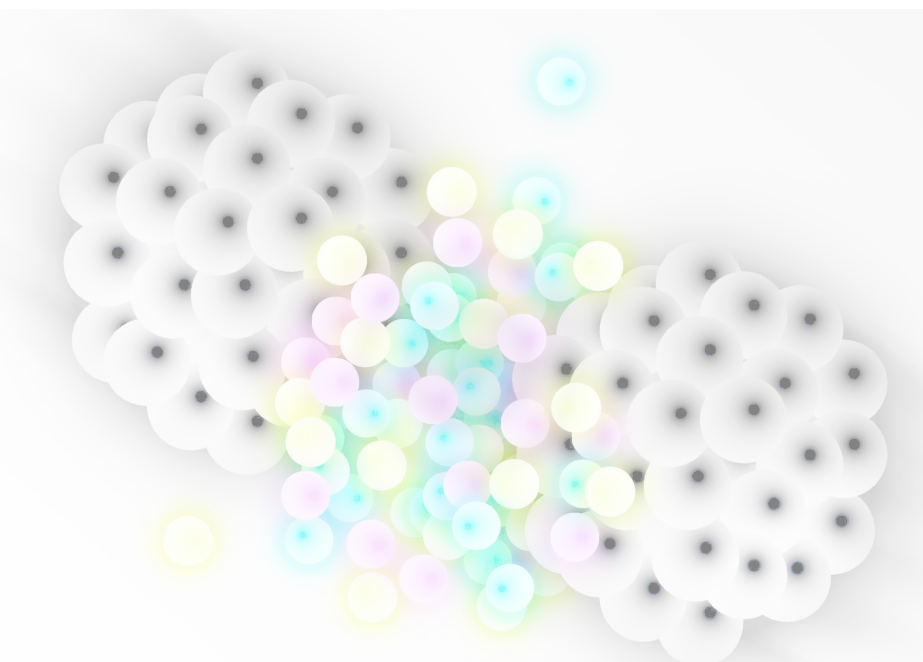
- Measuring the imperfection factor (viscosity)....



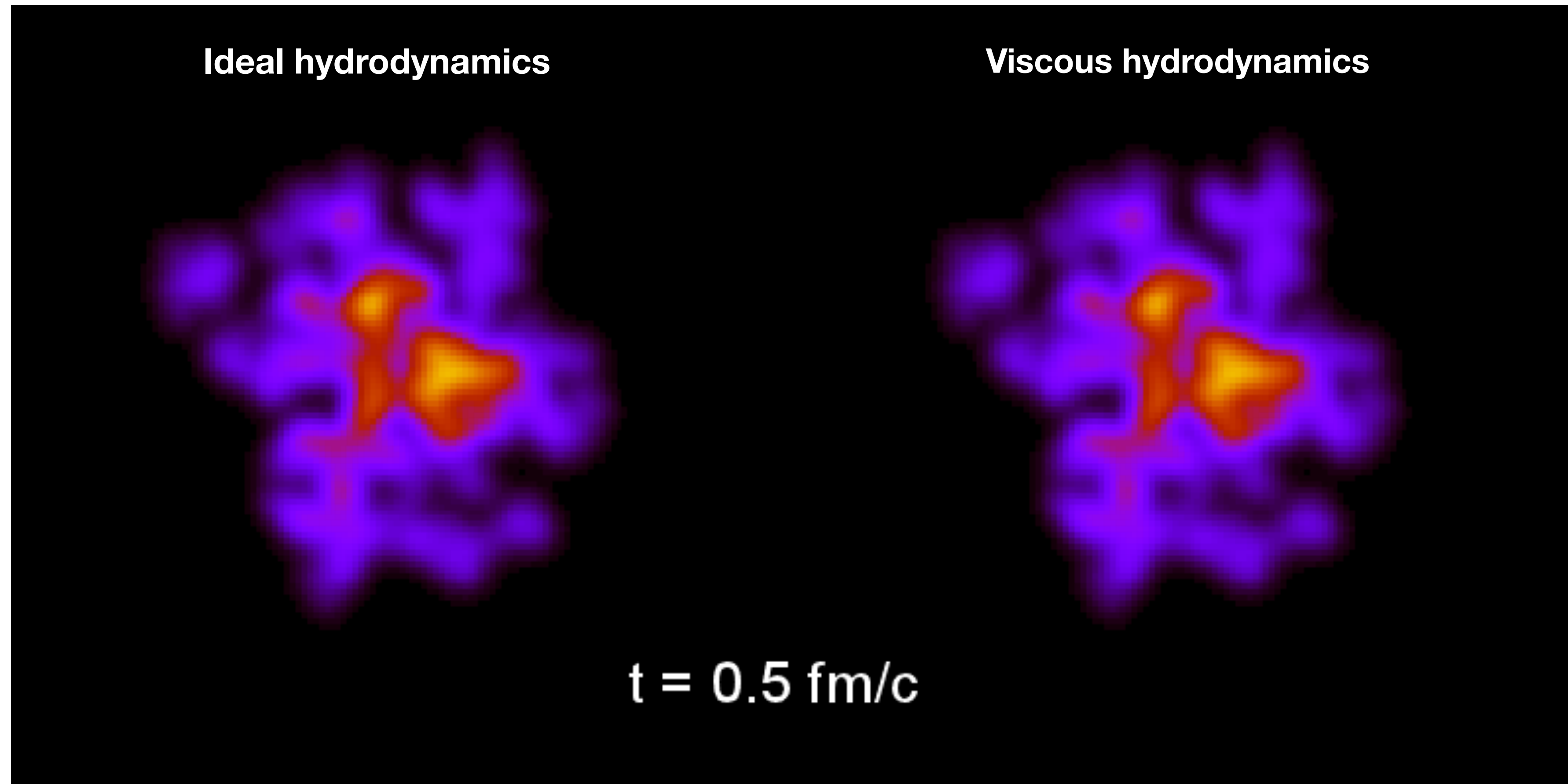
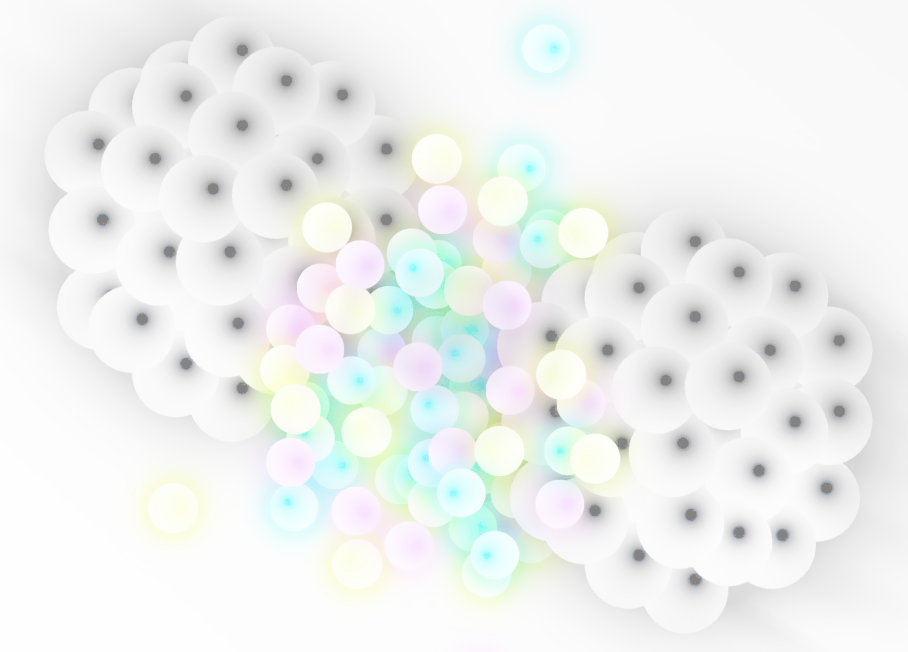
high viscosity



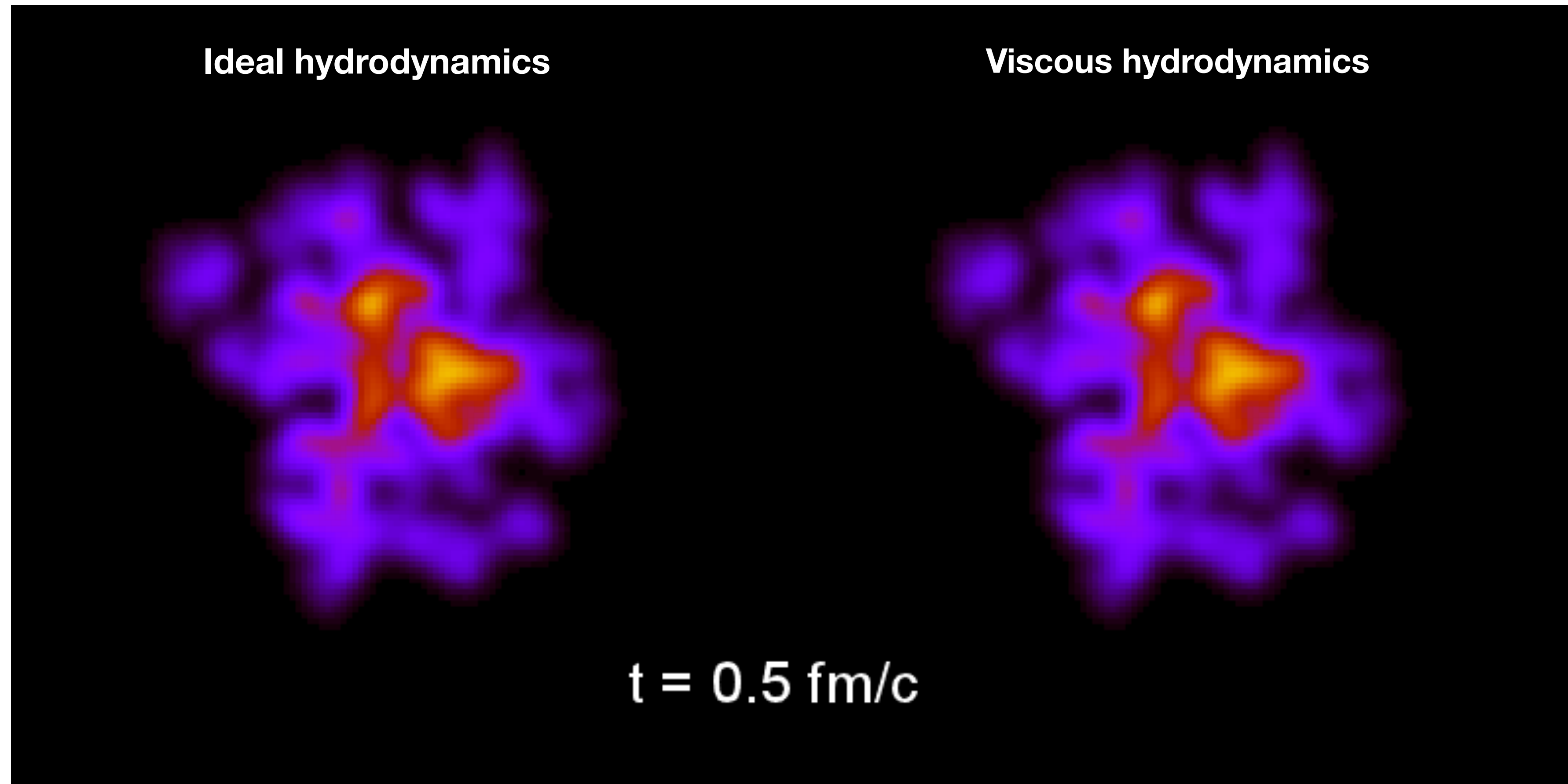
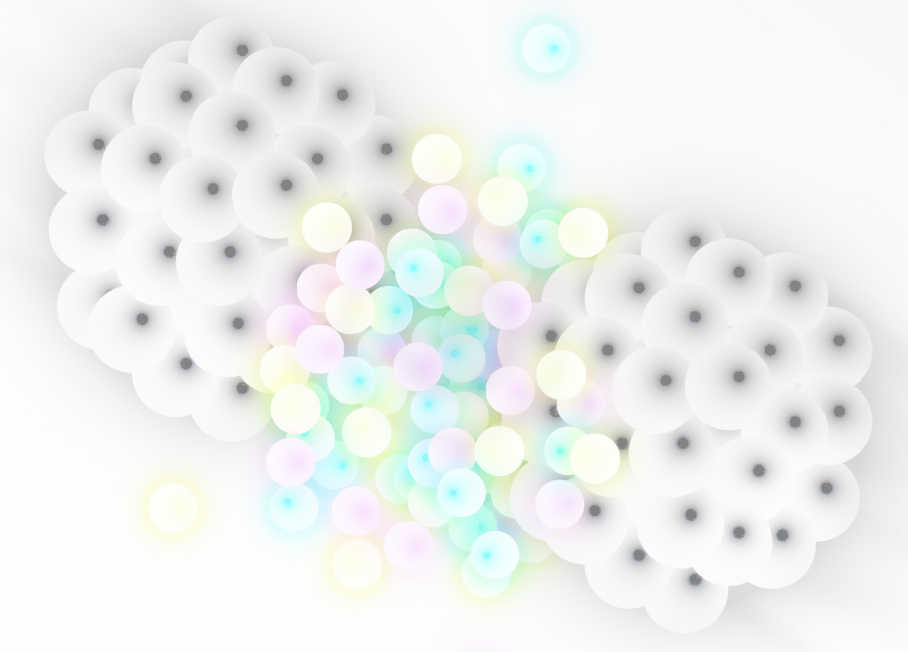
low viscosity



QGP: an almost perfect liquid

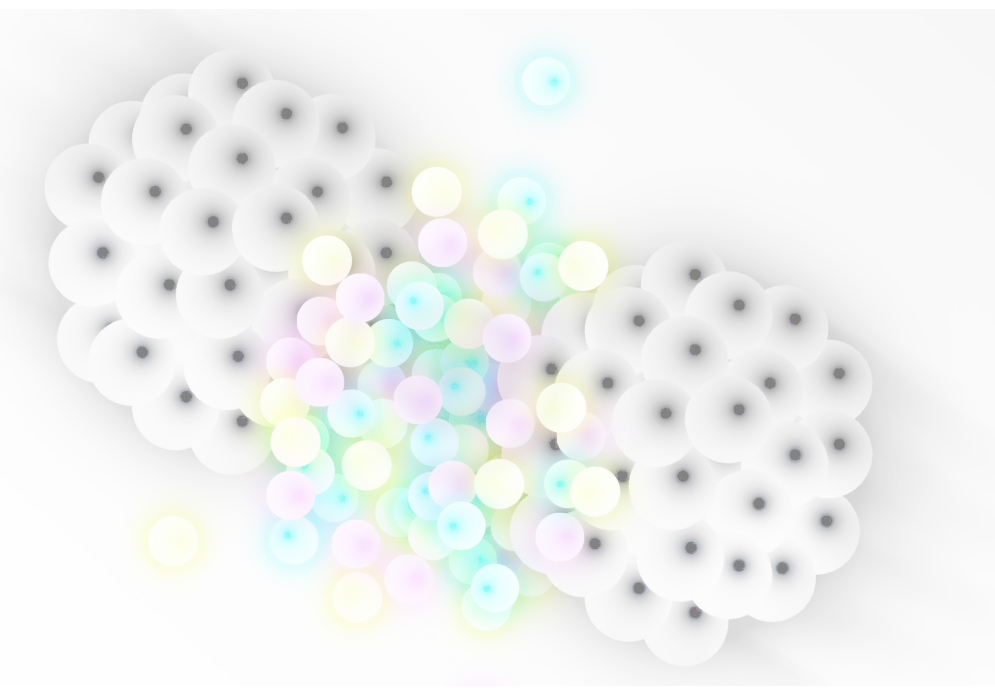
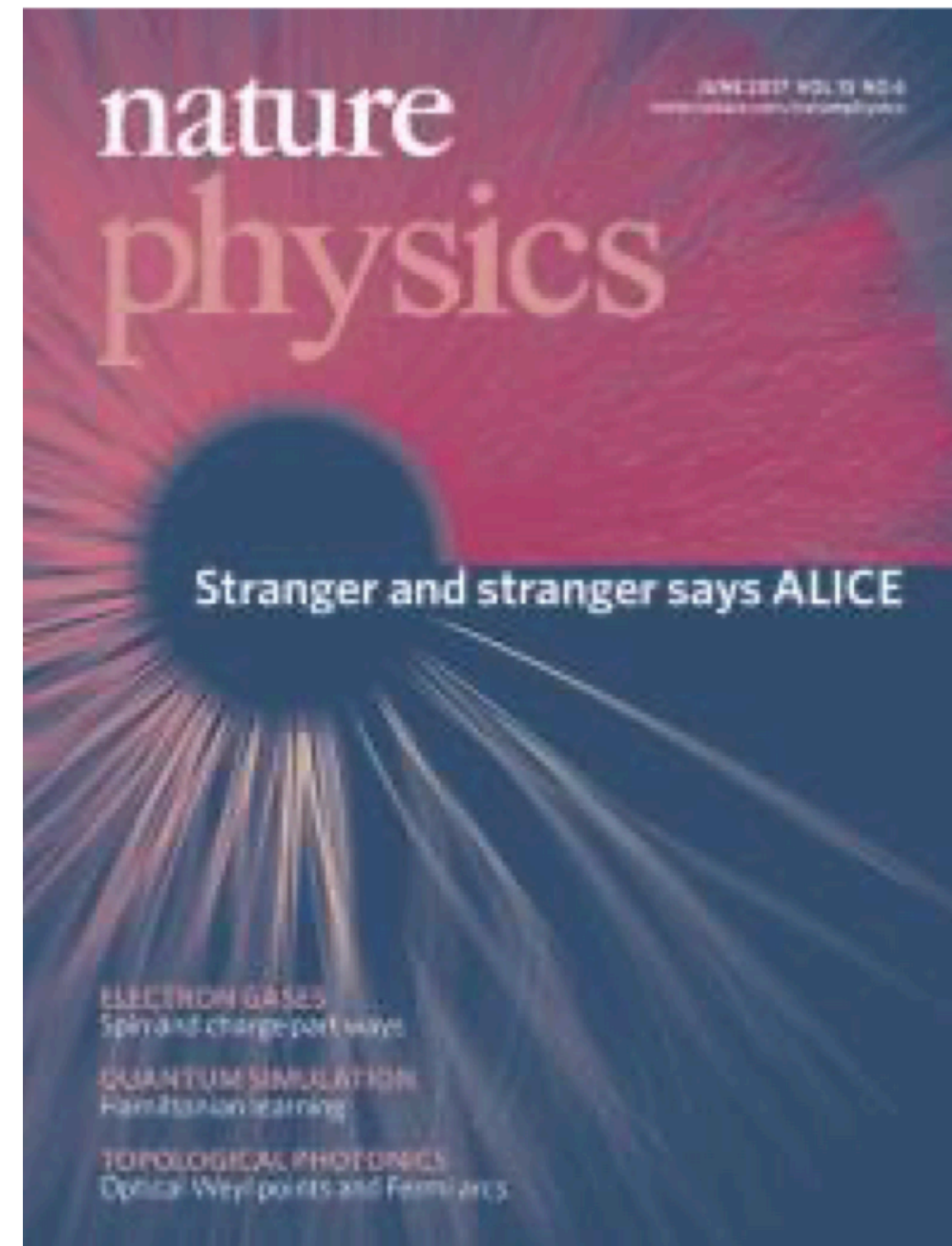


QGP: an almost perfect liquid



QGP properties:

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

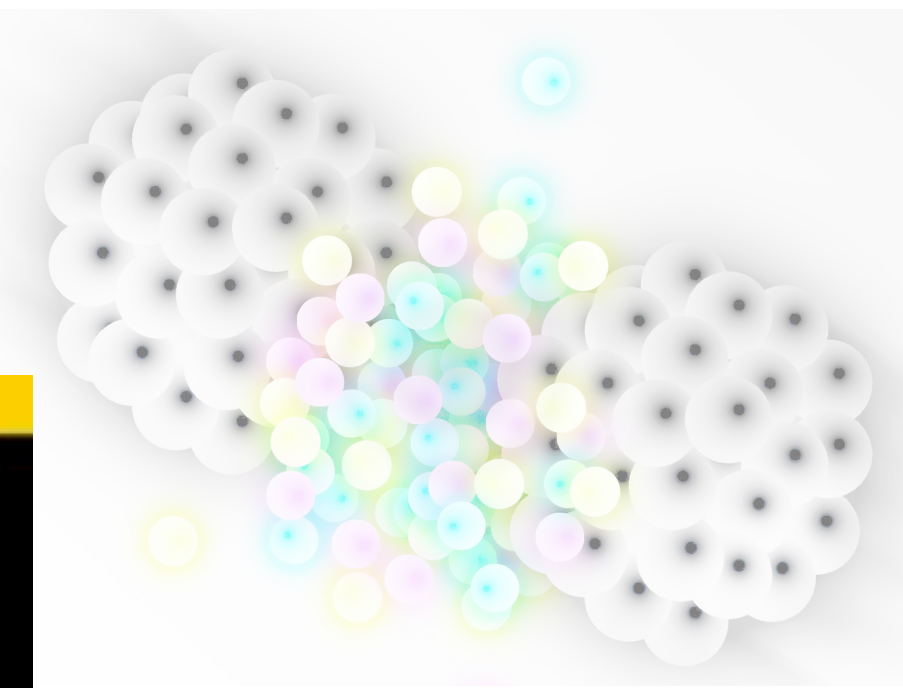


QGP properties:

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

Hottest liquid:
 10^{12}K

(100,000 x temperature of the Sun core)



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 \sim yoctosegundos (10^{-23})



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(100,000 x temperature of the Sun core)

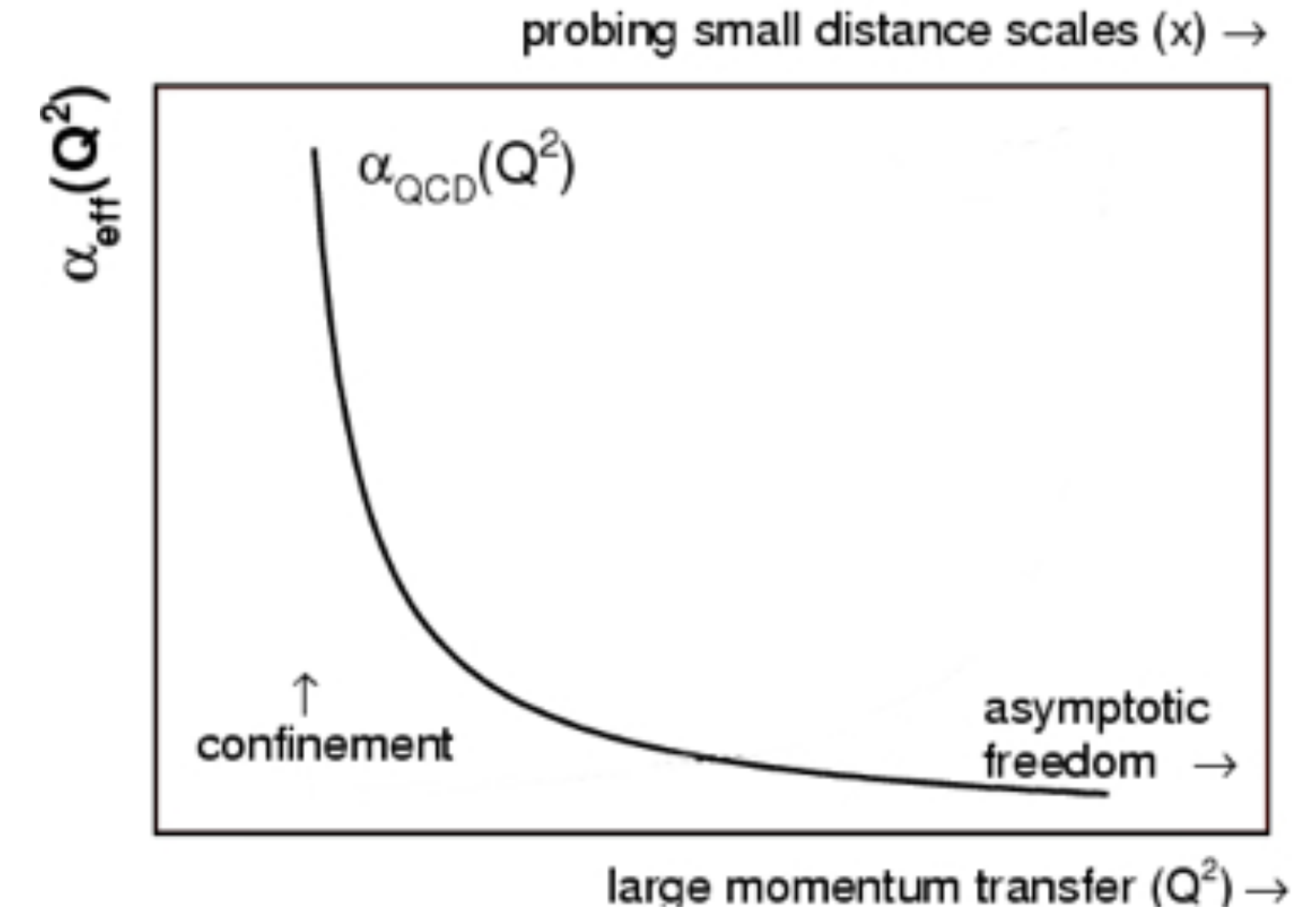
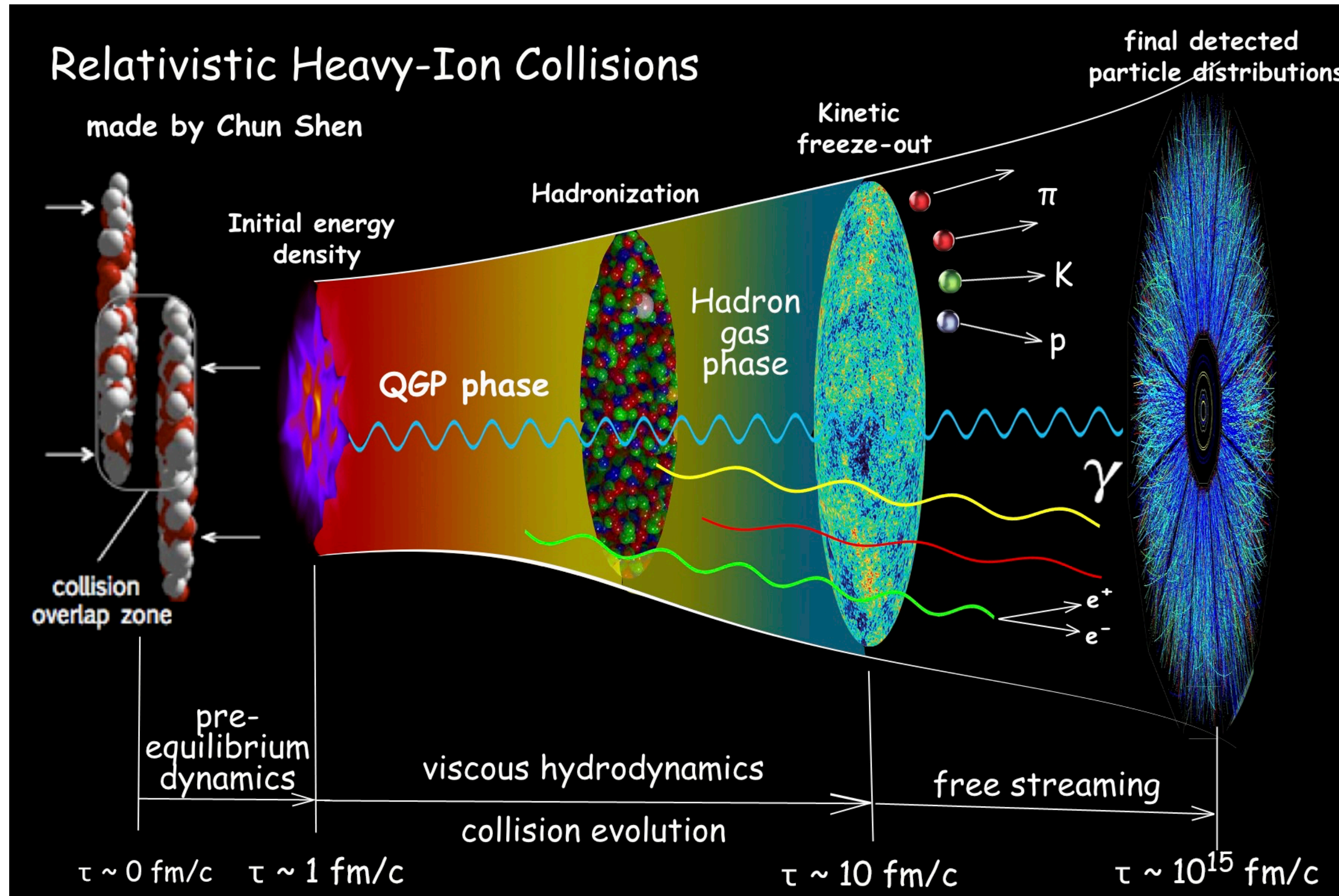
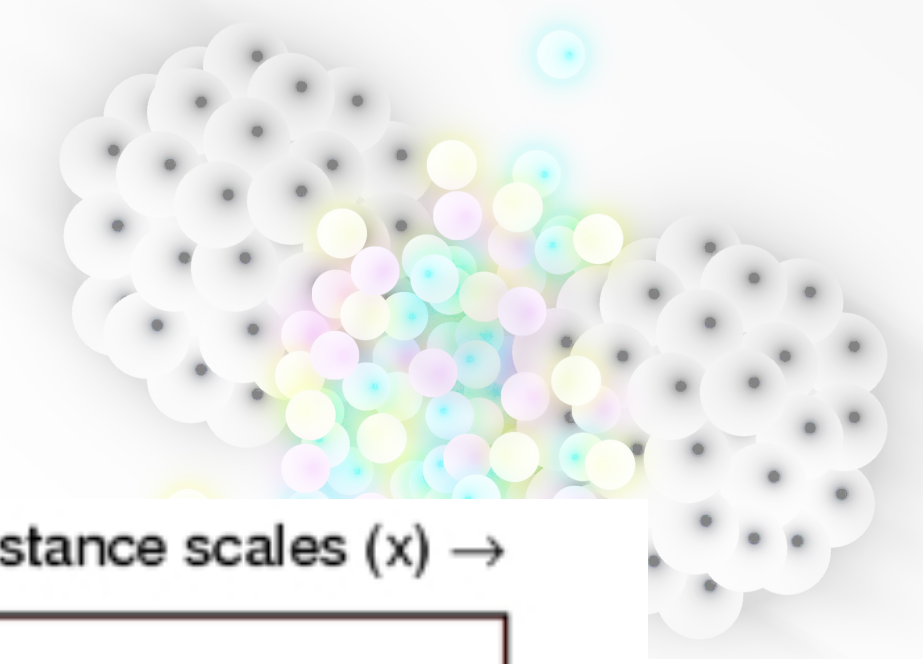
Smallest liquid:
~yoctosegundos (10^{-23})

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

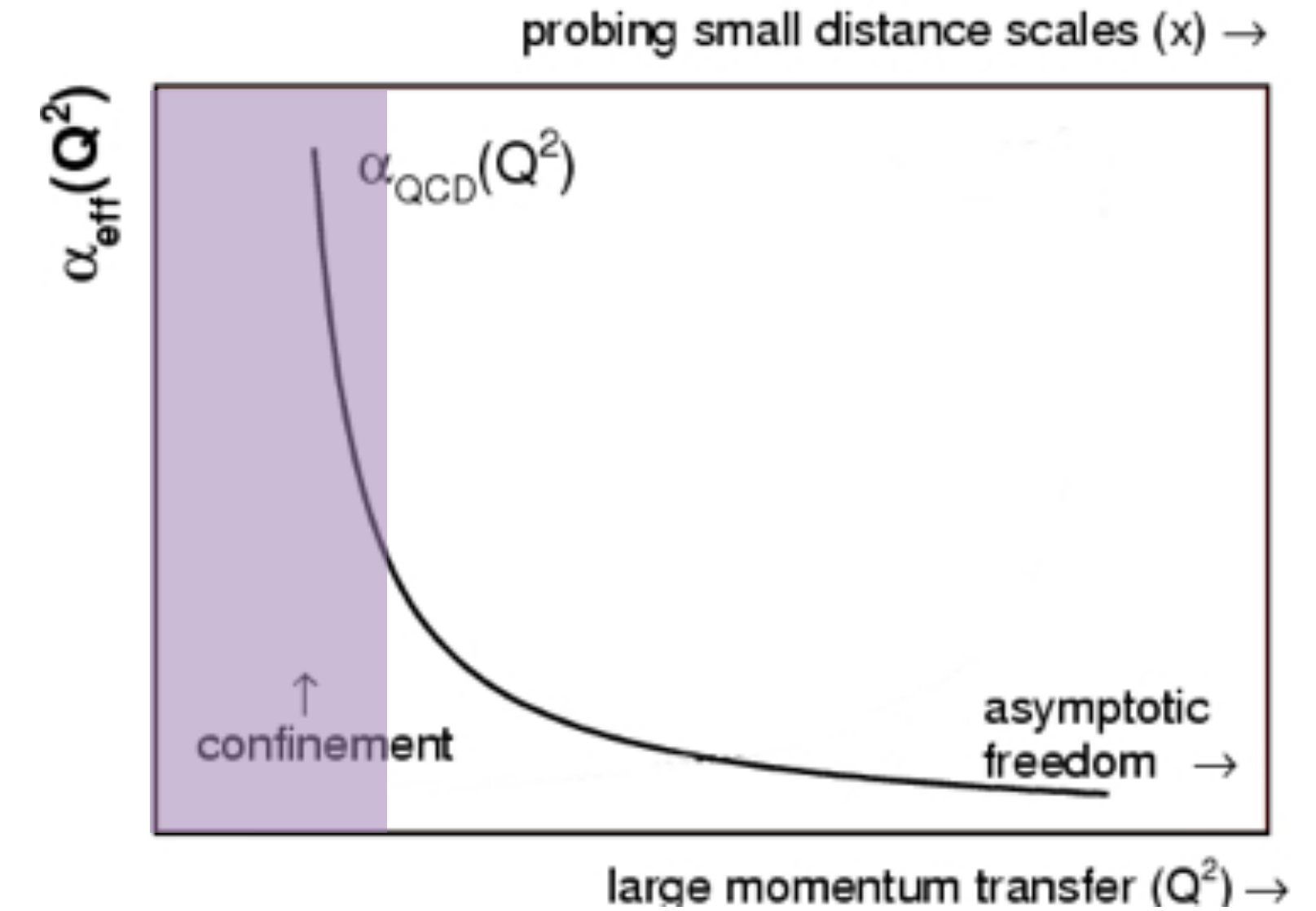
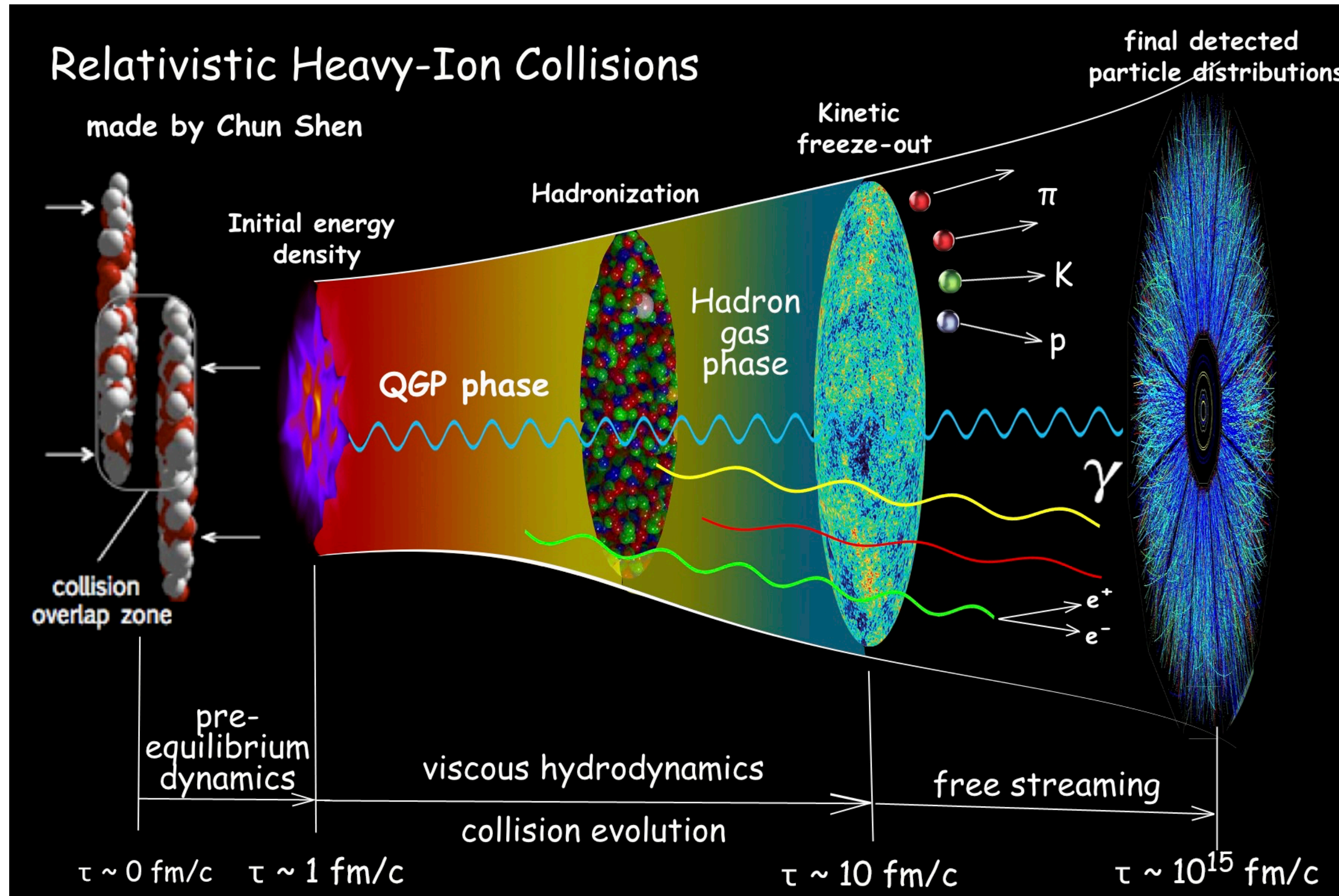
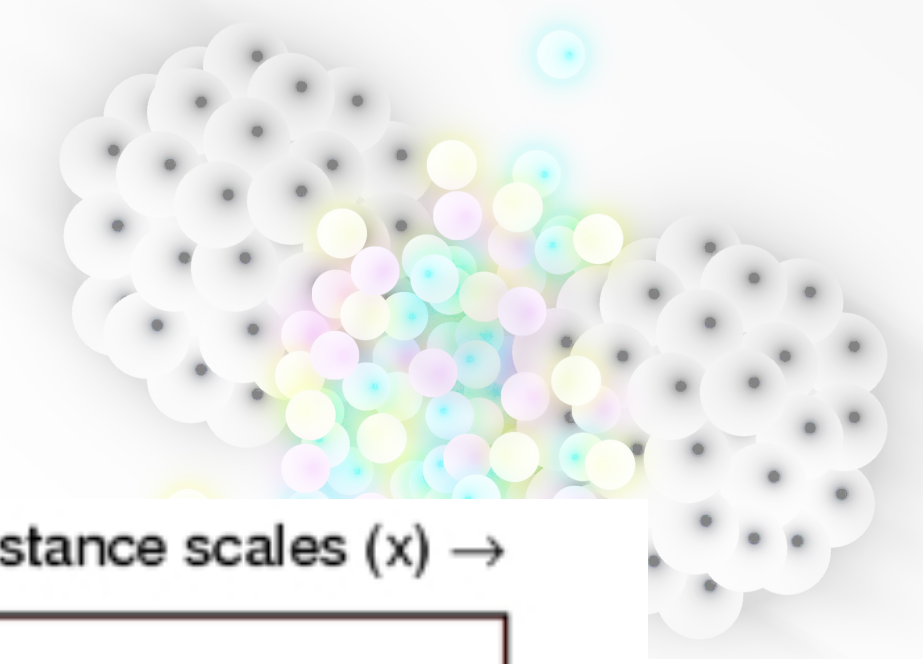
(Atmosphere: $\omega \sim 10^{-4}/s$
Tornado: $\omega \sim 10^{-1}/s$)



How to probe the QGP @ lab (v2)

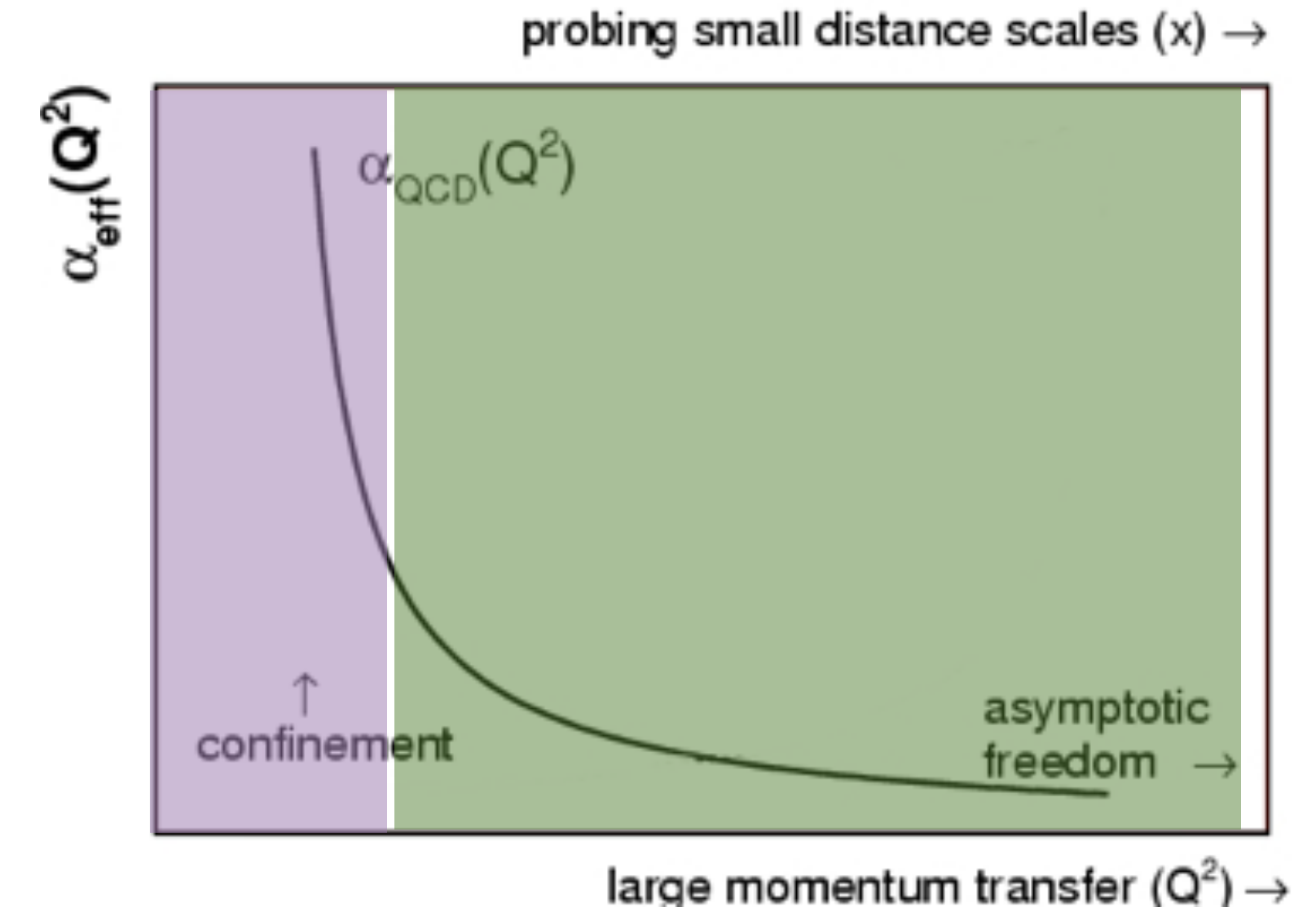
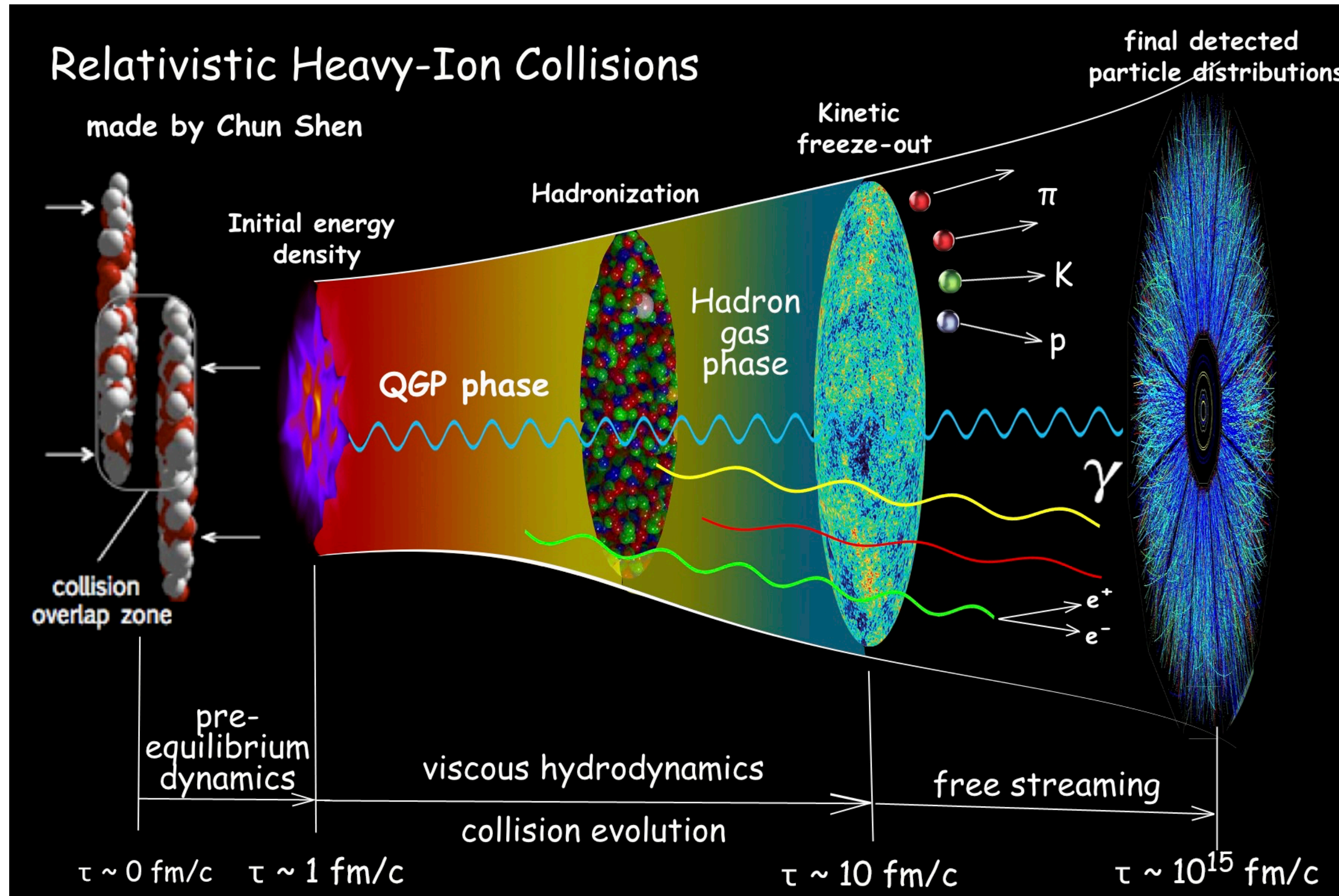
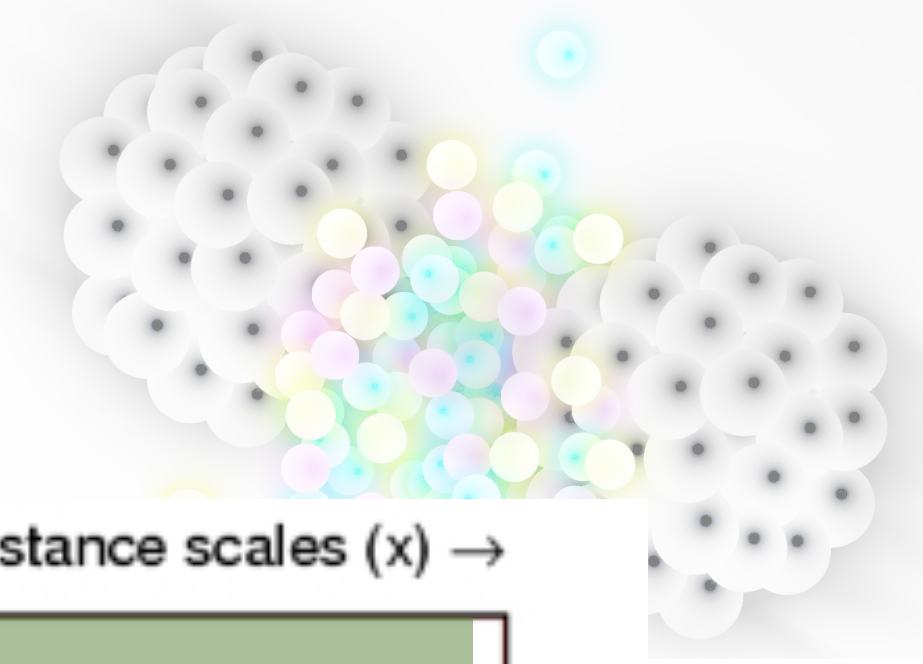


How to probe the QGP @ lab (v2)



Soft probes
non-pQCD

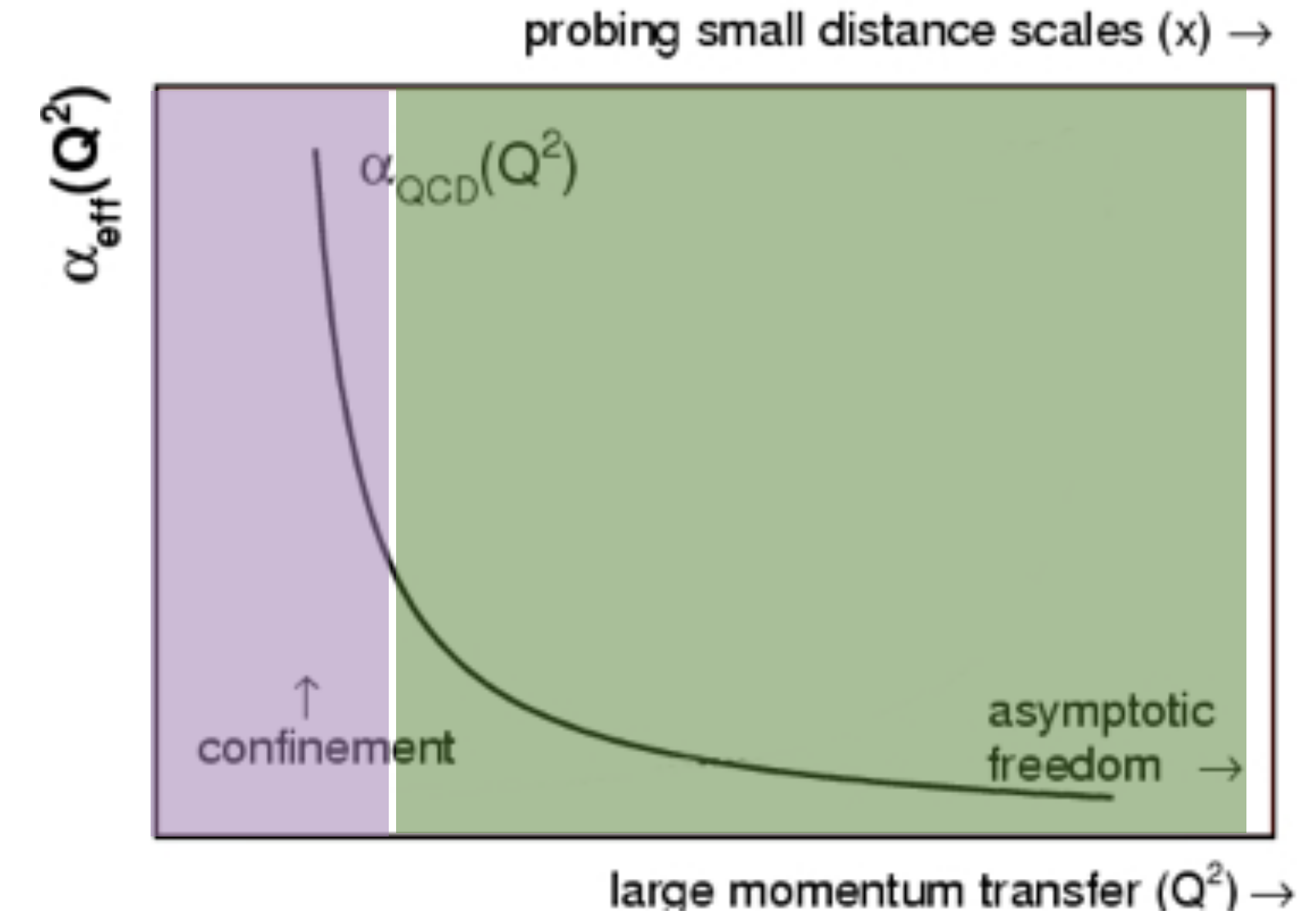
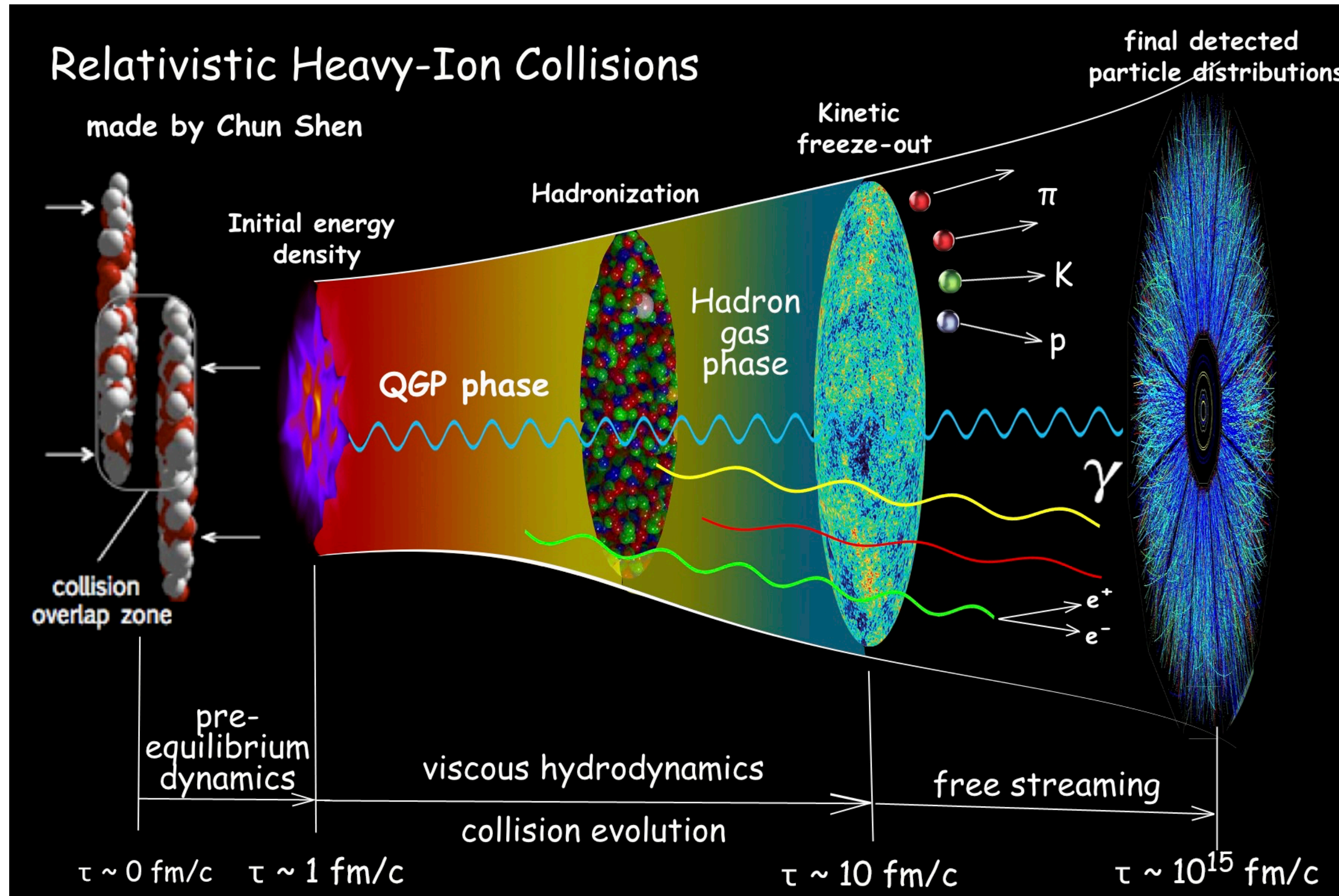
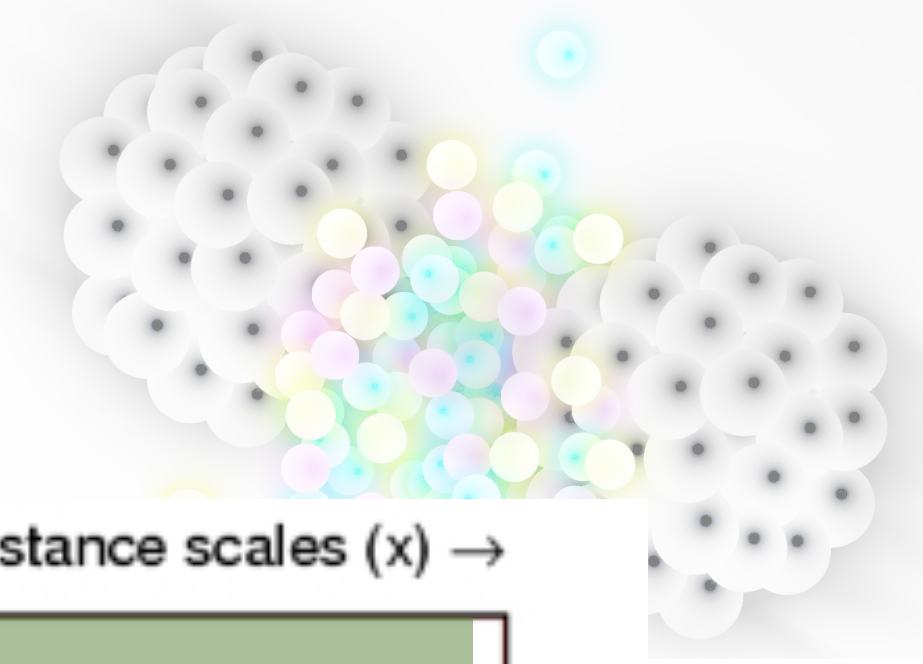
How to probe the QGP @ lab (v2)



Soft probes
non-pQCD

Hard probes
pQCD

How to probe the QGP @ lab (v2)



Soft probes

non-pQCD

Hard probes

pQCD

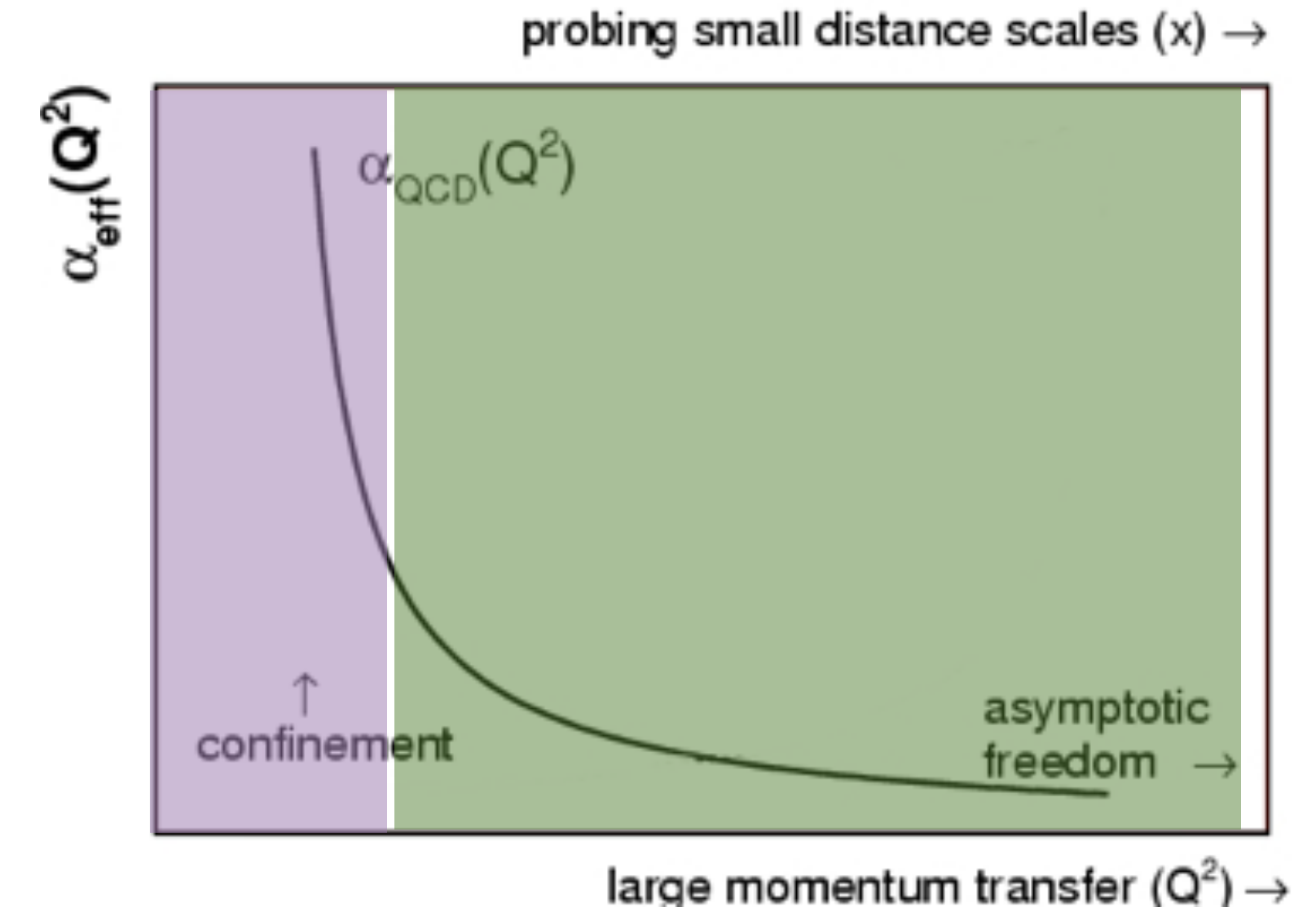
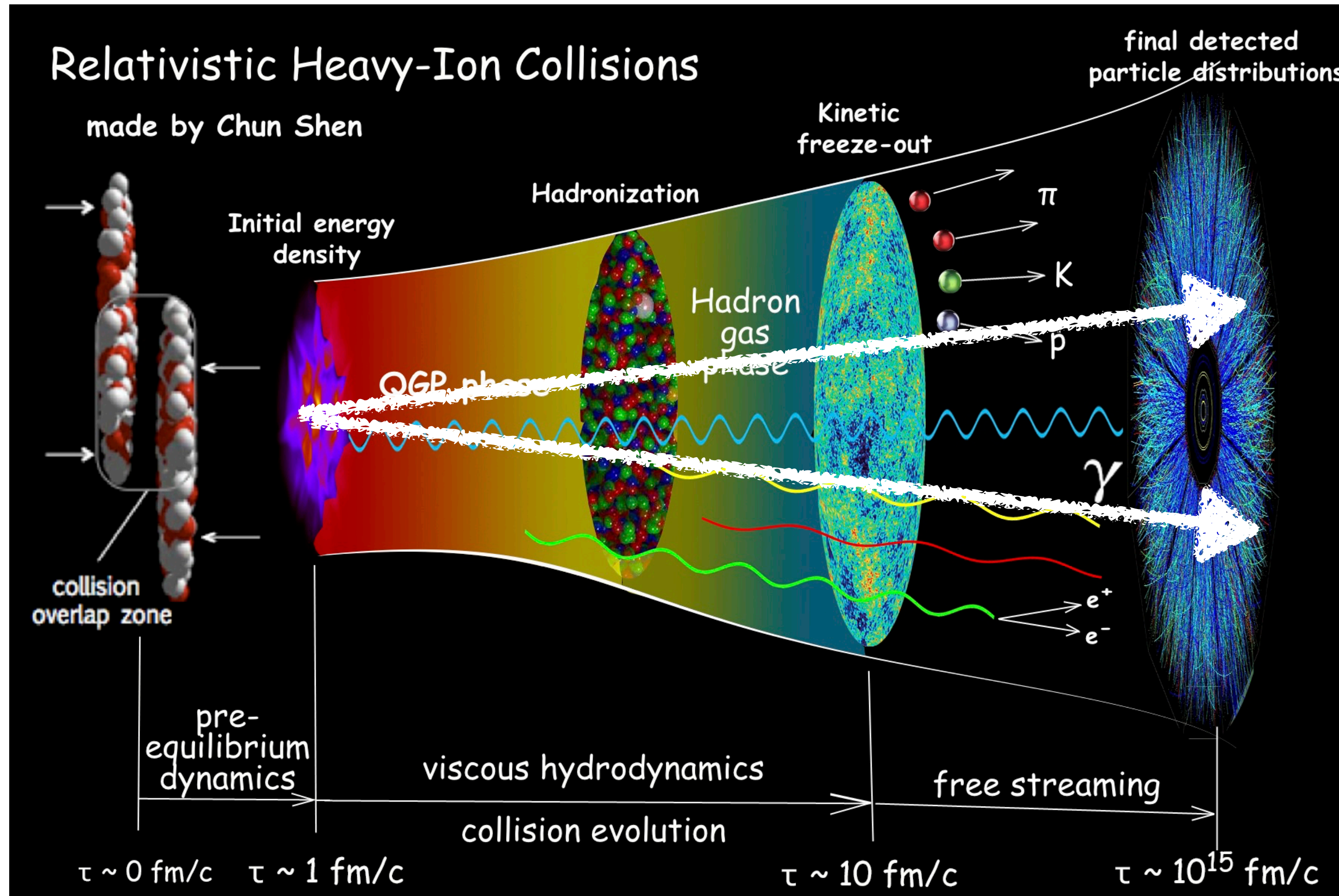
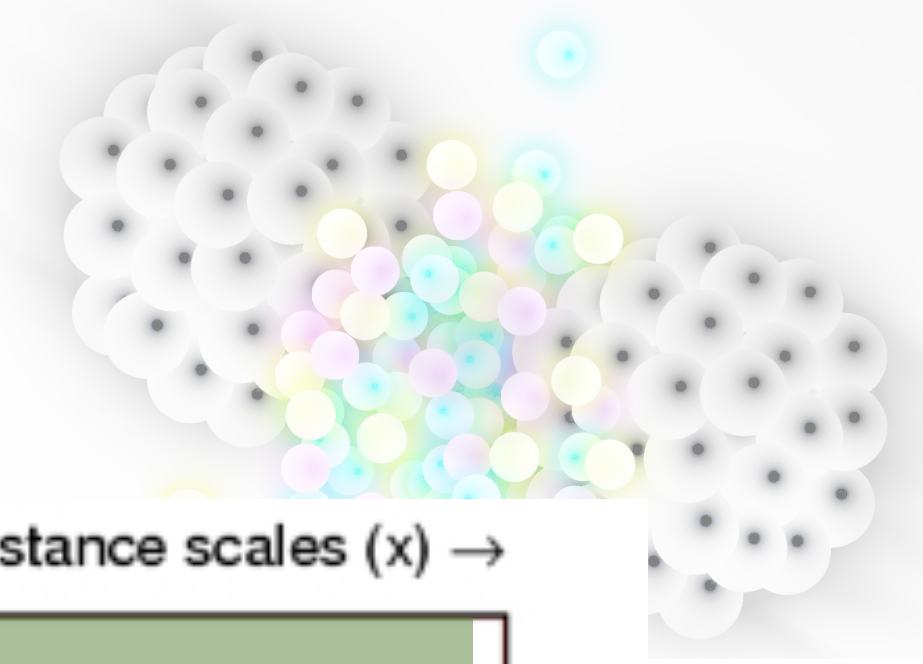
$$\mathcal{L} = \frac{1}{4g^2} G_{\mu\nu}^a G_{\mu\nu}^a + \sum_f \bar{\psi}_f (i \not{D} + m_f) \psi_f$$

where $G_{\mu\nu}^a \equiv \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + gf_{abc} A_\mu^b A_\nu^c$

and $D_\mu \equiv \partial_\mu + i t^a A_\mu^a$

That's it!

How to probe the QGP @ lab (v2)

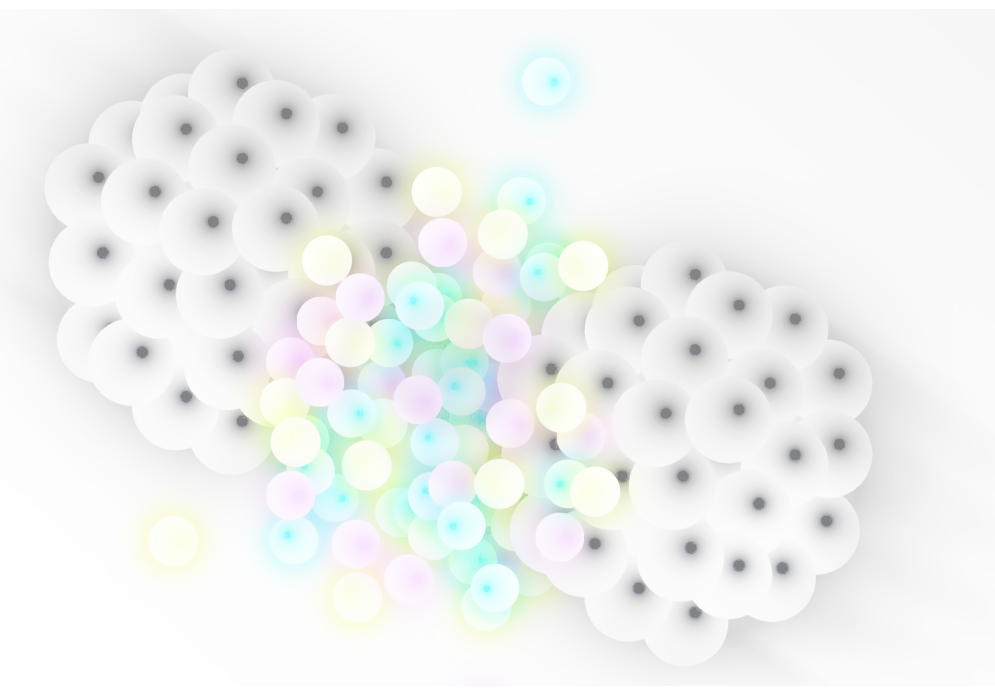


Soft probes
non-pQCD

Hard probes
pQCD

Caveat: need to rely on self-generated probes

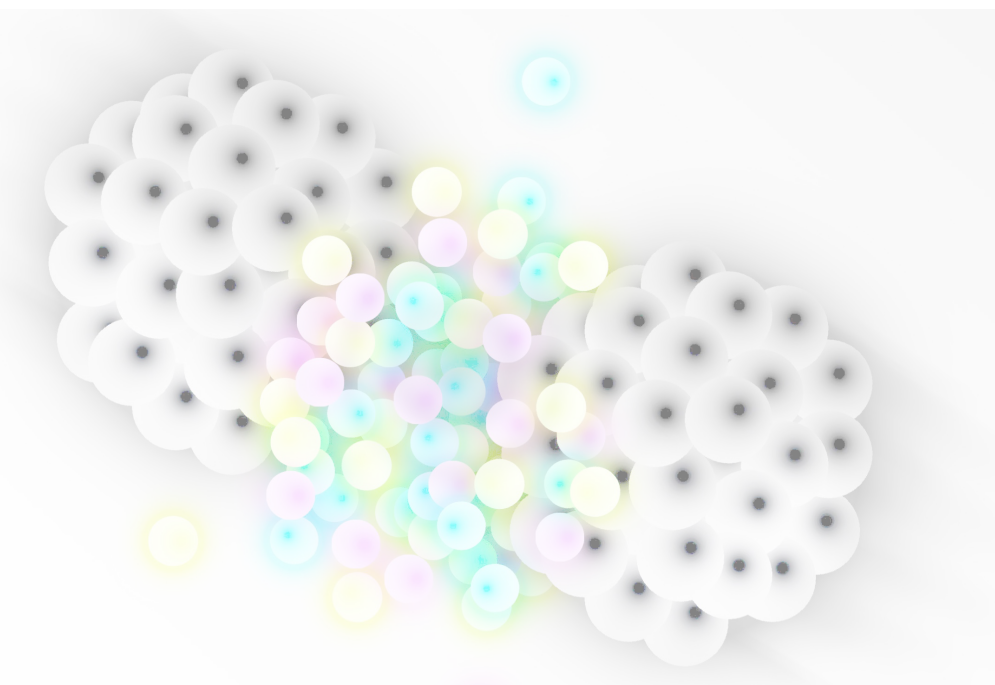
How to probe the QGP @ lab (v2)



- Using internal probes that can be self-calibrated:



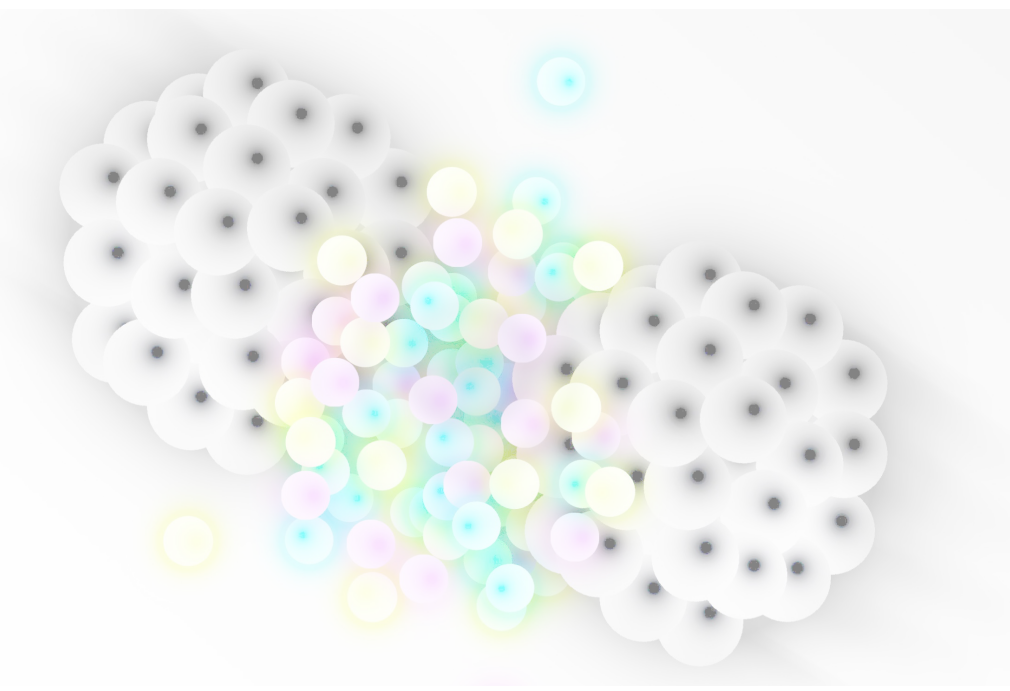
How to probe the QGP @ lab (v2)



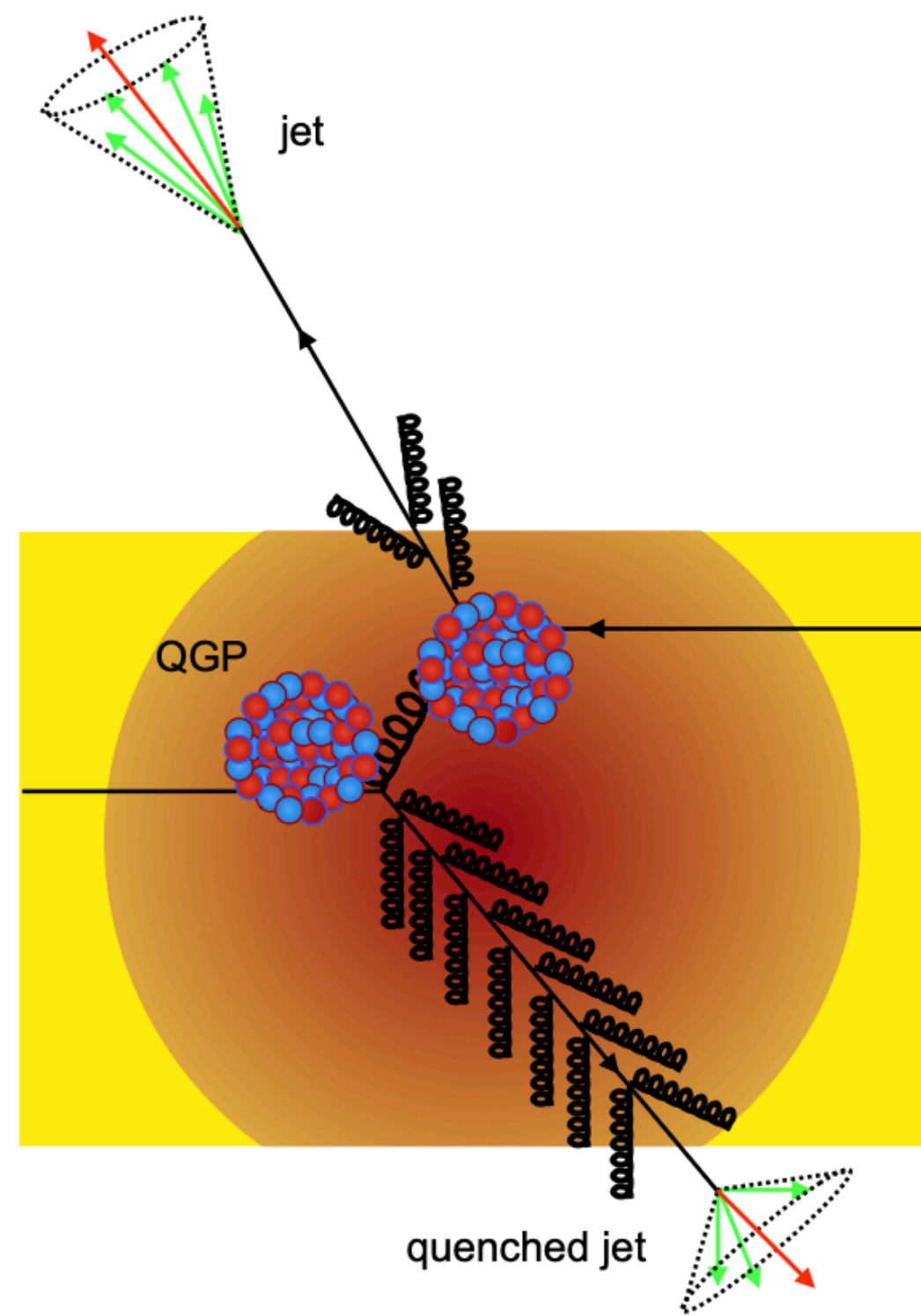
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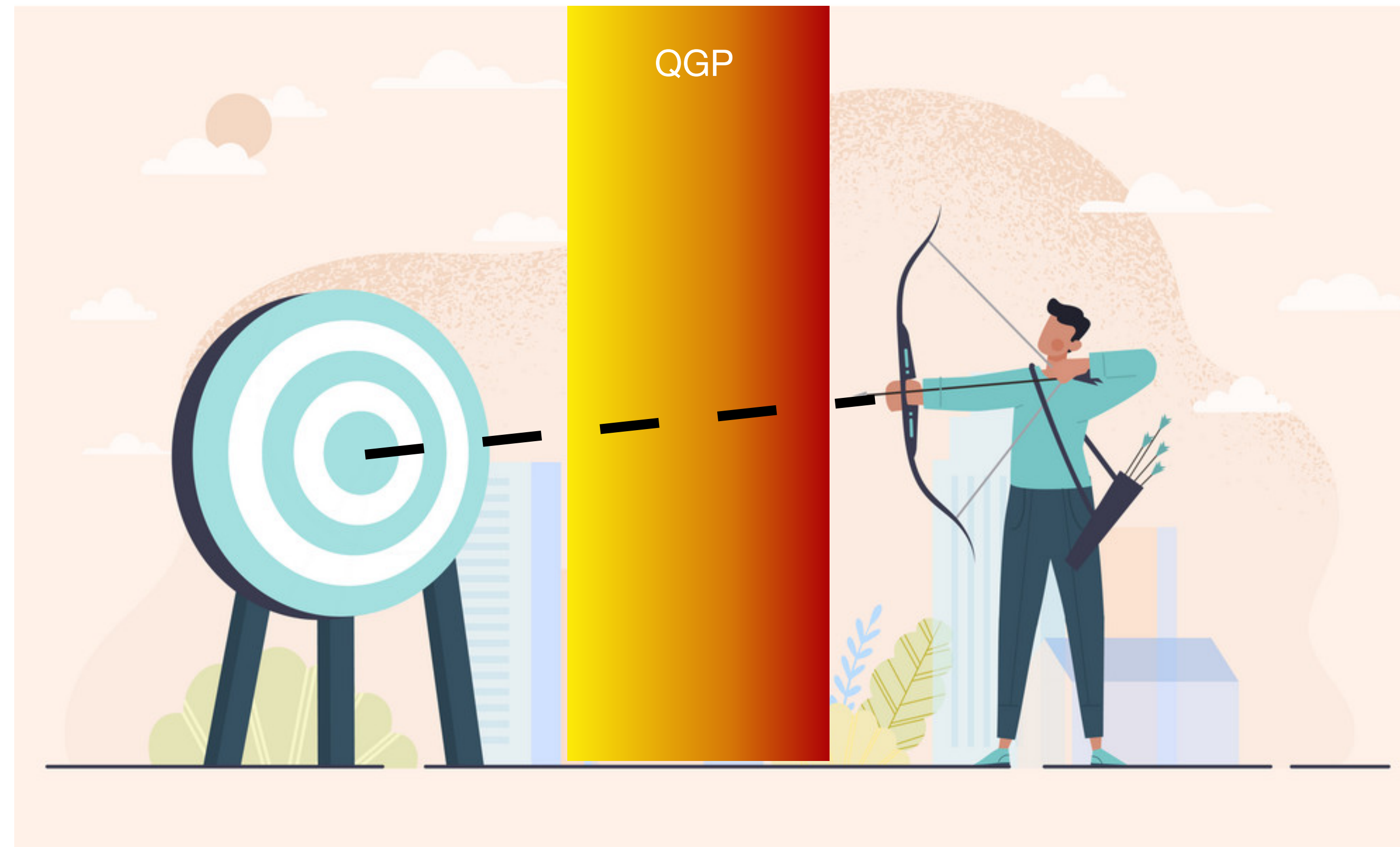
How to probe the QGP @ lab (v2)



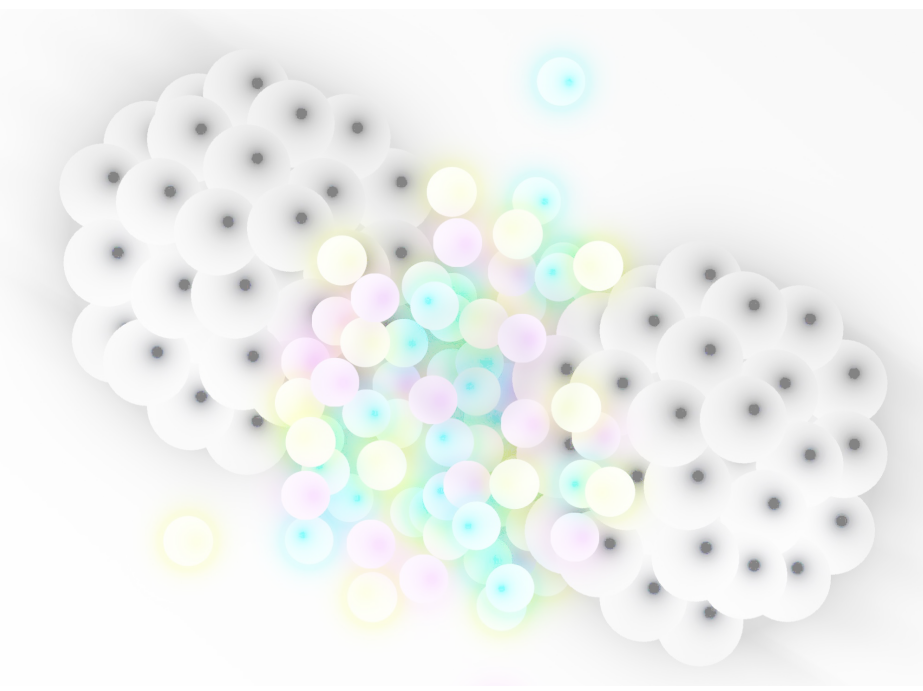
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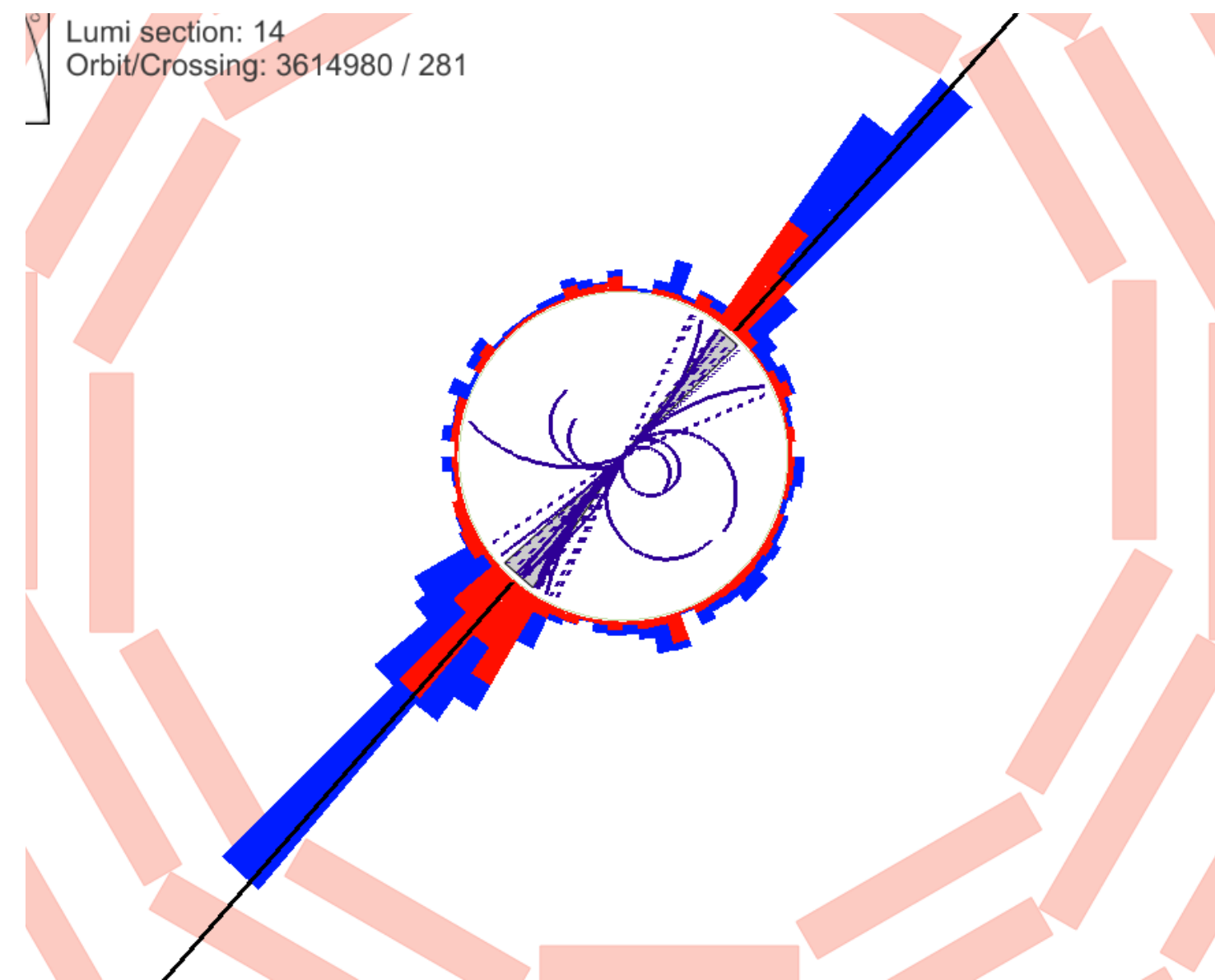
Jets in PbPb



Hard Probes

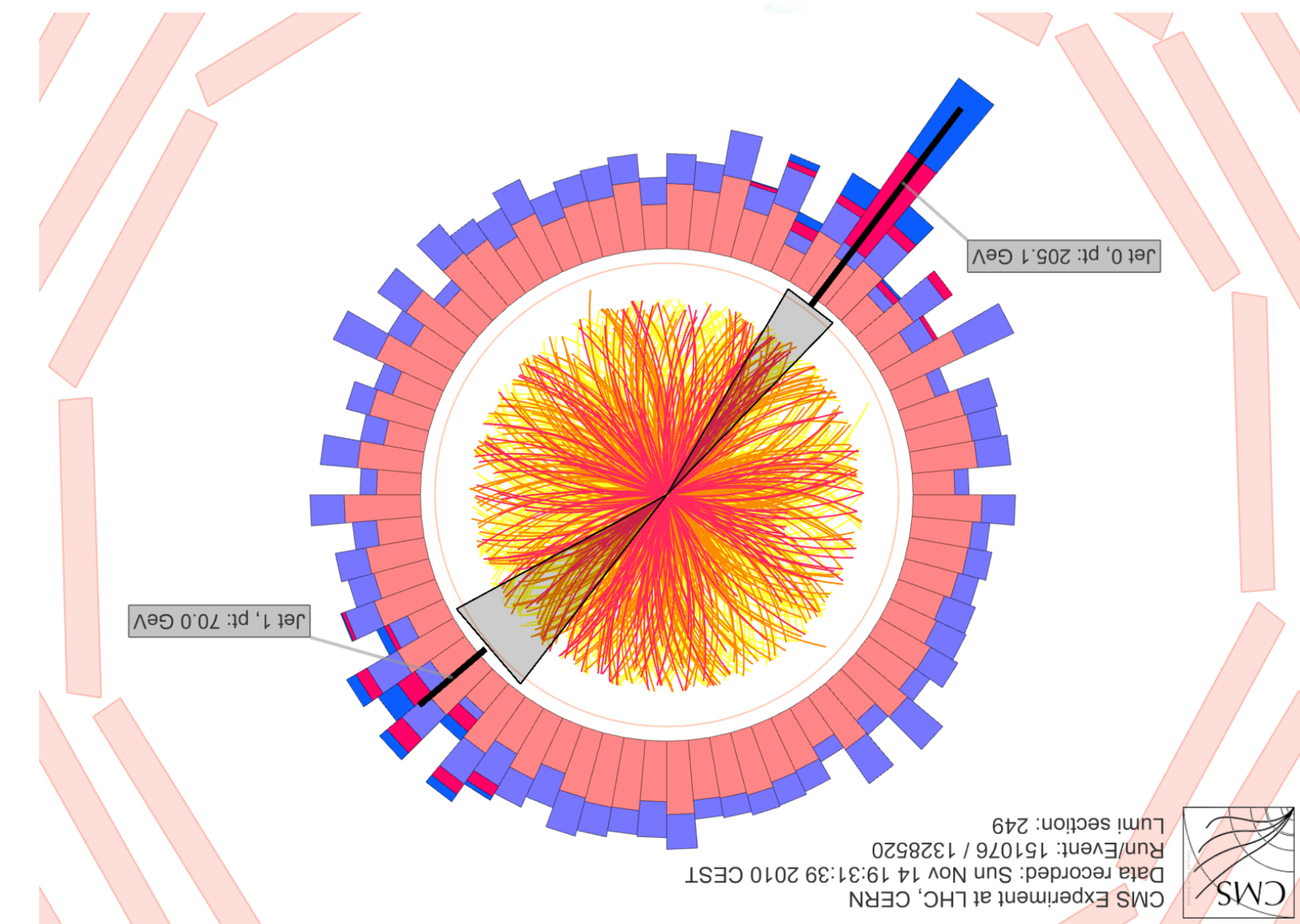


- “Shoot” a calibrated probe and see the final modifications with respect to a reference (usually pp)



Example: jets in pp

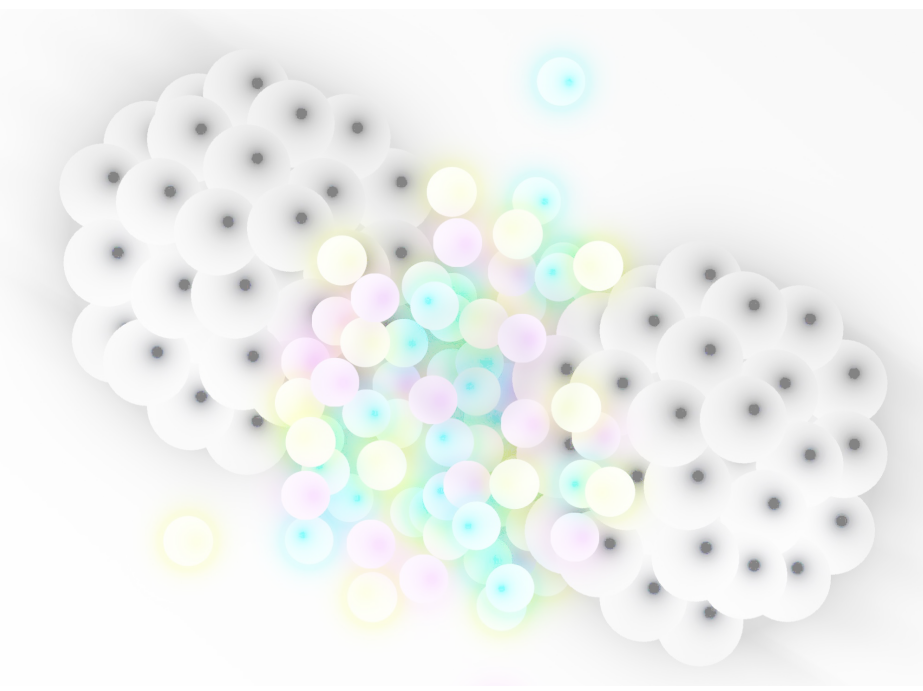
(well known and theoretically understood)



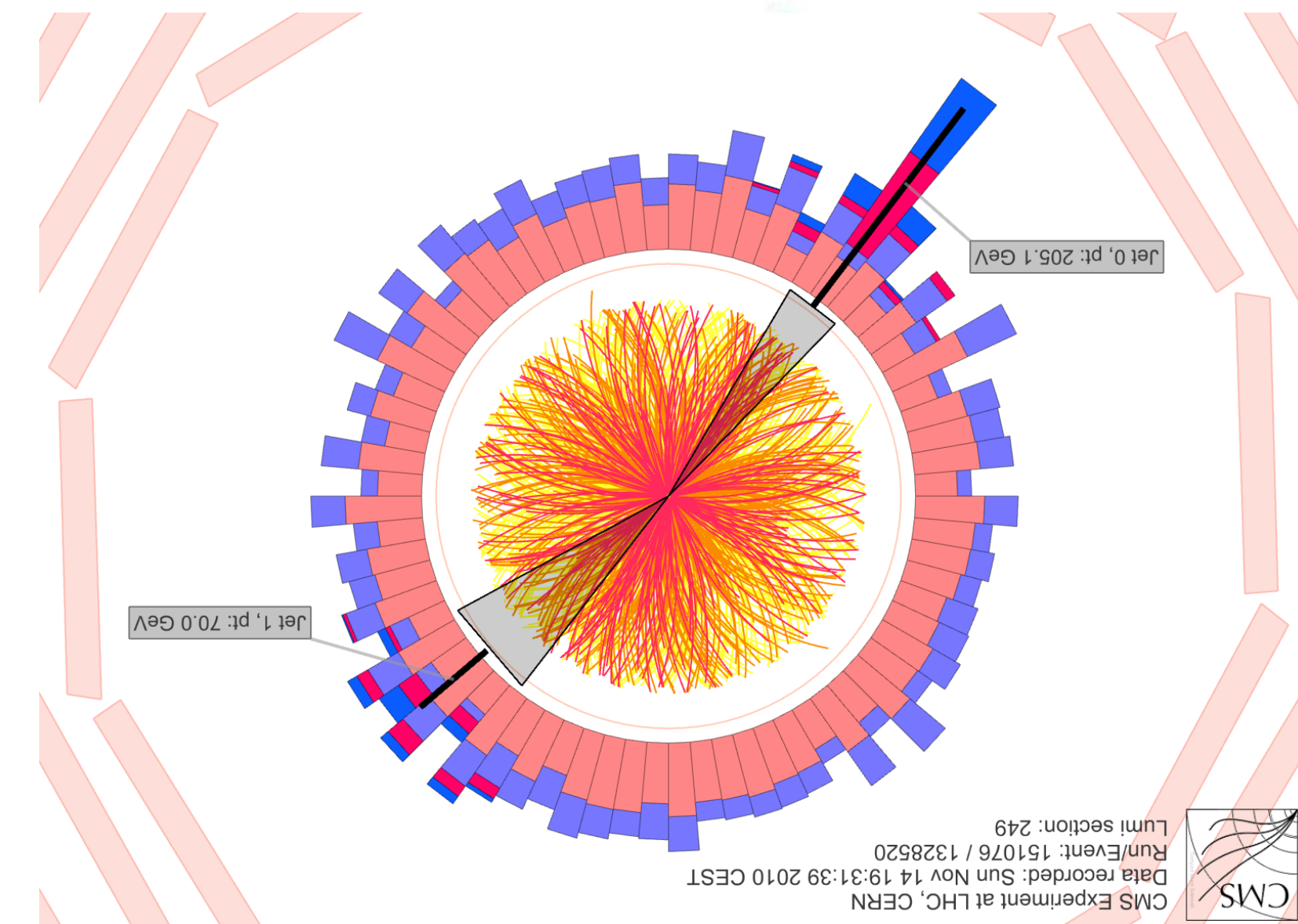
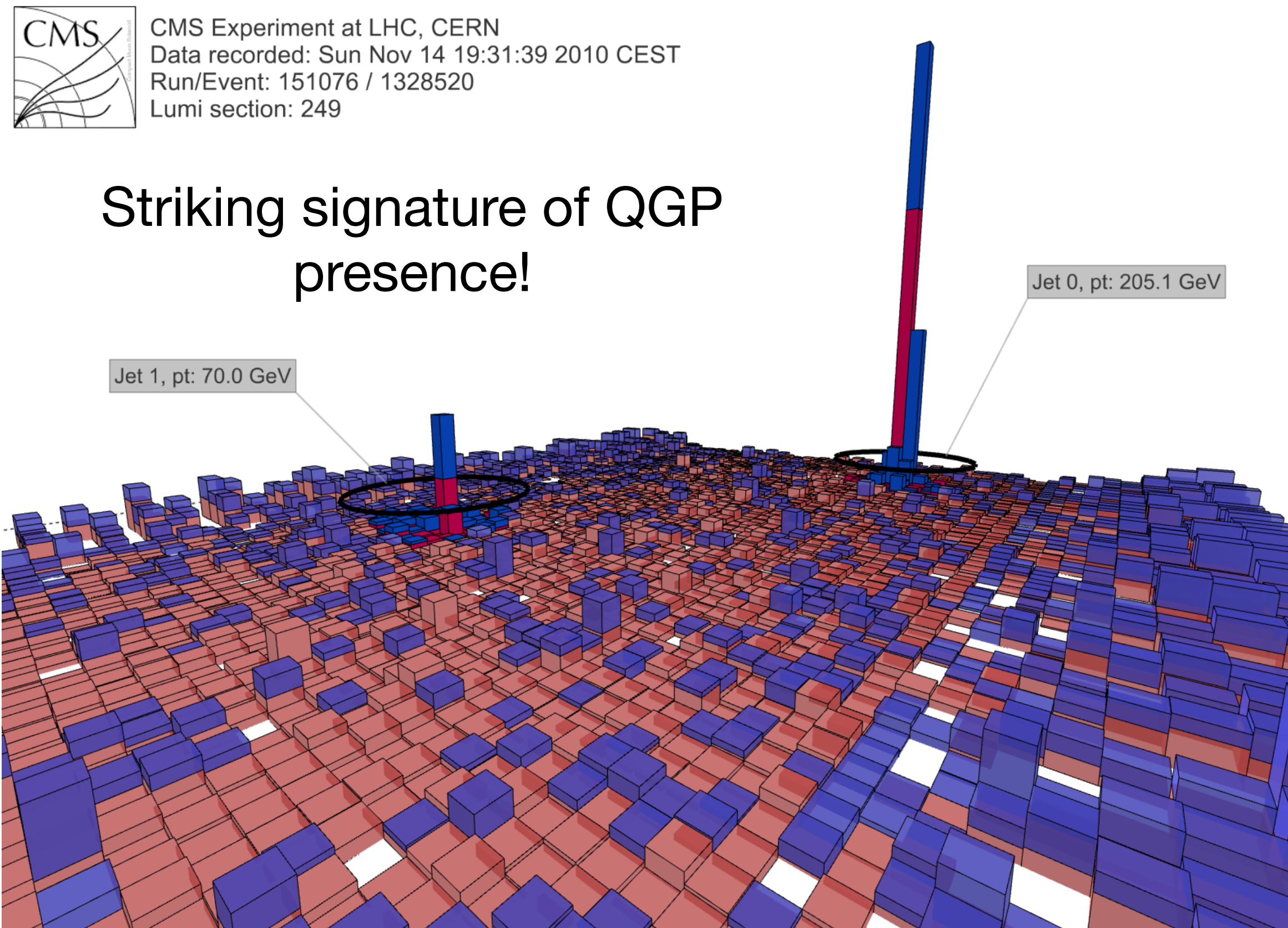
Example: jets in PbPb

(modifications related to the QGP microscopic properties)

Hard Probes

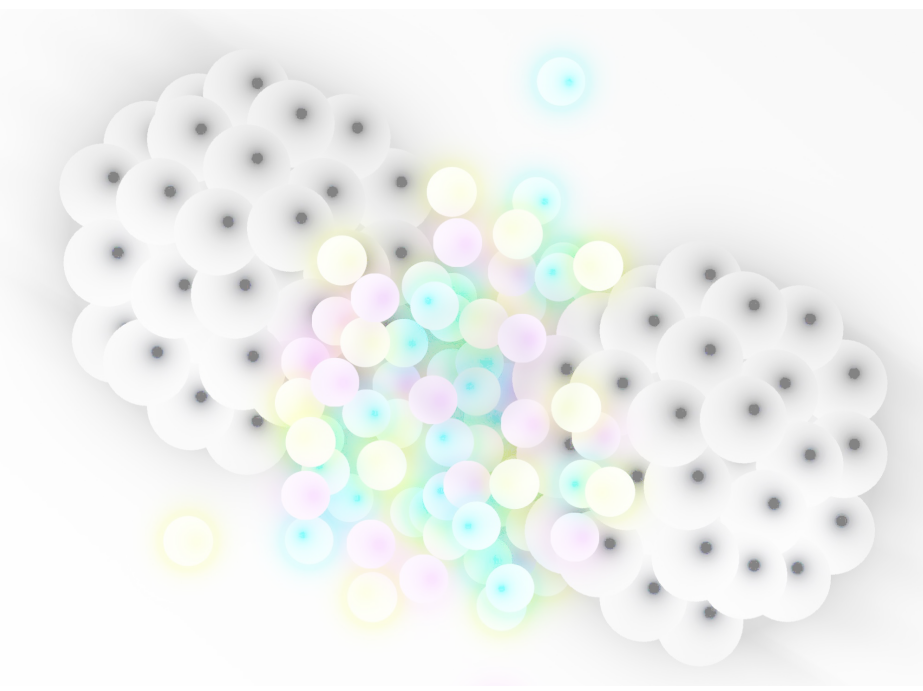


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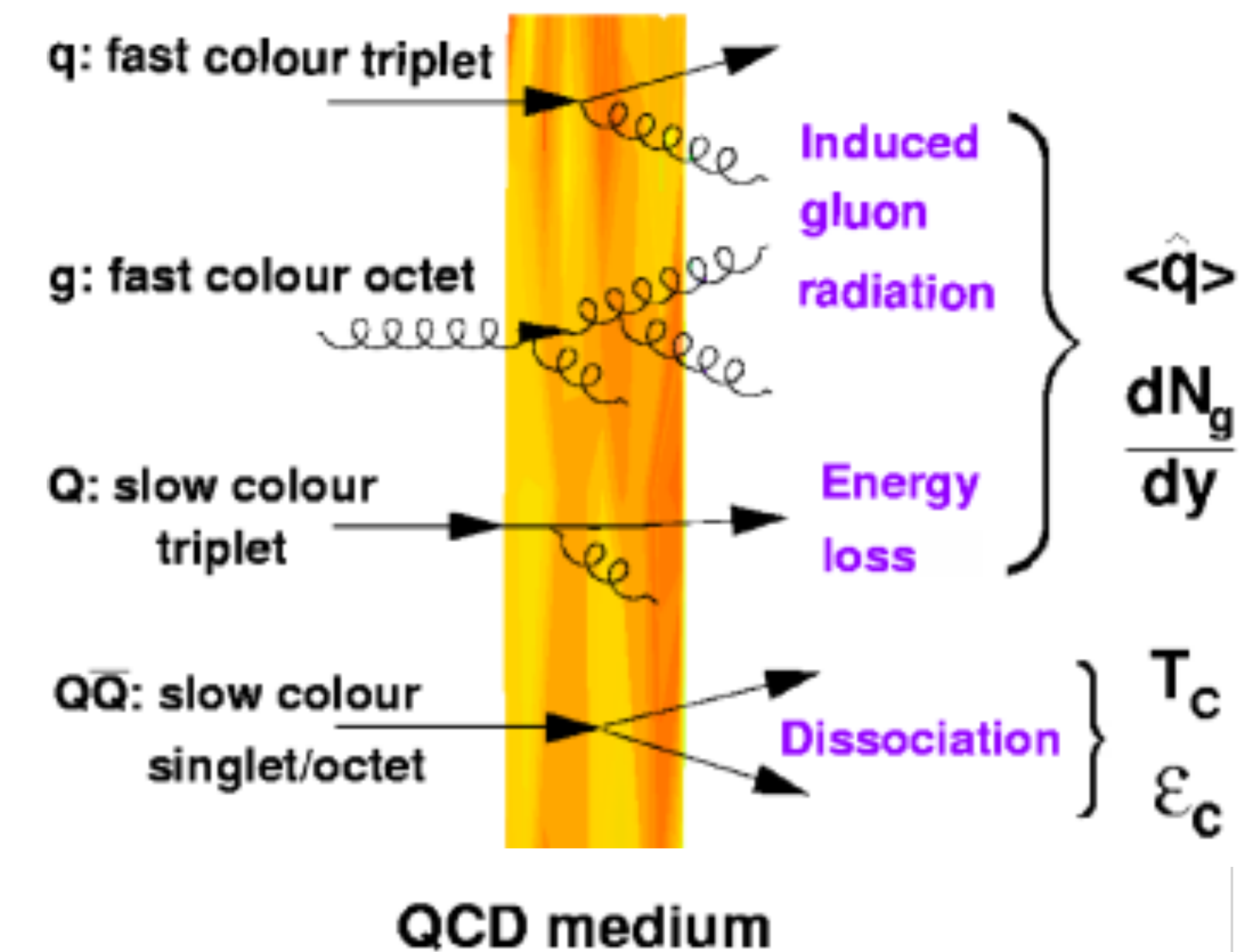


Example: jets in PbPb
(modifications related to the QGP
microscopic properties)

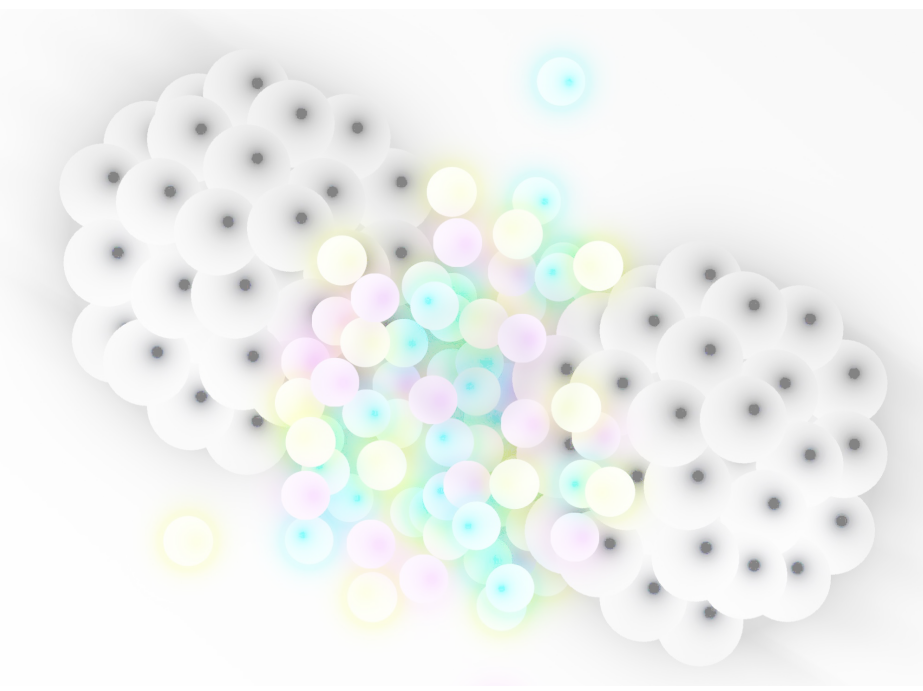
Hard Probes



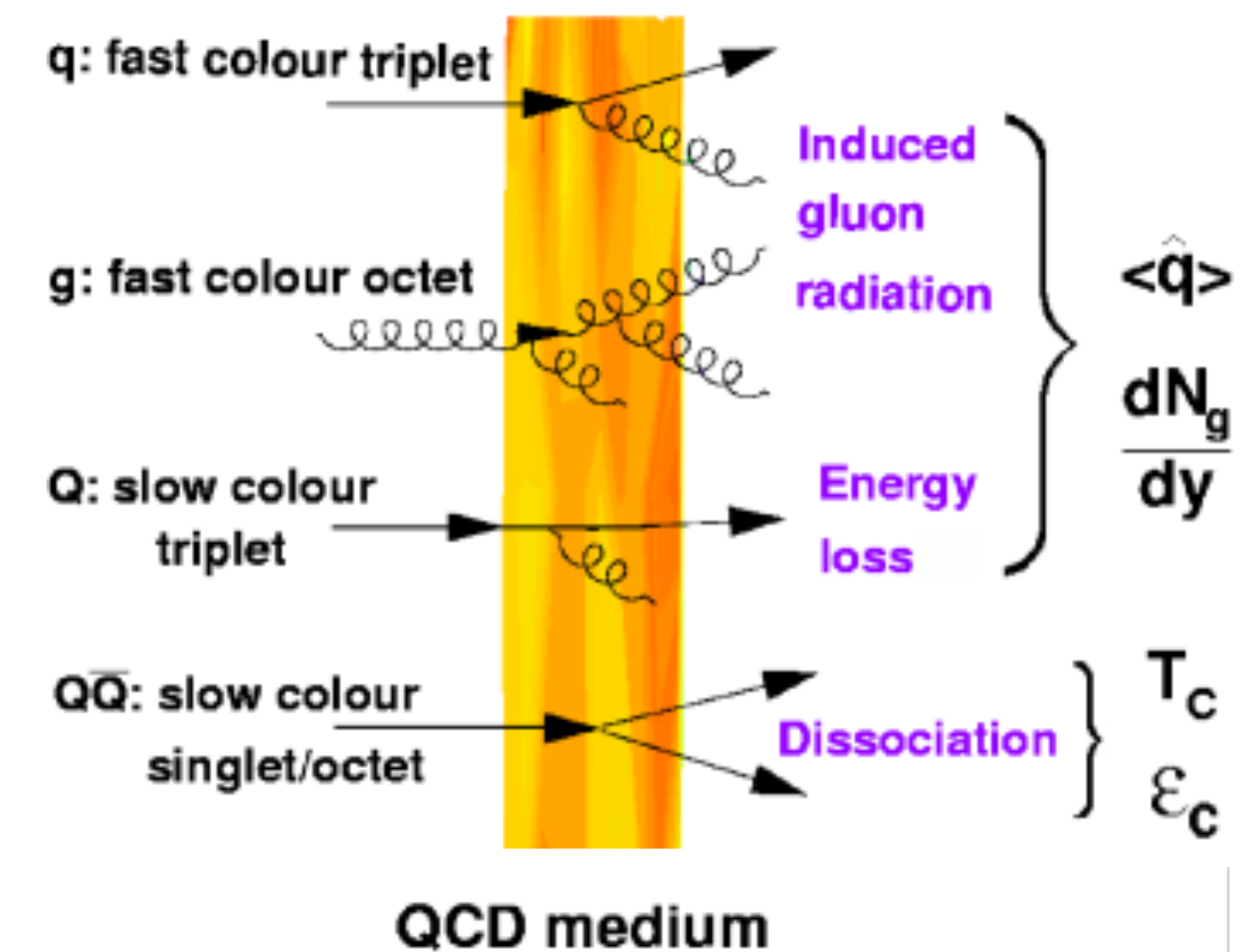
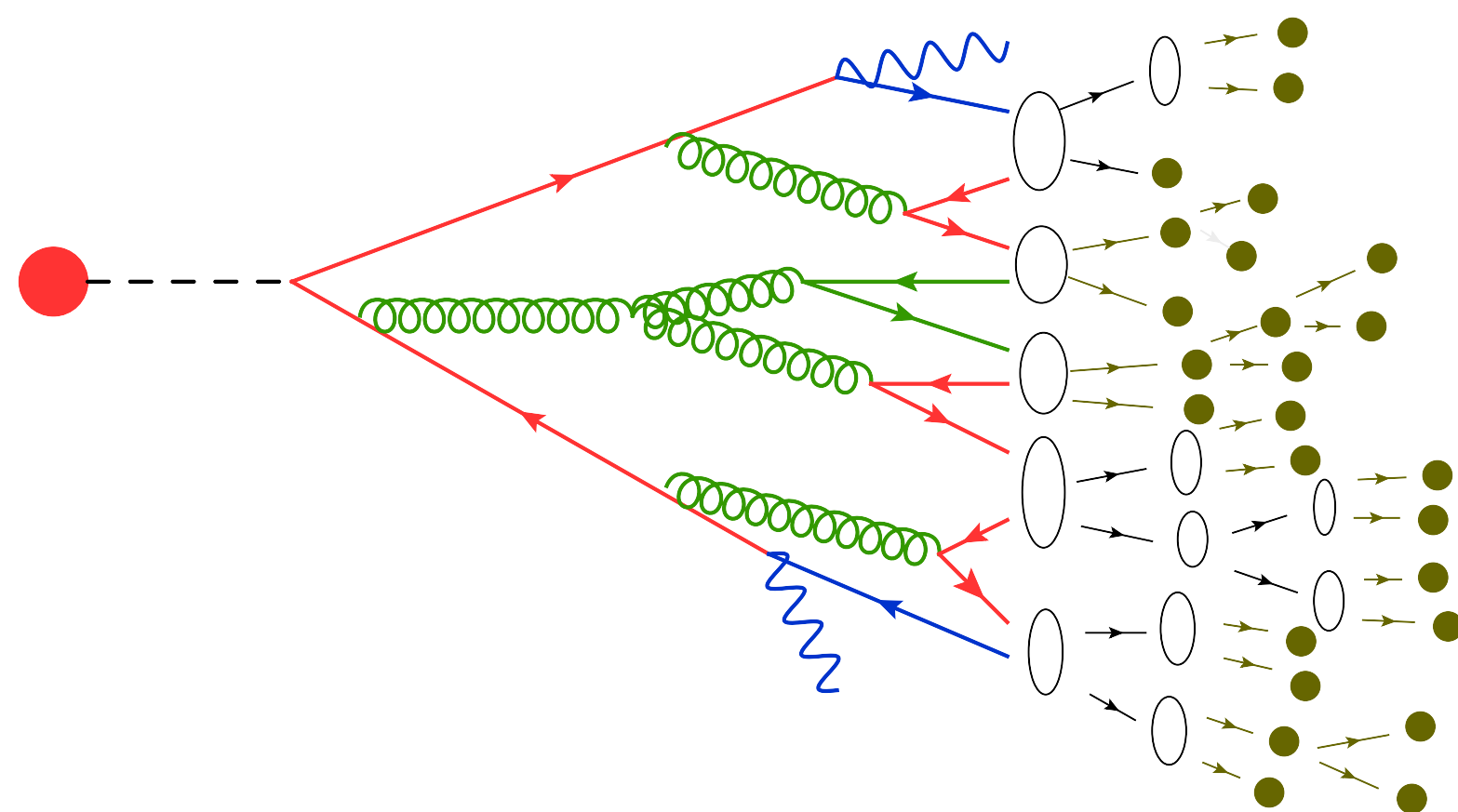
- Rare processes of high energy that are produced within the collision (hard scattering) and propagate through the QGP:
 - High momentum coloured objects:
 - Single particle measurements (B-meson, quarkonia,...)
 - Jets (Inclusive jets, b-initiated jets, ...)



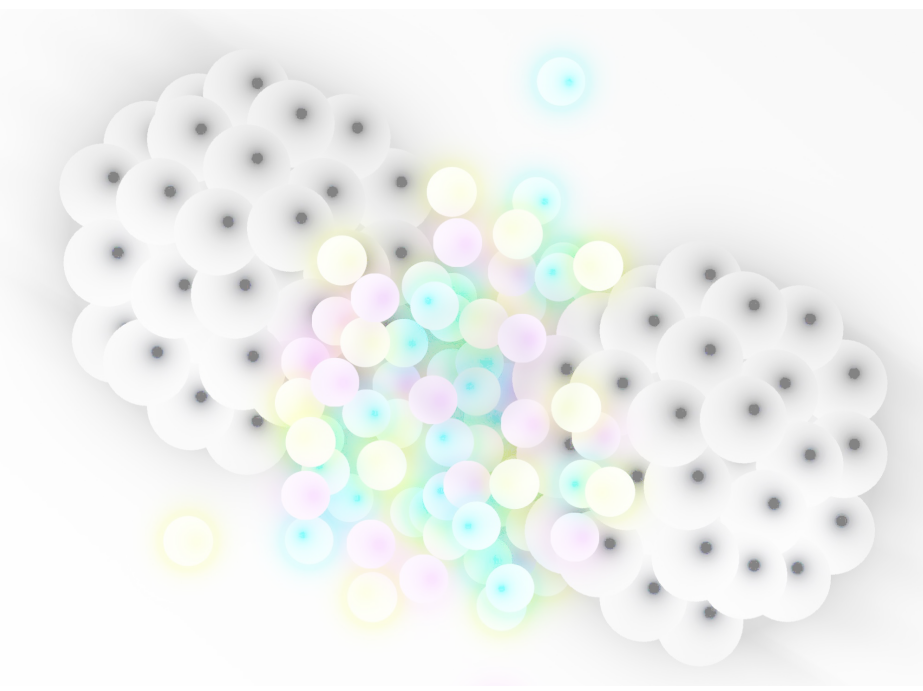
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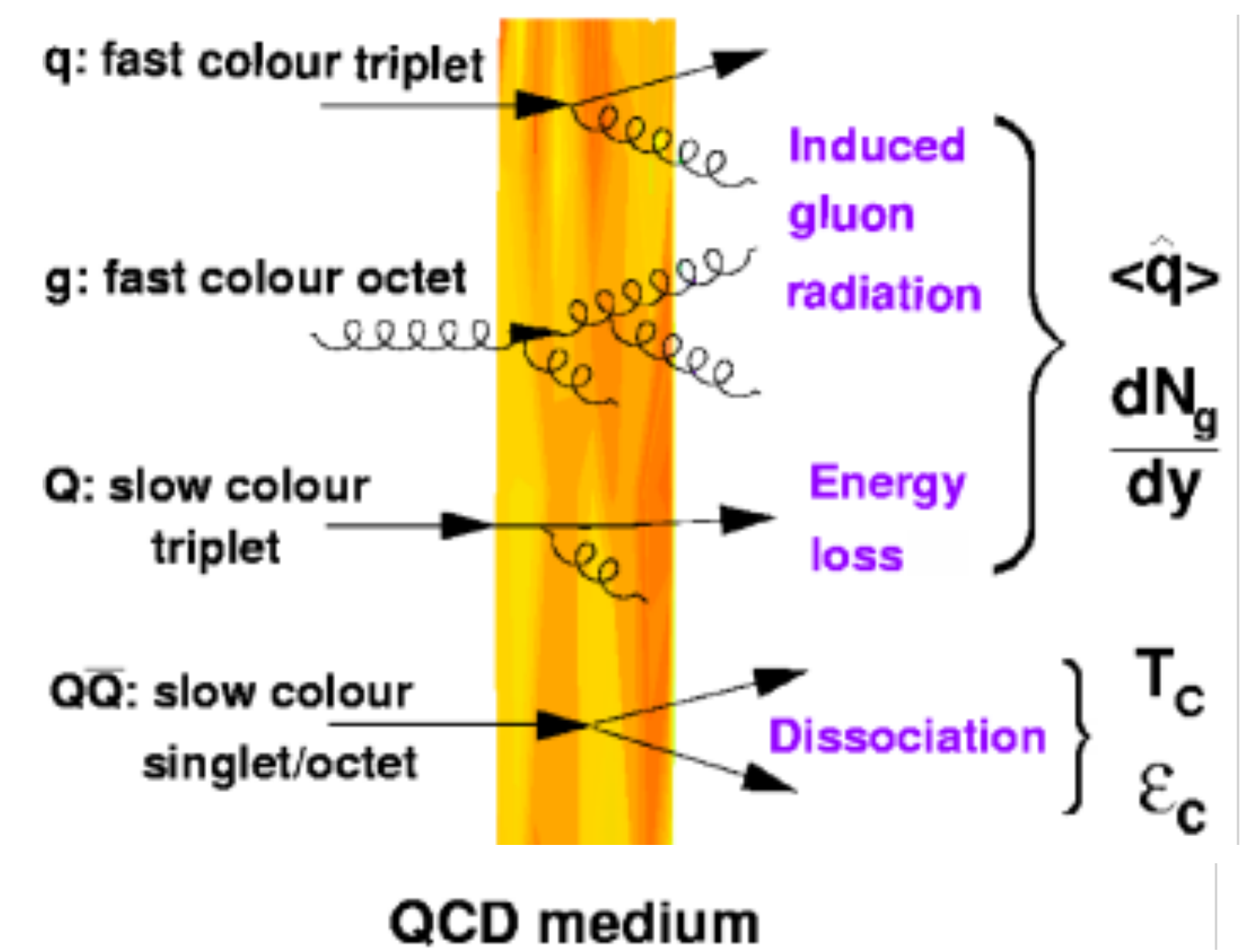
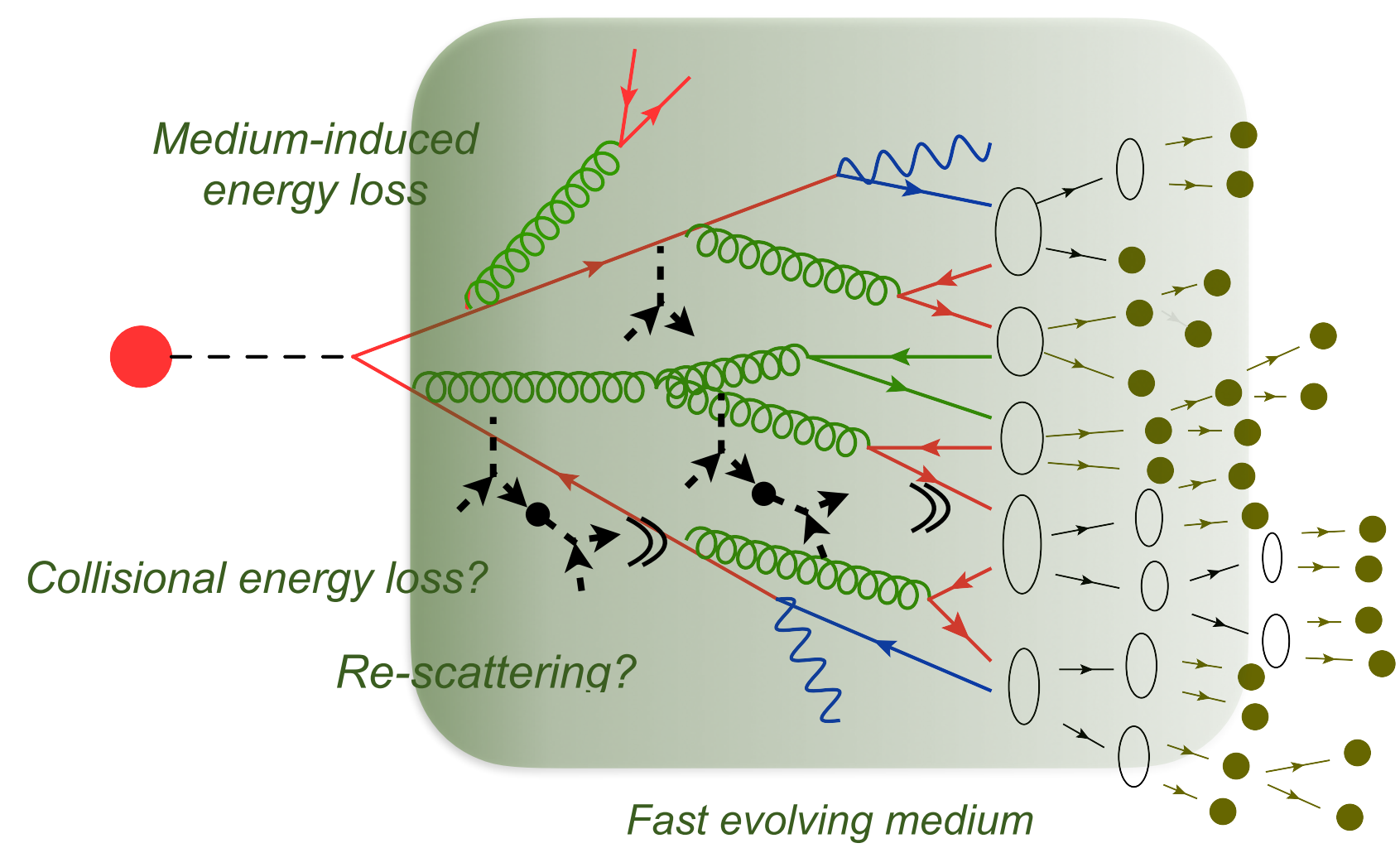
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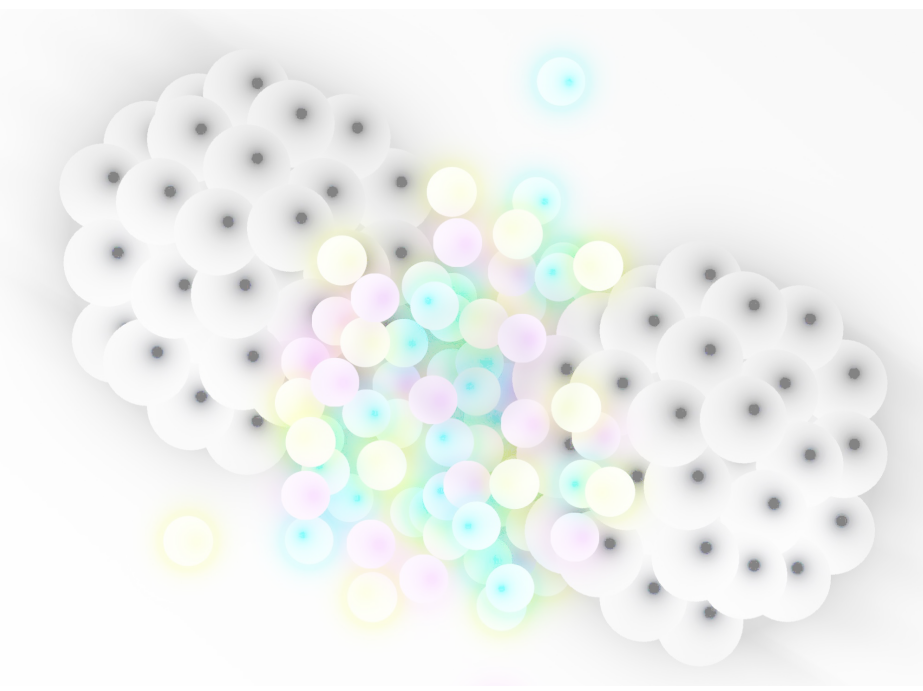
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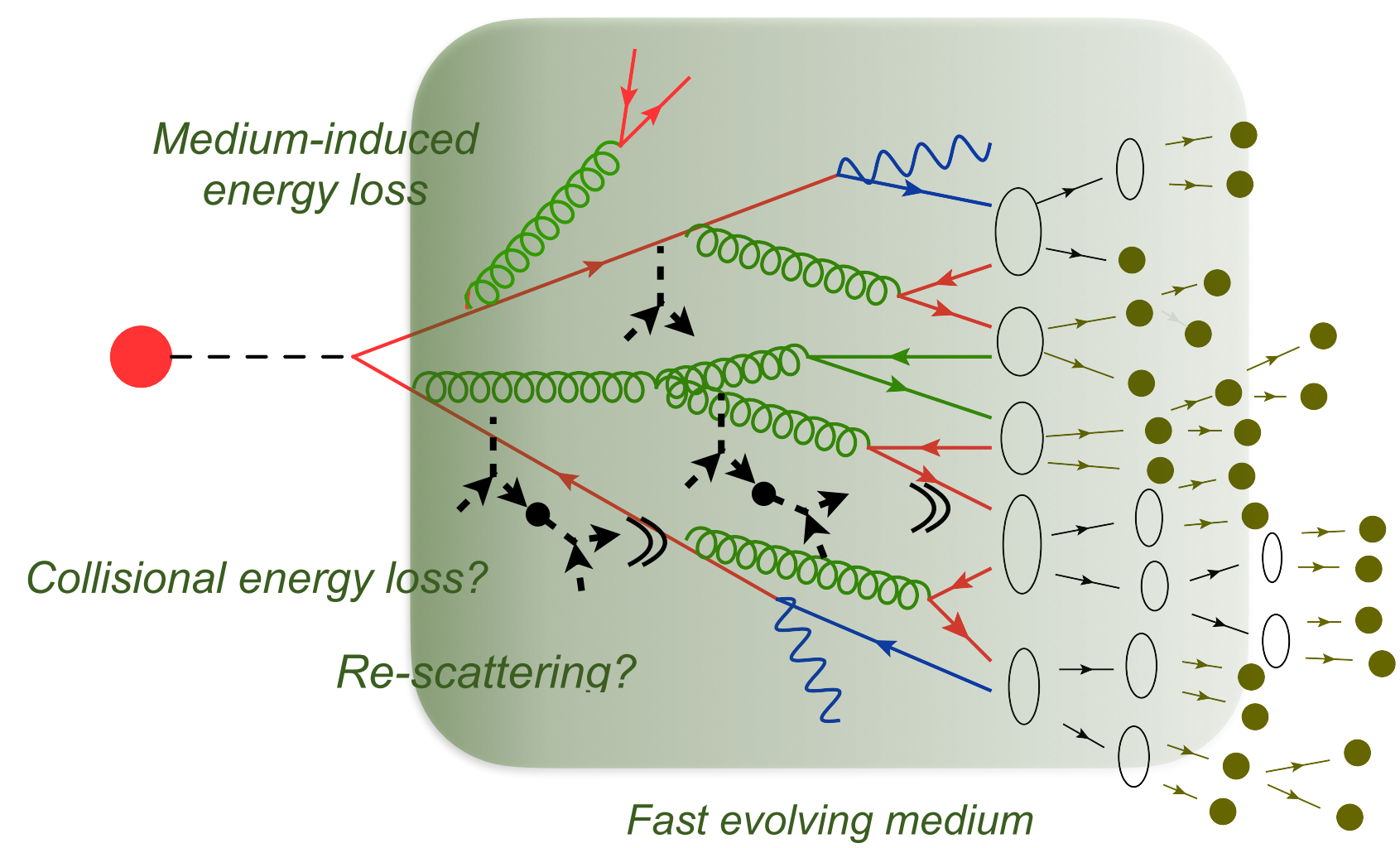
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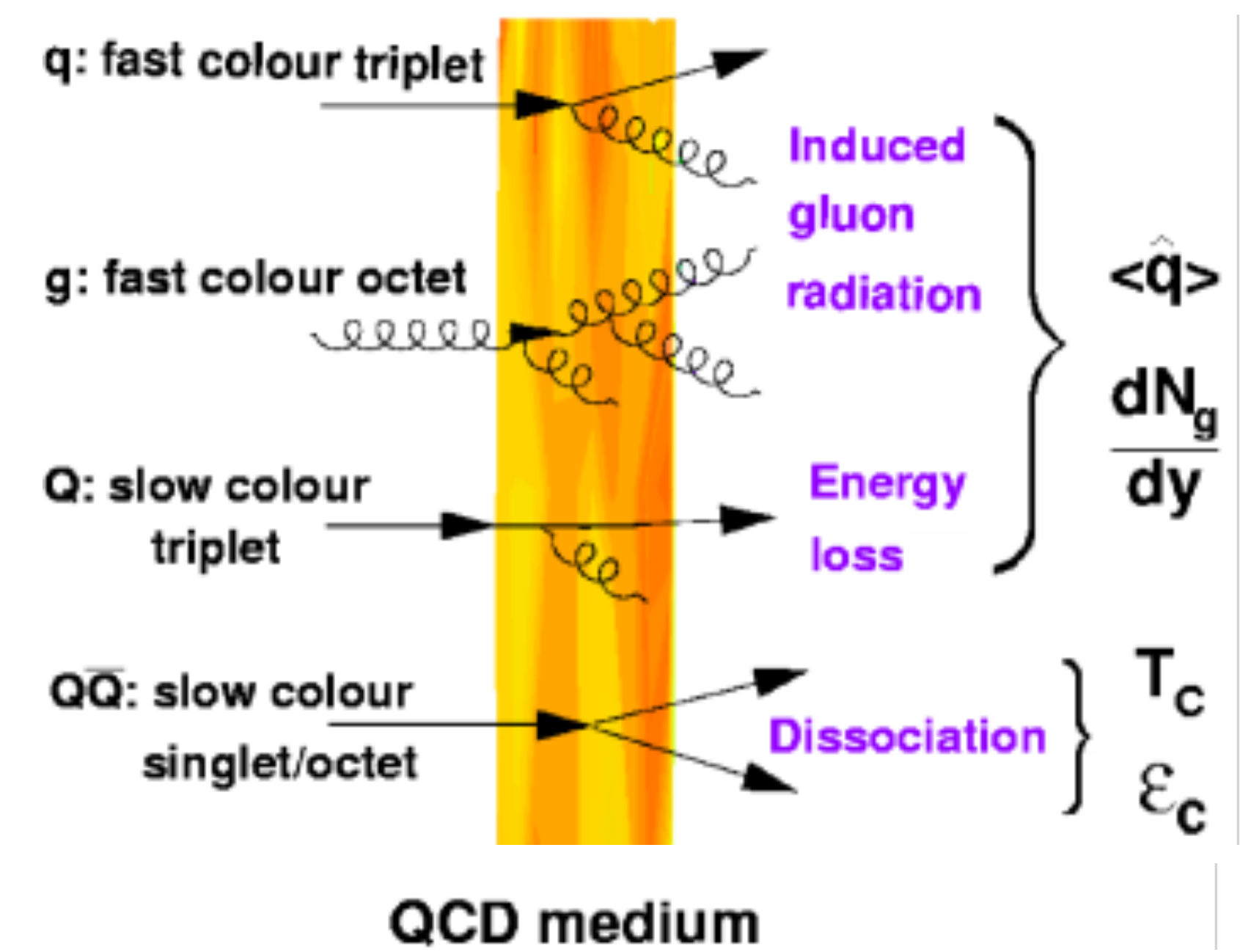
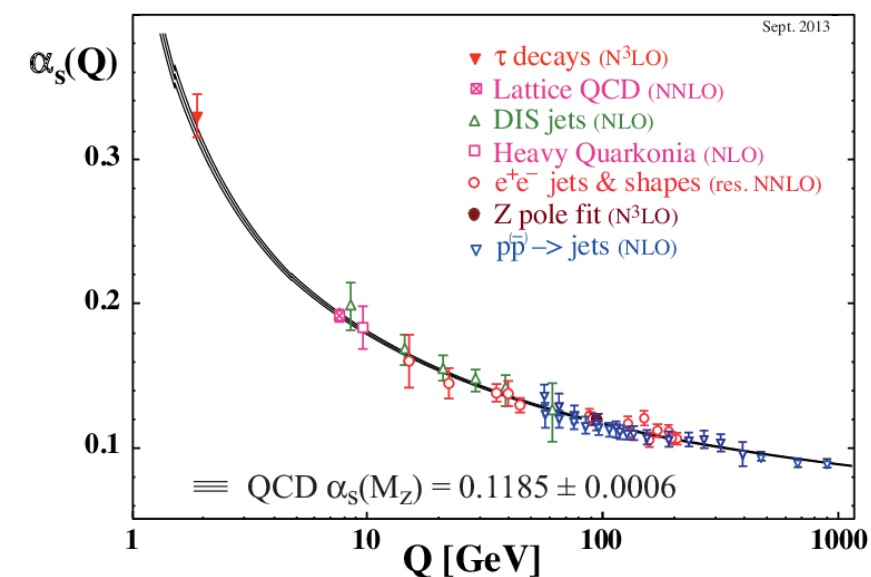


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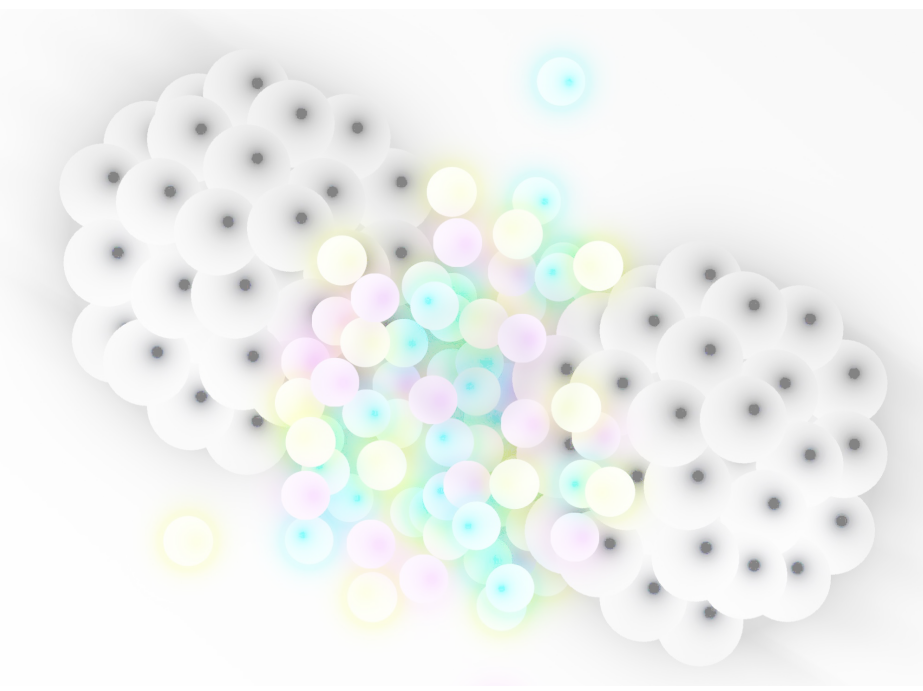
$$\mathcal{L} = \frac{1}{4} g_s^2 G_{\mu\nu}^a G_{\mu\nu}^a + \sum_f \bar{\psi}_f (i \not{D} - m_f) \psi_f$$

where $G_{\mu\nu}^a \equiv \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g_s f^{abc} A_\mu^b A_\nu^c$
 and $D_\mu = \partial_\mu + i g_s A_\mu^a$
 That's it!

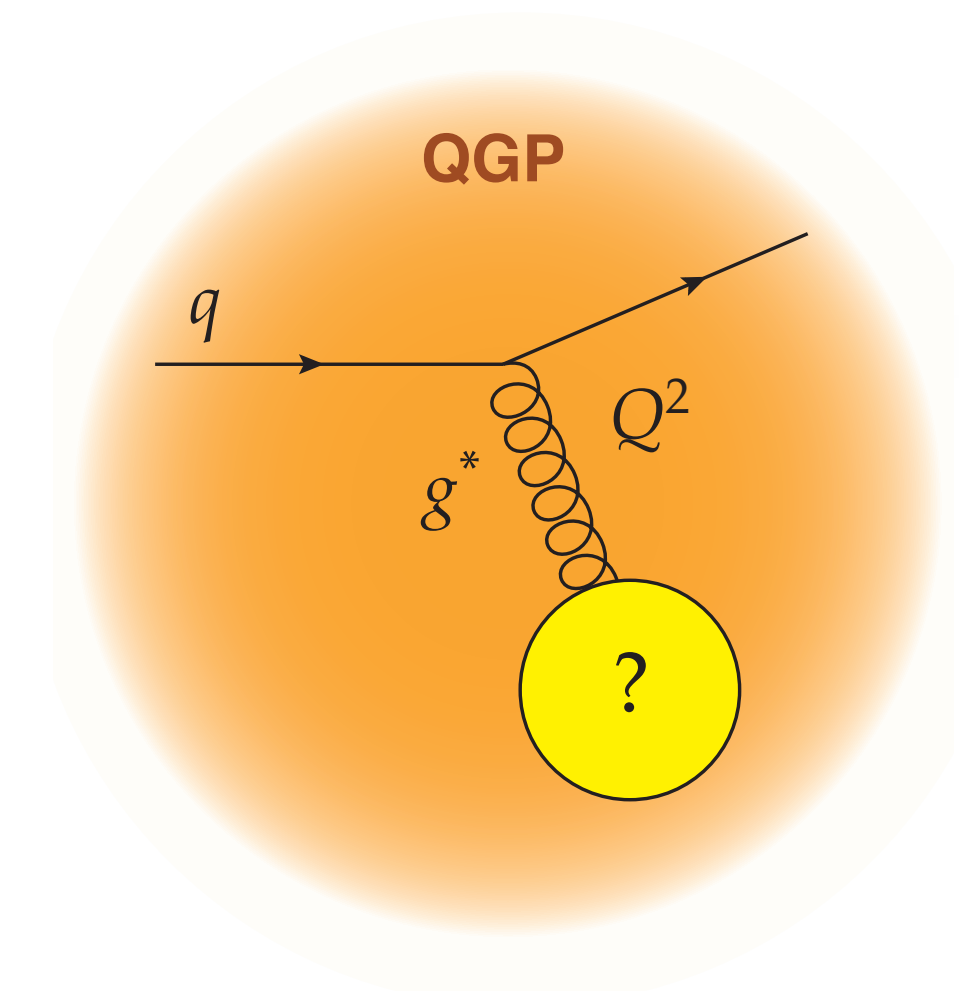
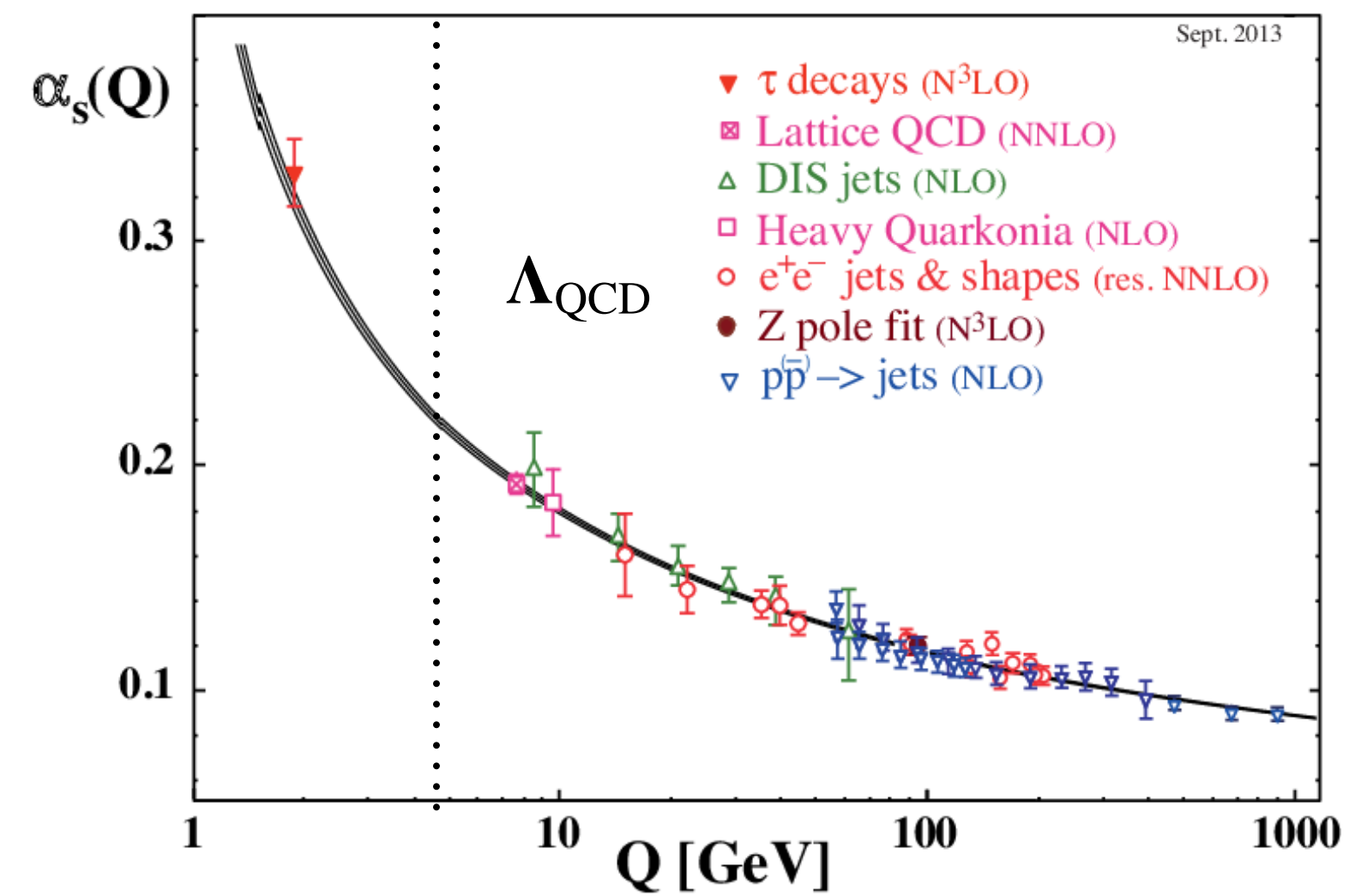
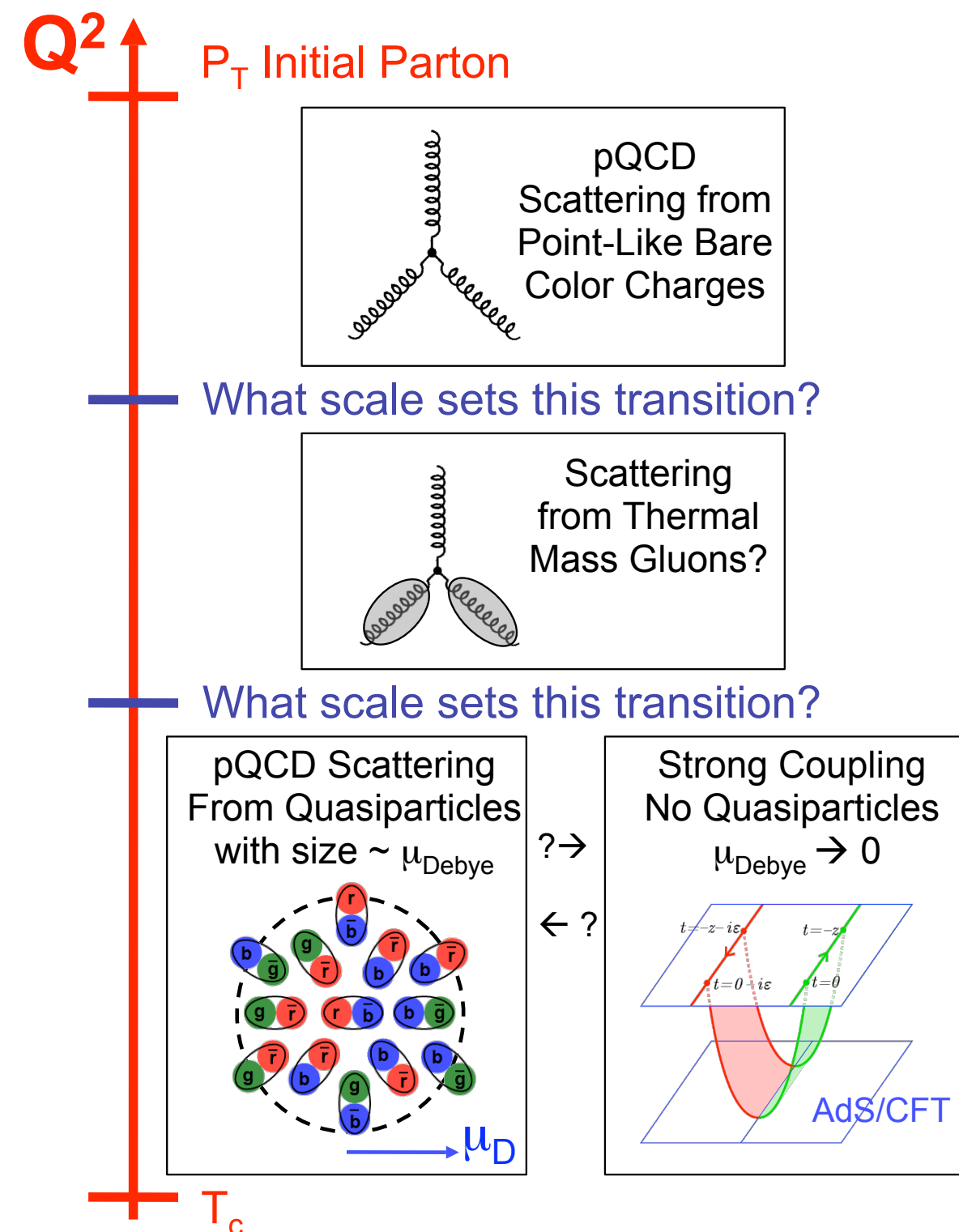


Probing the microscopic properties of the QGP
 Testing limits of pQCD

And more on Hard Probes



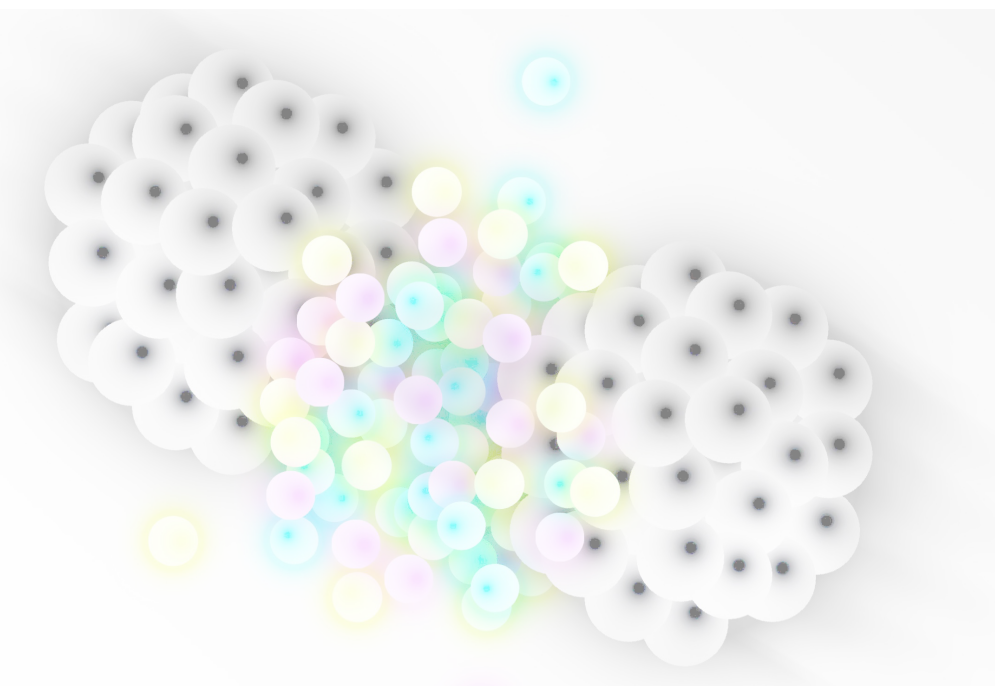
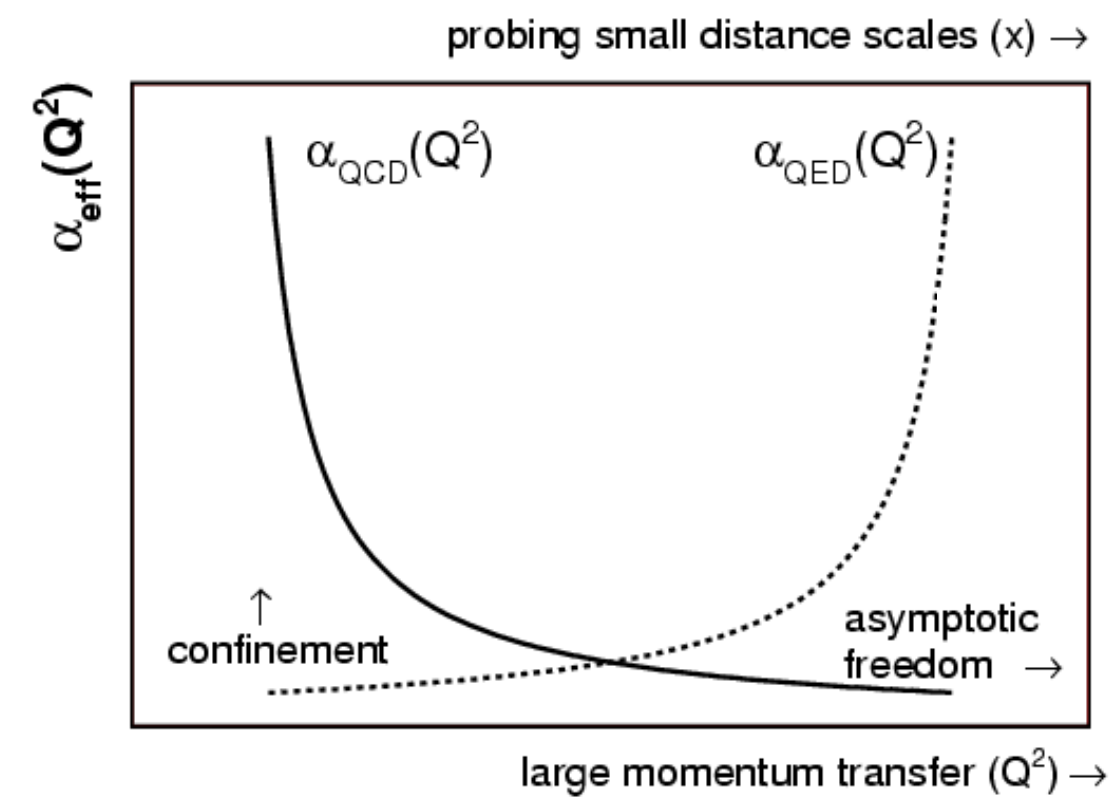
- Huge area! Not enough time to cover everything...
- Lots of new opportunities to test frontiers of QCD and unveil QGP characteristics



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]



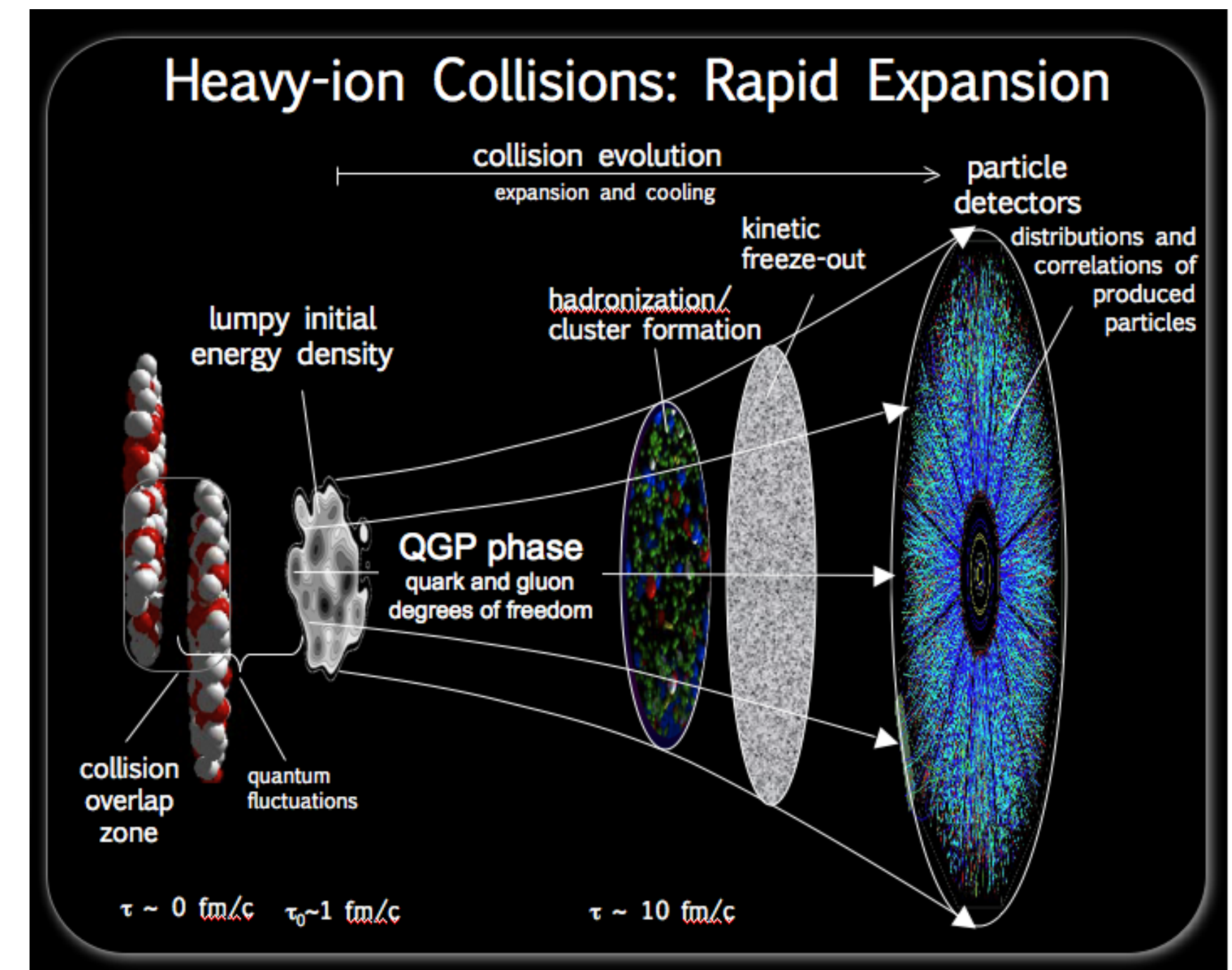
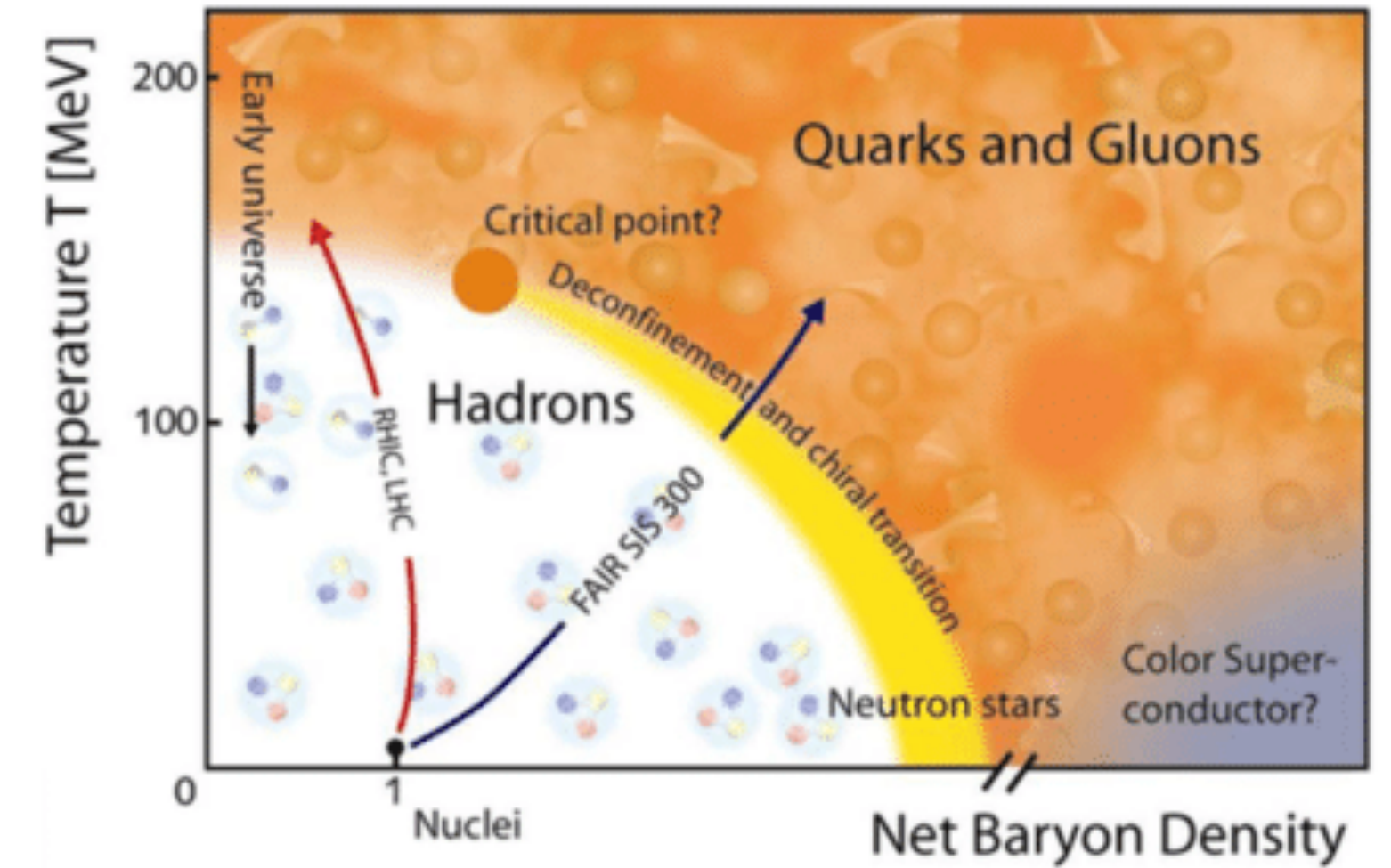
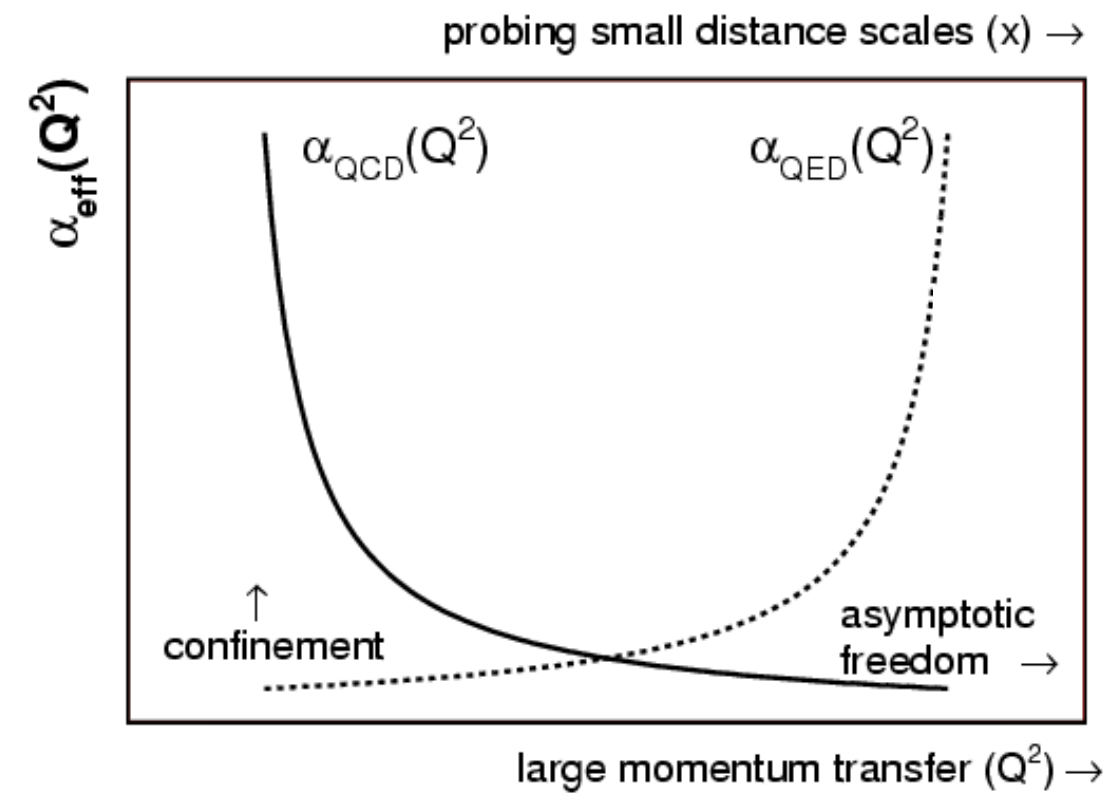
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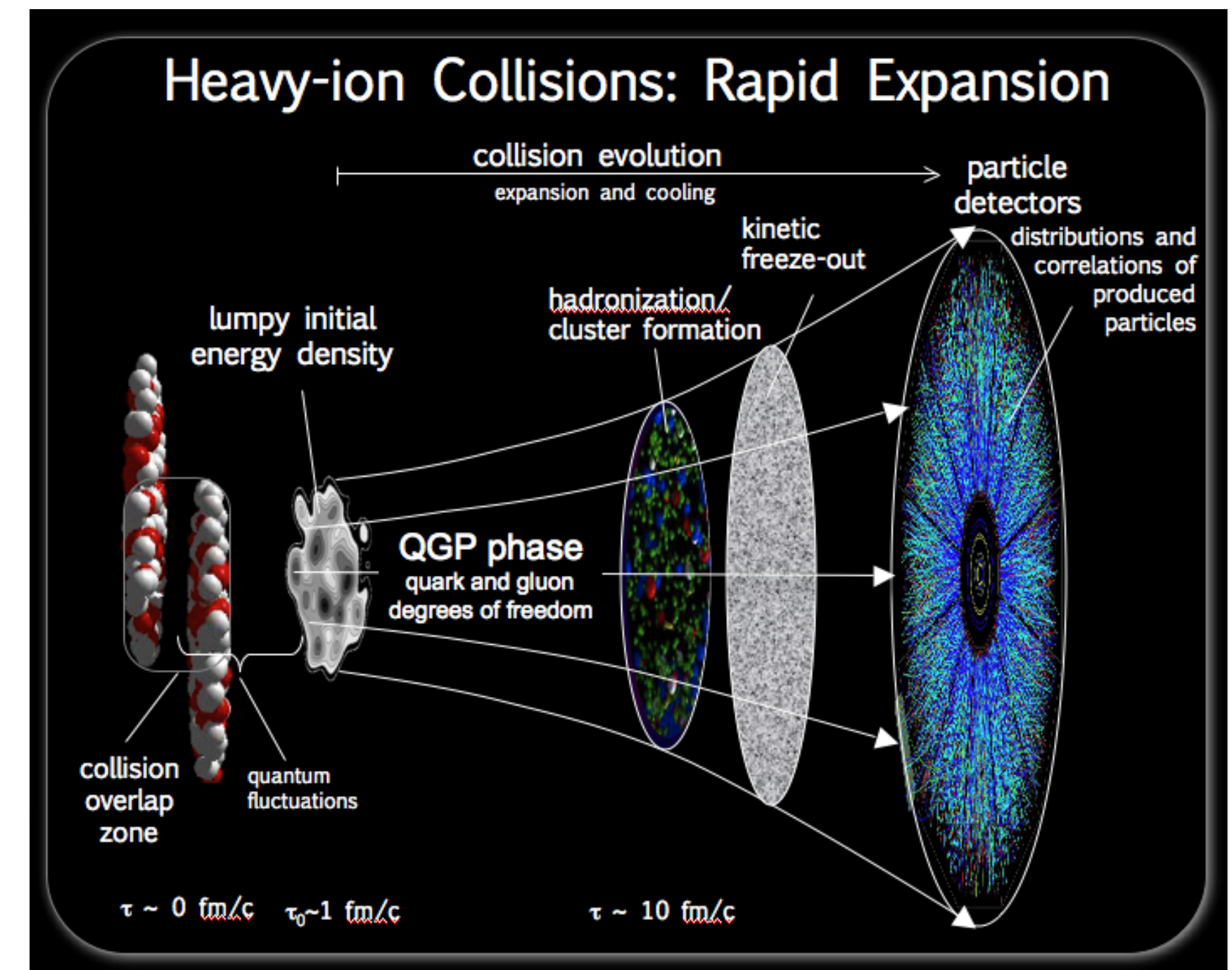
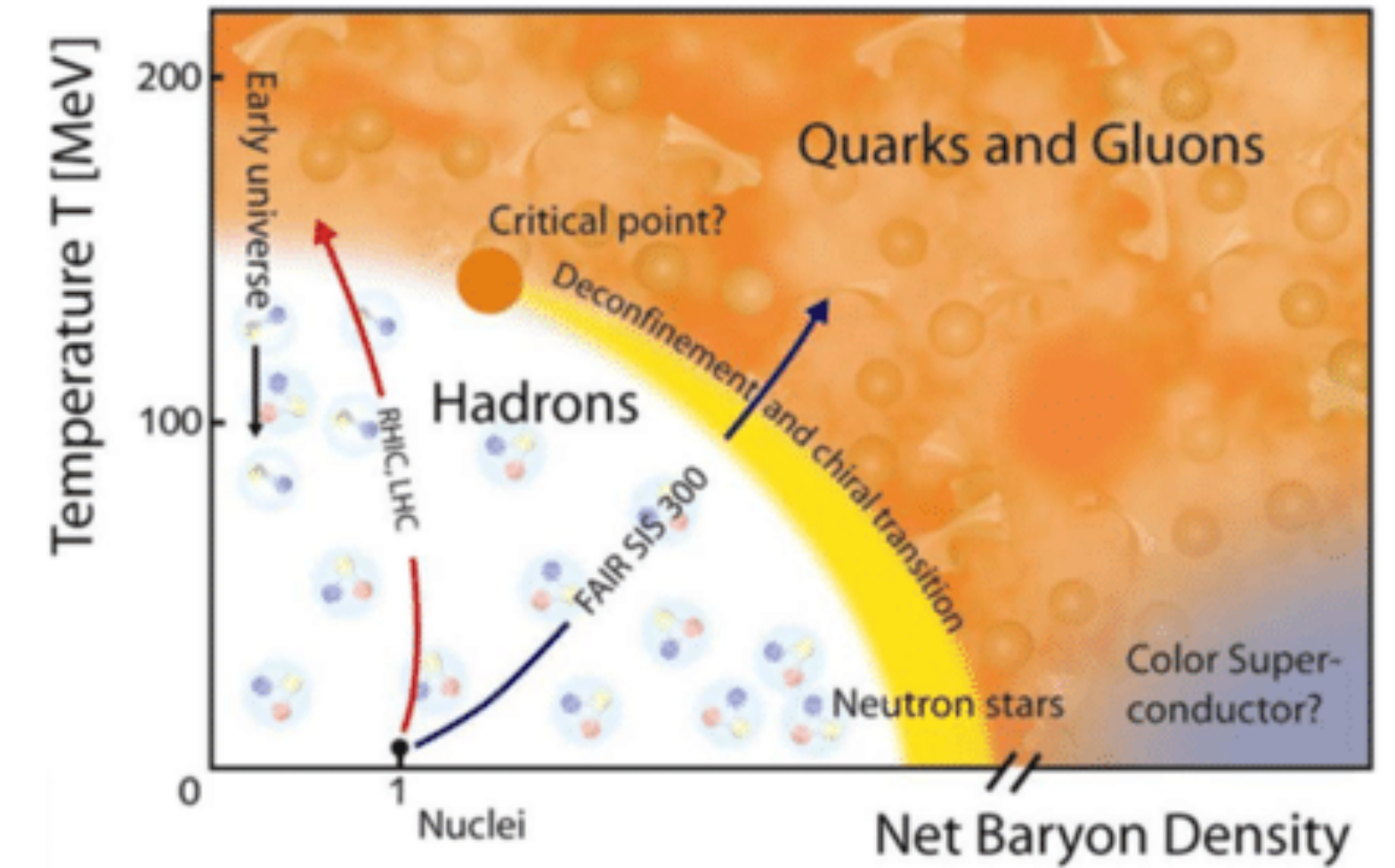
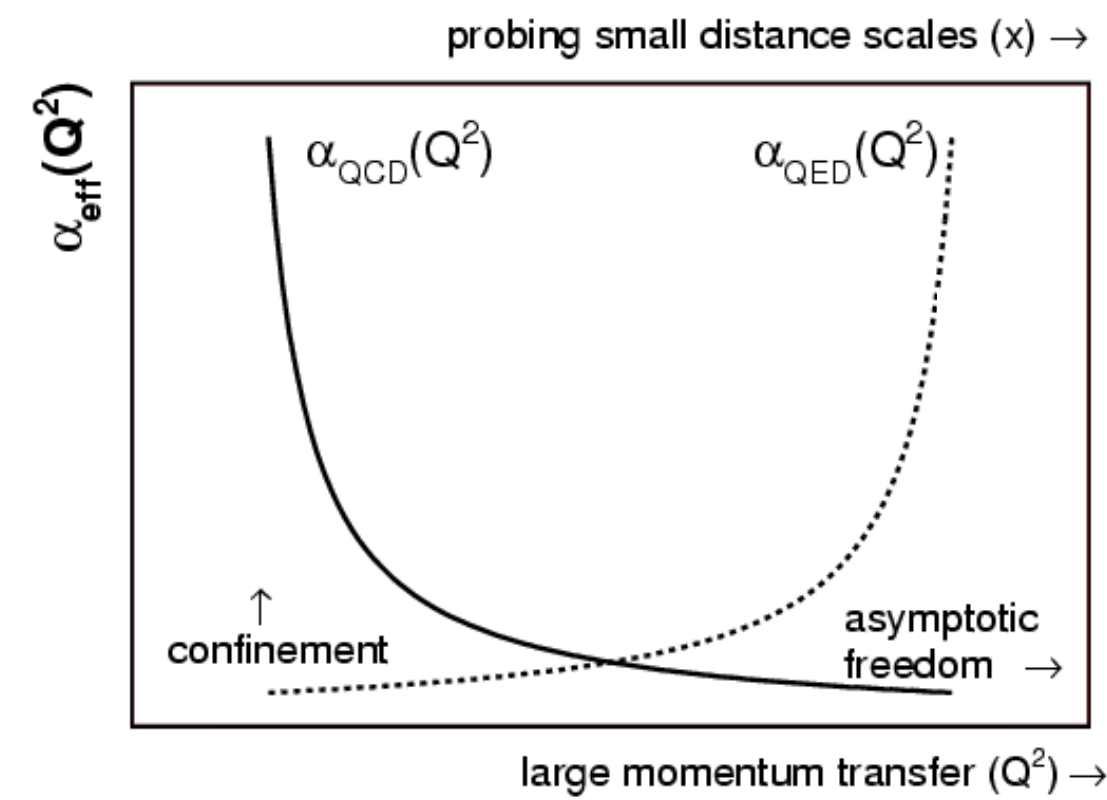
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Questions?