# Lecture 19 Strong Interactions

## ICPY473 Nuclear Physics, MUIC, 3-Trimester, 2021

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# Today Topics

- Quantum chromodynamics of quark interaction
- Asymptotic freedom
- Elementary interactions of hadrons
- Relativistic heavy ion collisions or RHICs

# Quantum Chromodynamics of Quark Interaction

# Hadrons are baryons (fermions) and mesons (bosons), where baryon is $qqq$-state, while meson is $q\bar{q}$-state
# Quark appear in 6 flavors and grouped to be three generations,i.e., (u,d), (c,s) and (t,b)
# Quarks get birth with color degrees of freedom (RBG), in order to overcome Pauli's exclusion principle for 3-quark state of baryon, and observed particles in nature must appear in white or colorless
# Quantum mechanically, quark is represented by *color triplet*, and have $SU(3)_C$ color symmetry, or invariant under SU(3) gauge transformation (number of symmetric states is 8, the octet model)
# Quarks are spin 1/2 fermions, so that they must have SU(2) spin symmetry, up-spin quark and down-spin quark are the same quark (with exactly the same mass)
# Quarks have electric charge $+2/3$ (u,c,t) and -1/3 (d,s,b) in unit of electric charge $e$, so that they also have U(1) symmetry of complex phase transformation

Gauge field with SU(3) gauge symmetry is called Yang-Mills (YM) field, it is non-abelian gauge field

Gluon is quantum particle of non-abelian gauge field (YM), and being bicolor

$$A_\mu = A^a_\mu = t^a, a = 1, 2, ..., 8$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - ig_c[A_\mu, A_\nu] = F^a_{\mu\nu} t^a$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_c f^{abc} A^b_\mu A^c_\nu$$

After we have used the su(3) algebra $[t^a, t^b] = if^{abc} t^c$. Gluon Lagrangian is

$$\mathcal{L}_{gluon} = -\frac{1}{4} F^a_\mu F^{a,\mu\nu} = -\frac{1}{2} \partial_\mu A^a_\nu (\partial^\mu A^{a,\nu} - \partial^\nu A^{a,\mu})$$

$$-\frac{1}{2} g_c f^{abc} A^b_\mu A^c_\nu (\partial^\mu A^{a,\nu} - \partial^\nu A^{a,\mu})$$

$$+\frac{1}{4} g_c^2 f^{xab} f^{xcd} A^b_\mu A^b_\nu A^{c,\mu} A^{d,\nu}$$

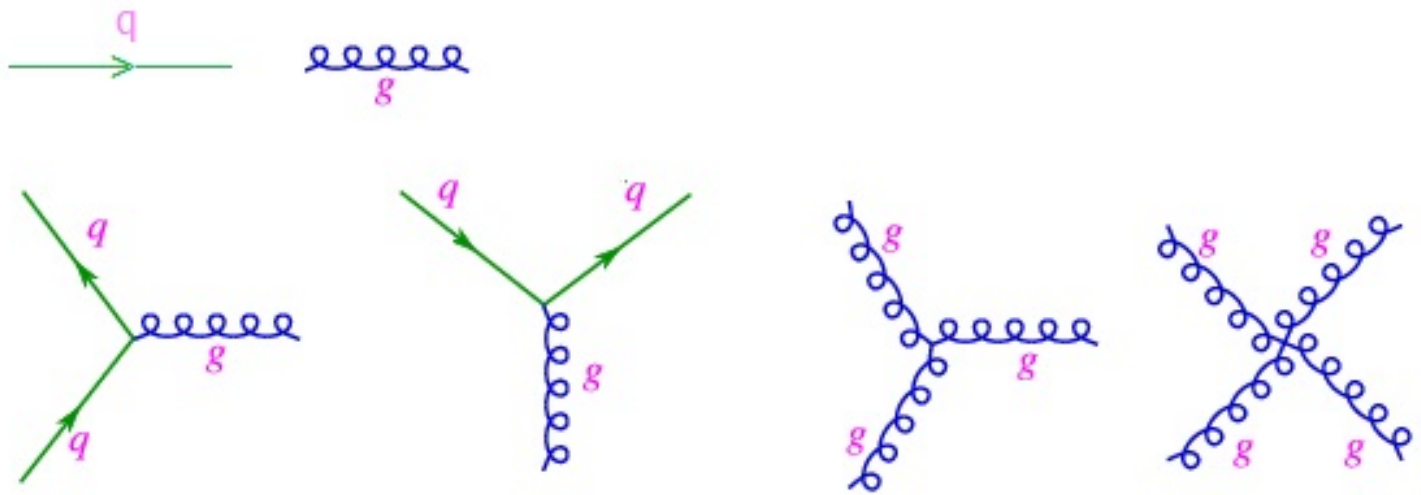
$$= \underbrace{\mathcal{L}_{gg}}_{kinetic} + \underbrace{\mathcal{L}_{ggg} + \mathcal{L}_{gggg}}_{self-coupling}$$

QCD Lagrangian

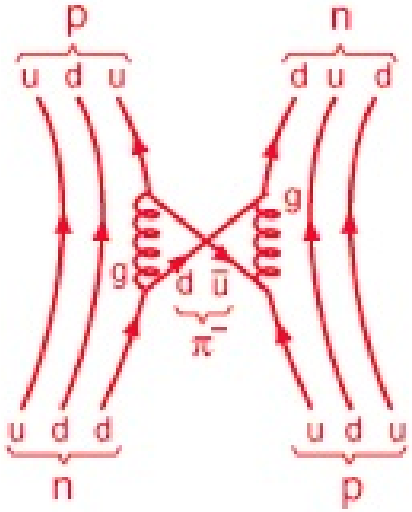
$$\mathcal{L}_{qcd} = \sum_{i,j} \bar{\psi}^i (i\gamma^\mu D_\mu - m)_{ij} \psi^j + \mathcal{L}_{gluon}$$

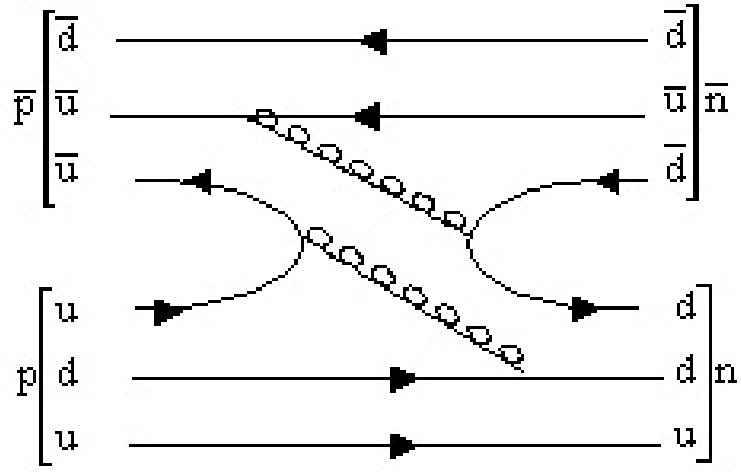
$$D_\mu = \partial_\mu - i g_c A^a_\mu t^a; \;\; i, j = R, G, B$$

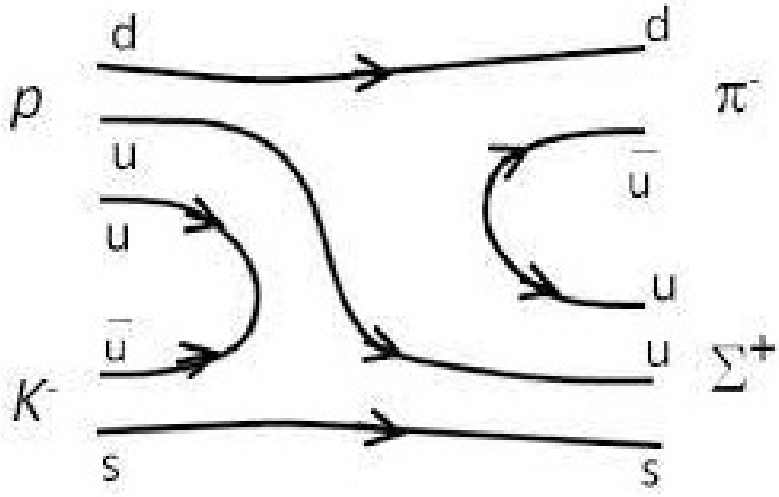
QCD Feynman diagrams

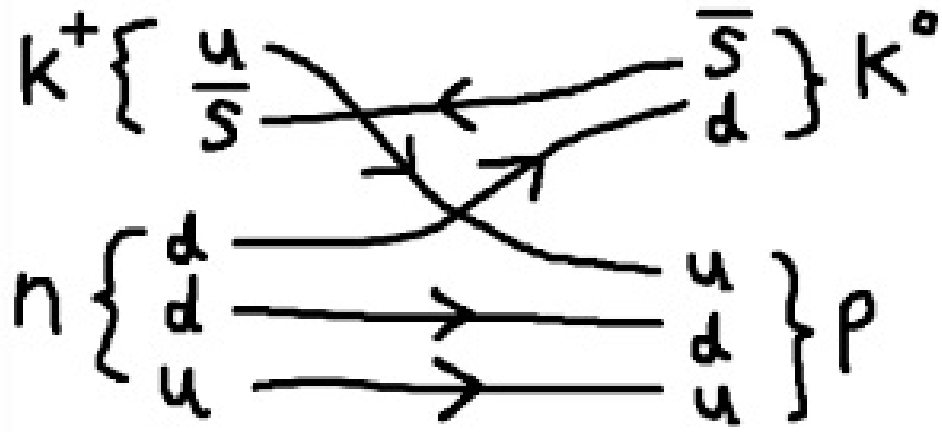


# Elementary QCD processes

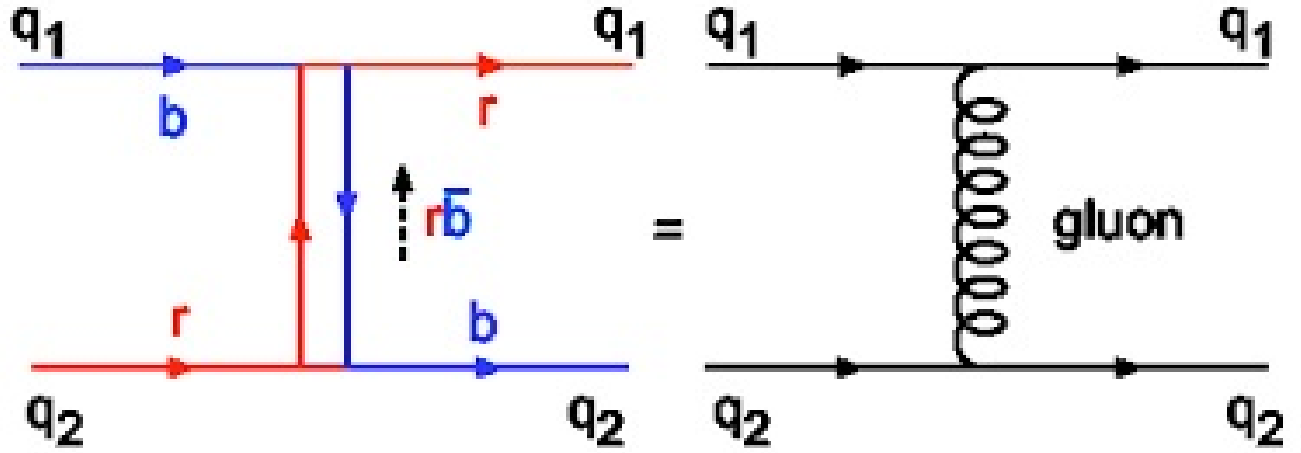


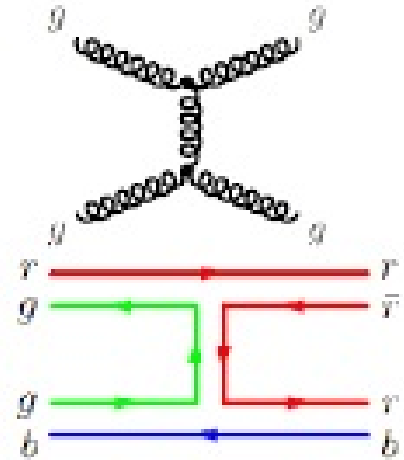



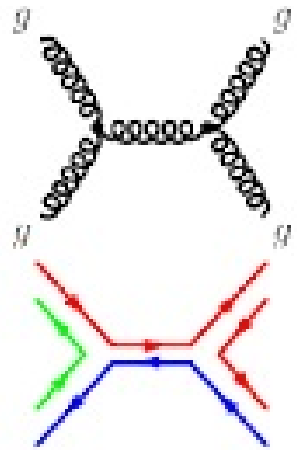



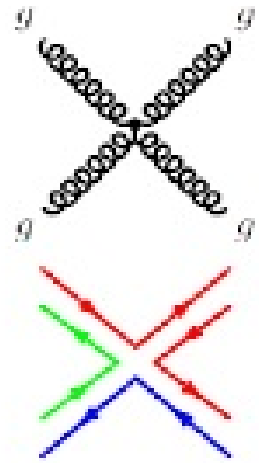



# Color flow diagrams



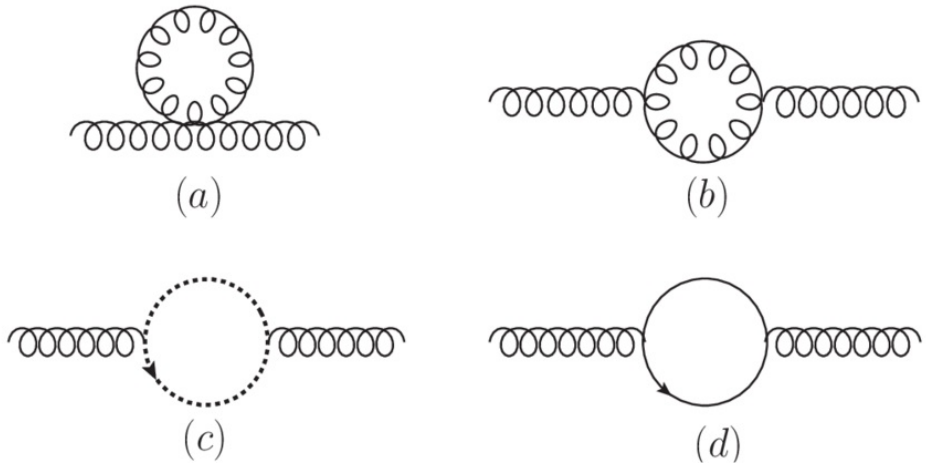



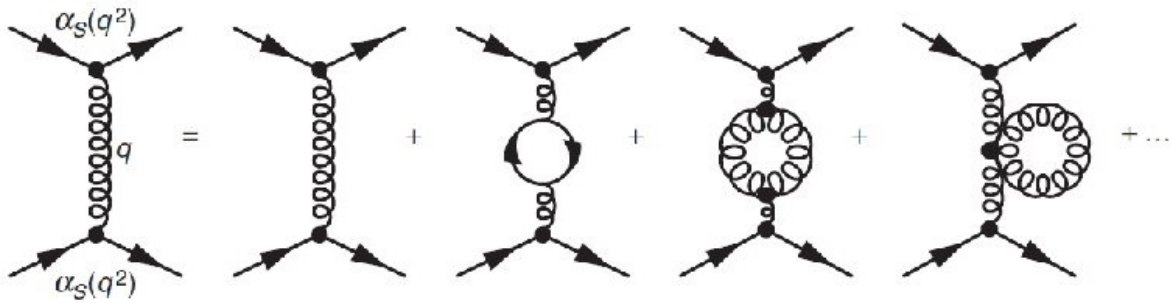



# Asymptotic Freedom

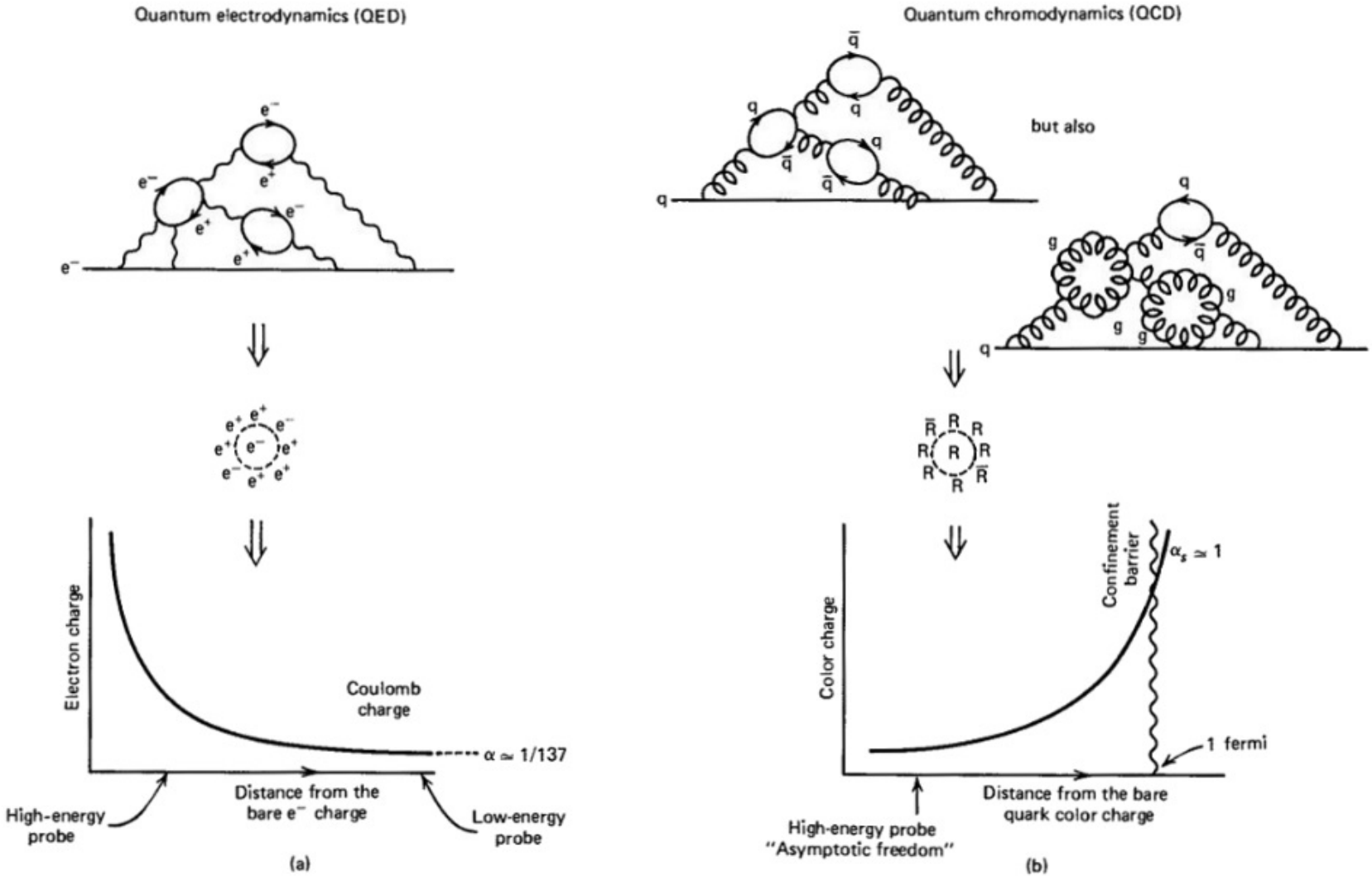
Gluon self-energy from self-coupling




Asymptotic freedom

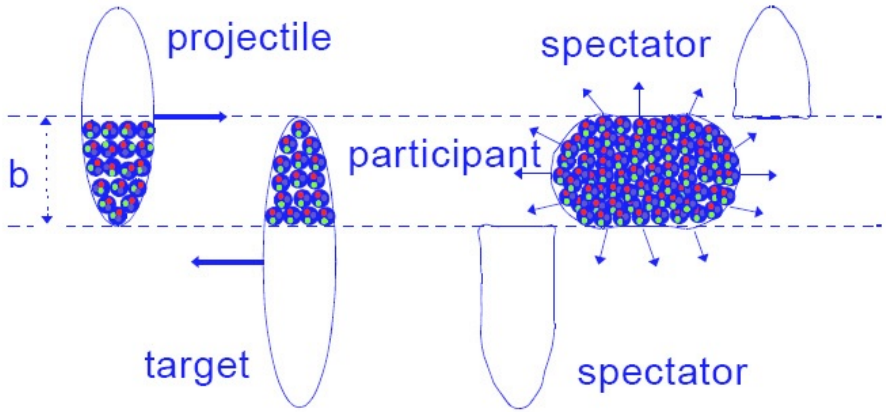


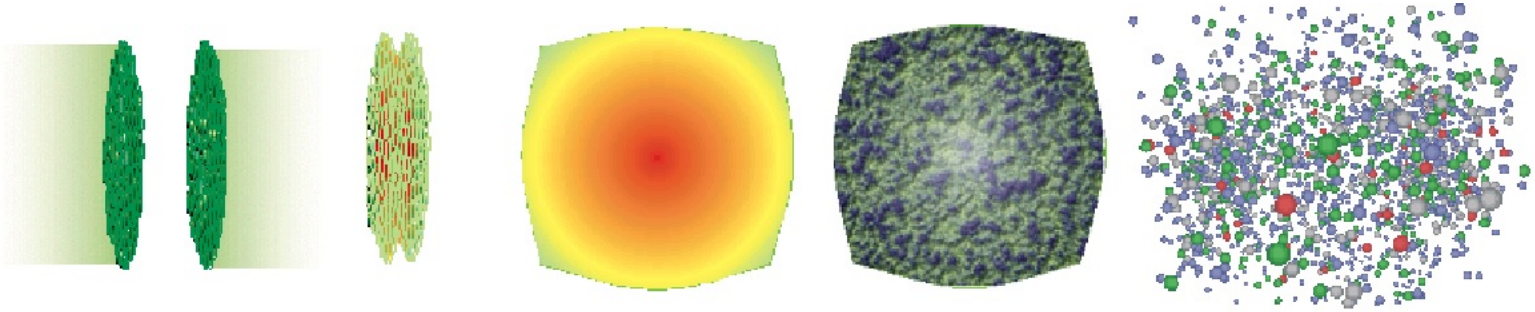
# Growing of color charge



# RHICs

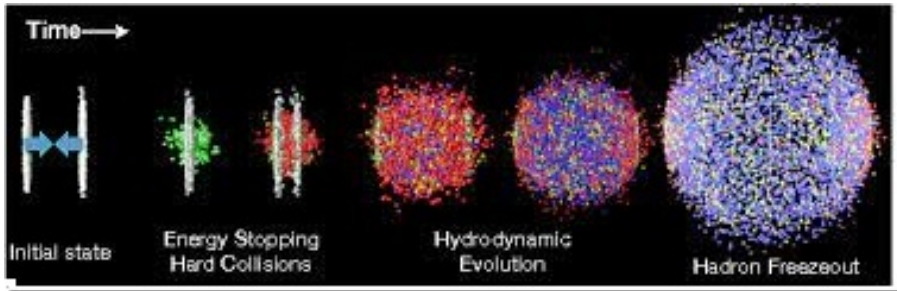
Relativistic heavy ions collisions

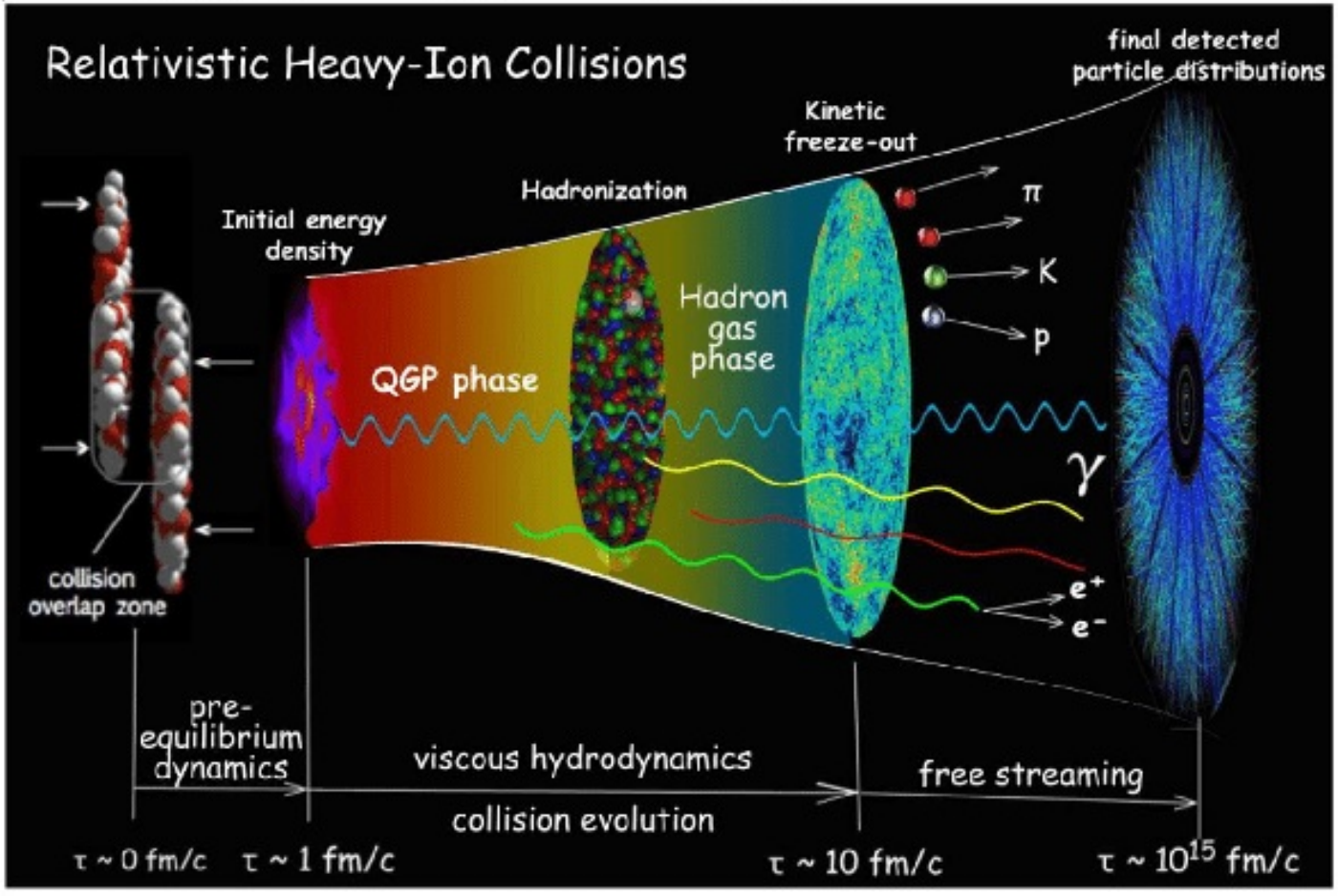


CGC | Initial Singularity | Glasma | Thermalized sQGP | Hadron Gas

# More figure on RHICs



# Big Bang nucleosynthesis of the every early Universe