Introduction to the theory of the QGP and the CGC

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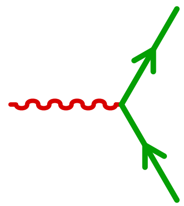
Outline

- Quark Gluon Plasma (QGP)
  - Basic features of QCD
  - Deconfinement phase transition
  - Physics of the quark gluon plasma
  - Signatures of the QGP
- Color Glass Condensate (CGC)
  - Parton model
  - Saturation
  - Color Glass Condensate
  - Signatures of the CGC

QGP

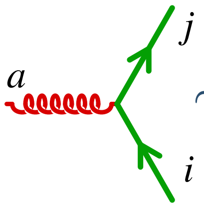
Quarks and gluons

- Electromagnetic interaction : Quantum electrodynamics
  - Matter : electron , interaction carrier : photon
  - Interaction :

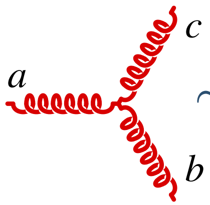


$\sim\ e$ (electric charge of the electron)

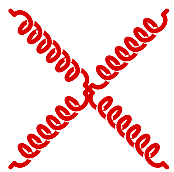
- Strong interaction : Quantum chromodynamics
  - Matter : quarks , interaction carriers : gluons
  - Interactions :



$\sim\ g\,(t^a)_{ij}$

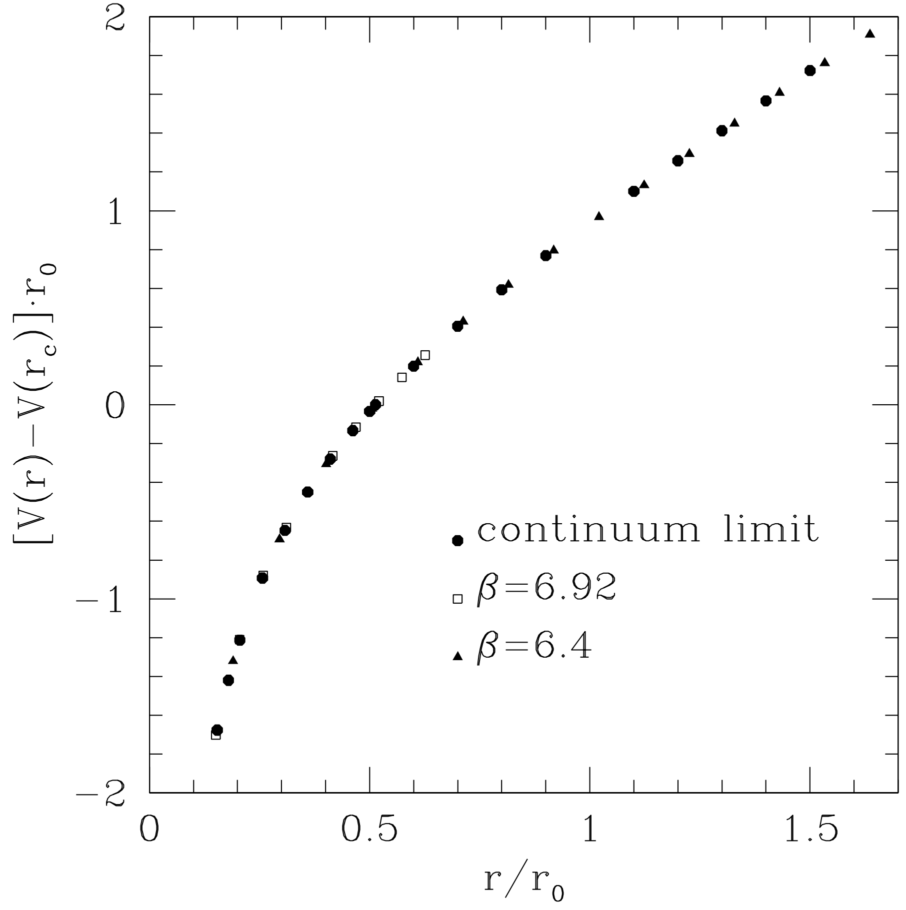


$\sim\ g\,(T^a)_{bc}$



  - i, j : colors of the quarks (3 possible values)
  - a, b, c : colors of the gluons (8 possible values)
  - $(t^a)_{ij}$: 3×3 matrix , $(T^a)_{bc}$: 8×8 matrix

Quark confinement

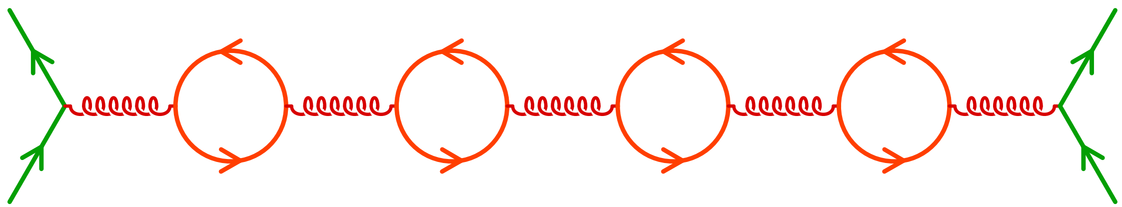


- The quark potential increases linearly with distance
- Quarks are confined into color singlet hadrons

Asymptotic freedom

- Running coupling : $\alpha_s = g^2/4\pi$

$$\alpha_s(r) = \frac{2\pi N_c}{(11N_c - 2N_f)\log(1/r\Lambda_{QCD})}$$



- The effective charge seen at large distance is screened by fermionic fluctuations (as in QED)

Asymptotic freedom

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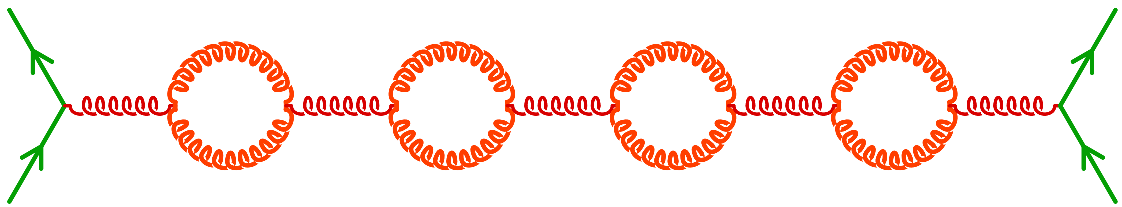
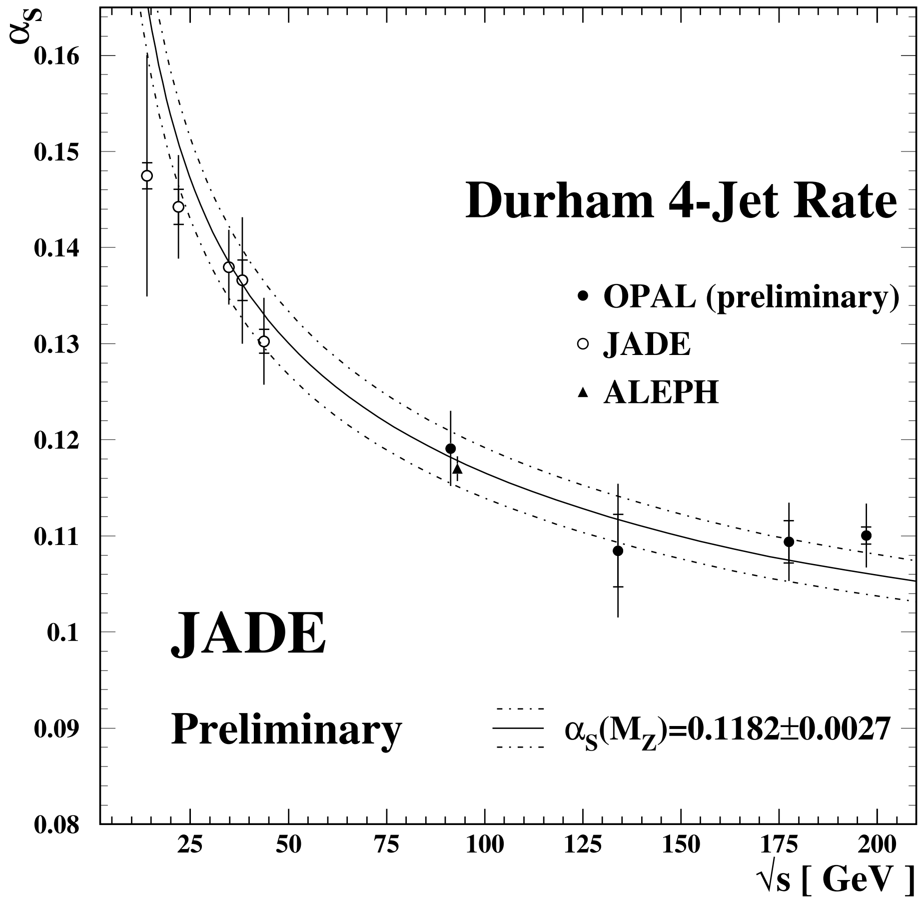


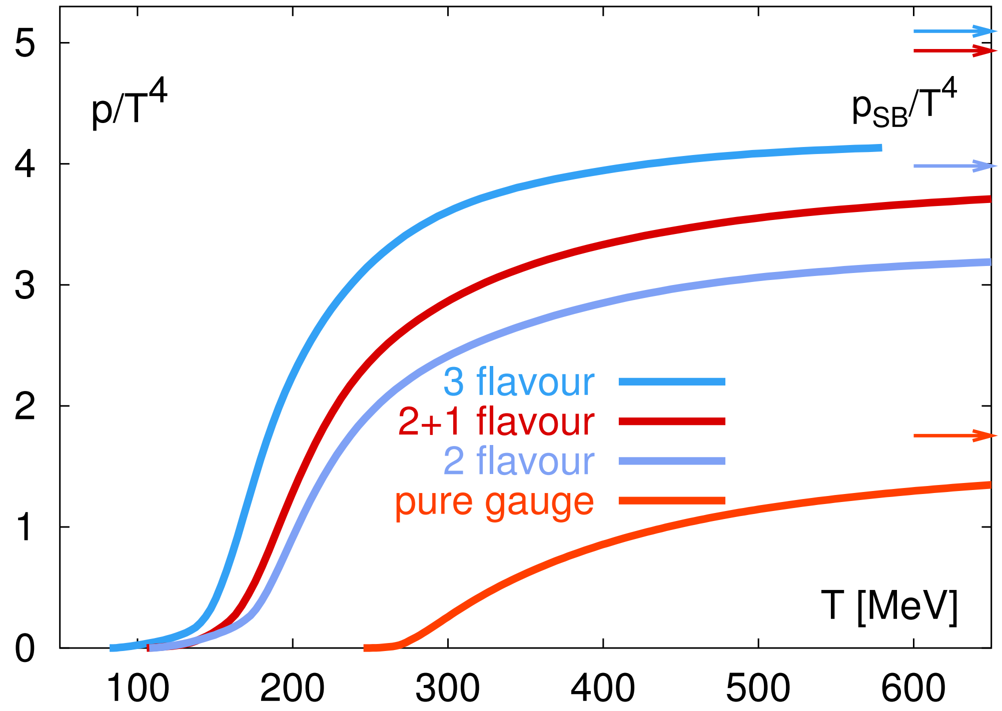
- The effective charge seen at large distance is screened by fermionic fluctuations (as in QED)
- But gluonic vacuum fluctuations produce an anti-screening (because of the non-abelian nature of their interactions)
- As long as $N_f < 11N_c/2 = 16.5$, the gluons win...

Asymptotic freedom



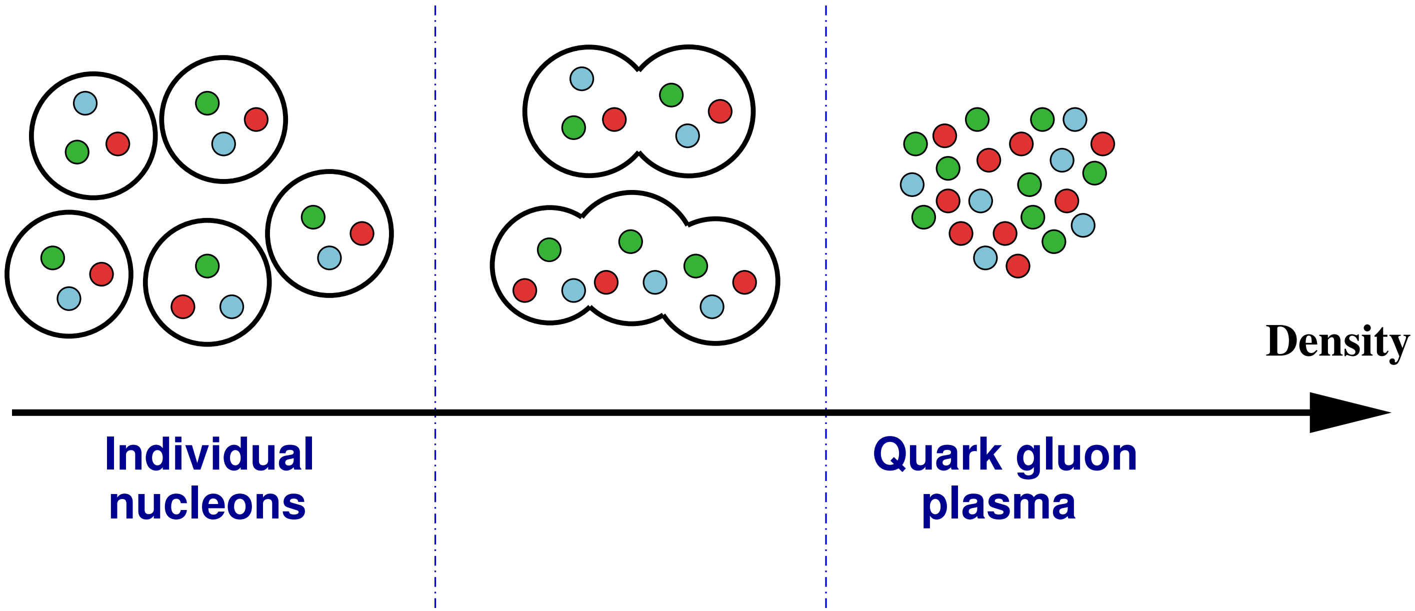
- The coupling constant is small at short distances
- At high density, a hadron gas may undergo deconfinement
  ▷ quark gluon plasma

Deconfinement



- Fast increase of the pressure :
  - at $T \sim 270$ MeV, if there are only gluons
  - at $T \sim 150$–170 MeV, depending on the number of light quarks

Deconfinement

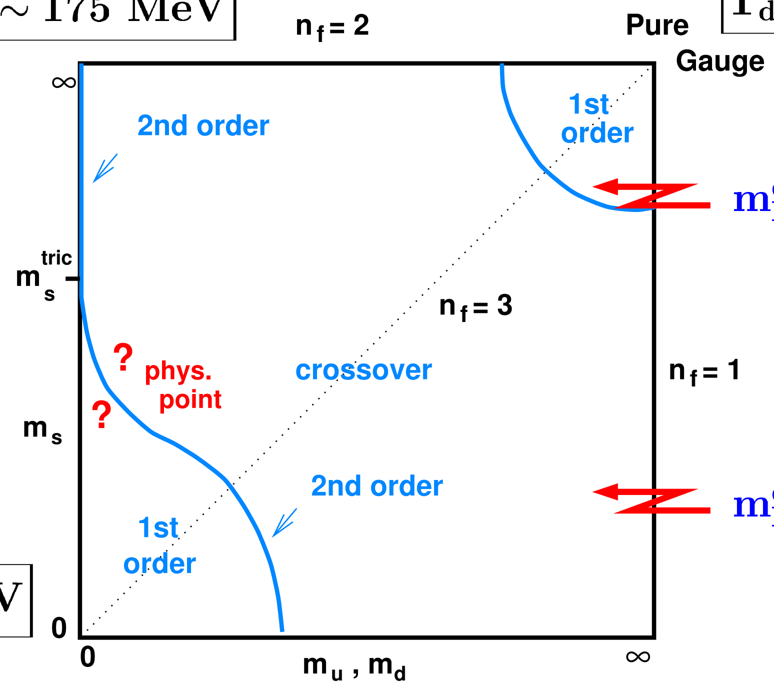


- When the nucleon density increases, they merge, enabling quarks and gluons to hop freely from a nucleon to its neighbors
- This phenomenon extends to the whole volume when the phase transition ends
- Note: if the transition is first order, it goes through a mixed phase containing a mixture of nucleons and plasma

3-flavour phase diagram

$T_\chi^{n_f=2} \sim 175$ MeV

$T_d \sim 270$ MeV

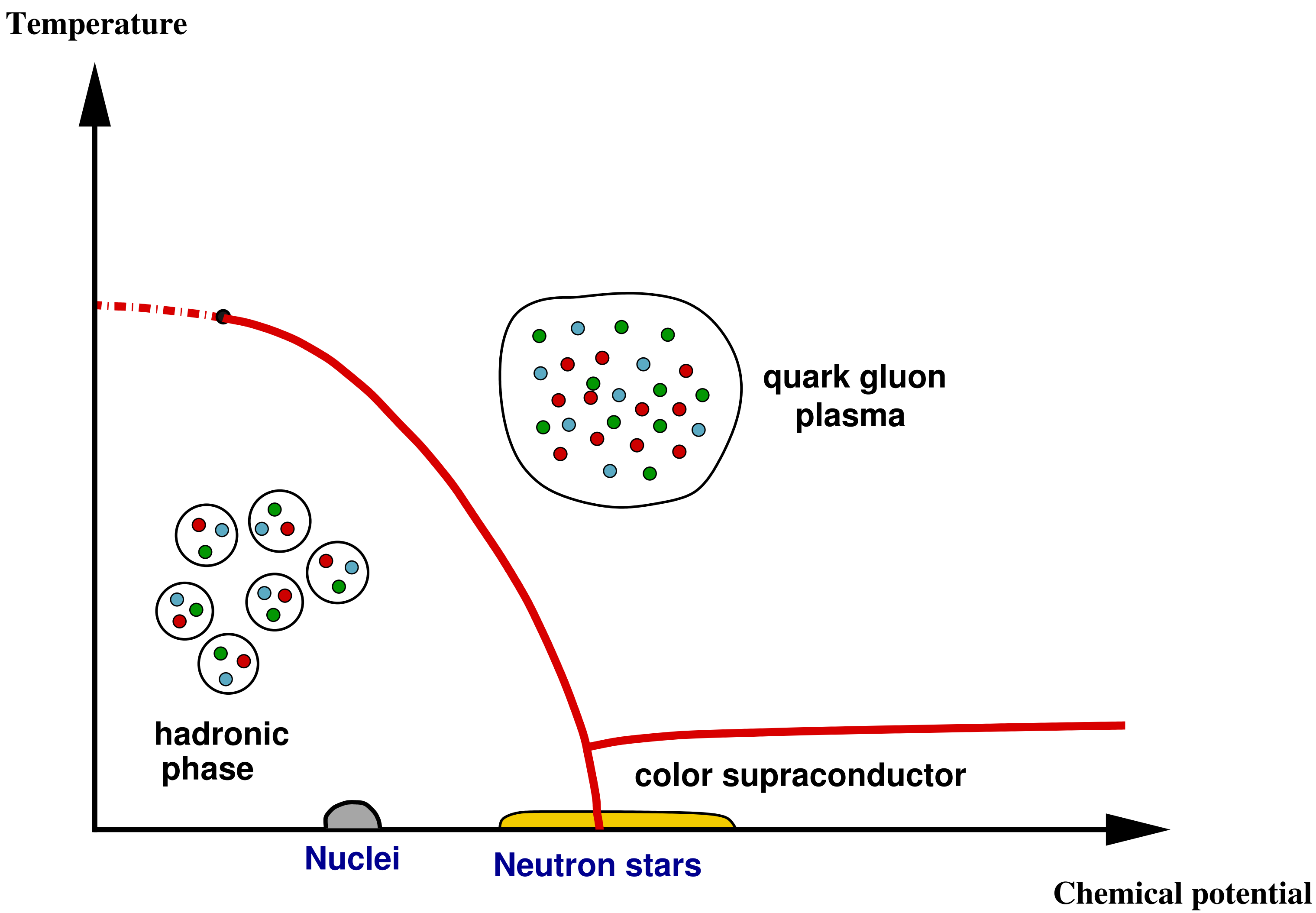


$m_{PS}^{crit} \simeq 2.5$ GeV

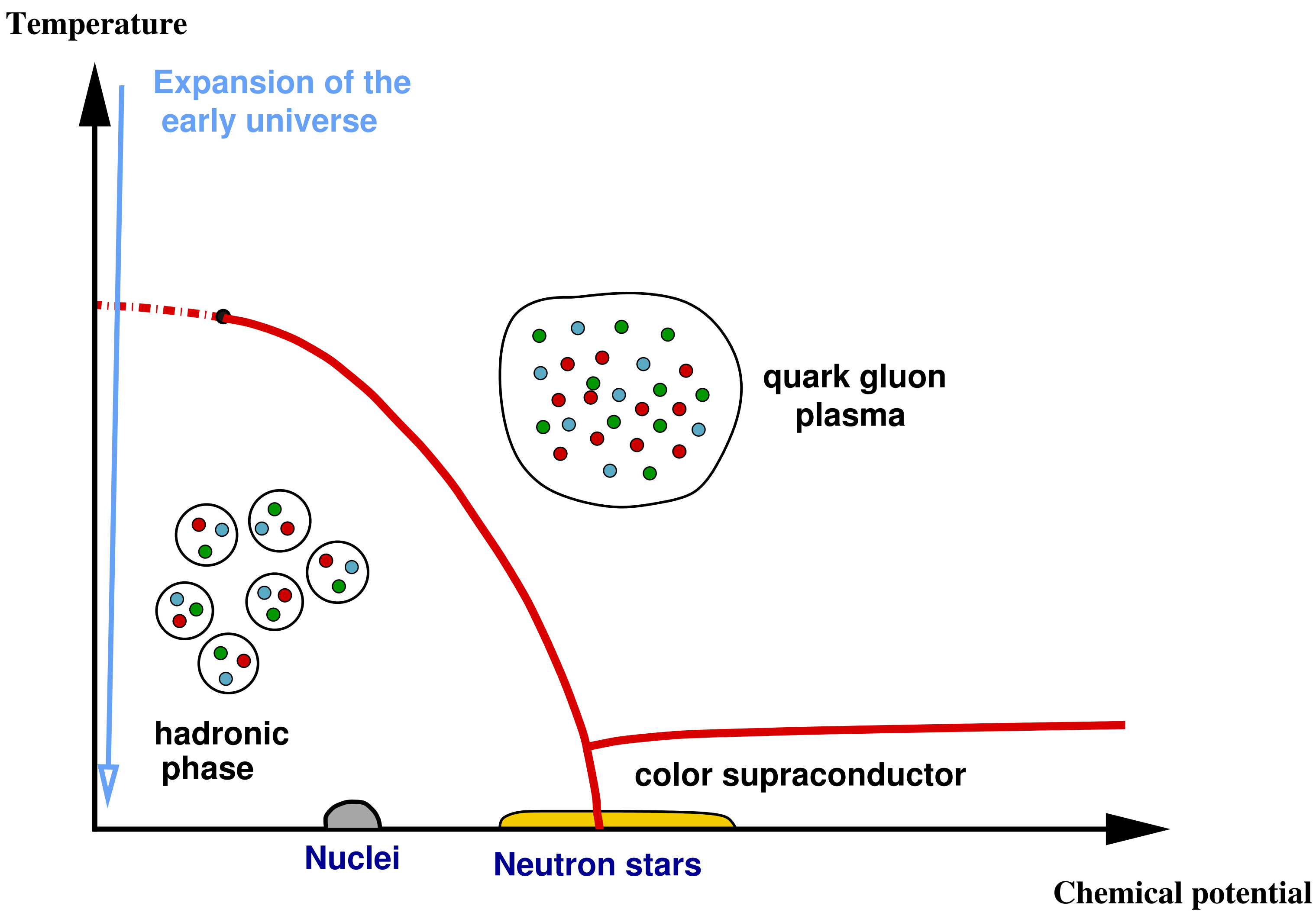
$m_{PS}^{crit} \simeq 200$ MeV

$T_\chi^{n_f=3} \sim 155$ MeV

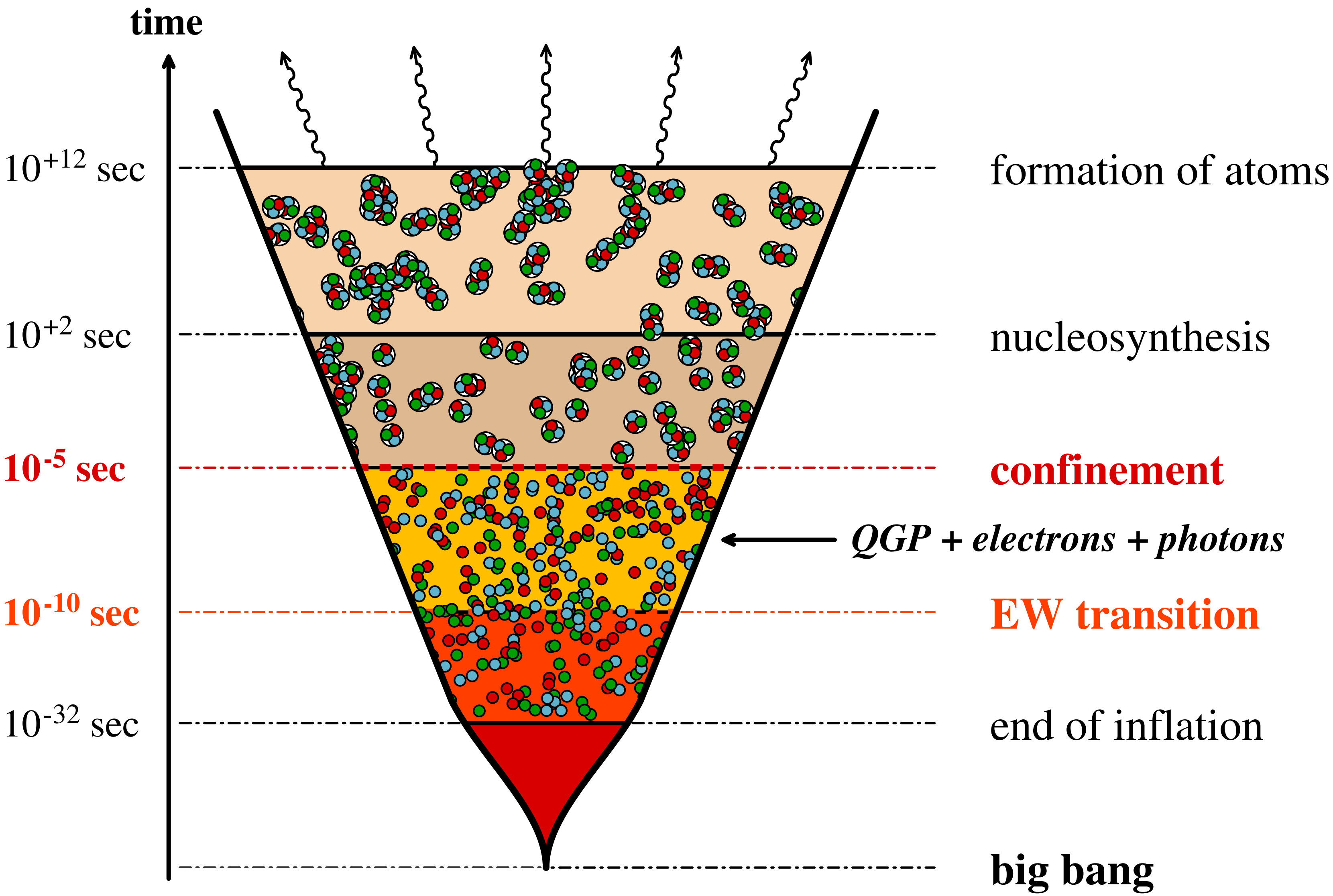
QCD phase diagram



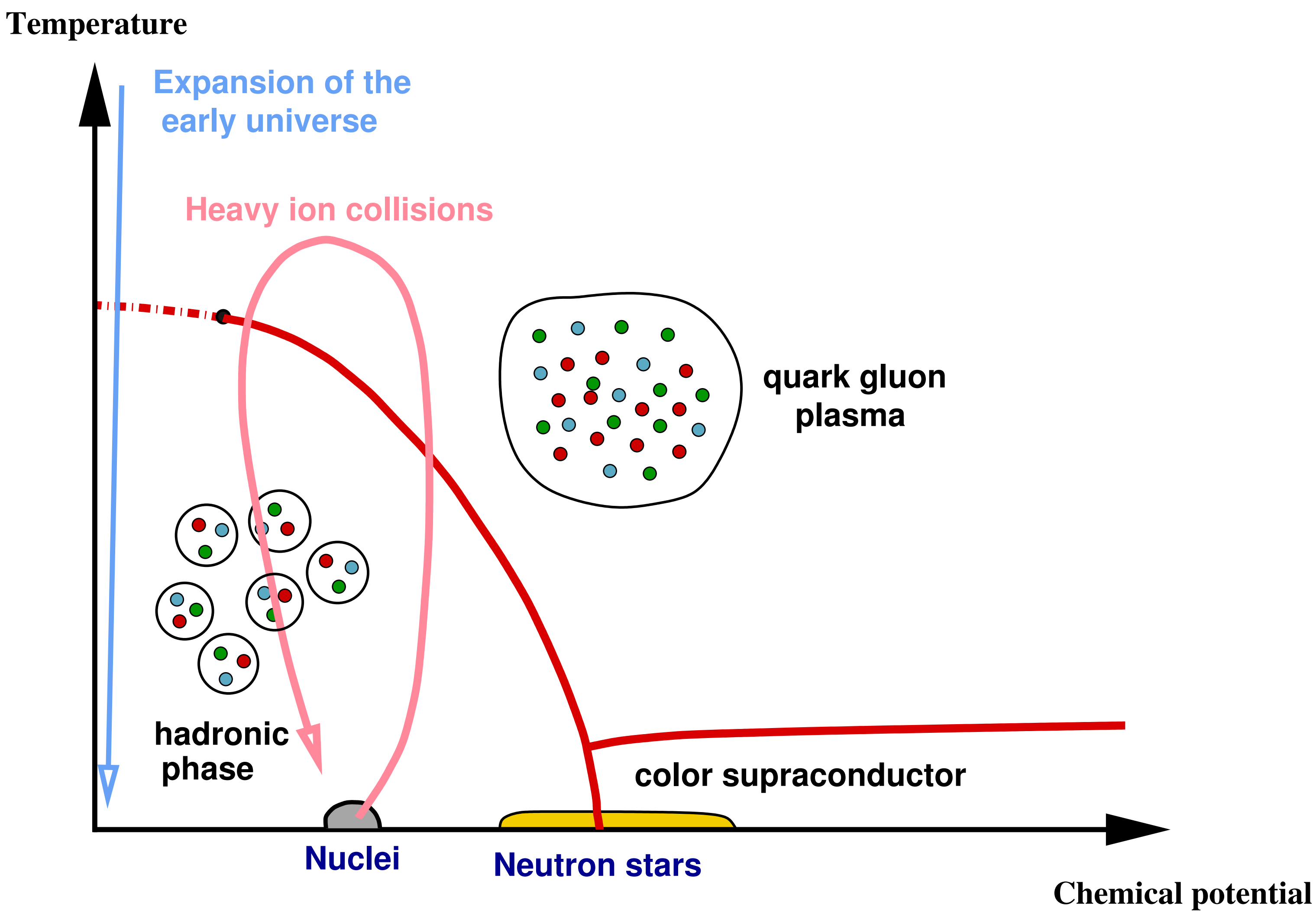
The QGP in the early universe



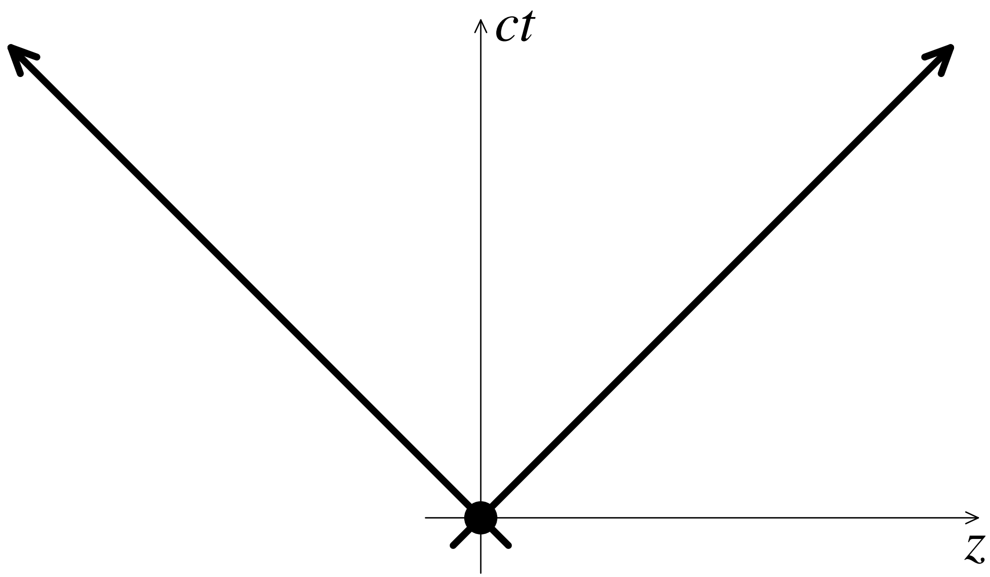
The QGP in the early universe



Heavy ion collisions

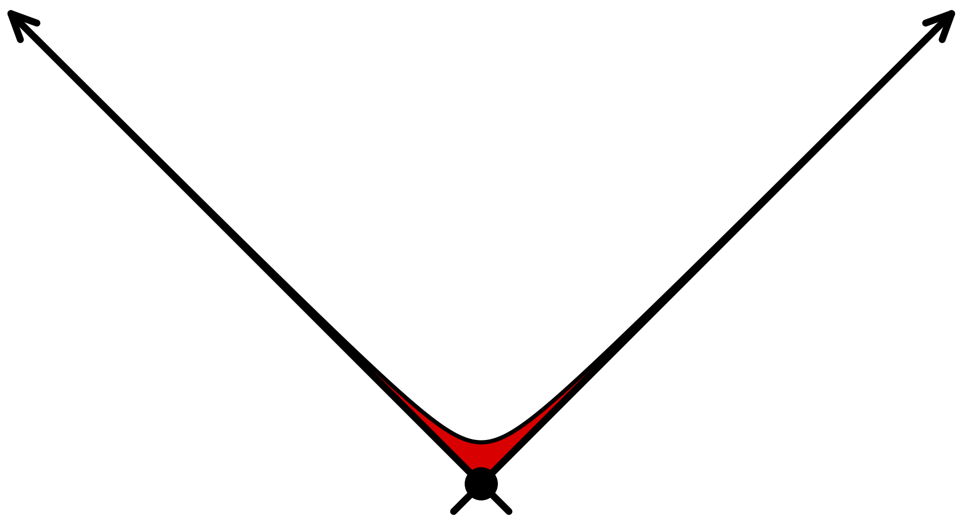


Heavy ion collisions



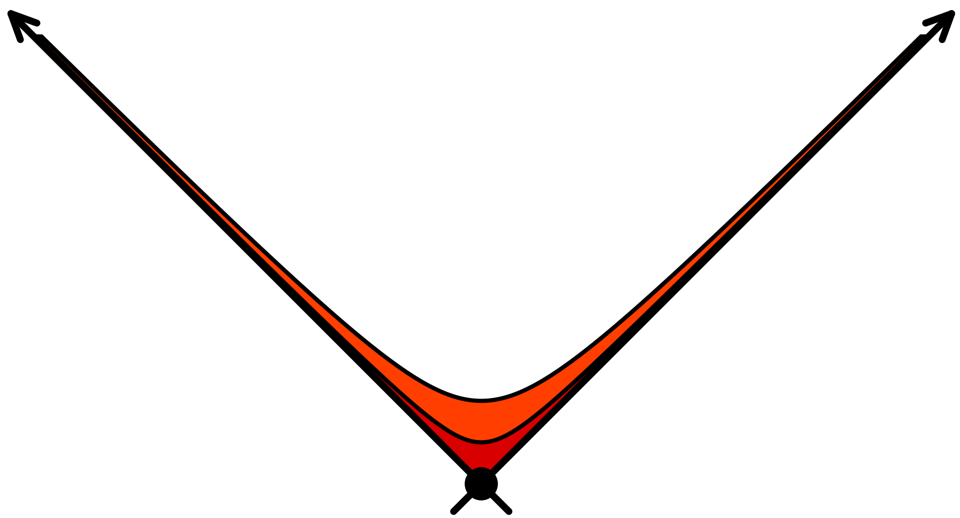
- $\tau \sim 0$ fm/c
- Production of hard particles :
  - jets
  - heavy quarks
  - direct photons
- calculable with the tools of perturbative QCD

Heavy ion collisions



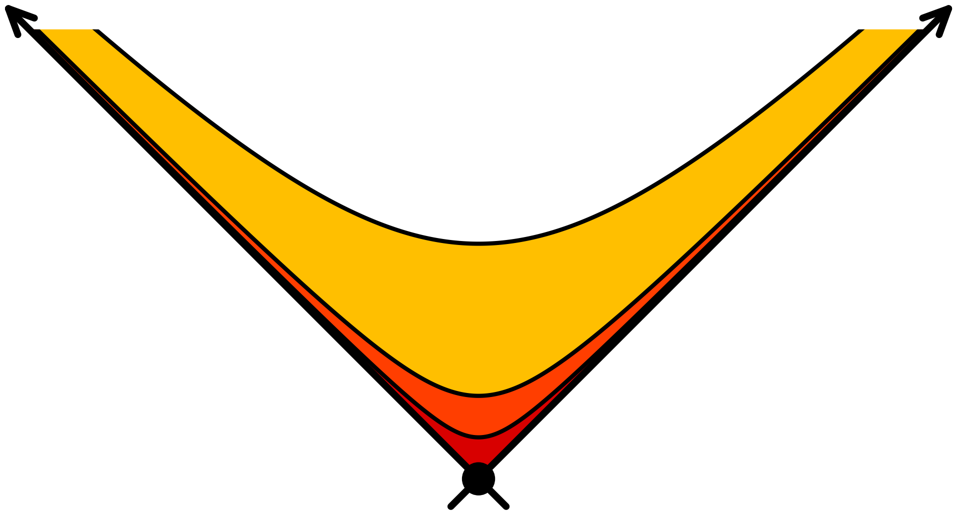
- $\tau \sim 0.2$ fm/c
- Production of semi-hard particles :
  - gluons, light quarks
- relatively small momentum : $p_\perp \lesssim 1$–2 GeV
- make up for most of the multiplicity
- sensitive to the physics of saturation (CGC)

Heavy ion collisions



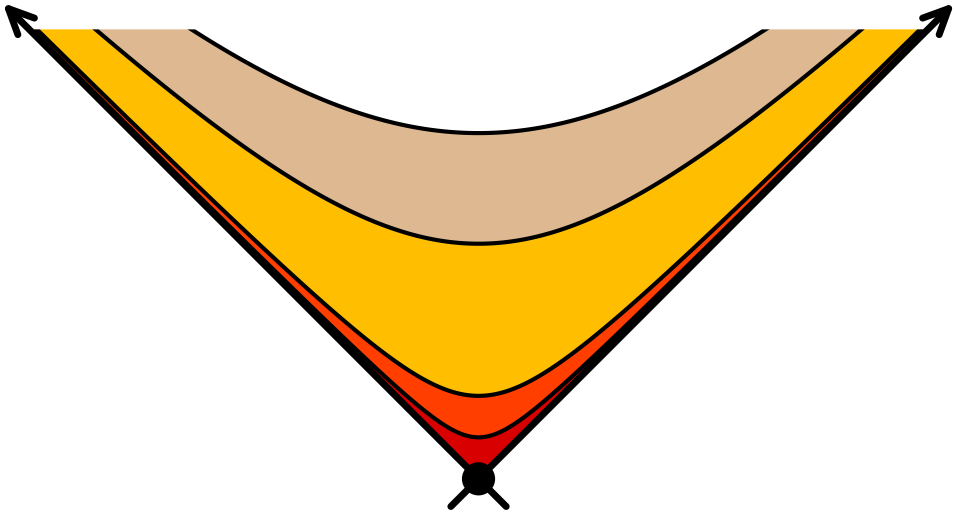
- $\tau \sim 1$–2 fm/c
- Thermalization
  - experiments suggest a fast thermalization
  - but this is still not understood from QCD

Heavy ion collisions



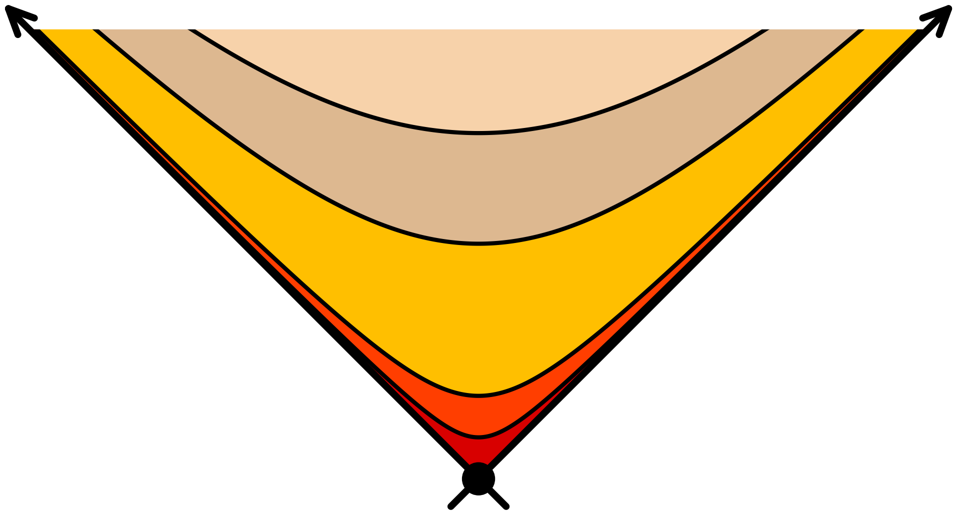
- $2 \leq \tau \lesssim 10$ fm/c
- Quark gluon plasma

Heavy ion collisions



- $10 \lesssim \tau \lesssim 20$ fm/c
- Hot hadron gas

Heavy ion collisions



- $\tau \to +\infty$
- Chemical freeze-out :
  density too small to have inelastic interactions
- Kinetic freeze-out :
  no more elastic interactions

Degrees of freedom

- Quarks : $2\,(\text{spin}) \times 3\,(\text{color}) = 6$ (per flavor)

$$\frac{dN_{\rm q}}{d^3\vec{\boldsymbol{x}}\,d^3\vec{\boldsymbol{k}}} = \frac{1}{e^{\omega/T}+1}$$ (Fermi-Dirac)

- Gluons : $3\,(\text{spin}) \times 8\,(\text{color}) = 24$

$$\frac{dN_{\rm g}}{d^3\vec{\boldsymbol{x}}\,d^3\vec{\boldsymbol{k}}} = \frac{1}{e^{\omega/T}-1}$$ (Bose-Einstein)

- Average energy per particle : $\langle\omega\rangle \sim T$
- Particle density : $\rho \sim T^3$
- Average distance between particles : $\ell \sim 1/T$

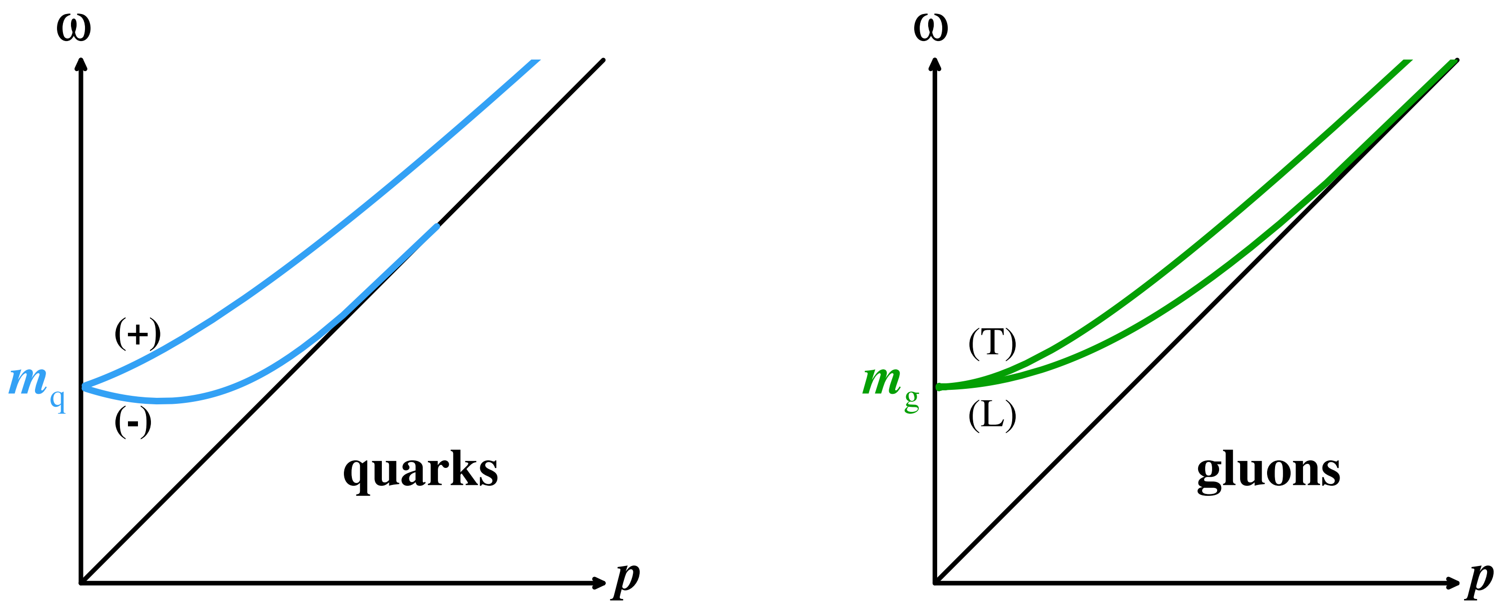
Collective phenomena

- Phenomena involving many elementary constituents
- Large wavelength compared to the typical distance between constituents
- Small frequency or energy
- The quantum numbers of collective excitations may not be related to those of the elementary constituents

- Major collective phenomena :
  - Quasi-particles
  - Debye screening
  - Landau damping
  - Collisional width

Quasi-particles

- Dispersion curves of particles in the plasma :



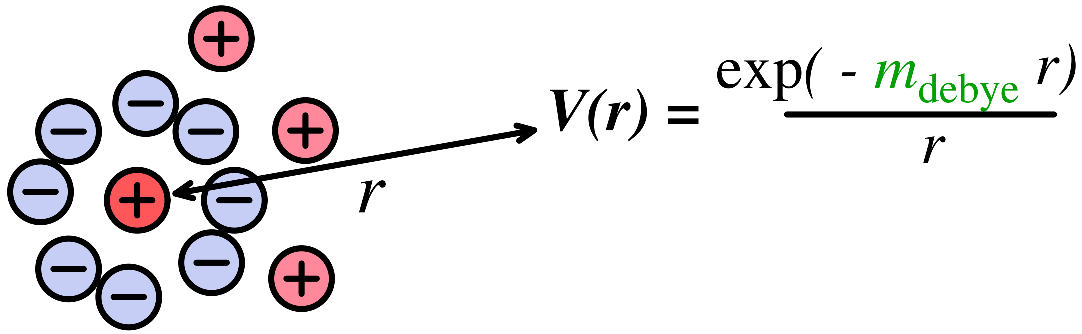
- Thermal masses due to interactions with the other particles in the plasma :

$$m_q \sim m_g \sim gT$$

- One needs a non-zero energy to make a particle of the plasma move

Debye screening

- A test charge polarizes the particles of the plasma in its vicinity, in order to screen its charge :



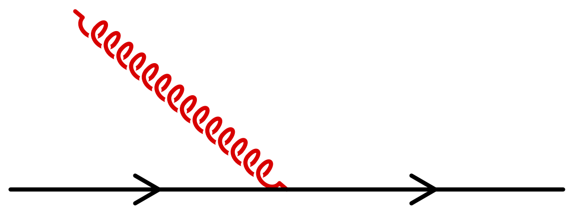
- The Coulomb potential of the test charge decreases exponentially at large distance. The effective interaction range is :

$$\ell \sim 1/m_{\rm debye} \sim 1/gT$$

- Note : static magnetic fields are not screened by this mechanism (they are screened over length-scales $\ell_{\rm mag} \sim 1/g^2T$)

Landau damping

- A wave propagating through the plasma is damped because its quanta may be absorbed by particles of the plasma :

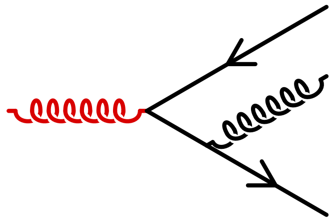


- The characteristic frequency of this damping is :

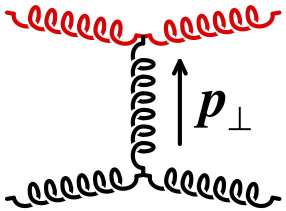
$$\omega_c \sim gT$$

Collisional width

- Decay width :

$$\Gamma_{\rm decay} = \left| \vphantom{\int} \right.$$  $$\left. \vphantom{\int} \right|^2 \sim g^4 T$$

- Collisional width :

$$\Gamma_{\rm coll} = \left| \vphantom{\int} \right.$$ 

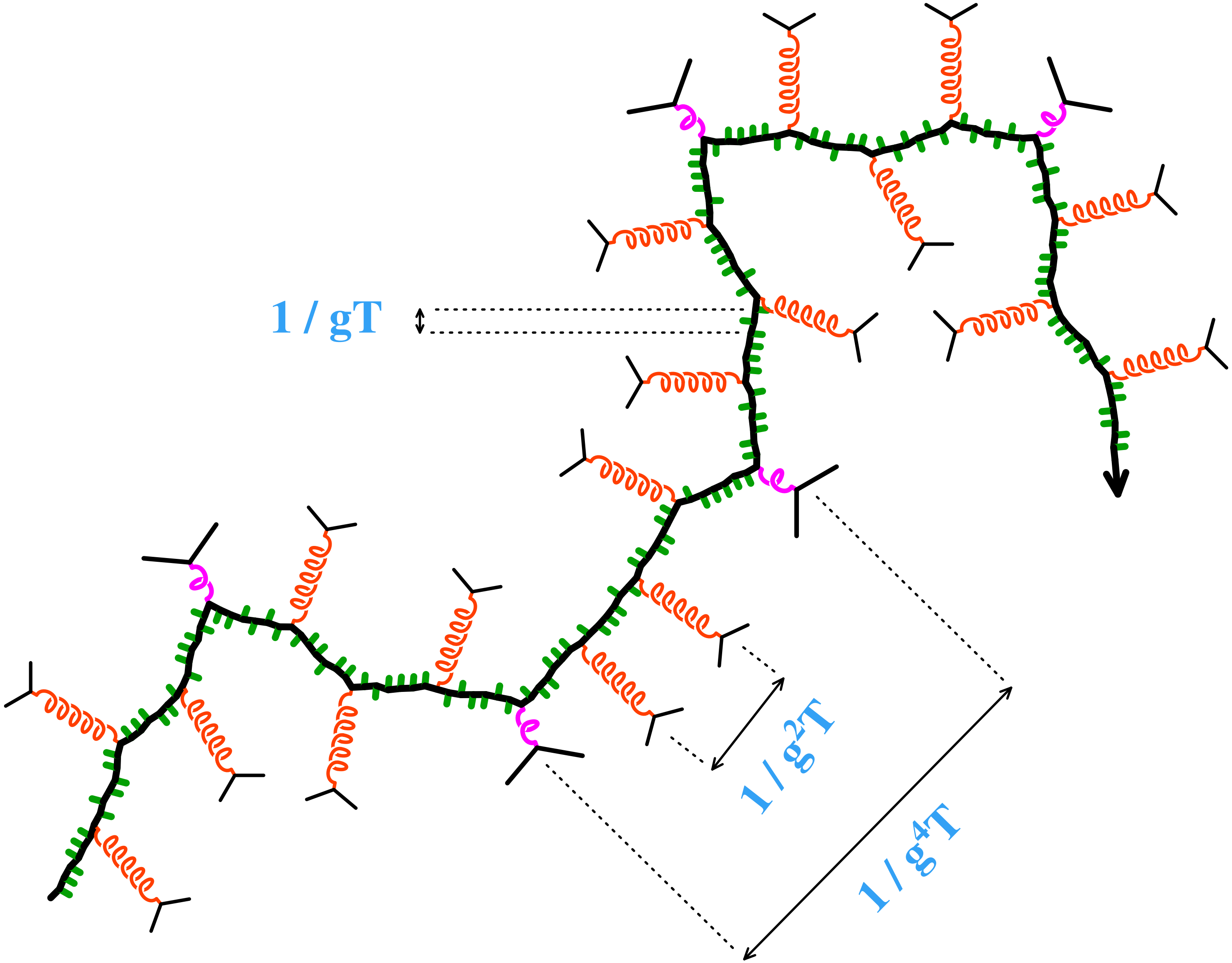
$$\left. \vphantom{\int} \right|^2 \sim g^4 T^3 \int_{m_{\rm debye}} \frac{d^2\vec{\boldsymbol{p}}_\perp}{p_\perp^4} \sim g^2 T$$

- $\lambda \equiv 1/\Gamma_{\rm coll}$ is the mean free path between two small angle scatterings ($\theta \sim g$)
- Note : the mean free path between two large angle scatterings ($\theta \sim 1$) is $\sim 1/g^4 T$

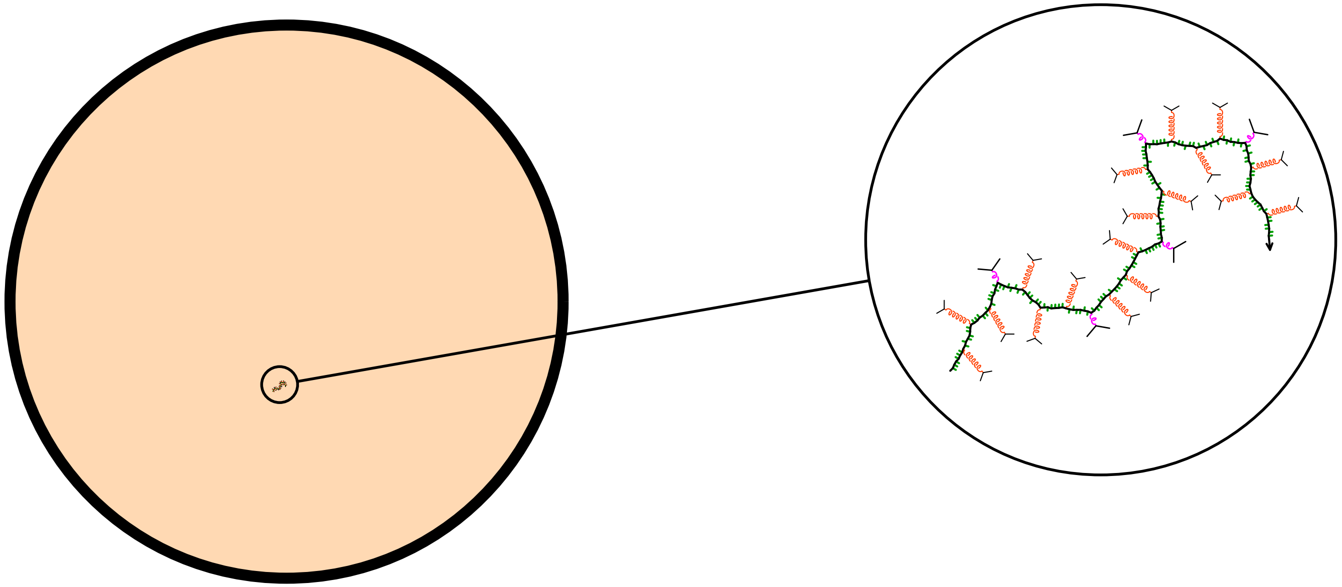
Length scales

- $1/T$: wavelength of particles in the plasma
- $1/gT$: typical distance for collective phenomena
  - Thermal masses of quasi-particles
  - Screening phenomena
  - Damping of waves
- $1/g^2T$: distance between two small angle scatterings
  - Color transport
  - Photon emission
- $1/g^4T$: distance between two large angle scatterings
  - Momentum, electric charge transport
    - ▷ characteristic scale of hydrodynamic modes
- In the weak coupling limit ($g \ll 1$), there is a clear hierarchy between these scales
- Distinct effective theories according to the characteristic scale of the problem under study

Length scales



Hydrodynamical regime

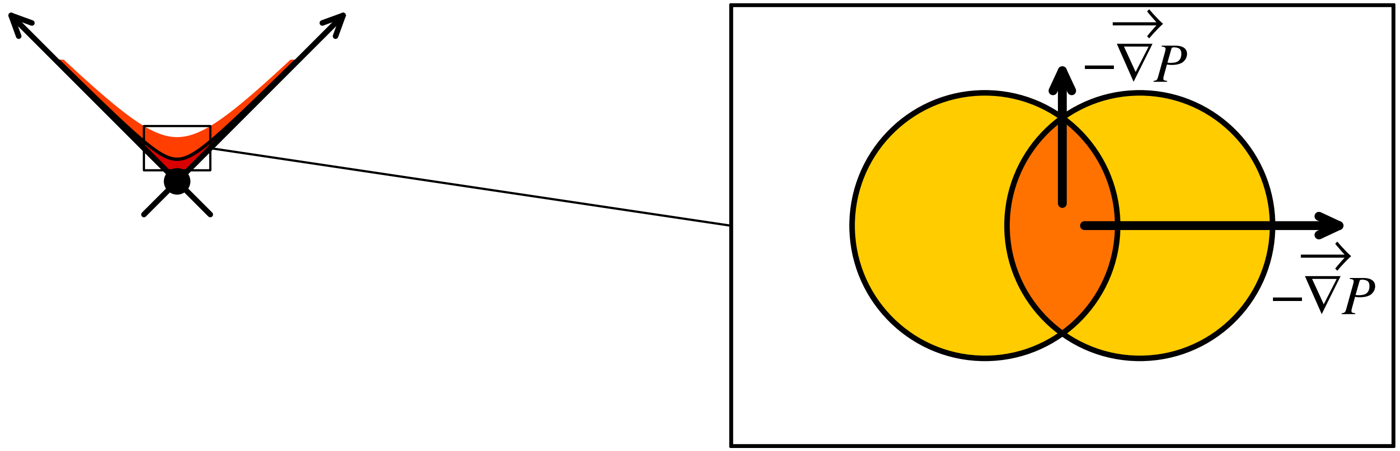


- The hydrodynamical regime is reached when one considers length scales that are much larger than the mean free path of the plasma constituents : $\lambda \ll R$
- In order to describe the system at such scales, one needs :
  - Hydrodynamical equations (Euler, Navier-Stokes)
  - Conservation equations for the various currents
  - Equation of state, viscosity

Strongly coupled plasma

- In the real world, $\alpha_s \sim 0.2$–0.3 (i.e. $g \sim 2$). No clear hierarchy between the various length scales...
- Lattice QCD :
  very difficult to extract transport coefficients
- Alternate approach : AdS/CFT correspondence
  - Maldacena conjecture :
    The strong coupling regime of a super-symmetric Yang-Mills theory (very complicated...) is equivalent to the weak coupling regime of a theory of super-gravity (calculable)
  - Viscosity of a plasma in the super-YM theory :
    $$\frac{\eta}{s} = \frac{1}{4\pi}$$
  - Major problem : Super-symmetric QCD $\neq$ QCD...

Collective flow



- In non-central collisions, pressure turns a spatial anisotropy into an anisotropy of the momenta
- Observable: 2^{nd} harmonic of the azimuthal distribution

$$dN/d\varphi \sim 1 + 2v_1 \cos(\varphi) + 2v_2 \cos(2\varphi) + \cdots$$

- **Note:** a large v_2 implies a strong transverse pressure, but says very little on the longitudinal degrees of freedom
  ▷ does not imply a tri-dimensional thermalization...

Strangeness enhancement

- In a nucleon, the distribution of strange quarks is smaller than that of u, d quarks (valence) by a factor of the order of $\alpha_s \sim 0.2$–0.3
  $\triangleright$ In pp collisions, less strange particles are produced than non-strange particles
- In the QGP, the average energy of u, d quarks and of the gluons is of the order of the temperature
  $\triangleright$ if T is large enough (compared to the mass of the strange quark), then the processes $u\bar{u} \to s\bar{s}$, $d\bar{d} \to s\bar{s}$, $gg \to s\bar{s}$ are not inhibited by the kinematical threshold due to the mass of the s quark
- In this case, the population of strange quarks will become identical to that of light quarks
  $\triangleright$ the production of strange hadrons will be enhanced compared to proton-proton collisions
- The interpretation of data based on statistical models works also for strange particles at RHIC

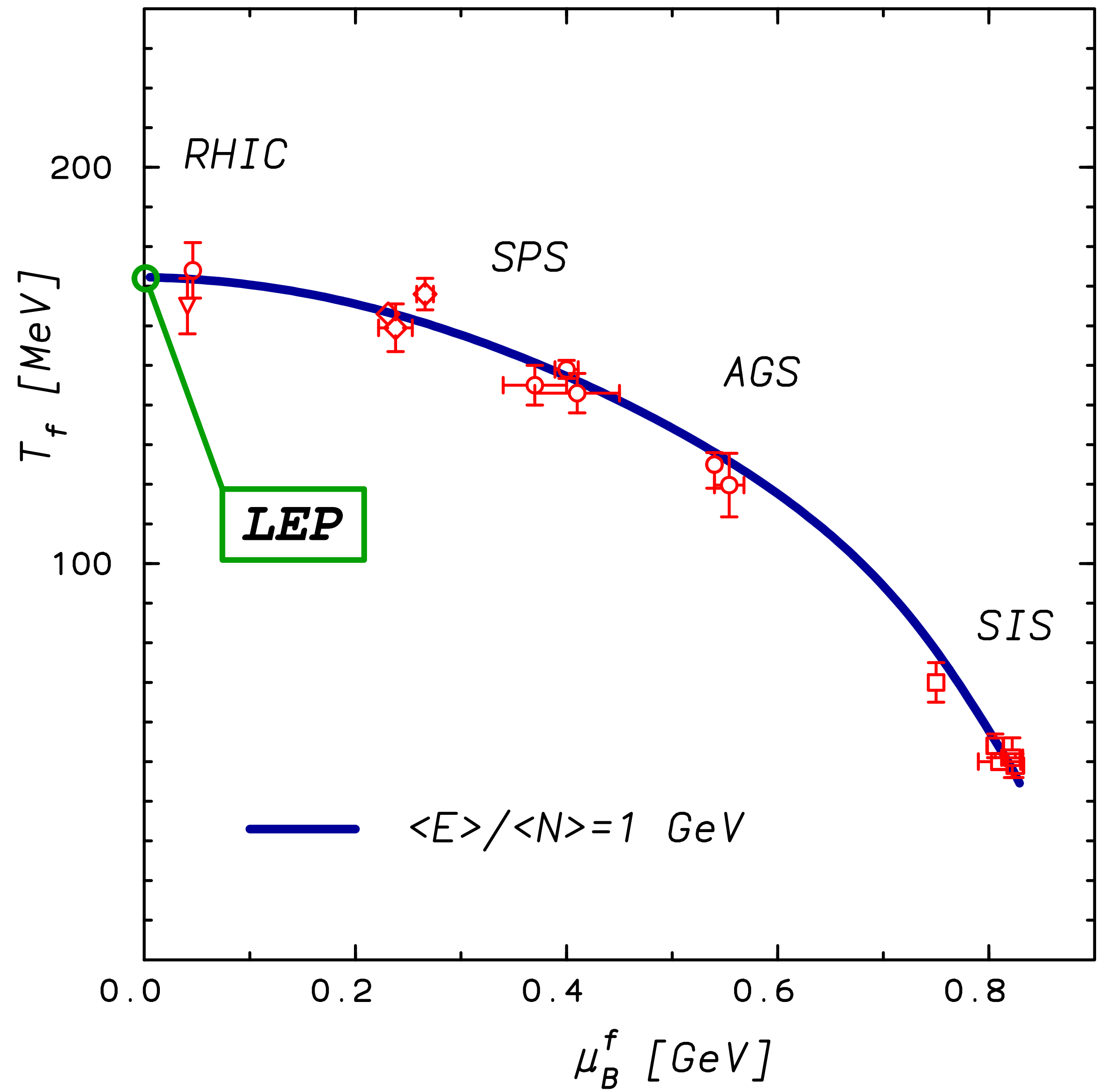
Statistical models

- One assumes that particles are produced by a thermalized system with temperature T and baryon chemical potential μ_B
- The number of particles of mass m per unit volume is :

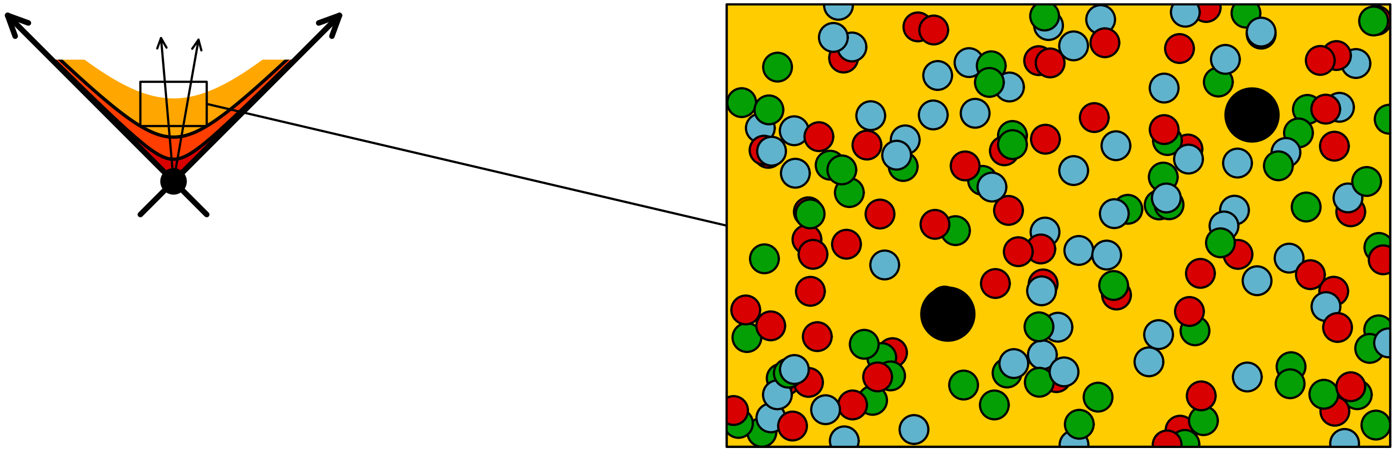
$$\frac{dN}{d^3\vec{\boldsymbol{x}}} = \int \frac{d^3\vec{\boldsymbol{p}}}{(2\pi)^3} \frac{1}{e^{(\sqrt{p^2+m^2}-\mu_B Q)/T} \pm 1}$$

- These models reproduce the ratios of particle yields with only two parameters
- The same models also work for e^+e^- collisions
  - Standard explanation: randomly filling a phase space leads to exponential distributions
  - However, this argument alone does not explain why the value of T that comes out is the same as in nucleus-nucleus collisions
    $\triangleright$ dynamical arguments (about the properties of the vacuum?) certainly play a role here...

Freeze-out parameters



J/Psi suppression



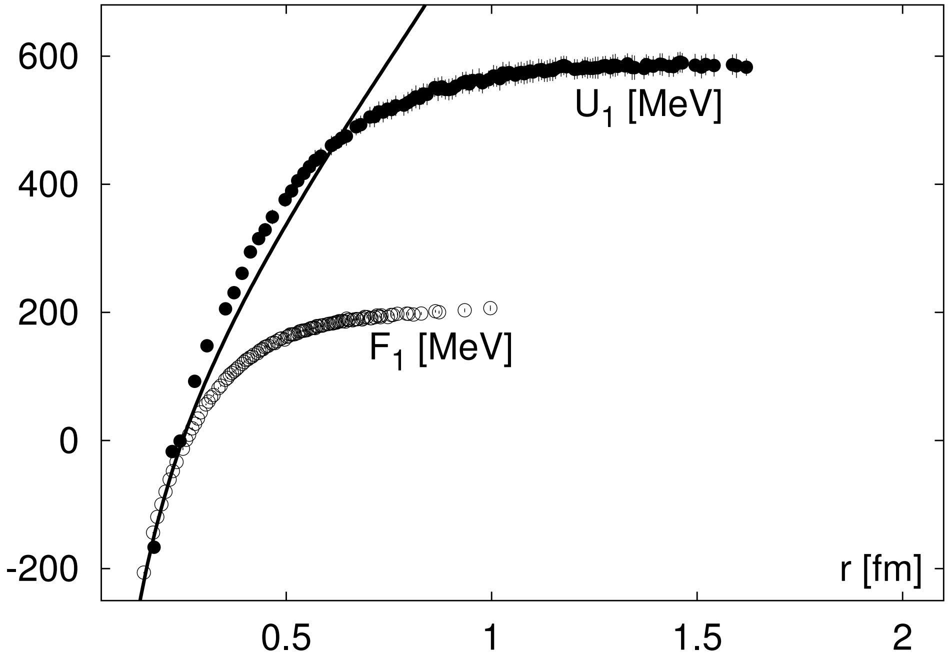
- Debye screening prevents the $Q\overline{Q}$ pair from forming a bound state   Matsui, Satz (1986)
  - each heavy quark pairs with a light quark in order to form a D meson
- The inter-quark potential can be calculated using lattice QCD
- Possible observable : $[J/\psi]\ /\ [\text{Open charm}]$
  ▷ complication : there is also a suppression in proton-nucleus collisions, due to multiple scattering

J/Psi suppression

- The free energy of a $Q\overline{Q}$ pair can be calculated on the lattice, and then converted into a potential by taking into account the entropy :

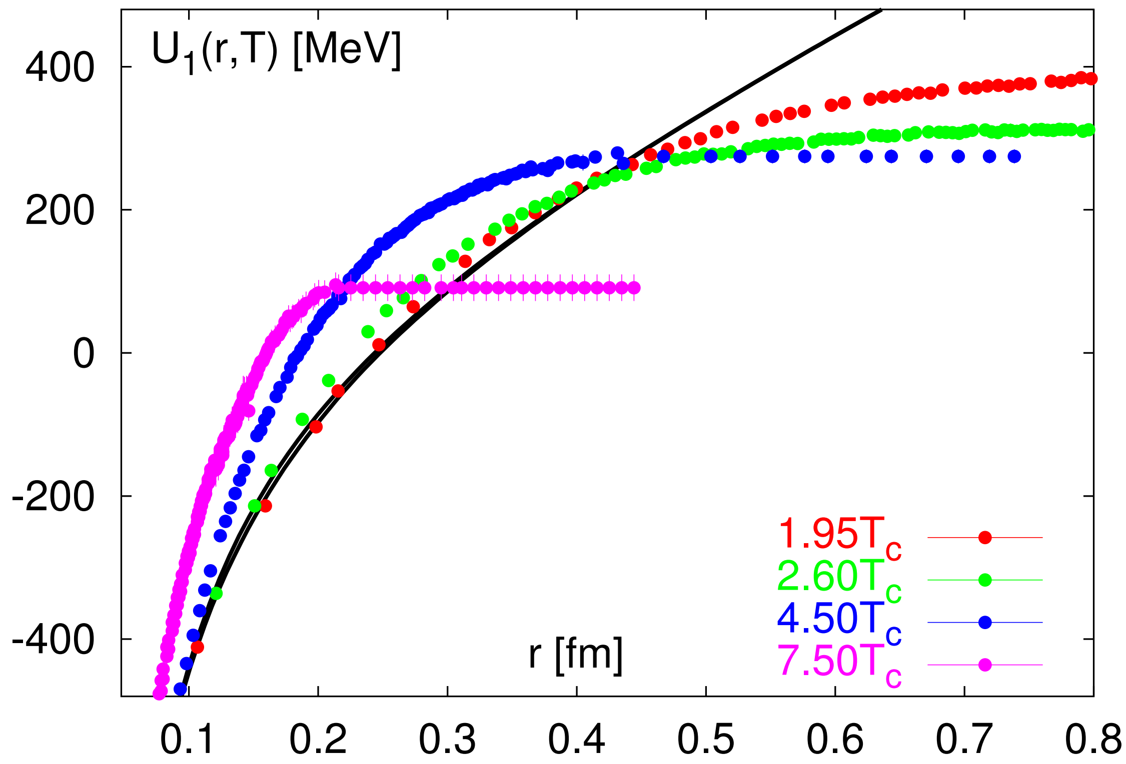
$$F = U - TS \quad , \quad S = -\frac{\partial F}{\partial T}$$

- Result for $T/T_c = 1.5$:



J/Psi suppression

- T dependence of the potential :



J/Psi suppression

- What do we do with this potential?
  - Shröedinger equation for a $Q\overline{Q}$ bound state :

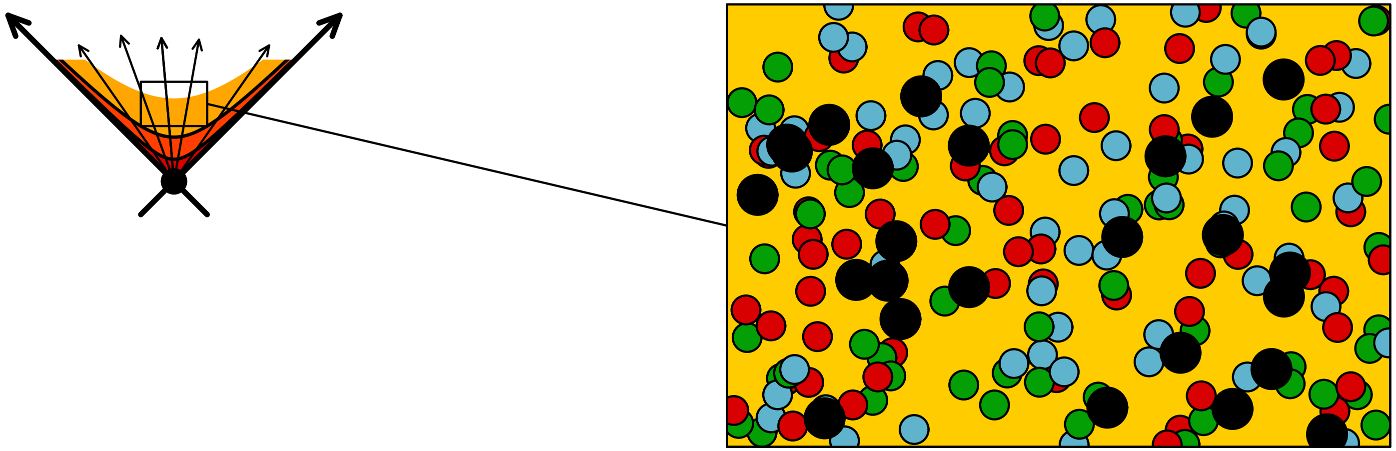
$$\left[2m_Q + \frac{1}{m_Q}\vec{\nabla}^2 + U_1(r,T)\right]\Psi = M(T)\Psi$$

  - Non-relativistic
  - Assumes that there are only two-body interactions
- Dissociation temperatures :

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'
T_d/T_c	2.0	1.1	1.1	4.5	2.0	2.0

▷ the $Q\overline{Q}$ states are not dissolved immediately above the critical temperature

... or enhancement ?



- Many $Q\overline{Q}$ pairs may be produced in each AA collision
  Braun-Munzinger, Stachel (2000)
  Thews, Schroedter, Rafelski (2001)
  - A Q from one pair may recombine with a $\overline{Q}$ from another pair
- Avoids the conclusion of Matsui and Satz's scenario, provided that the average distance between heavy quarks is smaller than the Debye screening length
- May lead to an enhancement of J/ψ production

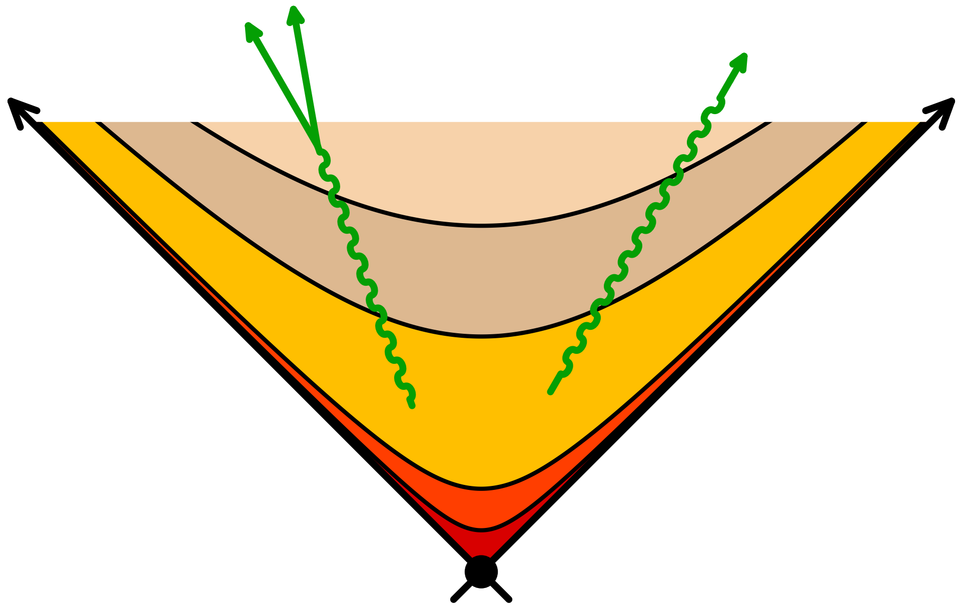
Coalescence models

- In proton-proton collisions, hadronization is described via fragmentation functions :

$$\frac{dN_H}{d^3\vec{\boldsymbol{p}}} = \sum_i \int_0^1 dz\; F_{i\to H}(z)\; \left.\frac{dN_i}{d^3\vec{\boldsymbol{q}}}\right|_{\vec{\boldsymbol{q}}=\vec{\boldsymbol{p}}/z}$$

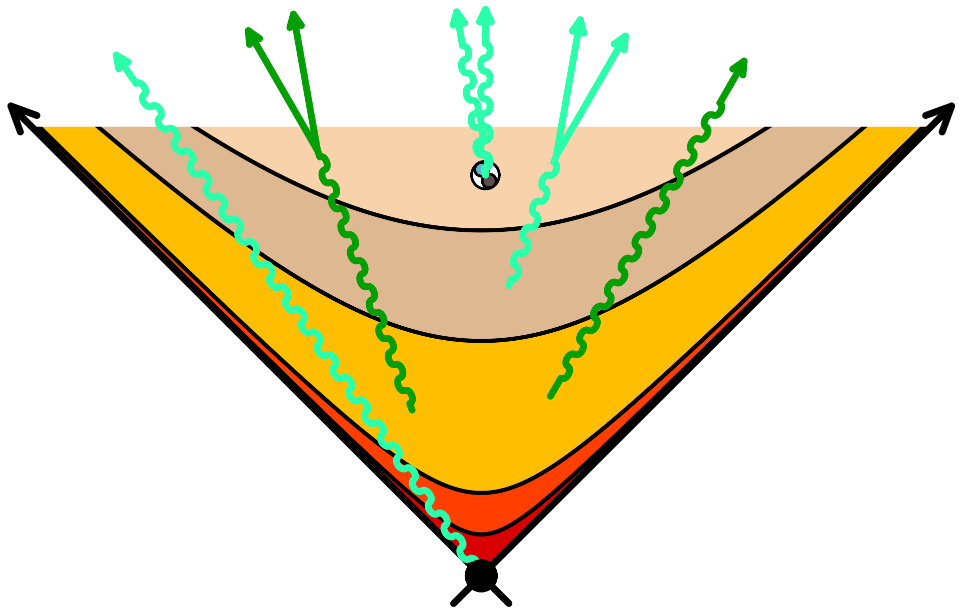
  - $F_{p\to H}(z)$ is the probability that a parton p gives the hadron H (accompanied by any other fragments), the hadron carrying the fraction z of the momentum of the parton
  - This formulation forbids that several partons combine into the same hadron
- In an environment having a large parton density, hadronization can occur via the coalescence of several partons (Note: present models are very primitive, and take into account only the valence quark)
- These models can explain some differences between baryons and mesons observed in RHIC data

Thermal photons



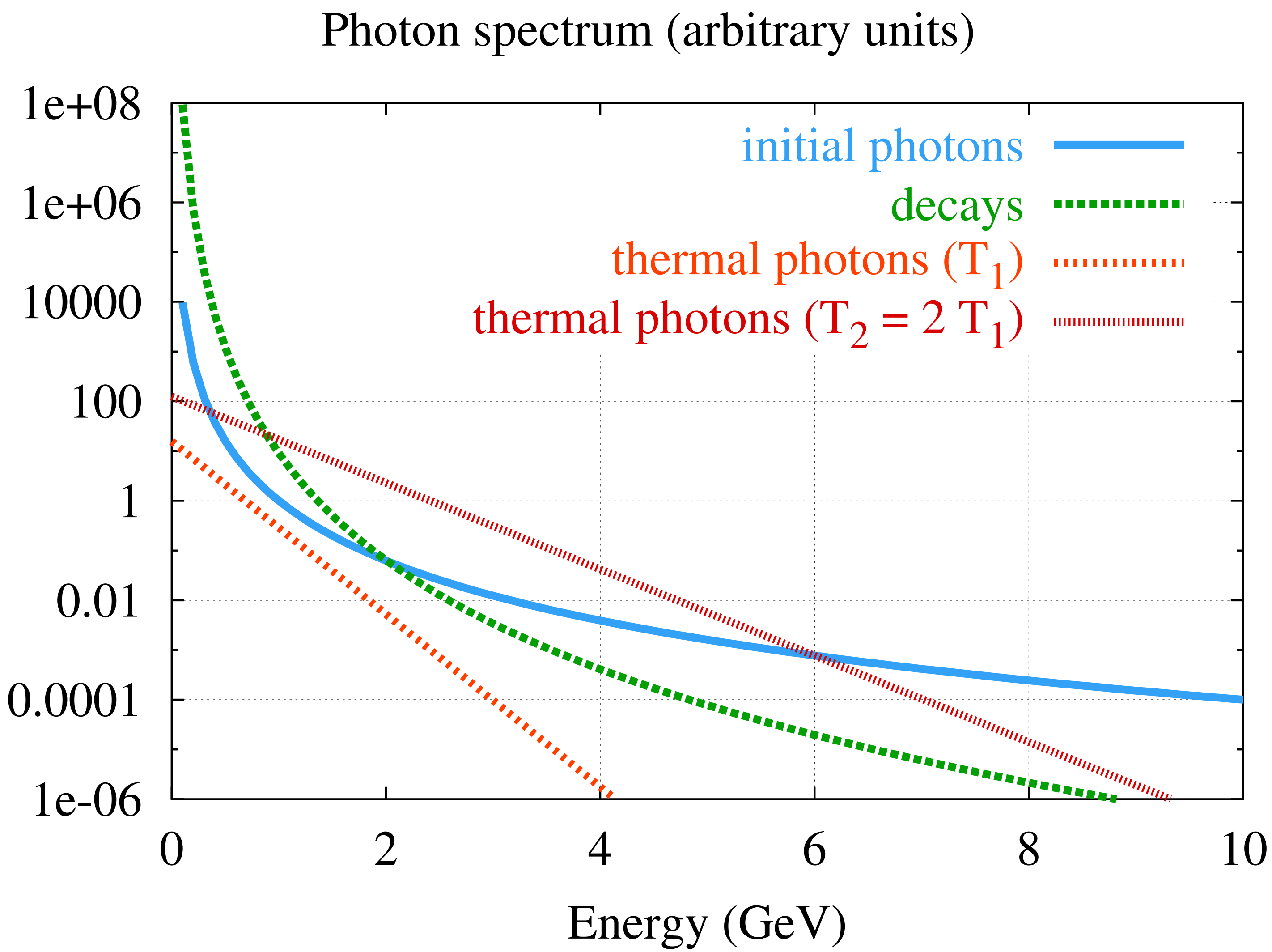
- Photons produced by the QGP :
  - Rate determined by physics at the scale g^2T
  - Very sensitive to the temperature : $dN_\gamma/dtd^3\vec{\boldsymbol{x}} \sim T^4$

Thermal photons



- Photons produced by the QGP :
  - Rate determined by physics at the scale g^2T
  - Very sensitive to the temperature : $dN_\gamma/dtd^3\vec{\boldsymbol{x}} \sim T^4$
- But very important background...
  - initial photons
  - photons produced by in-medium jet fragmentation
  - photons produced by the hadron gas
  - meson decays

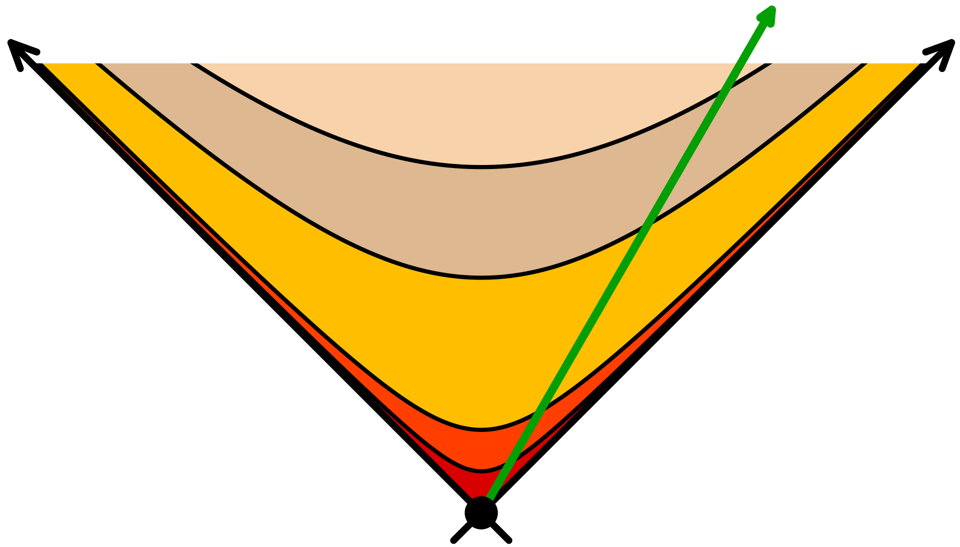
Thermal photons



Variant: thermal dileptons

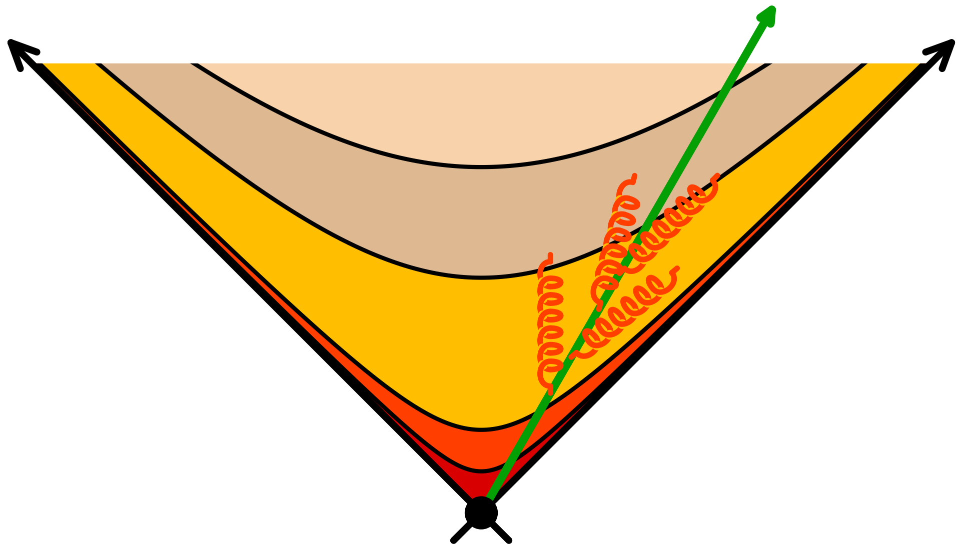
- Look for virtual photons, in the channel $\ell^+\ell^-$
- Chose the invariant mass of the lepton pair in a region which is not too contaminated by resonance decays
- Note : if the invariant mass of the virtual photon is small, then the production mechanisms are the same as for the production of real photons
- Difficulty : the decay $\gamma^* \to \ell^+\ell^-$ brings another power of the electromagnetic coupling $\alpha_{\rm em} \approx 1/137$ in the production rate
  $\triangleright$ problem of statistics

Jet quenching



- Jets are produced at the initial impact
  - Not very interesting by themselves...

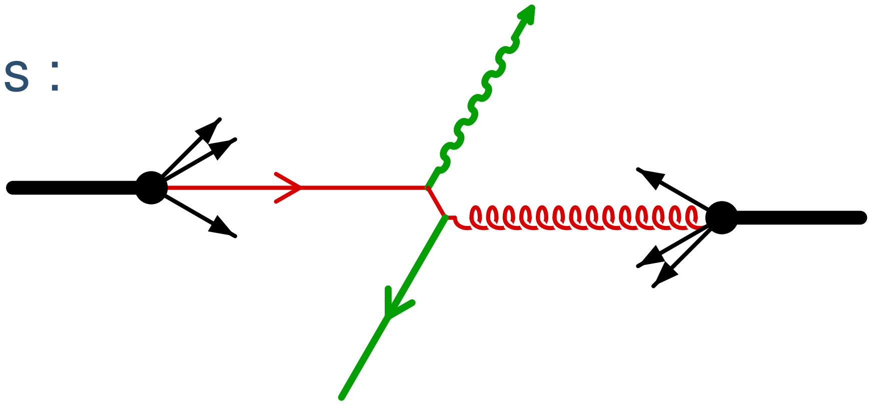
Jet quenching



- Jets are produced at the initial impact
  - Not very interesting by themselves...
- Radiative energy loss when they travel through the QGP
  - Sensitive to the energy density of the medium
  - Depends on the path length as L^2
  - Important modification of the azimuthal correlations (at RHIC, complete absorption of the opposite jet)

Jet quenching

- Photon-jet correlations :



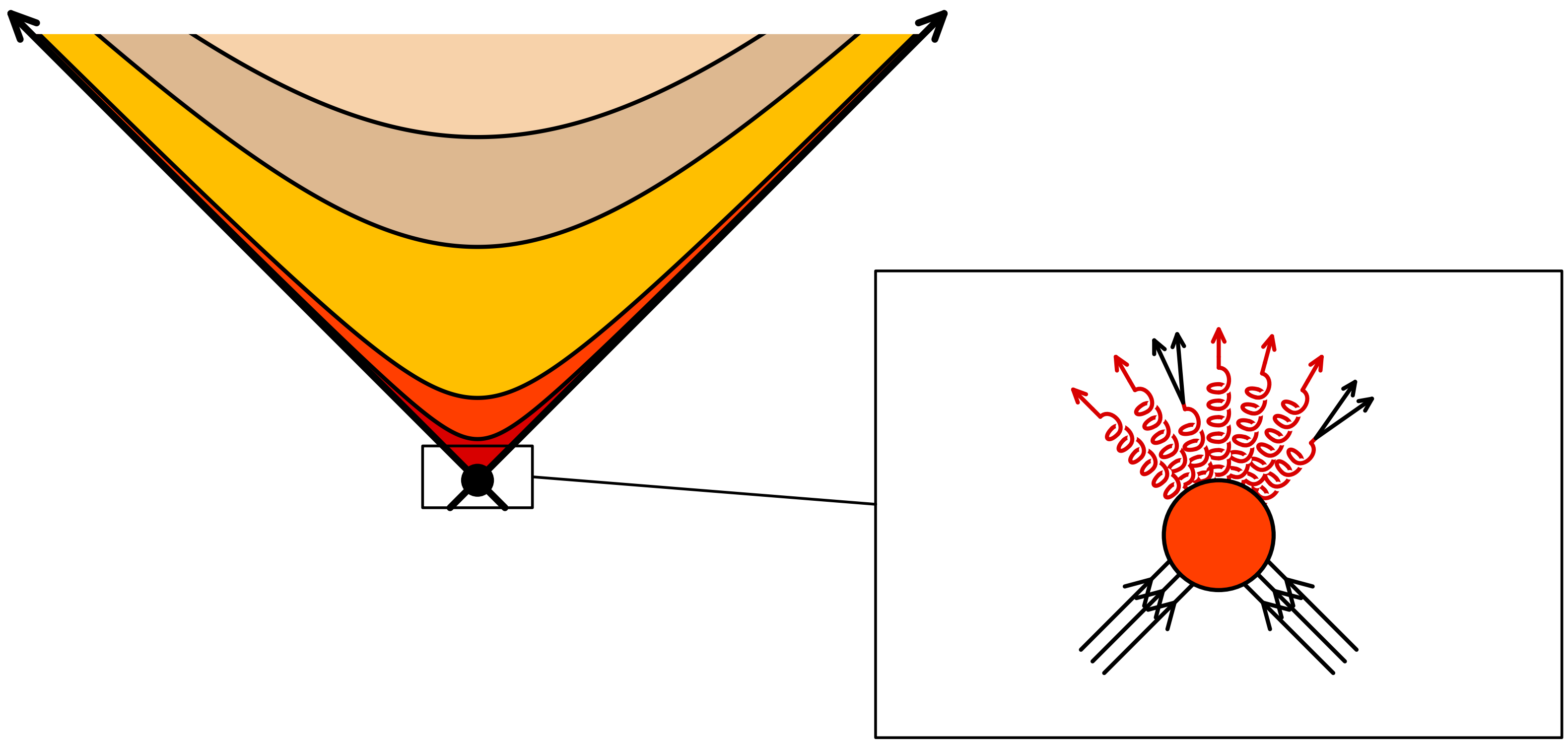
  - At leading order, the photon and the jet have opposite $\vec{p}_\perp$'s
  - The photon escapes without any energy loss, and gives a reference for the energy of the jet ▷ one can compare the properties of jet after going through the medium to those of a jet of the same $\vec{p}_\perp$ which has been produced in the vacuum

- Complications due to higher order corrections :
  - Final state with photon + two jets
  - Photon produced by fragmentation of a quark

  ▷ in both cases, the momentum of the photon is not directly related to the initial momentum of a jet

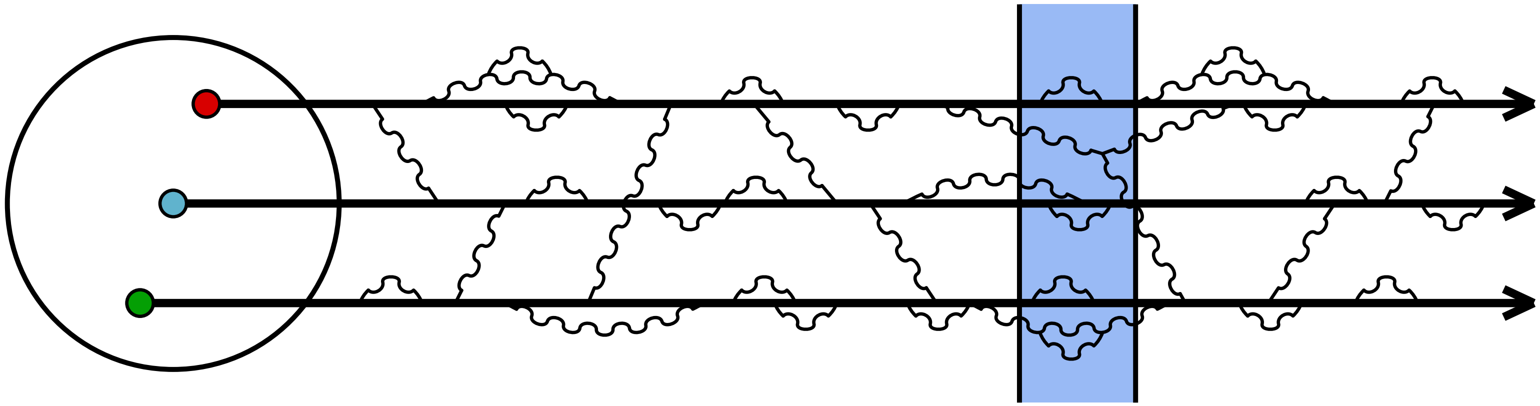
CGC

Where does the CGC stand ?



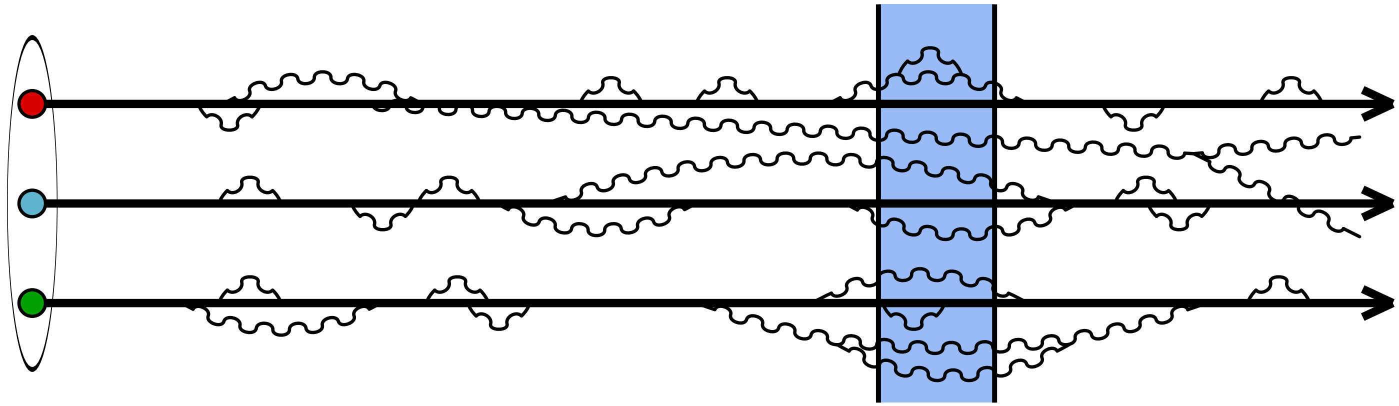
- describes the content of nucleons and nuclei at small x
- framework to calculate the production of semi-hard particles
- provides initial conditions for the subsequent evolution

Nucleon at rest



- Very complicated non-perturbative object...
- Contains fluctuations at all space-time scales smaller than its own size
- Only the fluctuations that are longer lived than the external probe participate in the interaction process
- The only role of short lived fluctuations is to renormalize the masses and couplings
- Interactions are very complicated if the constituents of the nucleon have a non trivial dynamics over time-scales comparable to those of the probe

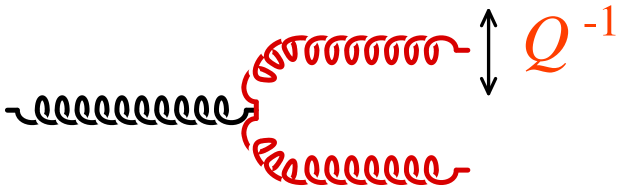
Nucleon at high energy



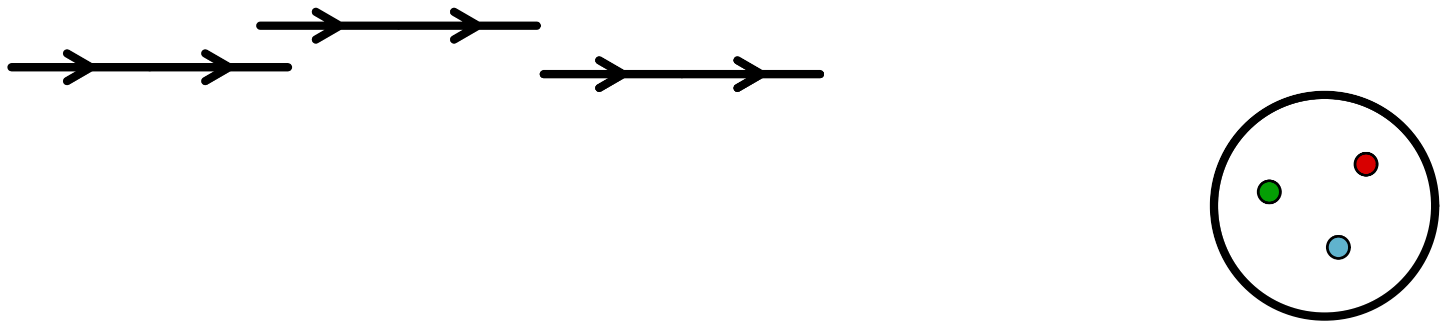
- Dilation of all internal time-scales of the nucleon
- Interactions among constituents now take place over time-scales that are longer than the characteristic time-scale of the probe
  - ▷ the constituents behave as if they were free
- Many fluctuations live long enough to be seen by the probe. The nucleon appears denser at high energy (it contains more gluons)
- Pre-existing fluctuations are totally frozen over the time-scale of the probe, and act as static sources of new partons

Parton model

- At the time of the interaction, the nucleon can be seen as a collection of free constituents, called partons
- The nucleon content is described by parton distributions, that depend on the momentum fraction x of the parton
- One needs only to calculate the cross-section between the probe and the partons. If the parton density is low, only one parton interacts
- One can separate the hard diffusion, perturbative, from the non-perturbative parton distributions, because the strong interactions responsible for these non-perturbative effects act on much longer time-scales ("factorization")
- Note: parton distributions also depend on a "transverse resolution scale", Q :

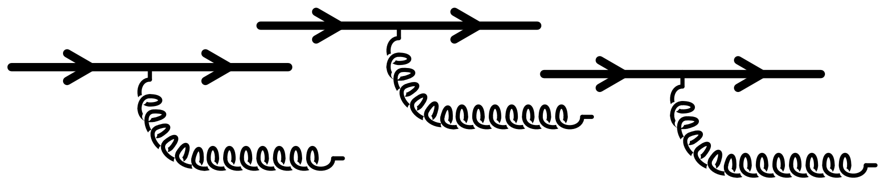


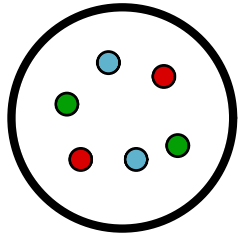
Saturation



▷ at low energy, only valence quarks are present in the hadron wave function

Saturation



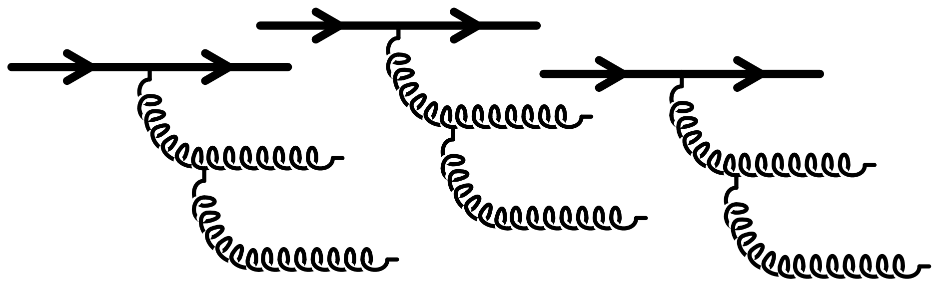


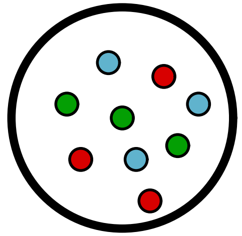
▷ when energy increases, new partons are emitted

▷ the emission probability is $\alpha_s \int \frac{dx}{x} \sim \alpha_s \ln(\frac{1}{x})$, with x the longitudinal momentum fraction of the gluon

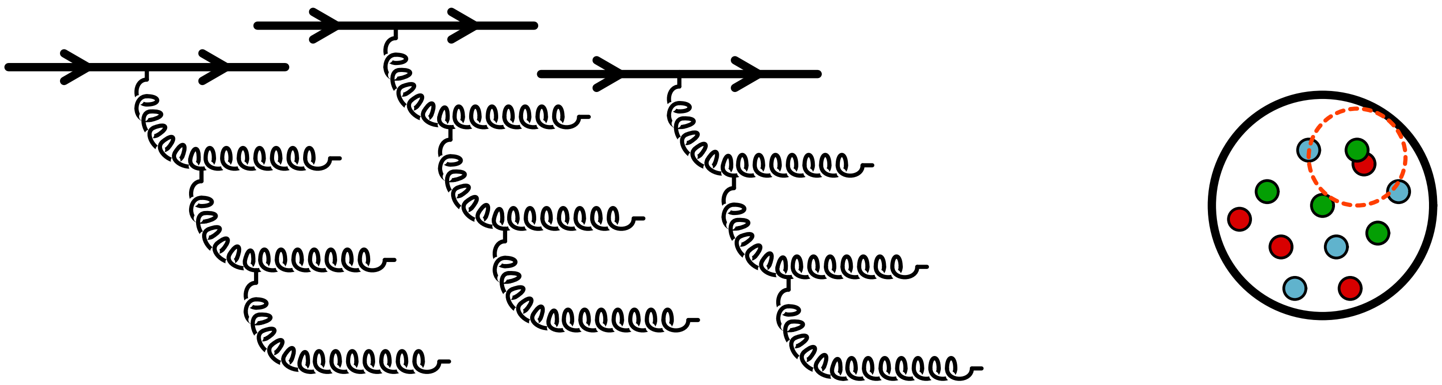
▷ at small-x (i.e. high energy), these logs need to be resummed

Saturation



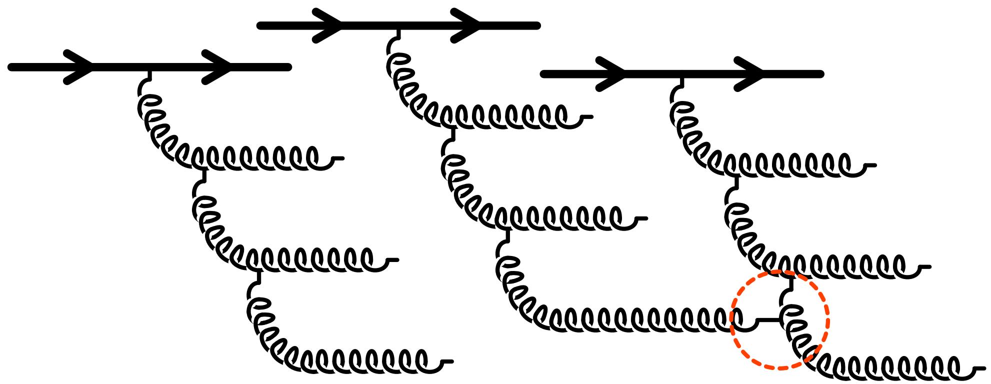


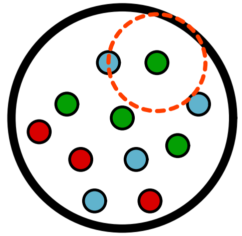
▷ as long as the density of constituents remains small, the evolution is linear: the number of partons produced at a given step is proportional to the number of partons at the previous step (BFKL)



▷ eventually, the partons start overlapping in phase-space

Saturation





▷ parton recombination becomes favorable

▷ after this point, the evolution is non-linear:
the number of partons created at a given step depends non-linearly on the number of partons present previously

Saturation criterion

Gribov, Levin, Ryskin (1983)

- Number of gluons per unit area:

$$\rho \sim \frac{xG(x,Q^2)}{\pi R^2}$$

- Recombination cross-section:

$$\sigma_{gg\to g} \sim \frac{\alpha_s}{Q^2}$$

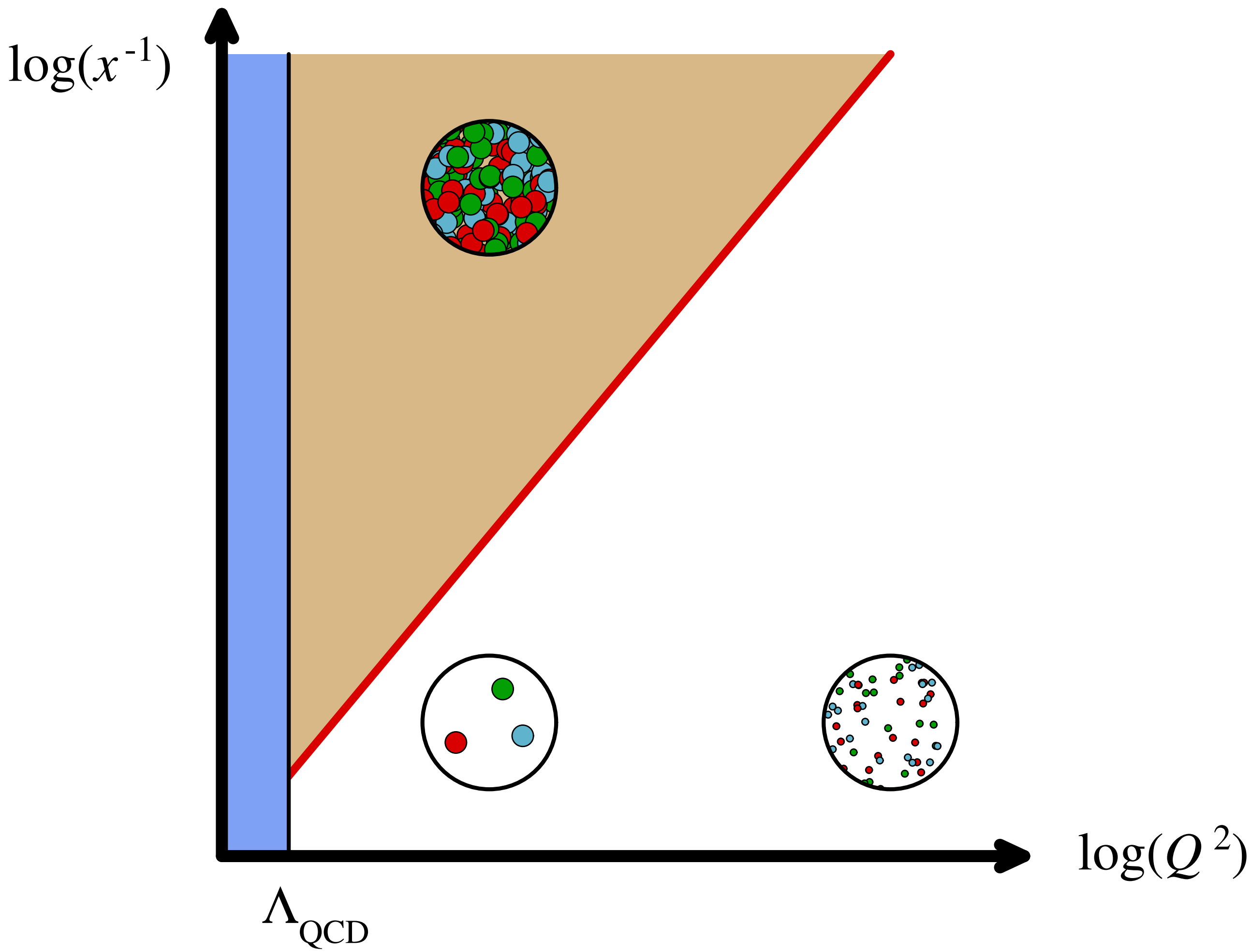
- Recombination happens if $\rho\sigma_{gg\to g} \gtrsim 1$, i.e. $Q^2 \lesssim Q_s^2$, with:

$$Q_s^2 \sim \frac{\alpha_s xG(x,Q_s^2)}{\pi R^2}$$

- At saturation, the phase-space density is:

$$\frac{dN_g}{d^2\vec{\boldsymbol{x}}_\perp d^2\vec{\boldsymbol{p}}_\perp} \sim \frac{\rho}{Q^2} \sim \frac{1}{\alpha_s}$$

Saturation domain



- Boundary defined by $Q^2 = Q_s^2(x)$

Degrees of freedom

McLerran, Venugopalan (1994)
Iancu, Leonidov, McLerran (2001)

- Small x modes have a large occupation number
  - ▷ they can be described by a classical color field A^μ
- Large x modes, slowed down by time dilation, are described as static color sources ρ
- The classical field obeys Yang-Mills equations :

$$D_\nu F^{\nu\mu} = J^\mu = \delta^{\mu +}\delta(x^-)\rho(\vec{\boldsymbol{x}}_\perp)$$

- The color sources ρ are random, and described by a statistical distribution $W_{x_0}[\rho]$, where x_0 is the separation between "small x" and "large x"
- An evolution equation (JIMWLK) controls the changes of $W_{x_0}[\rho]$ with x_0 (generalizes BFKL to the saturated regime)

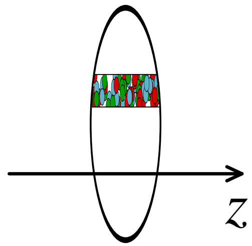
A brief lesson of semantics...

McLerran (mid 2000)

- Color : more or less obvious...
- Glass : the system has degrees of freedom whose time-scale is much larger than the typical time-scales for interaction processes. Moreover, these degrees of freedom are stochastic variables, like in “spin glasses” for instance
- Condensate : the soft degrees of freedom are as densely packed as they can (the density remains finite, of order α_s^{-1}, due to repulsive interactions between gluons)

McLerran-Venugopalan model

- The JIMWLK equation must be completed by an initial condition, given at some x_0
- As with DGLAP, the initial condition is in general non-perturbative
- The McLerran-Venugopalan model is often used as an initial condition at moderate x_0 for a large nucleus :
  - partons are randomly distributed
  - many partons in each “tube”
  - absence of correlations at different $\vec{\boldsymbol{x}}_\perp$

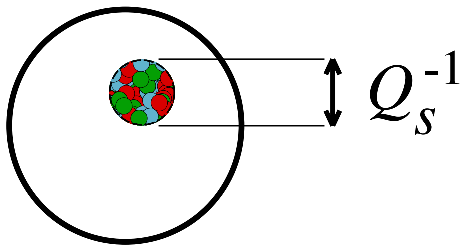


- The MV model assumes that the density of color charges $\rho(\vec{\boldsymbol{x}}_\perp)$ has a gaussian distribution :

$$W_{x_0}[\rho] = \exp\left[-\int d^2\vec{\boldsymbol{x}}_\perp \frac{\rho(\vec{\boldsymbol{x}}_\perp)\rho(\vec{\boldsymbol{x}}_\perp)}{2\mu^2(\vec{\boldsymbol{x}}_\perp)}\right]$$

Correlation length

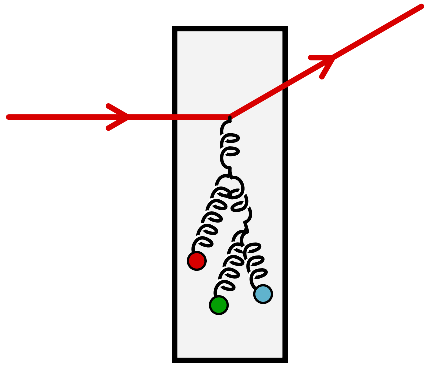
- In a nucleon at low energy, the typical correlation length among color charges is of the order of the nucleon size, i.e. $\Lambda_{QCD}^{-1} \sim 1\ \mathrm{fm}$. Indeed, at low energy, color screening is due to confinement, controlled by the non-perturbative scale Λ_{QCD}
- At high energy (small x), partons are much more densely packed, and it can be shown that color neutralization occurs in fact over distances of the order of $Q_s^{-1} \ll \Lambda_{QCD}^{-1}$



- This implies that all hadrons, and nuclei, behave in the same way at high energy. In this sense, the small x regime described by the CGC is universal

Leading twist shadowing

- Interactions between the partons of the target :



- At small x, the wave function of a parton “spreads” outside of the nucleon it belongs to, so that it can interact with partons from other nucleons. This implies :

$$xG_{\text{noyau}}(x, Q^2) \quad < \quad A\, xG_{\text{nucleon}}(x, Q^2)$$

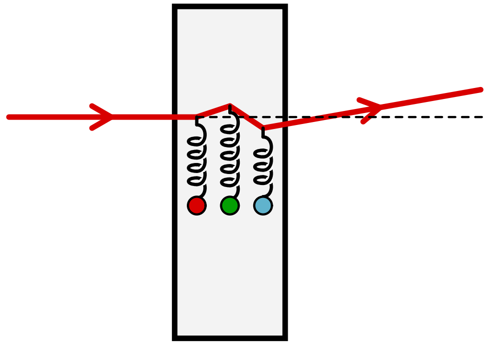
- At small x, one has a suppression of cross-sections :

$$d\sigma_{pA}/d^2\vec{\boldsymbol{p}}_\perp \sim A^\alpha \quad \text{with} \quad \alpha < 1$$

- Note: these interactions are the same as those involved in saturation

Multiple scatterings

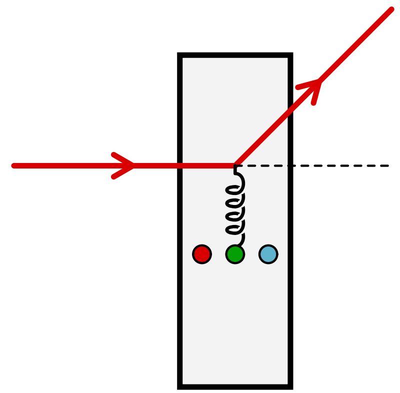
- Because of the large parton density at small x in the target, the external probe can interact several times :



- One of the scatterings "produces" the final state, and the others merely change its momentum ("higher twist" shadowing)
- Each additional scattering brings a correction $\alpha_s A^{1/3}\Lambda^2/p_\perp^2$
  ▷ important effect at small $p_\perp$, despite the α_s suppression
- At leading order, multiple scattering only affect the momentum distribution of the final particles, but not their total number. The suppression at small $p_\perp$ is compensated by an increase at larger $p_\perp$ (Cronin effect)

Multiple scatterings

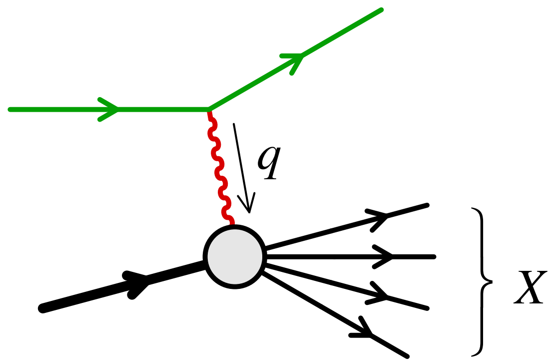
- At high $p_\perp$, a single scattering dominates :



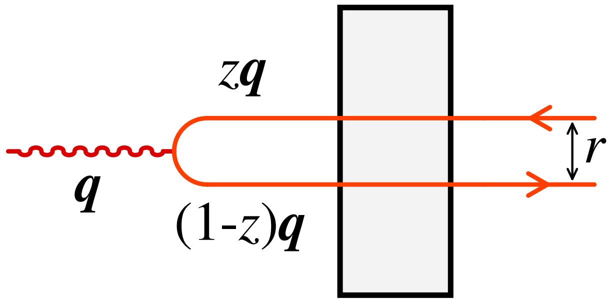
  - Standard result for a random walk in an external potential, when the potential does not decrease fast at large momentum ("intermittency")
  - Differential cross-sections scale like the atomic number A at high $p_\perp$

- Note : the MV model describes correctly multiple scatterings, but does not contain any "leading twist" shadowing at small x

Deep Inelastic Scattering



- In a frame in which the virtual photon has a large energy :

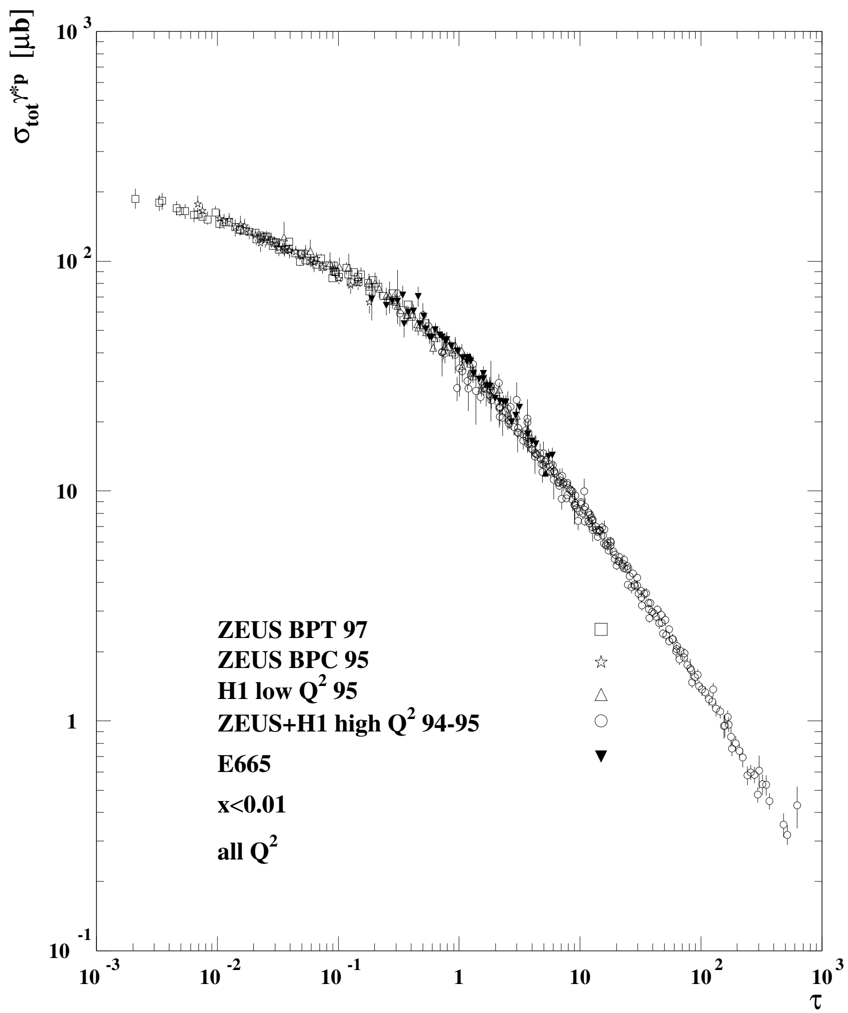


- The structure function F_2 can be expressed in terms of the "dipole" cross-section :

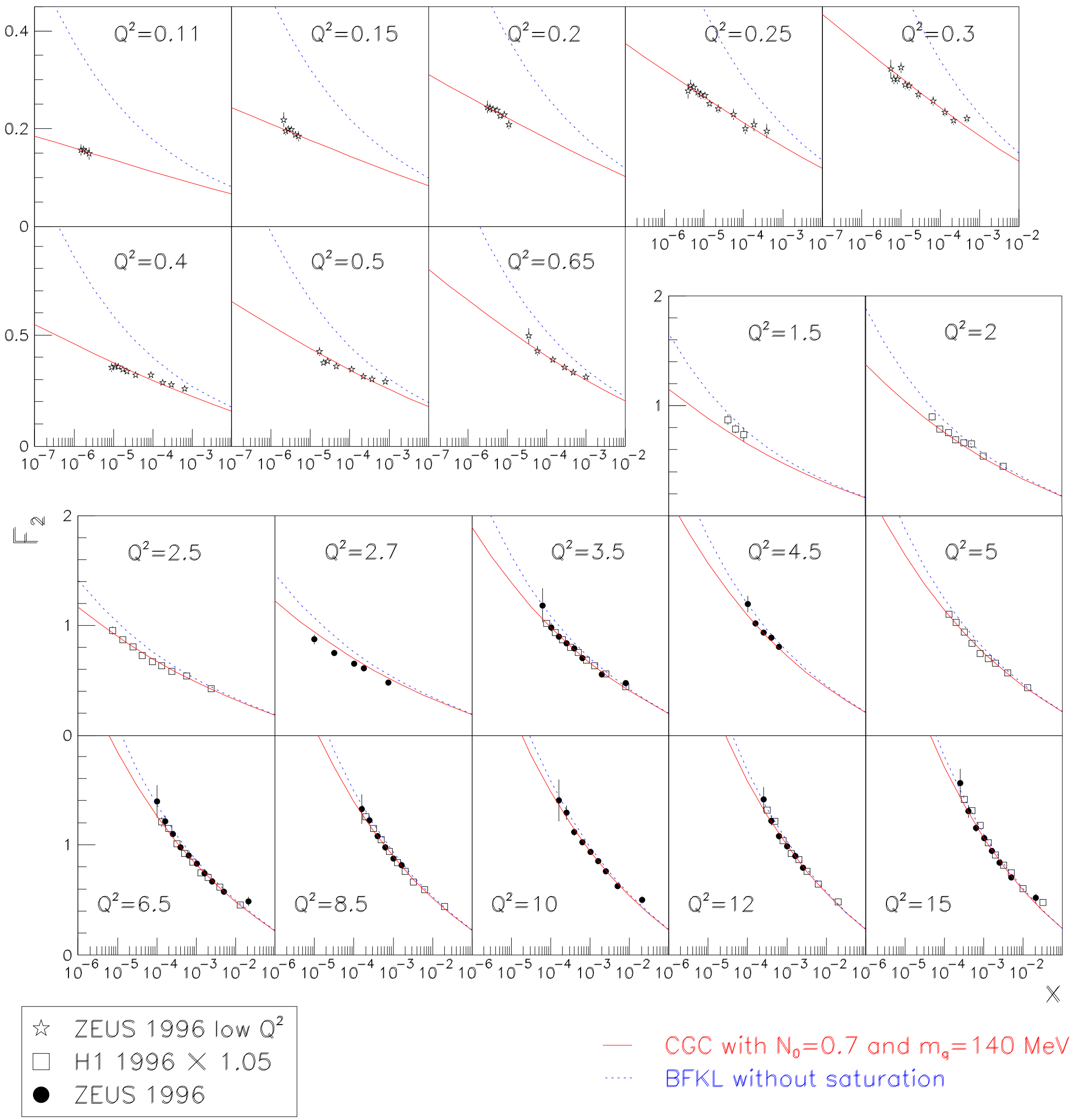
$$F_2 \sim \sigma_{\gamma^* p}(x, Q^2) = \int_0^\infty r dr \int_0^1 dz \left|\psi(z, r, Q^2)\right|^2 \sigma_{\text{dipole}}(x, r)$$

Deep Inelastic Scattering

- “Geometrical” scaling : $F_2(x, Q^2) = F_2(\tau \equiv Q^2/Q_s^2(x))$



Deep Inelastic Scattering



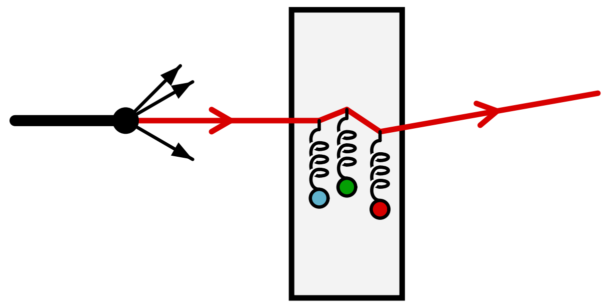
Nucleus-nucleus collisions

- The major problem is that the CGC only describes the very first instants after the collision ($\tau \lesssim 0.2$ fm/c), while most of the observables undergo important modifications due to their interactions with the plasma
- In fact, by definition, thermalization (if it happens) implies that the system "forgets" all about the details of its initial state...
- Only inclusive quantities, like the multiplicity, have a chance of staying unchanged until the end

- The dependence of the total multiplicity at RHIC on the center of mass energy $\sqrt{s}$ and on the centrality of the collision is correctly predicted by the CGC
- Some hydrodynamical descriptions of the evolution of the system have successfully used "CGC inspired" initial conditions

Proton-nucleus collisions

- The produced particles escape without having to go through an extended dense medium
  ▷ the phenomena predicted in the CGC framework can be measured rather directly
- The proton is much less dense than the nucleus, and can be described with the standard structure functions :

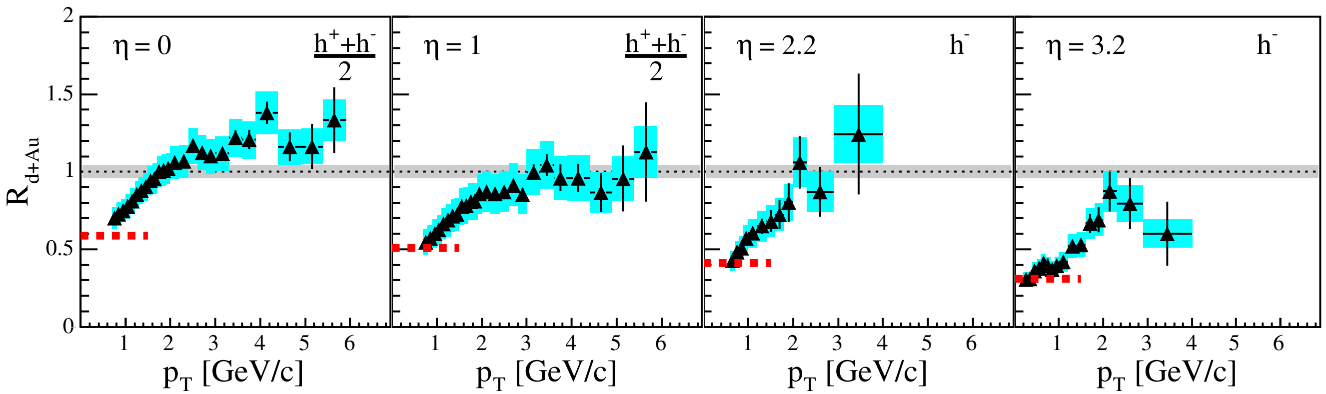


- The matrix elements that enter in cross-sections are directly calculable in the CGC framework (they are known for a number of processes, like gluon or quark production)
- Note : contrary to DIS, one does not know exactly the momentum of the incoming parton

Proton-nucleus collisions

- Results of the BRAHMS experiment at RHIC for deuteron-gold collisions :

$$R_{\rm dAu} \equiv \frac{1}{N_{\rm coll}} \frac{\left.\frac{dN}{dp_\perp d\eta}\right|_{\rm dAu}}{\left.\frac{dN}{dp_\perp d\eta}\right|_{\rm pp}}$$



  - At small rapidity, suppression at low $p_\perp$ and enhancement at high $p_\perp$ (multiple scatterings – Cronin effect)
  - At large rapidity, suppression at all $p_\perp$'s (shadowing)