Quark-Gluon Plasma and Heavy Ion Collisions

I – Introduction to Heavy Ion Collisions

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General outline

- I : Introduction to Heavy Ion Collisions
- II : QCD at finite temperature
- III : Hydrodynamical behavior
- IV : Kinetic theory

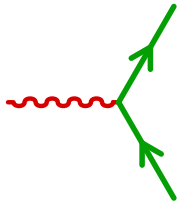
Lecture I

- QCD reminder
- Deconfinement transition
- Heavy Ion Collisions
- Observables

QCD reminder

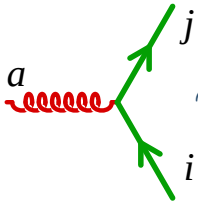
QCD : Quarks and gluons

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

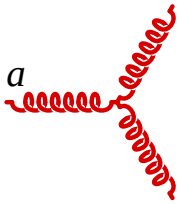


$\sim \quad e$ (electric charge of the electron)

- Strong interaction : Quantum chromo-dynamics
  - Matter : quarks , interaction carriers : gluons
  - Interactions :



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



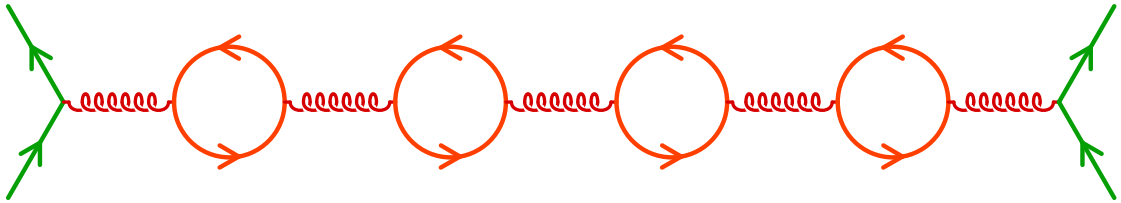
$\sim \quad g\,(T^a)_{bc}$

  - 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

QCD : 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)

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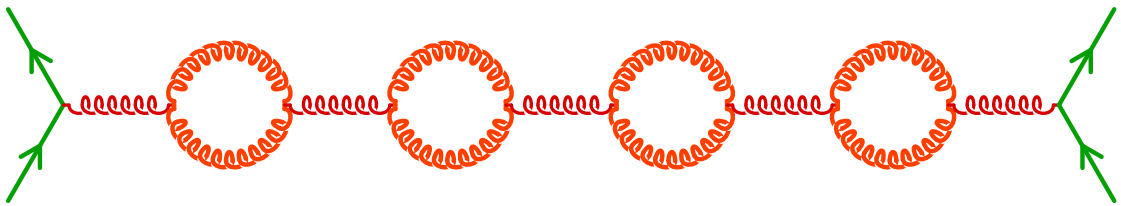
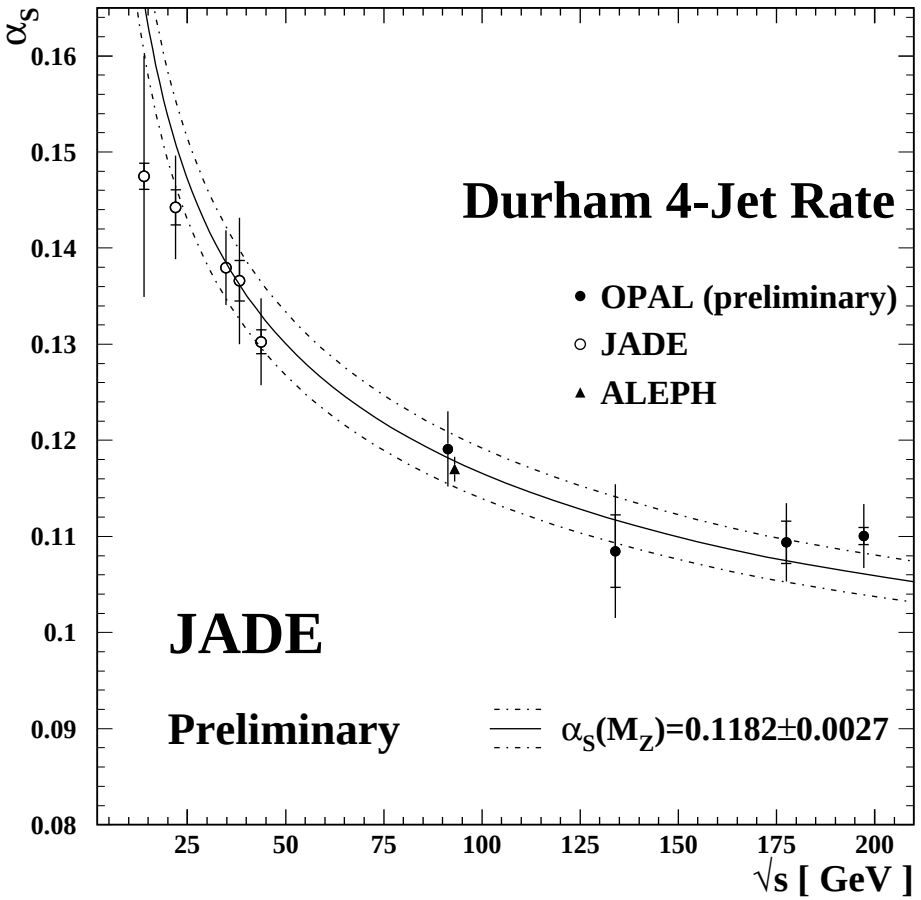


- The effective charge seen at large distance is screened by fermionic fluctuations (as in QED)
- But gluonic vacuum fluctuations produce an anti-screening (because of the non-abelian nature of their interactions)
- As long as $N_f < 11N_c/2 = 16.5$, the gluons win...

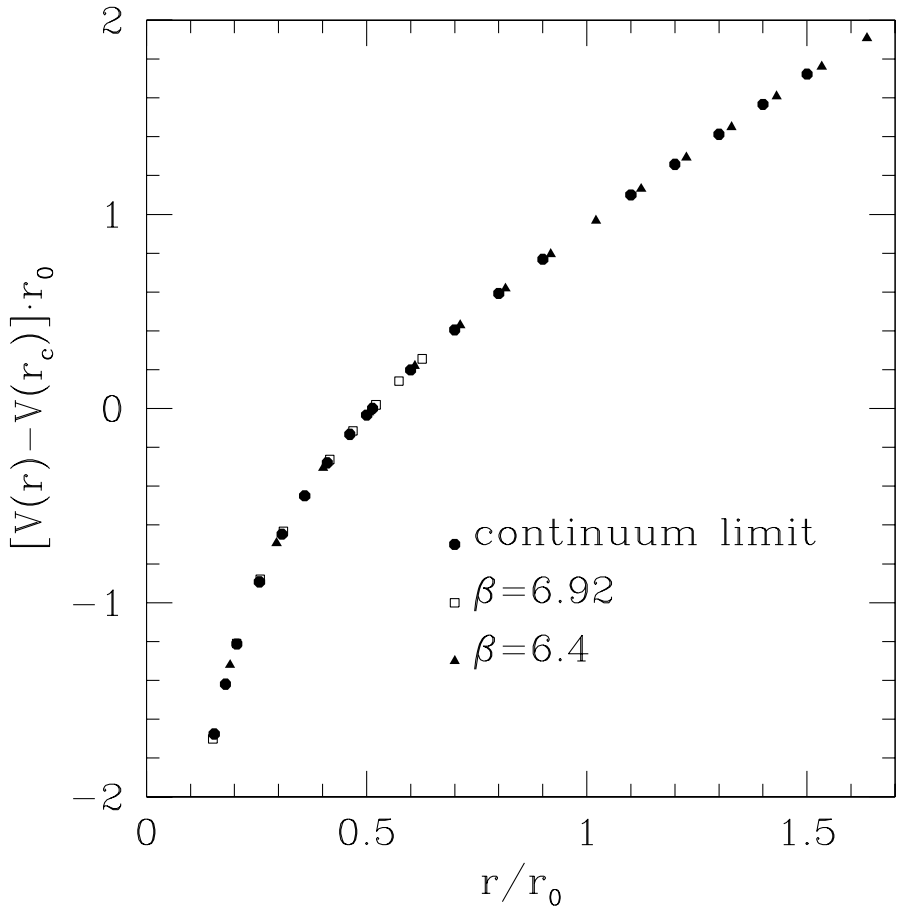
QCD : Asymptotic freedom



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

Deconfinement transition

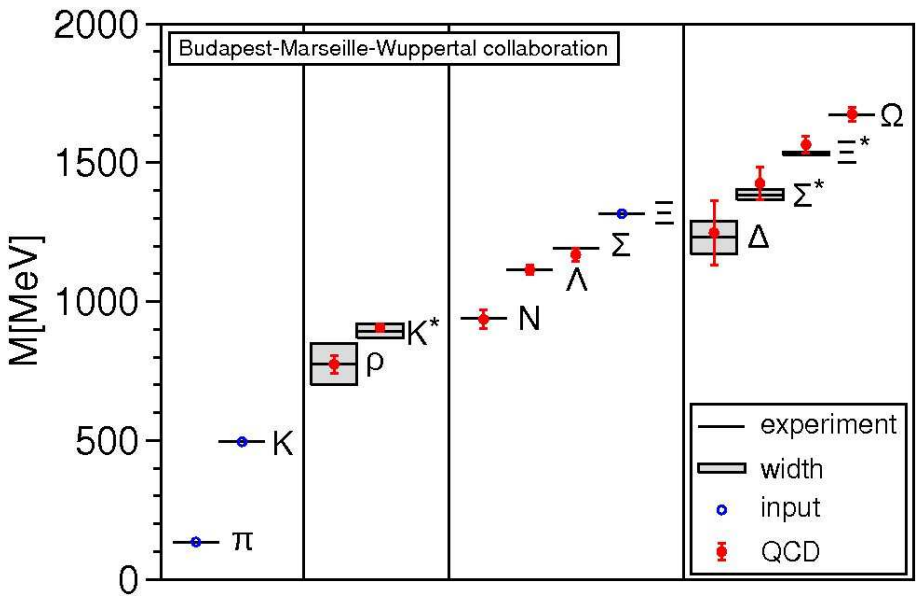
Quark confinement



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

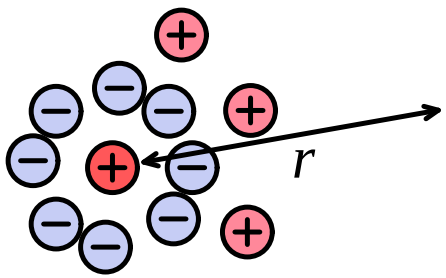
Color confinement

- In nature, we do not see free quarks and gluons (the closest we have to actual quarks and gluons are jets)
- Instead, we see hadrons (quark-gluon bound states):



- The hadron spectrum is uniquely given by $\Lambda_{\mathrm{QCD}}, m_f$
- But this dependence is non-pertubative (it can now be obtained fairly accurately by lattice simulations)

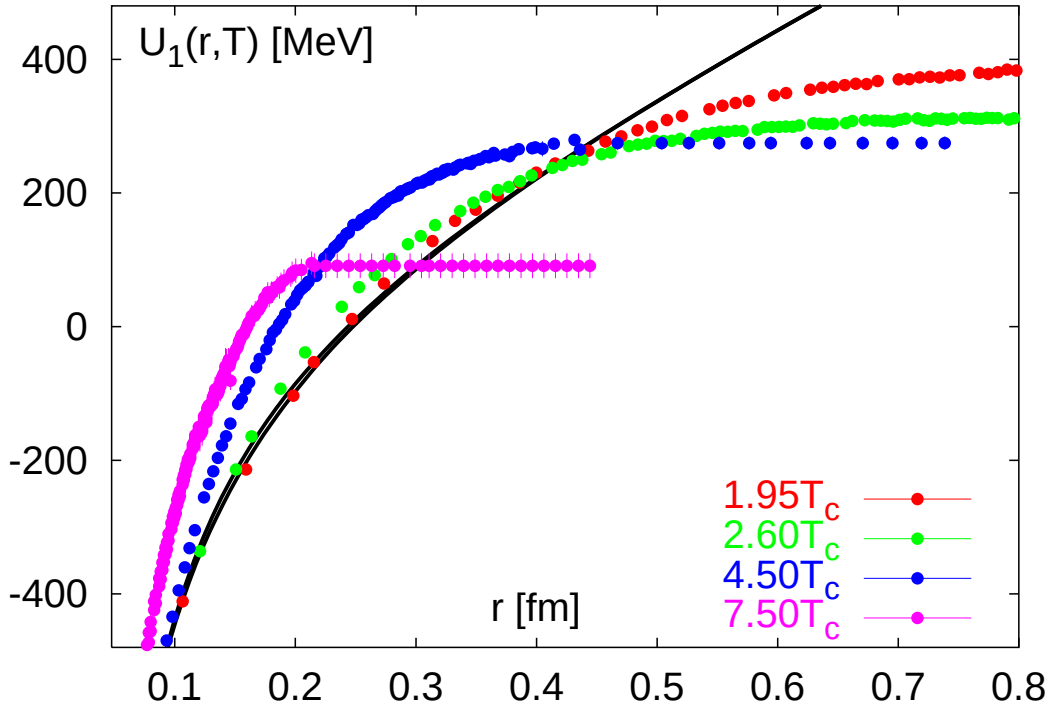
Debye screening



$$V(r) = \frac{\exp(-r / r_{\mathrm{debye}})}{r}$$

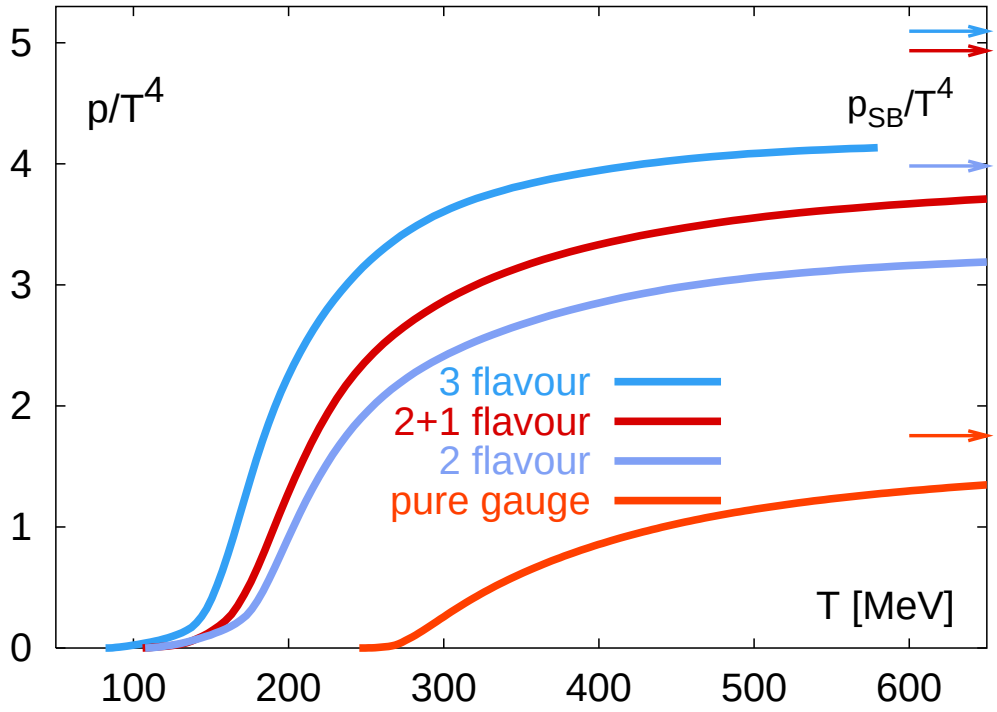
- In a dense medium, color charges are screened by their neighbours
- The interaction potential decreases exponentially beyond the Debye radius r_{debye}
- Hadrons whose radius is larger than r_{debye} cannot bind

Debye screening



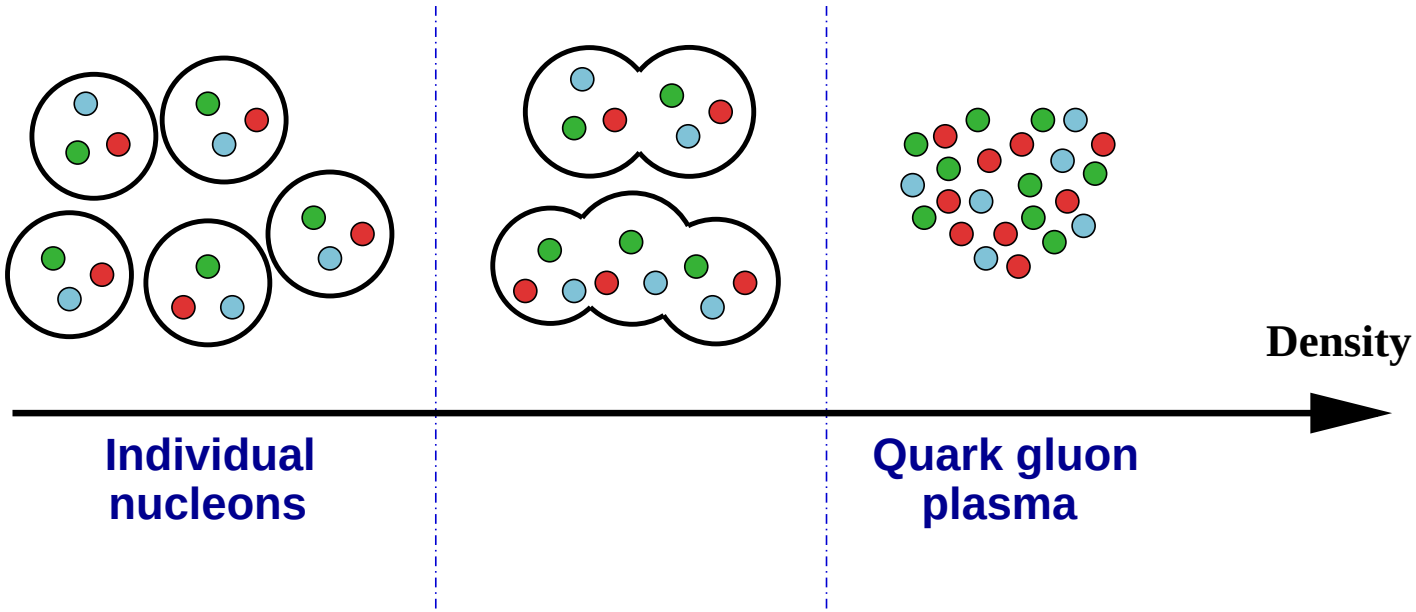
- In lattice calculations, one sees the $q\bar{q}$ potential flatten at long distance as T increases

Deconfinement transition



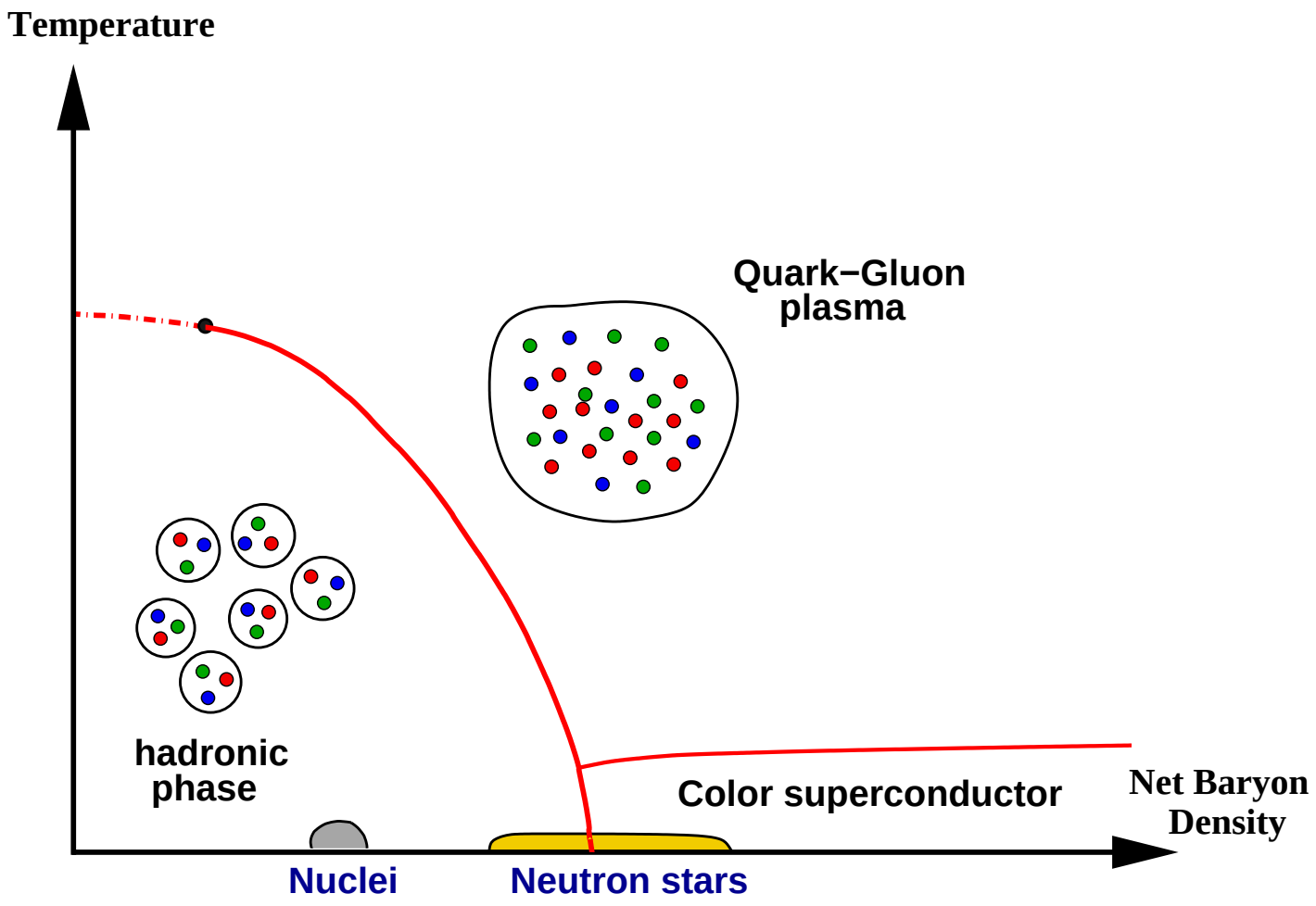
- Fast increase of the pressure :
  - at $T \sim 270$ MeV, if there are only gluons
  - at $T \sim 150$–170 MeV, depending on the number of light quarks

Deconfinement transition

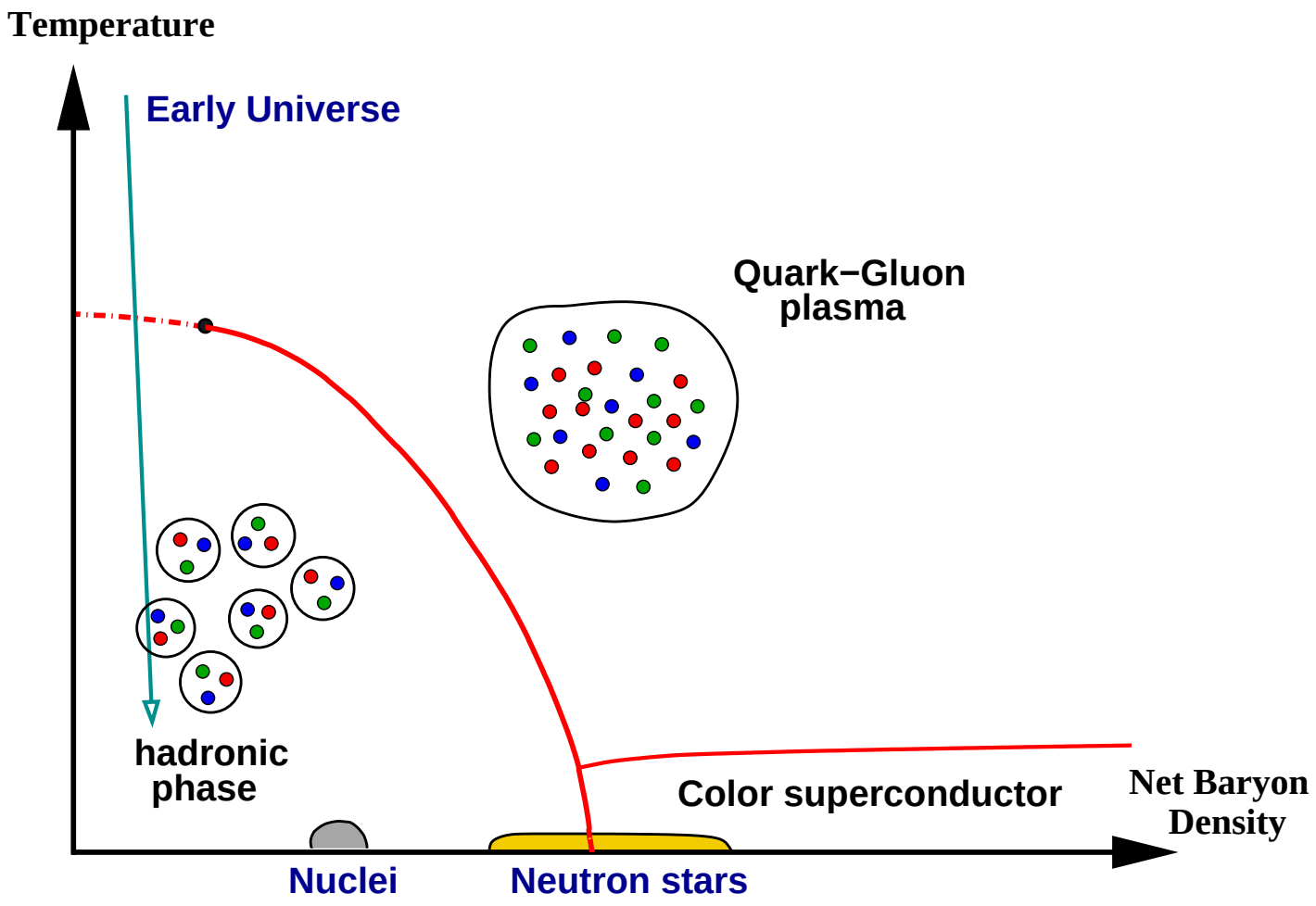


- When the nucleon density increases, they merge, enabling quarks and gluons to hop freely from a nucleon to its neighbors
- This phenomenon extends to the whole volume when the phase transition ends
- Note: if the transition is first order, it goes through a mixed phase containing a mixture of nucleons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

QCD phase diagram



QGP in the early universe



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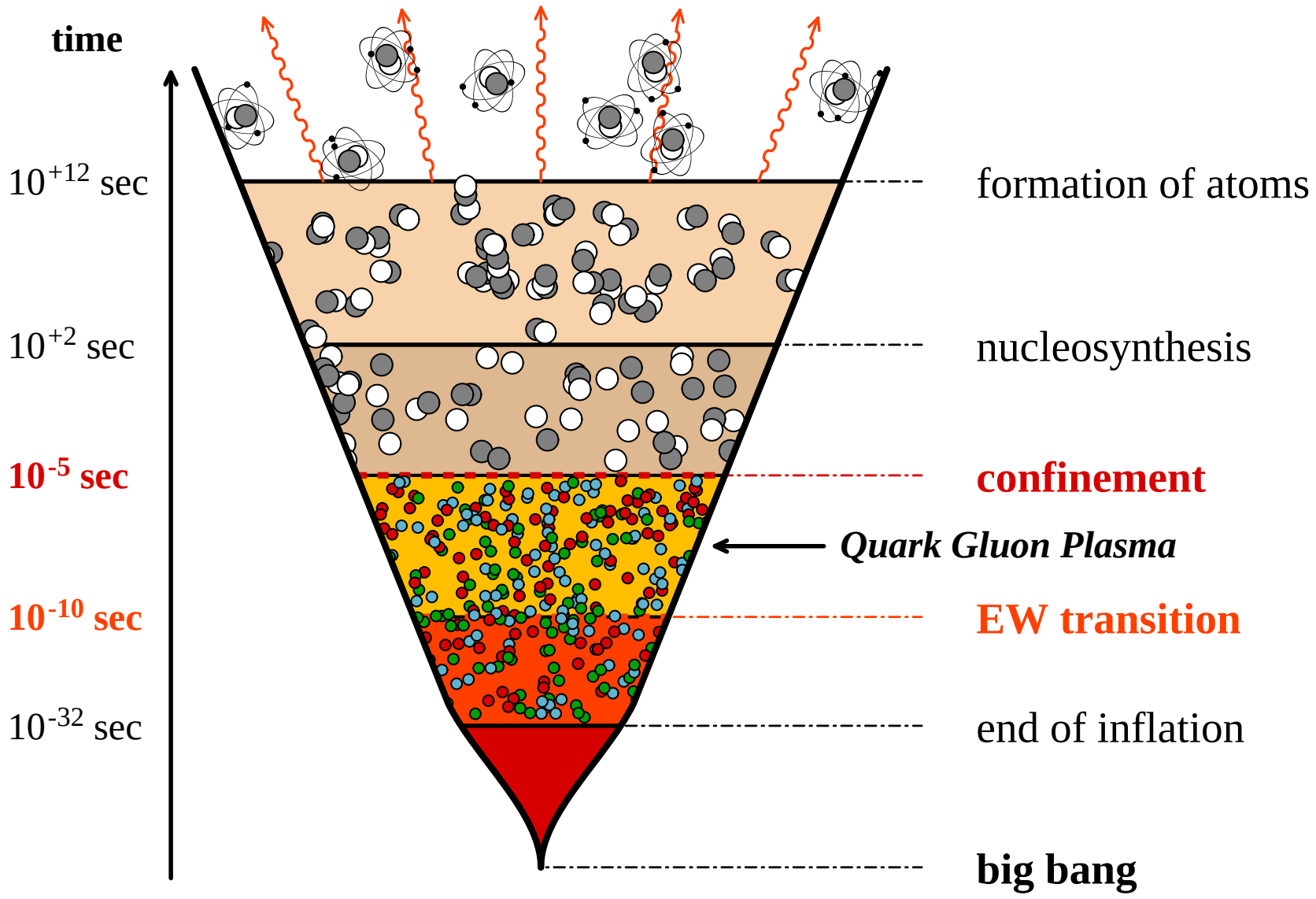
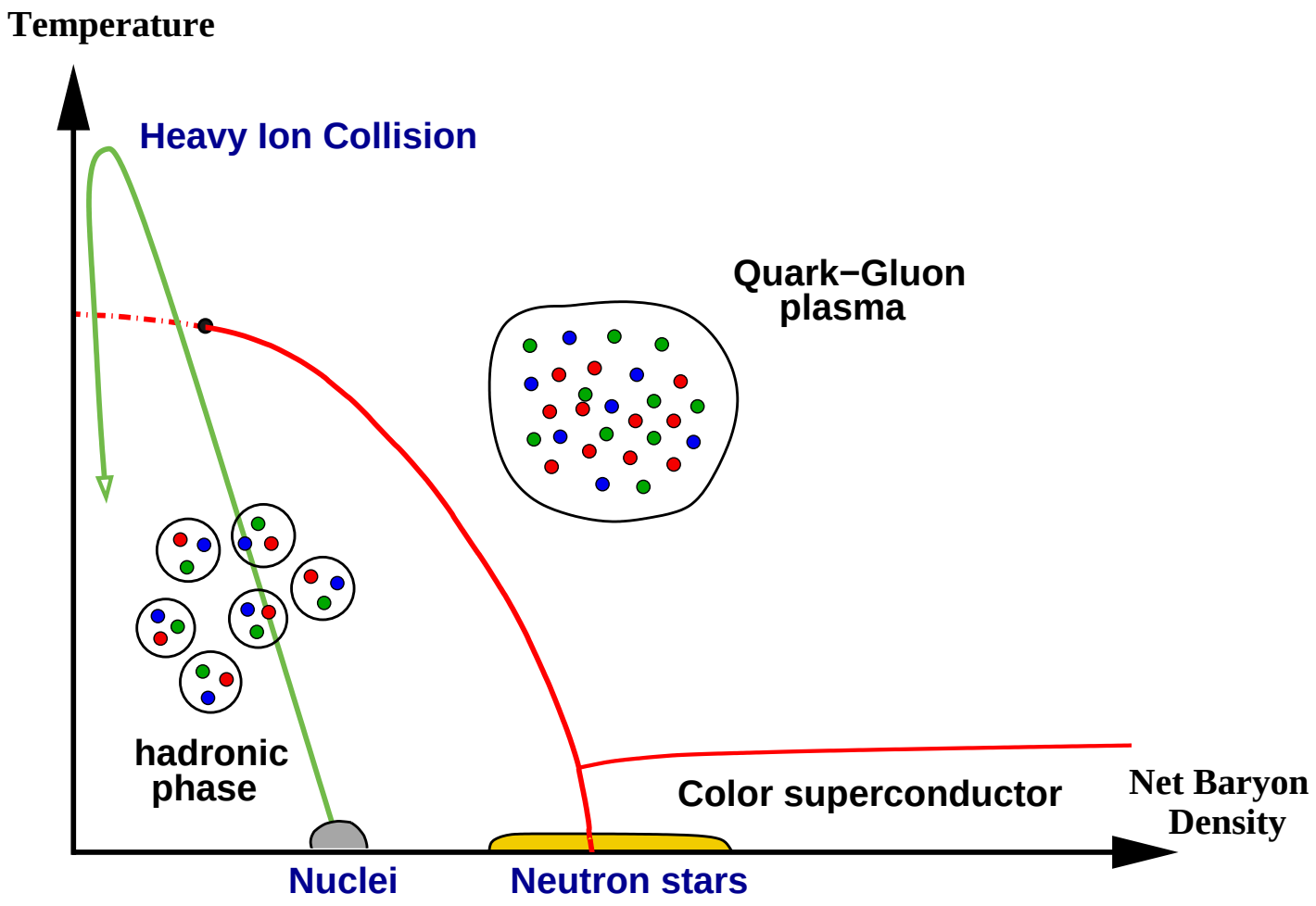
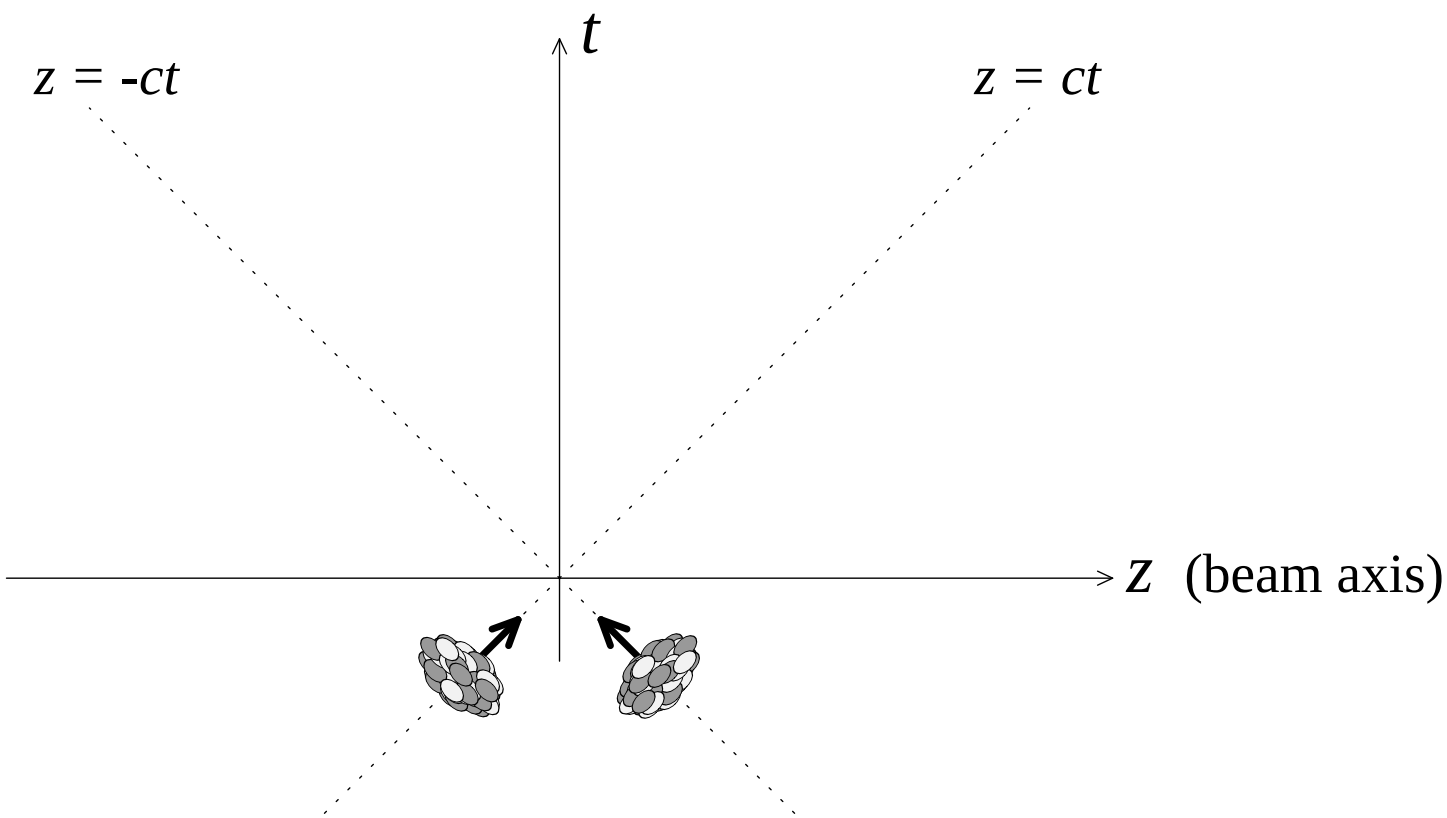


Heavy Ion Collisions

Heavy ion collisions



Stages of a nucleus-nucleus collision



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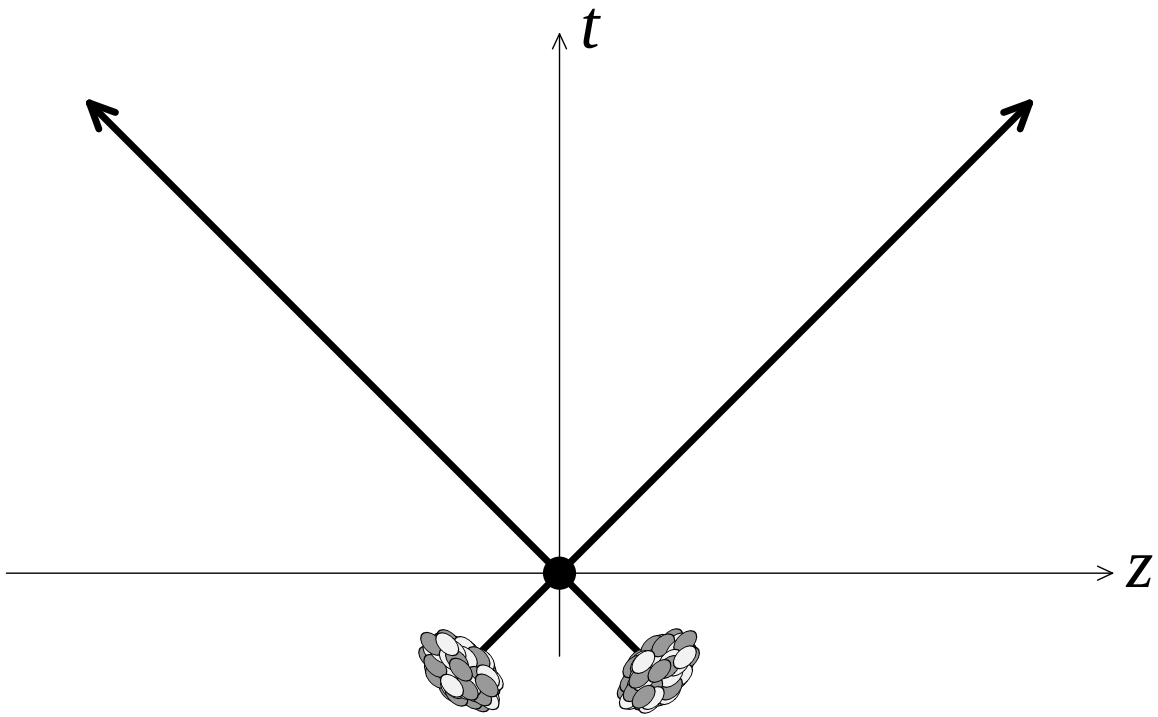
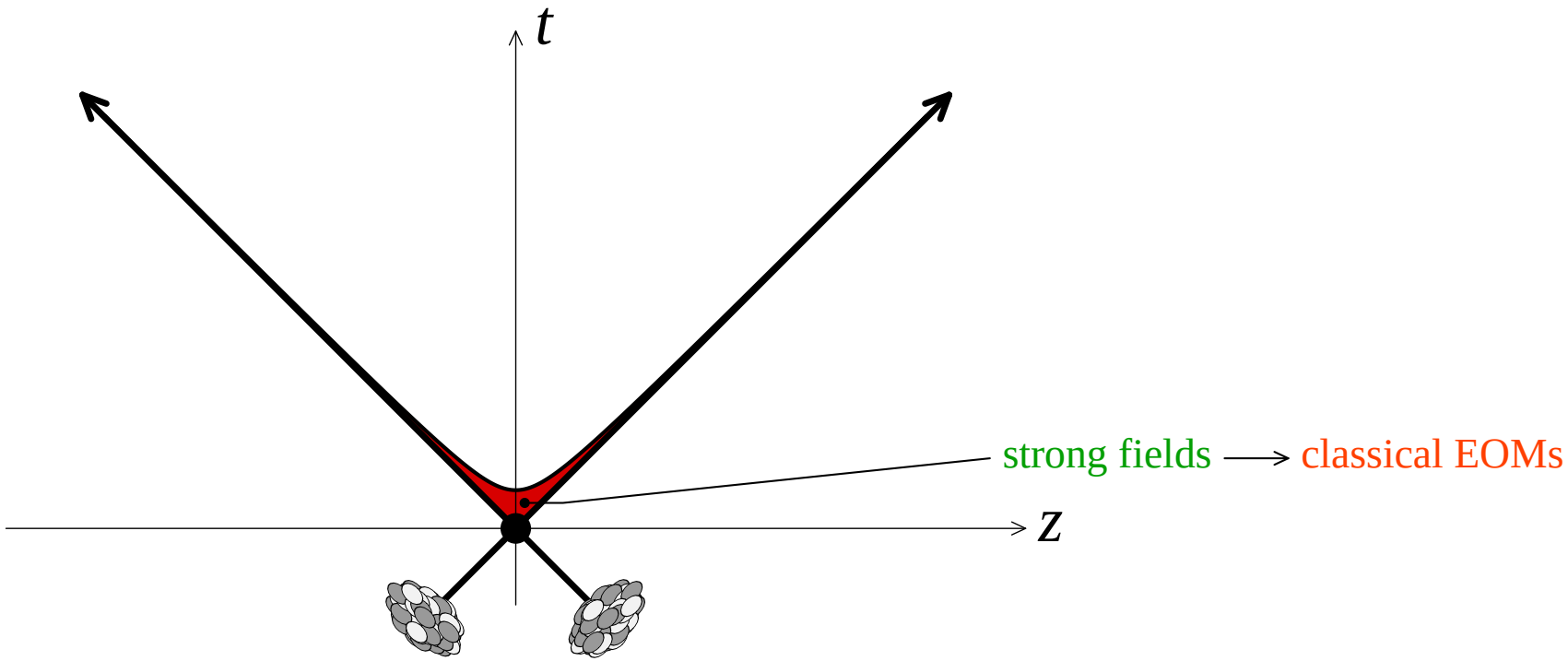


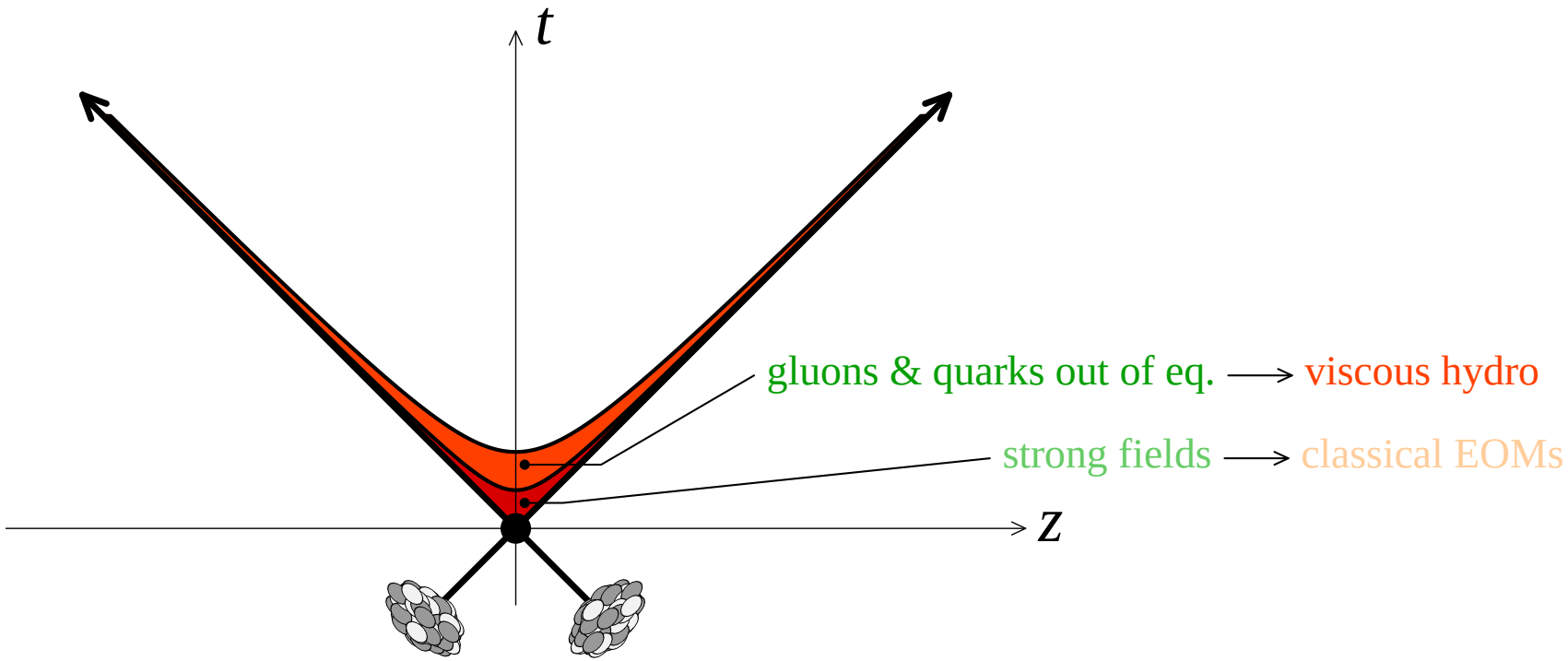
- $\tau \sim 0$ fm/c
- Production of hard particles :
  - jets, direct photons
  - heavy quarks
- calculable with perturbative QCD (leading twist)

Stages of a nucleus-nucleus collision



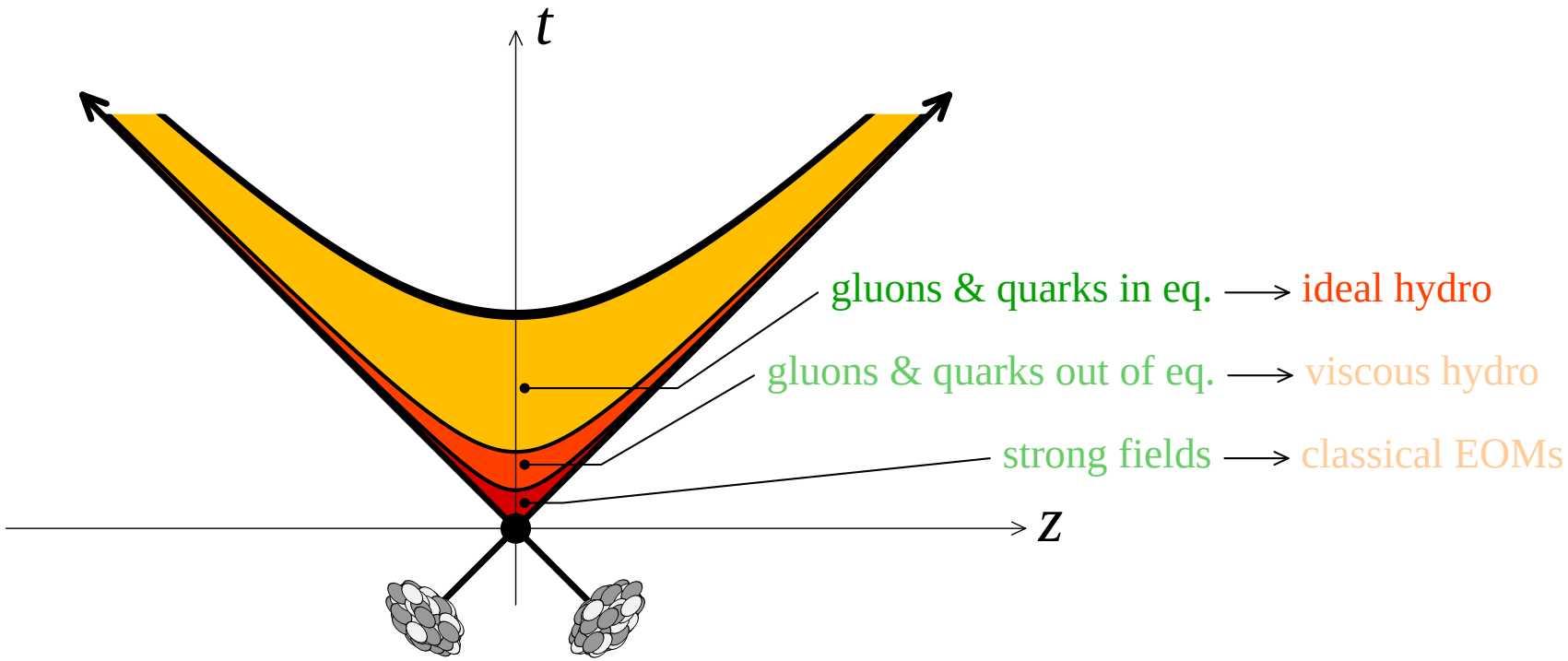
- $\tau \sim 0.2$ fm/c
- Production of semi-hard particles : gluons, light quarks
- relatively small momentum : $p_\perp \lesssim 2$–3 GeV
- make up for most of the multiplicity
- sensitive to the physics of saturation (higher twist)

Stages of a nucleus-nucleus collision



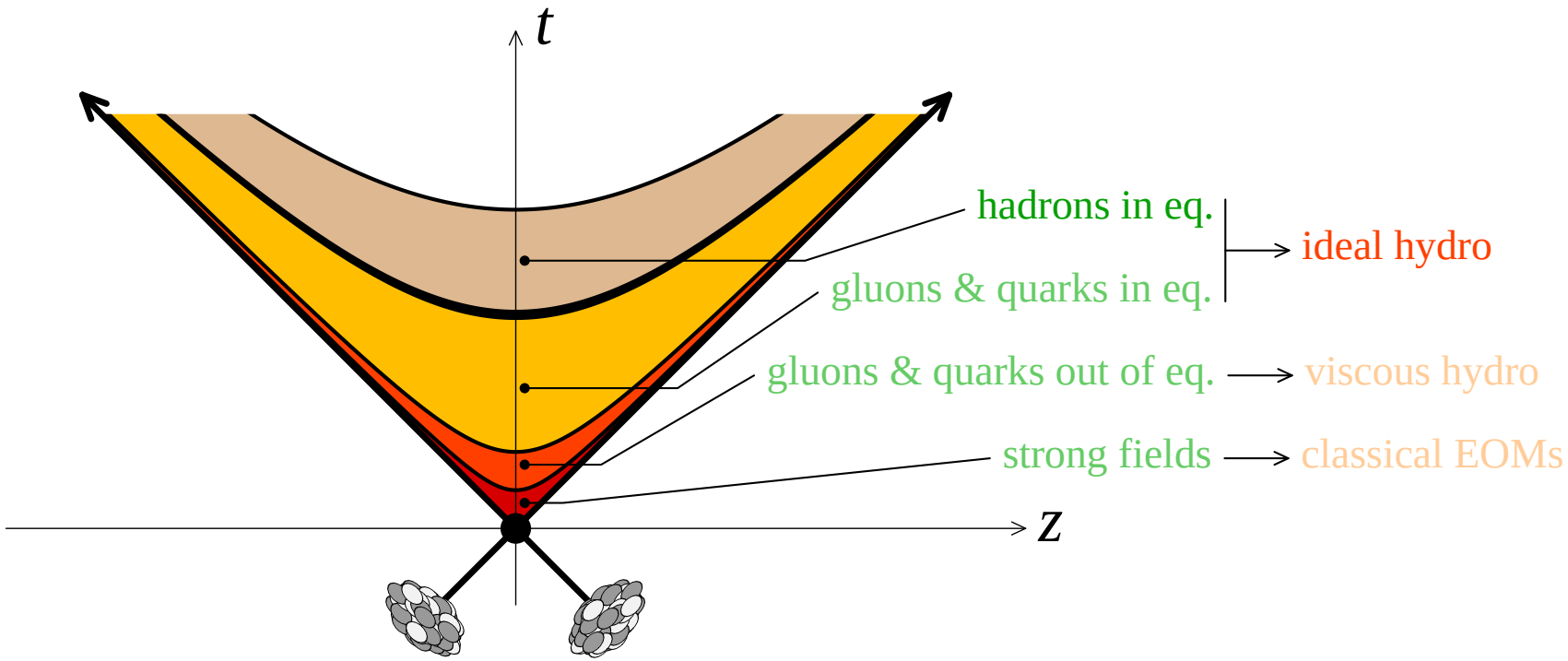
- $\tau \sim 1$–2 fm/c
- Thermalization
  - experiments suggest a fast thermalization
  - but this is still not well understood from QCD

Stages of a nucleus-nucleus collision



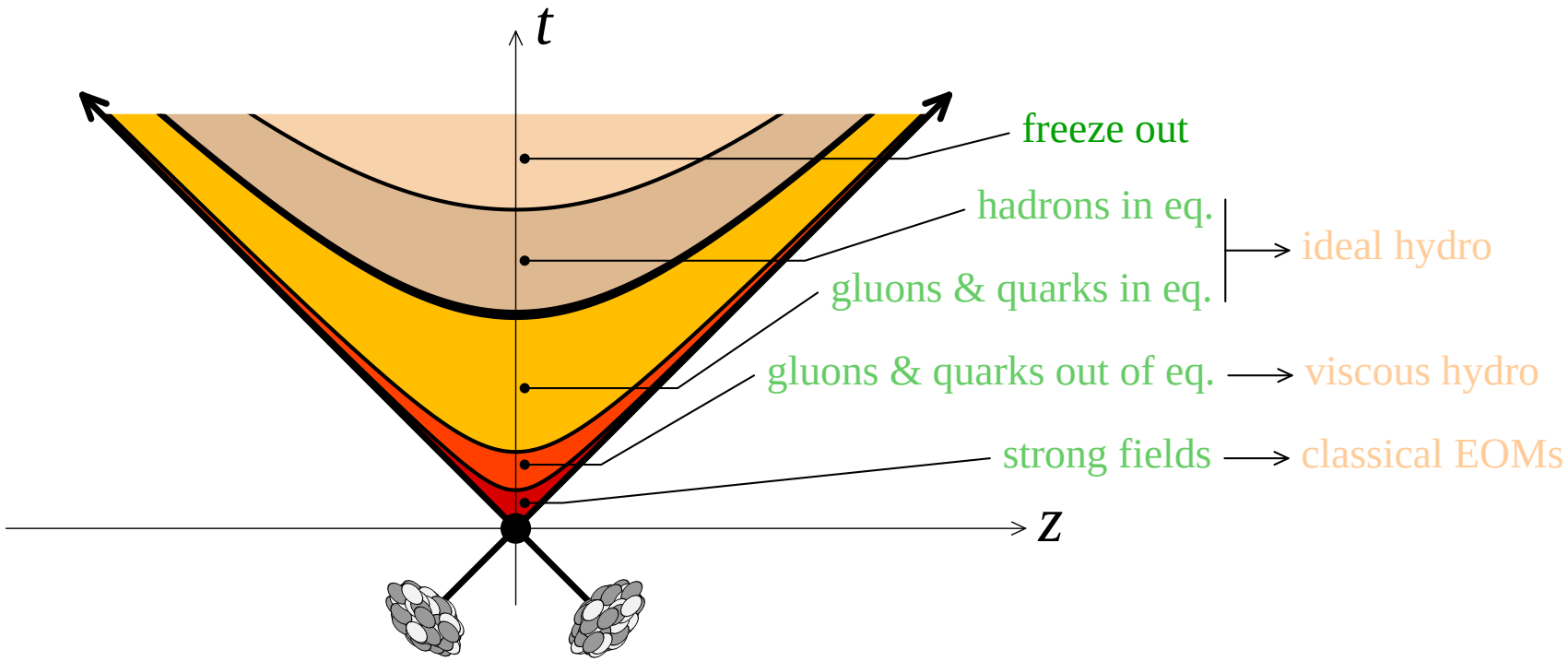
- $2 \leq \tau \lesssim 5$ fm/c
- Quark gluon plasma

Stages of a nucleus-nucleus collision



- $5 \lesssim \tau \lesssim 10$ fm/c
- Hot hadron gas

Stages of a nucleus-nucleus collision



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

Observables

Initial energy density

- Bjorken estimate :

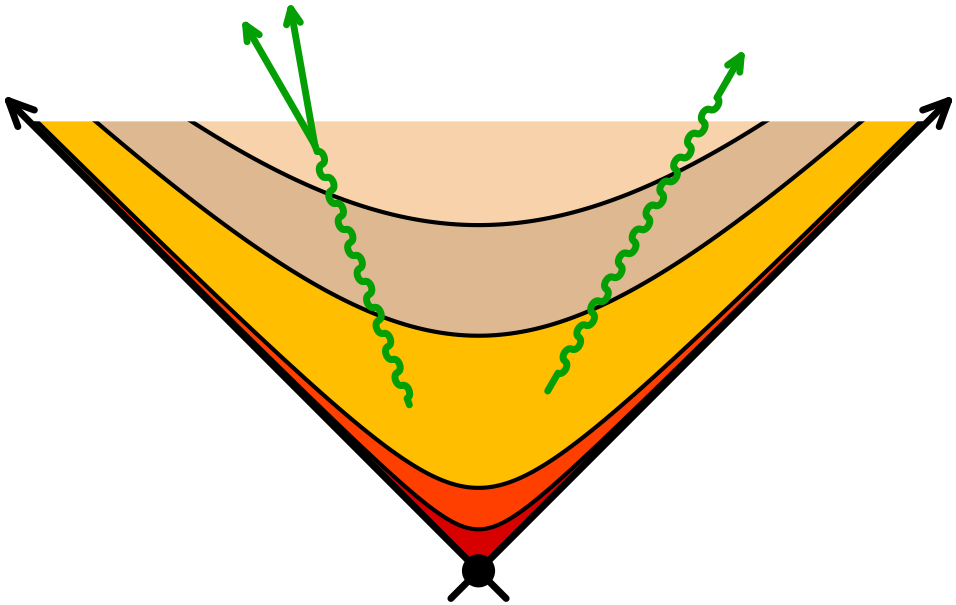
$$\epsilon_0 \approx \frac{1}{S_\perp \tau_0} \frac{dE_\perp}{dy}$$

- $dE_\perp/dy \approx 620$ GeV at RHIC ($\sqrt{s} = 200$ GeV, gold nuclei)
- $S_\perp \approx 140$ fm^2 for central collisions
- $\tau_0 \approx 0.15$ fm

$$\triangleright \quad \epsilon_0 \approx 30 \text{ GeV/fm}^3$$

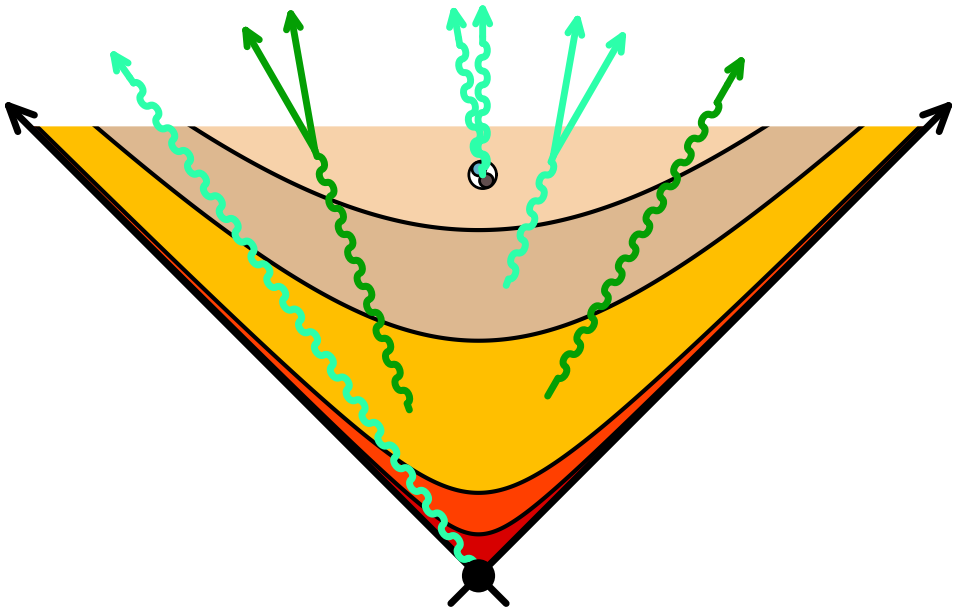
- Reminder : lattice QCD predicts deconfinement at $\epsilon_{\rm crit} \sim 1$ GeV/fm^3
- Note : things look less impressive in terms of the temperature since $\epsilon \sim T^4 \quad \Rightarrow \quad T/T_{\rm crit} \sim 30^{1/4} \sim 2.3$

Thermal photons



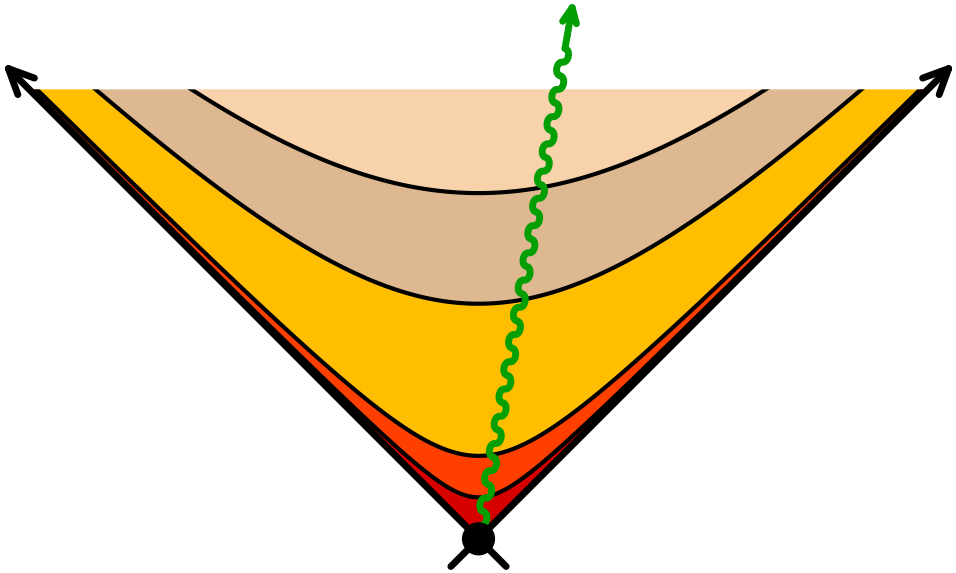
- Photons produced by the QGP :
  - Rate determined by physics at the scale g^2T
  - Very sensitive to the temperature : $dN_\gamma/dtd^3\vec{\boldsymbol{x}} \sim T^4$

Thermal photons



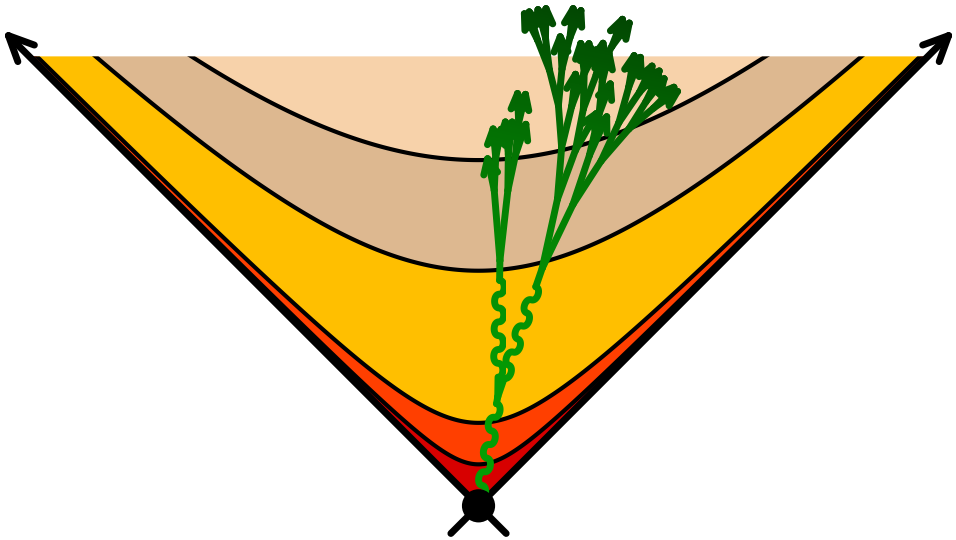
- Photons produced by the QGP :
  - Rate determined by physics at the scale g^2T
  - Very sensitive to the temperature : $dN_\gamma/dtd^3\vec{\boldsymbol{x}} \sim T^4$
- But very important background...
  - initial photons
  - photons produced by in-medium jet fragmentation
  - photons produced by the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

Jet quenching



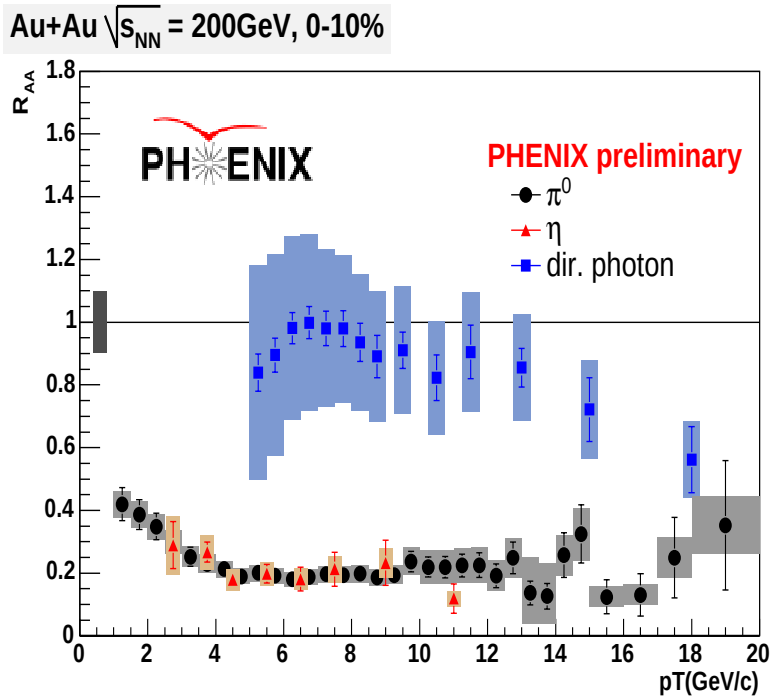
- High $p_\perp$ jets are produced at the initial impact
  - Not very interesting by themselves...

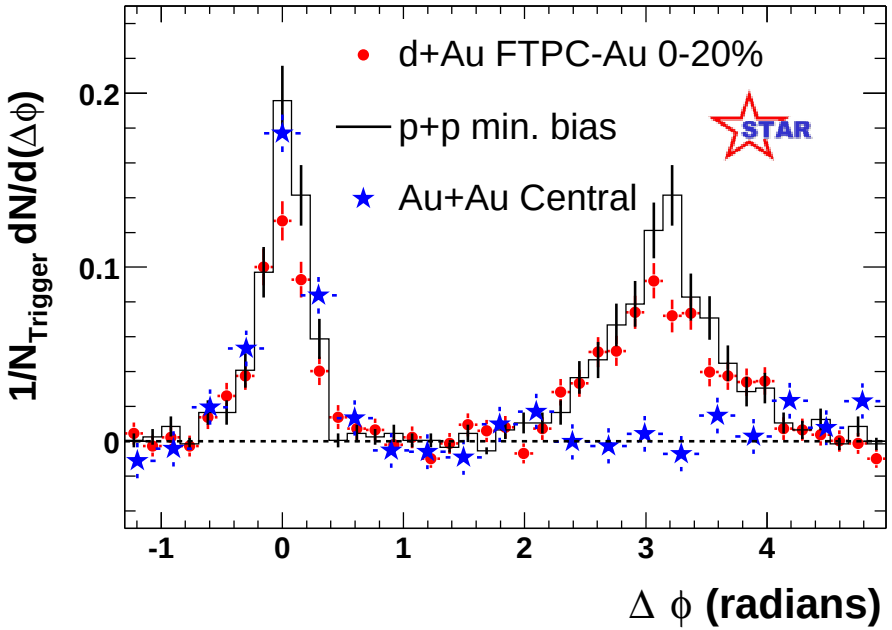
Jet quenching



- High $p_\perp$ 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

Jet quenching

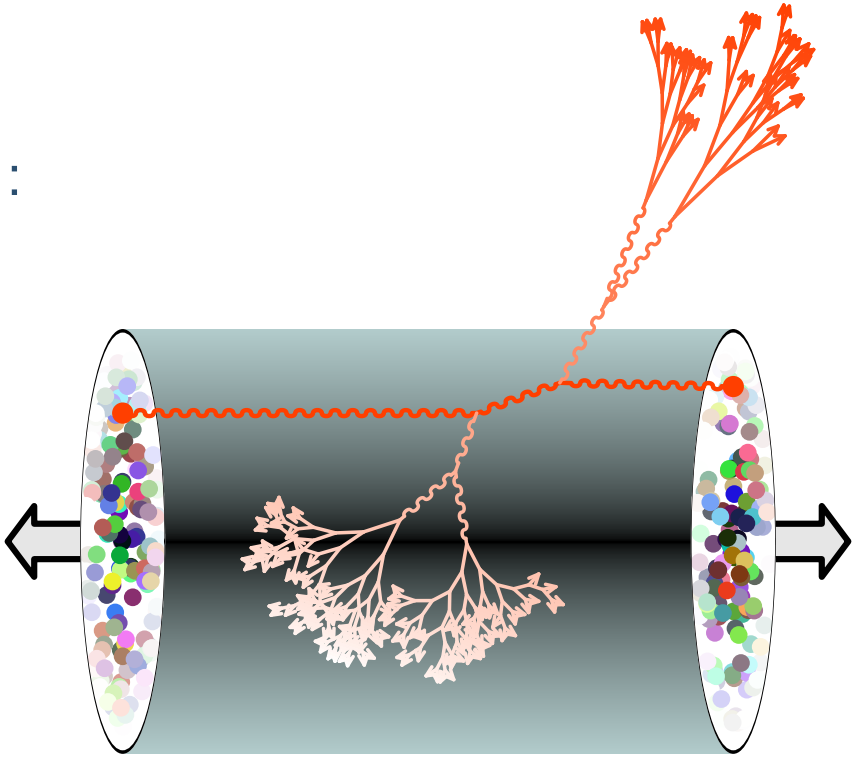




- Hadrons are strongly suppressed
  - Mesons involving heavy quarks (e.g. D) are also suppressed
  - Photons are not suppressed
- The correlation at 180° disappears in AA collisions

Jet quenching

- Interpretation :

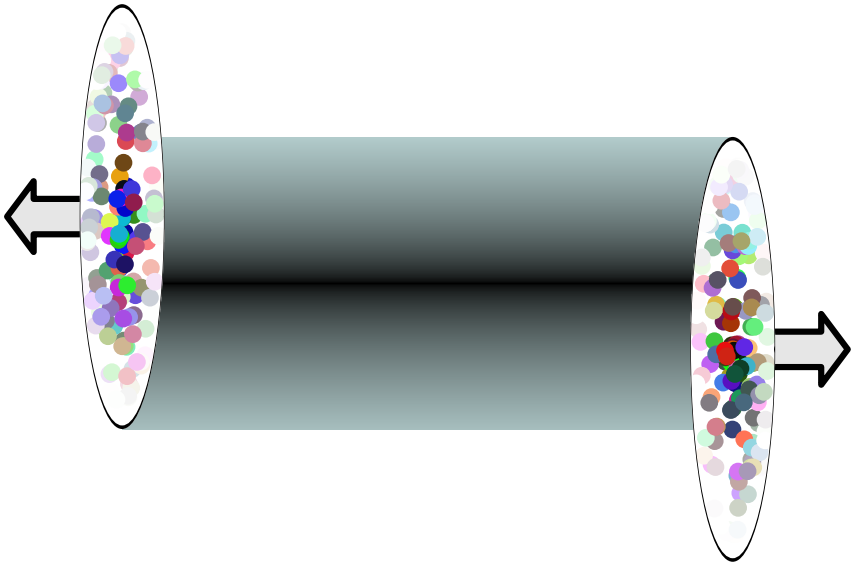


  - Jets escape only if they are produced near the edge and are directed outwards
  - The opposite jet is totally absorbed

    ▷ confirms the very large energy density

Collective flow

- Consider a non-central collision :



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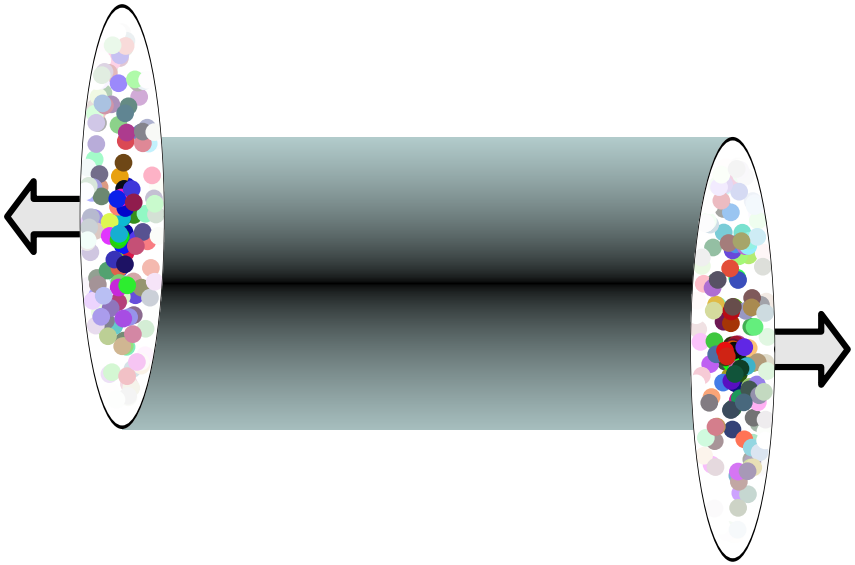

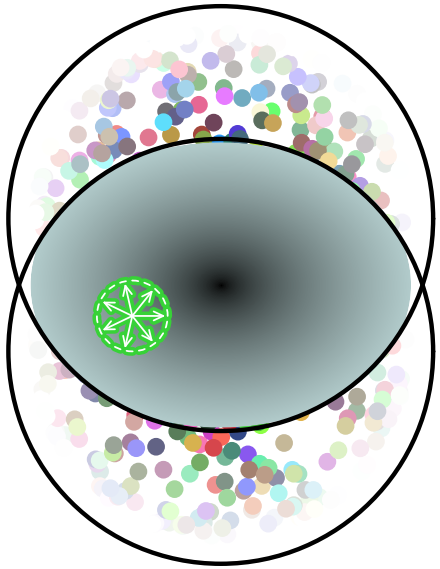

  - Initially, the momentum distribution of particles is isotropic in the transverse plane, because their production comes from local partonic interactions

Collective flow

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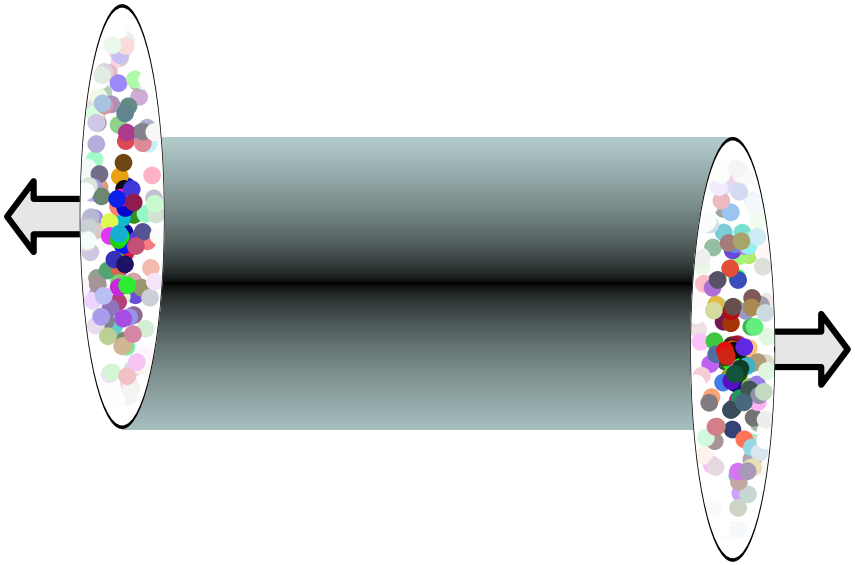

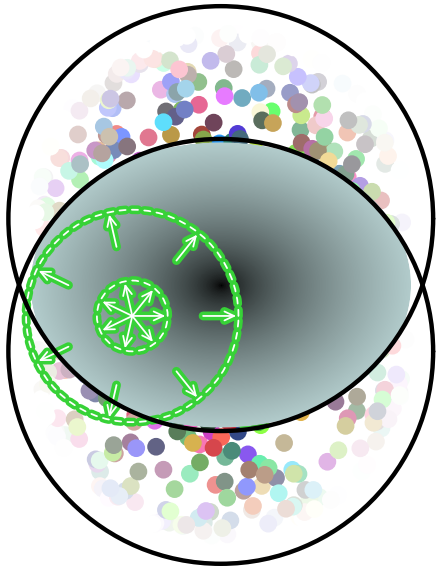

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Collective flow

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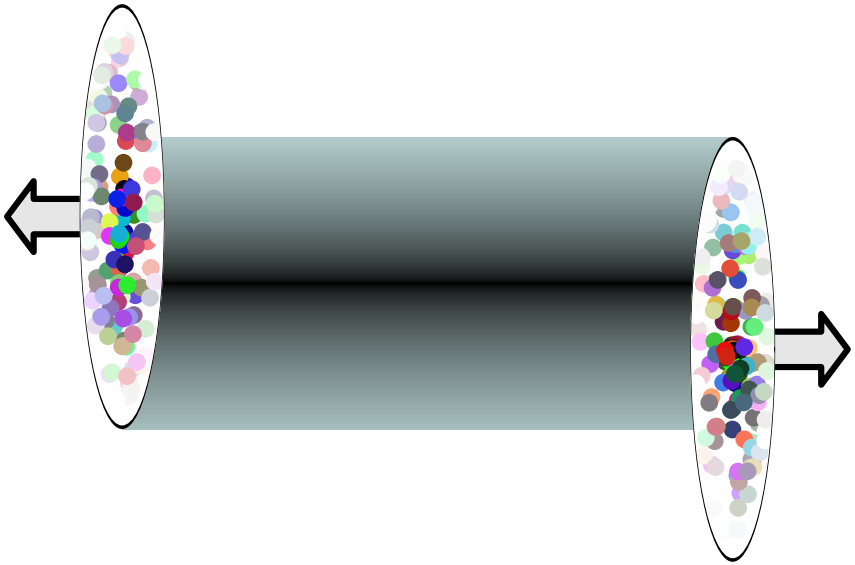
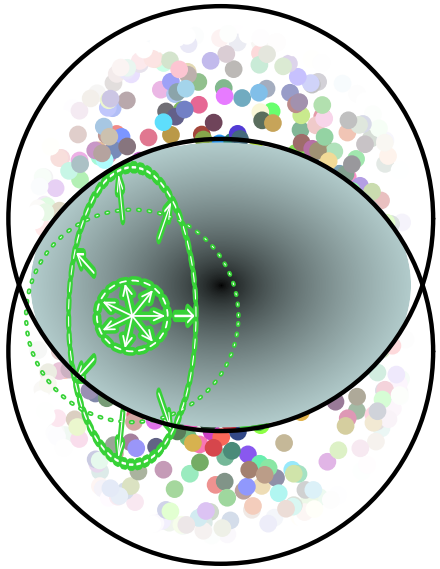




  - Initially, the momentum distribution of particles is isotropic in the transverse plane, because their production comes from local partonic interactions
  - If these particles were escaping freely, the distribution would remain isotropic at all times
  - If the system has a small mean free path, pressure gradients are anisotropy and induce an anisotropy of the distribution

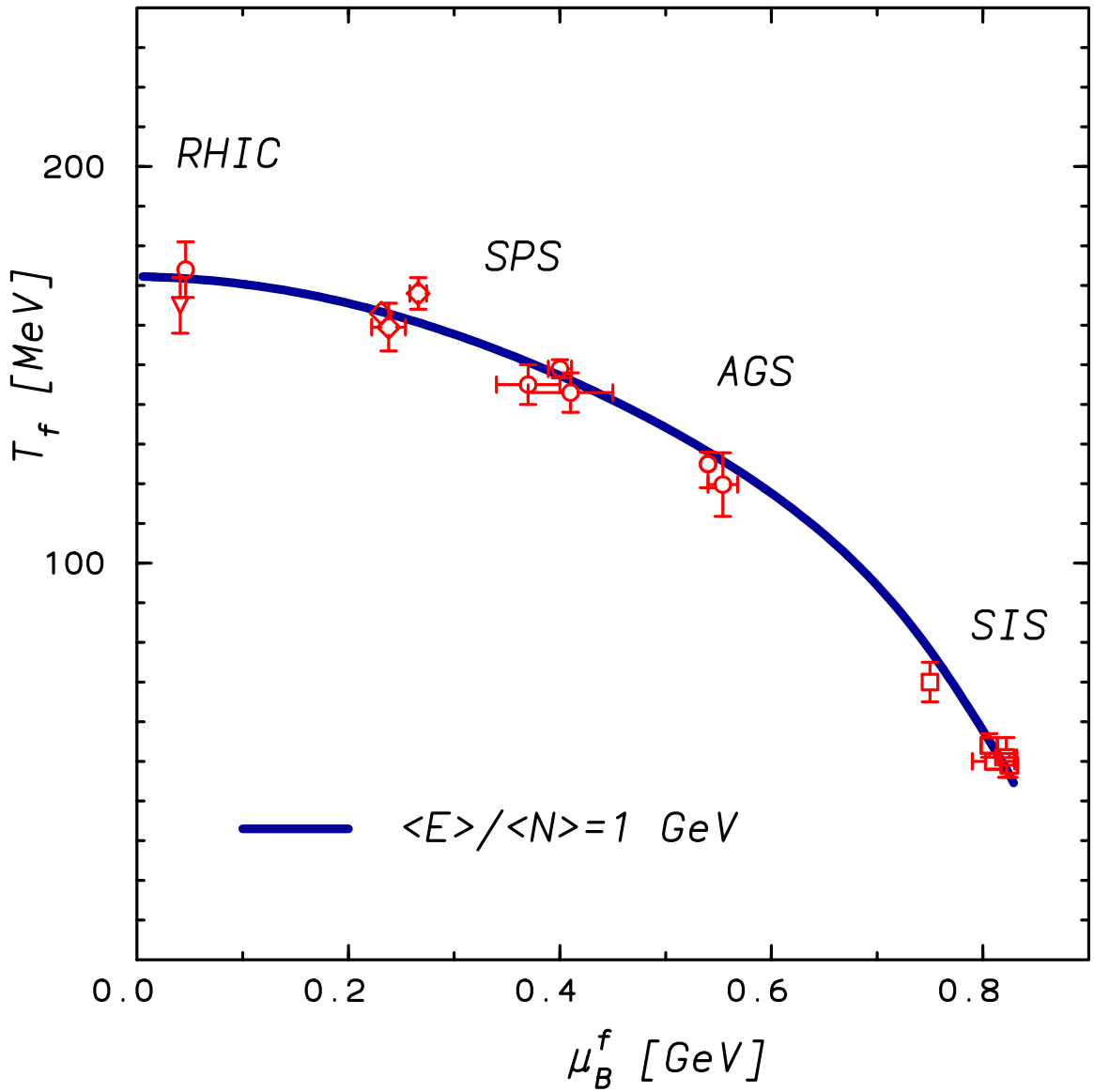
Freeze-out parameters

- Assume that particles are produced by a thermal source with temperature T and baryon chemical potential μ_B
- The number of particles of mass m per unit volume is :

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

- Fit the parameters T and μ_B by measuring the ratios between the yields of particles of different species

Freeze-out parameters



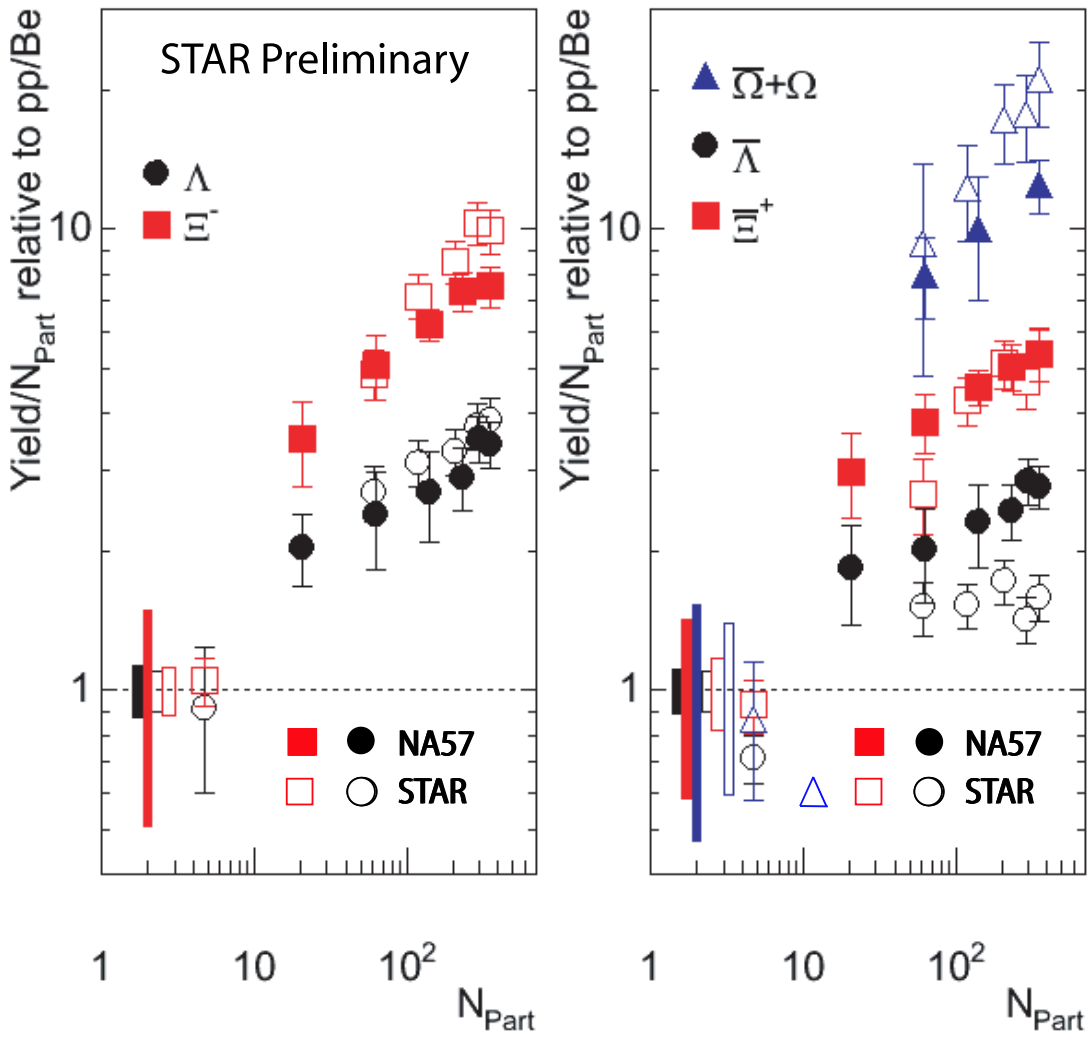
Strangeness enhancement

- 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
  ▷ In pp collisions: more non-strange than strange particles

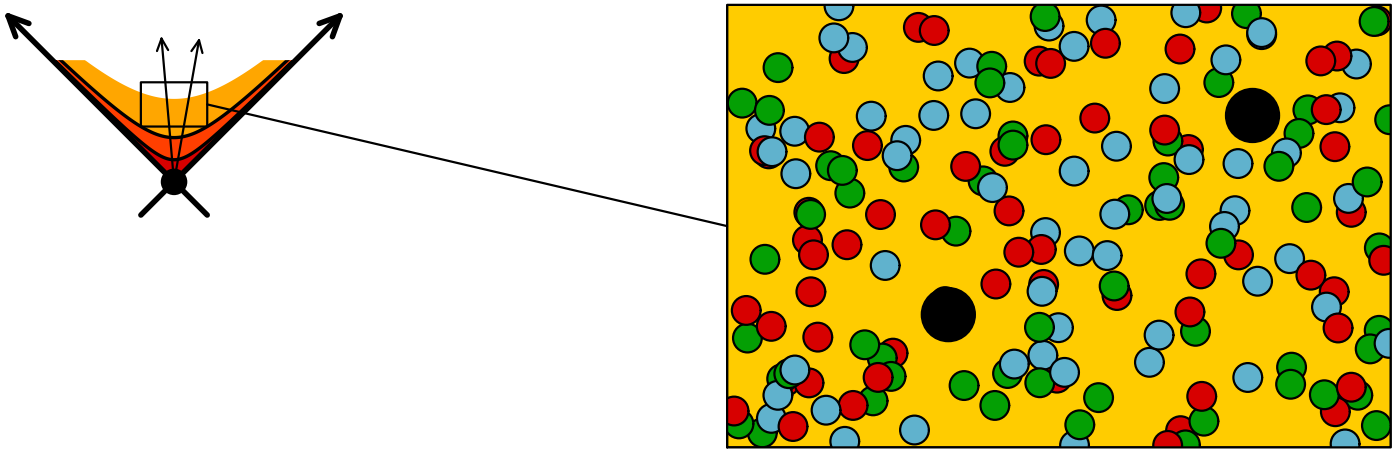
- In the QGP, the average energy of u, d quarks and of the gluons is of the order of the temperature
  ▷ at large T, the processes $u\bar{u} \to s\bar{s}$, $d\bar{d} \to s\bar{s}$, $gg \to s\bar{s}$ are not inhibited

- In this case, the population of strange quarks is identical to that of light quarks
  ▷ more strange particles than in proton-proton collisions

Strangeness enhancement



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 : $[J/\psi]$ / $[\text{Open charm}]$
  $\triangleright$ complication : there is also a suppression in proton-nucleus collisions, due to multiple scattering

J/Psi suppression

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

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

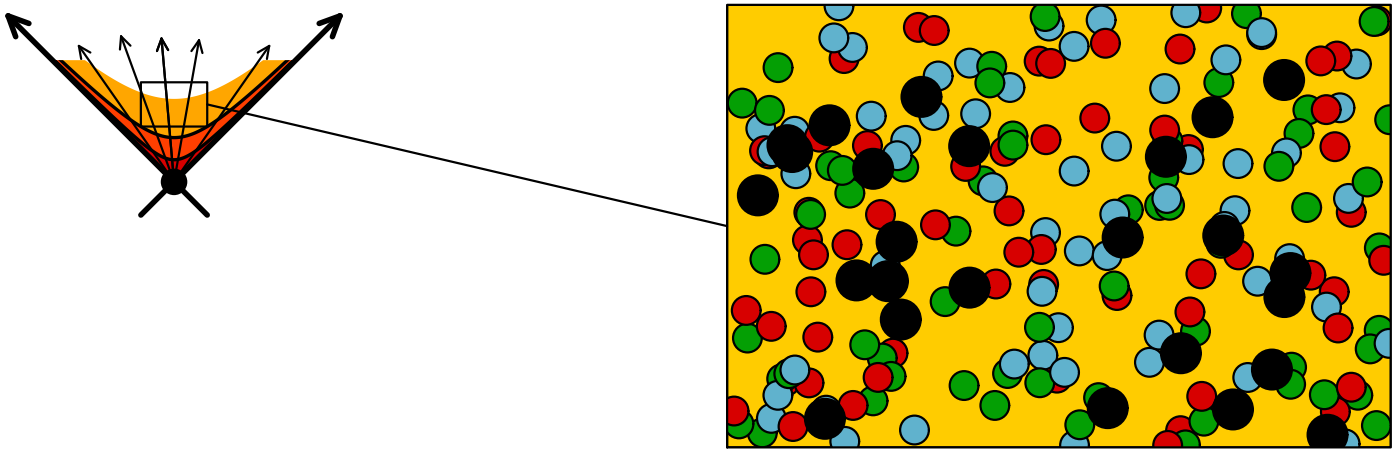
  - Non-relativistic
  - Assumes that there are only two-body interactions

- 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

$\triangleright$ 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