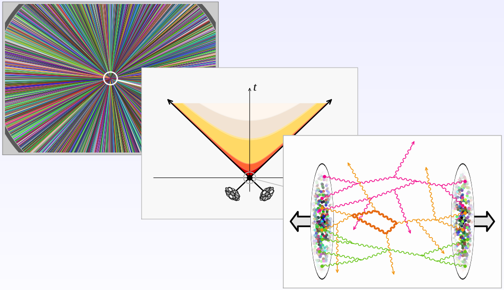
The Quark-Gluon plasma in the LHC era

Journées de prospective IN2P3-IRFU, Giens, Avril 2012



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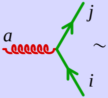
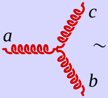
Quarks and gluons

Strong interactions : Quantum Chromo-Dynamics

- Matter : quarks ; Interaction carriers : gluons



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



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

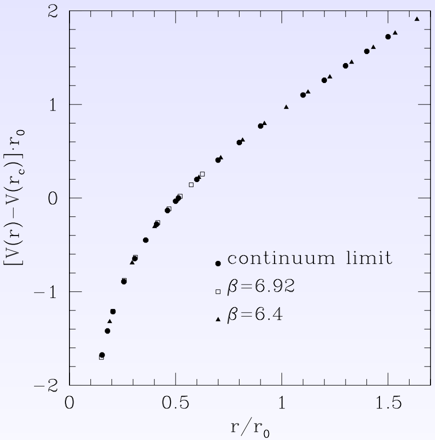
- i, j : quark colors ; a, b, c : gluon colors
- $(t^a)_{ij}$: 3×3 SU(3) matrix ; $(T^a)_{bc}$: 8×8 SU(3) matrix

Lagrangian

$$\mathcal{L} = -\frac{1}{4}F^2 + \sum_f \overline{\psi}_f (i\not{D} - m_f)\psi_f$$

- Free parameters : quark masses m_f, scale $\Lambda_{\rm QCD}$ (or $\alpha_s(M_z)$)

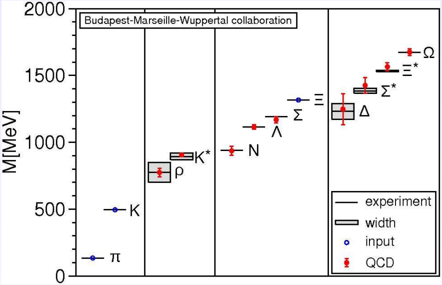
Color confinement



- Lattice evidence : linear rise of the $Q\overline{Q}$ potential

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 $\Lambda_{\rm QCD}, m_f$
- But this dependence is non-perturbative (it can now be obtained fairly accurately by lattice simulations)

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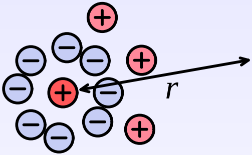
Debye screening

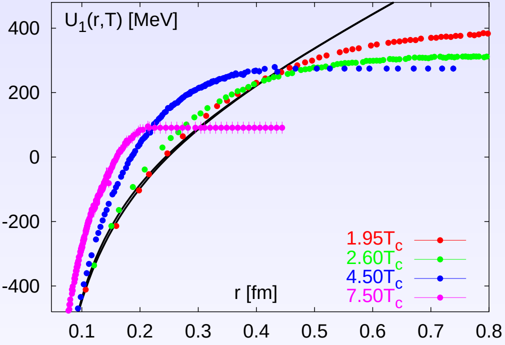
What happens when many hadrons
are packed in a small volume?



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

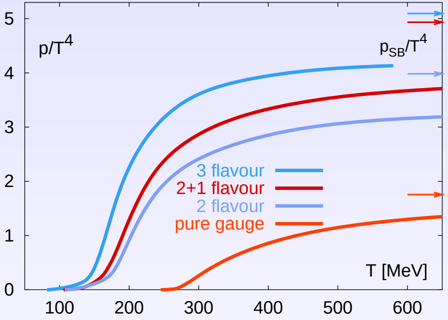
- In a dense medium, color charges are screened by their neighbors
- The interaction potential decreases exponentially beyond the Debye radius r_{debye}
- Hadrons whose radius is larger than r_{debye} cannot bind

Debye screening



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

Deconfinement transition



- Rapid increase of the pressure :
  - at $T \sim$ 270 MeV, with gluons only
  - at $T \sim$ 150 to 180 MeV, with light quarks

▷ interpreted as the increase in the number of degrees of freedom due to the liberation of quarks and gluons

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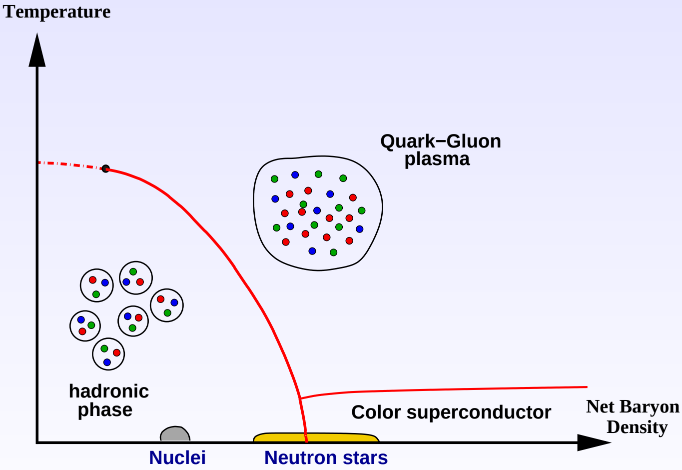
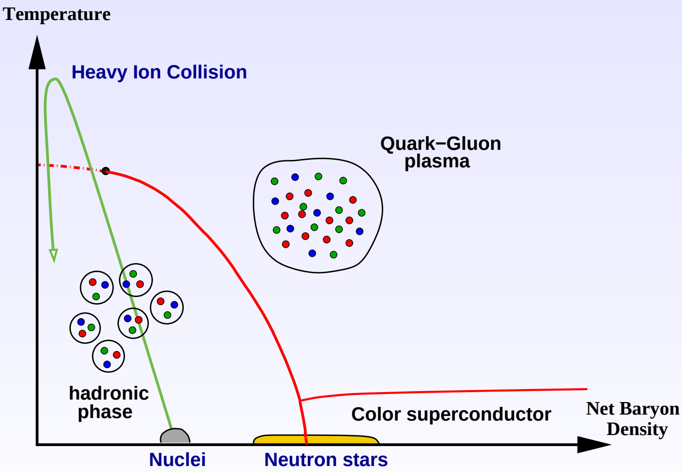
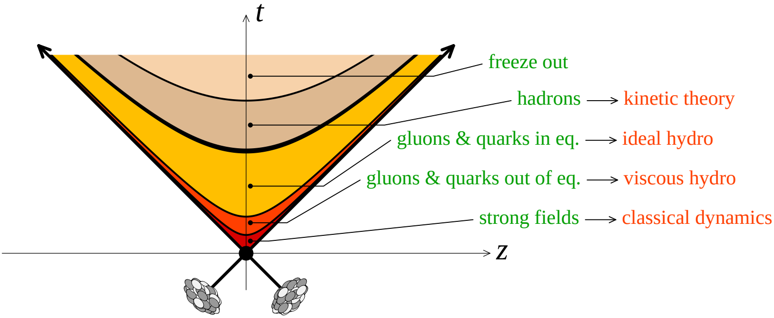
QCD phase diagram



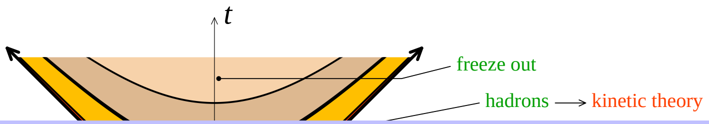
Heavy ion collisions



Stages of a nucleus-nucleus collision



Stages of a nucleus-nucleus collision



What would we like to learn?

i. Thermalization? to what degree? initial T?

ii. Do heavy hadrons survive in the QGP?

iii. Transport properties of deconfined matter

iv. Hadronization mechanisms

v. Existence and location of a 2nd order critical point

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Is the QGP in equilibrium?

Why is it important?

- If the QGP is not in equilibrium, then it remembers many details about the initial condition $\Longrightarrow$ what we measure is not a simple property of the QGP
- Theory predictions are much easier in equilibrium (lattice QCD works ONLY in equilibrium)
- Hydrodynamics is applicable only to systems close enough to equilibrium

Questions

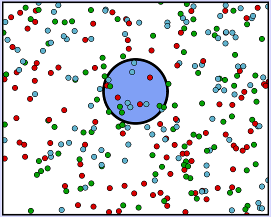
- At what time is the system thermalized?
- What is its temperature at that time?

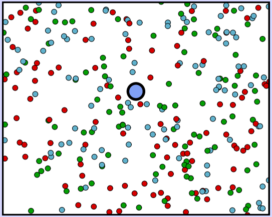
Probes

- Indirect evidence from hydrodynamical models
- Thermal direct photons

Do heavy states survive?

Large hadrons melt, while the small ones should survive





- Bound state sizes decrease as their mass increase
- Excited states are larger than ground states

$\Longrightarrow$ Melting order: light mesons, χ_c, ψ', J/ψ, Υ'', Υ', Υ

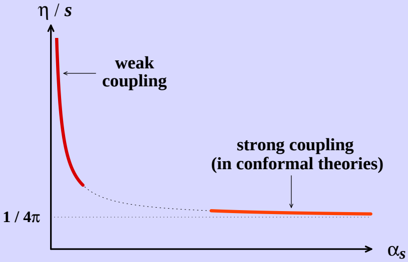
Probes

- Quarkonia yields, up to the upsilon family
- Open heavy flavors would help disentangle various models
- Reference yields in proton-proton and proton-nucleus

Transport properties (I)

- The viscosity η tells us how good a fluid the QGP is (small viscosity = better fluid)

What do the theorists expect?

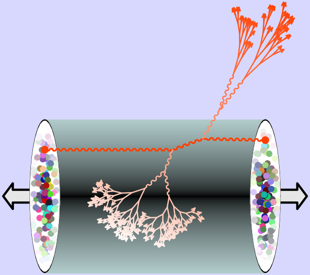


What we would like to learn from flow measurements

- How small is it really?
- So far, only a gross average value: can we get the viscosity at several stages of the evolution?
- Do heavier partons (**c** and **b** quarks) flow?

Transport properties (II)

How are parton cascades modified in a dense medium?



- Are jets completely absorbed?
- What fraction of hadrons manage to get out?
- Modifications of angular correlations
- Modifications of jet fragmentation functions
- Mass dependence: do heavy quarks also lose energy?

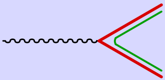
Hadronization mechanism

Hadronization by fragmentation (dominant in vacuum)

- $V(Q,\overline{Q})$ increases

Hadronization mechanism

Hadronization by fragmentation (dominant in vacuum)



- $V(Q, \overline{Q})$ increases
- At some point, there is enough energy to extract a new $q\overline{q}$ pair from the vacuum

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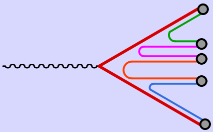

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- This process repeats, and hadrons are formed at the end of the cascade

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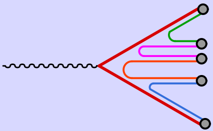
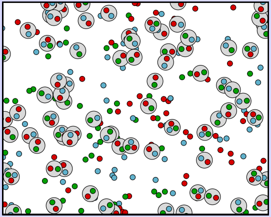


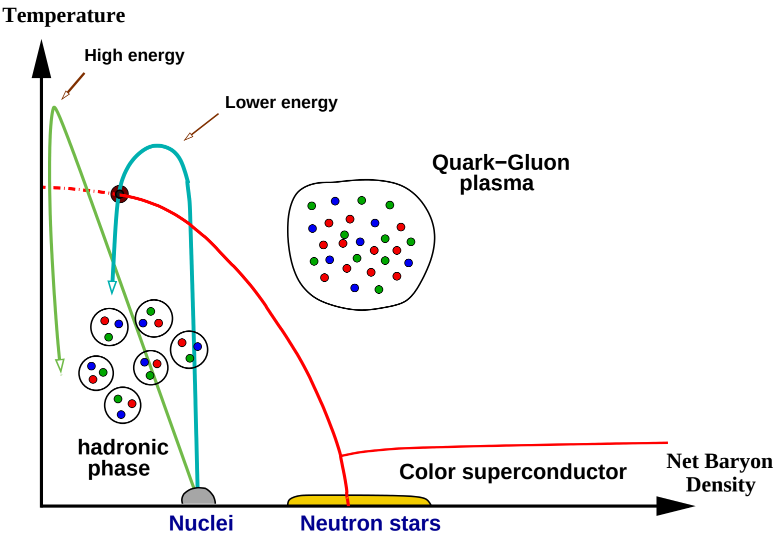
- $V(Q, \overline{Q})$ increases
- At some point, there is enough energy to extract a new $q\bar{q}$ pair from the vacuum
- This process repeats, and hadrons are formed at the end of the cascade

Hadronization by coalescence

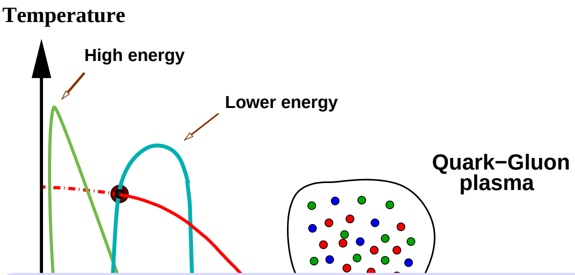


- Nearby partons in the QGP bind together
- Larger yield of baryons
- More strange hadrons if $T \gtrsim 2m_s$

Critical point



Critical point



- At zero density: crossover (known from lattice QCD)
- At high density: first order transition line?
- If true, there should be a 2nd order critical endpoint
- How do we get there? collisions at lower energy
- What do we look for? unusually large fluctuations

Outlook

Projects (see J. Castillo and M. Estienne presentations)

- **ALICE** upgrades: Inner tracking, Calorimetry, Muon forward tracking, Vzero
- **CBM** experiment at FAIR (GSI, Germany)
- **CHIC**, **AFTER**