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Deconfinement in QCD and in Nuclear Collisions

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1. States of Matter in QCD

2. High Energy Nuclear Collisions

3. Experimental Signatures

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1. States of Matter in QCD

What happens to strongly interacting matter in the limit of high temperature and/or density?

- **hadrons have intrinsic size $r_h \simeq 1$ fm**

  hadron needs $V_h \simeq (4\pi/3) r_h^3$ to exist

  $\Rightarrow$ limiting density of hadronic matter

  $n_c = 1/V_h \simeq 1.5\ n_0$ **[Pomeranchuk 1951]**

- **hadronic resonance dynamics $\rightarrow$**

  exponential growth of hadron species

  $\rho(m) \sim \exp(bm)$

  – statistical bootstrap model

  [Hagedorn 1968]

  – dual resonance model

  [Fubini & Veneziano 1969; Bardakçi &Mandelstam 1969]

  $\Rightarrow$ limiting temperature of hadronic matter $T_c = 1/b \simeq 150 - 200$ MeV

- **what happens beyond n_c, T_c?**

  QCD: hadrons are dimensionful color-neutral bound states of pointlike coloured quarks and gluons

  hadronic matter: colourless constituents

  $\Downarrow$

  quark-gluon plasma: coloured constituents

  deconfinement $\sim$ insulator-conductor transition

- **effective quark mass shift**

  at $T = 0$, quarks 'dress' with gluons

  $m_q \to M_q \Rightarrow$ **constituent quarks**

  in hot medium, dressing 'melts' $M_q \to 0$

  for $m_q = 0$, $\mathcal{L}_{QCD}$ **has chiral symmetry**

  $M_q \neq 0$**: spontaneous chiral symmetry breaking**

  $M_q \to 0 \Rightarrow$ **chiral symmetry restoration**

- **diquark matter**

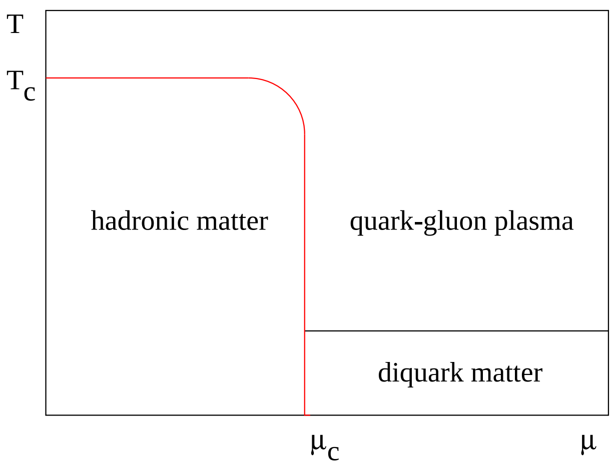
  deconfined quarks $\sim$ attractive interaction

  $\to$ coloured bosonic 'diquark' pairs (Cooper pairs of QCD)

  $\Rightarrow$ diquark condensate $\sim$ colour superconductor

  thermal agitation can break diquark binding: transition superconductor $\to$ conductor

- **expected phase diagram of QCD:**



baryochemical potential $\mu \sim$ baryon density.

- **statistical QCD:**

  given QCD as dynamics dynamics input, calculate resulting thermodynamics, based on QCD partition function $Z_{QCD}(T,V)$

  Ab initio calculation:

  $\Rightarrow$ **finite temperature/finite density lattice QCD**

- **order parameters**

  – **deconfinement**

  Polyakov loop $L \sim \exp\{-V_{Q\bar{Q}}/T\}$

  $V_{Q\bar{Q}}$: **potential energy of** $Q\bar{Q}$ **pair for** $r \to \infty$

  $\Rightarrow$ **L=0 : confinement**
  L≠0 : deconfinement

  $\to$ **deconfinement temperature** T_L

  – **chiral symmetry restoration**

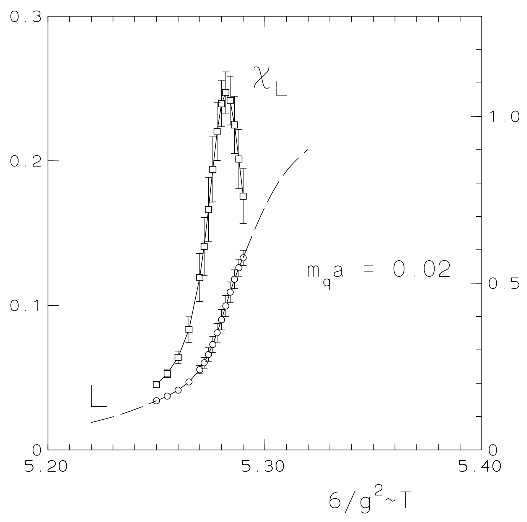
  chiral condensate $\chi \equiv \langle\bar{\psi}\psi\rangle \sim M_q$
  measures 'constituent' quark mass

  $\Rightarrow$ $\chi \neq$**0 : chiral symmetry broken**
  $\chi =$**0 : chiral symmetry restored**

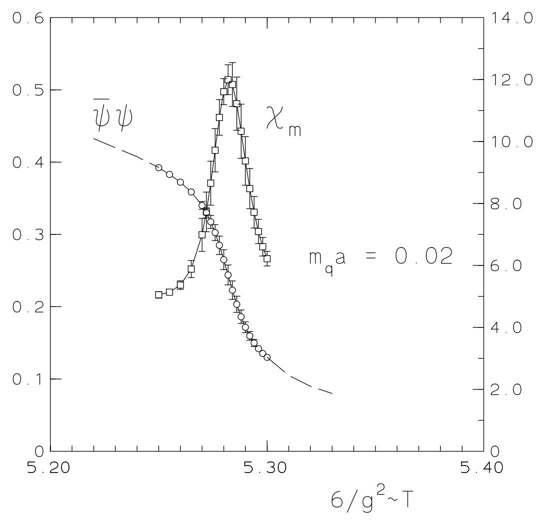
  $\to$ **chiral symmetry restoration temperature** T_χ

  – **how are** T_L **and** T_χ **related?**

lattice results



Polyakov loop



chiral condensate

conclude:

deconfinement and chiral symmetry restoration coincide, determine critical temperature T_c

$$\boxed{N_f = 2, 2+1: \; T_c \simeq \; 175 \text{ MeV}}$$

in chiral limit ($m_q \to 0$).

- **energy density**

ideal gas of massless pions

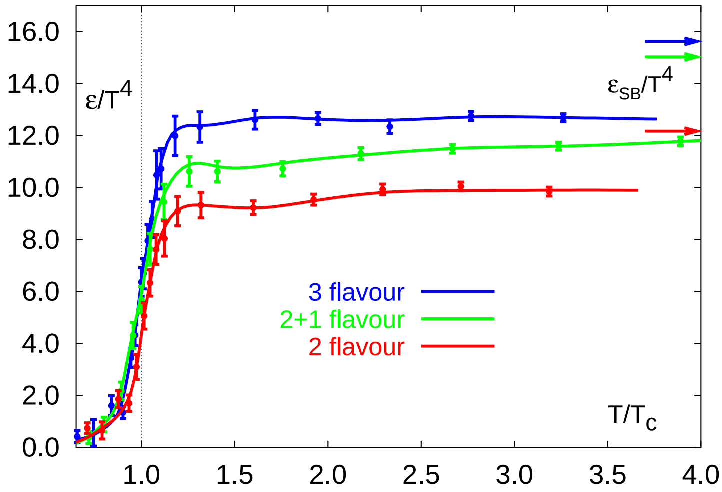
$$\epsilon_h = 3 \, \frac{\pi^2}{30} \, T^4 \simeq T^4$$

ideal gas of massless quarks (N_f=2) and gluons

$$\epsilon_{QGP} = 37 \, \frac{\pi^2}{30} \, T^4 \simeq 12 \, T^4$$

deconfinement $\Rightarrow$ sudden increase in energy density: "<u>latent heat of deconfinement</u>"

lattice results

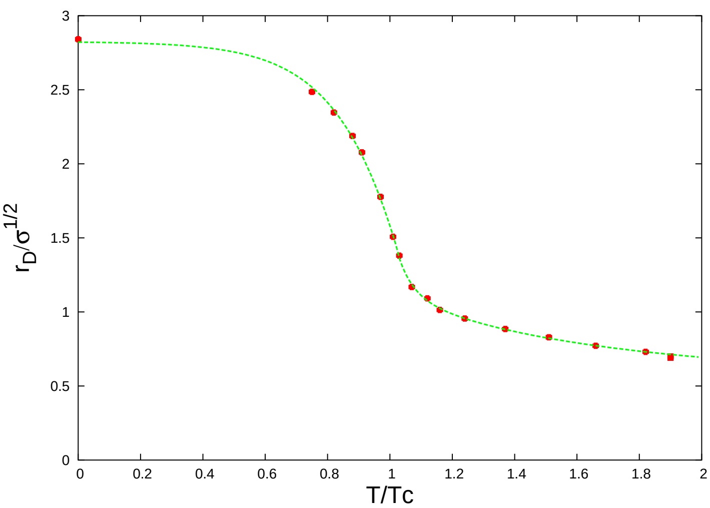


with

$$N_f = 2, 2+1: \ \ \epsilon(T_c) \simeq 0.5 - 1.0 \ \mathrm{GeV/fm^3}$$

for deconfinement energy density.

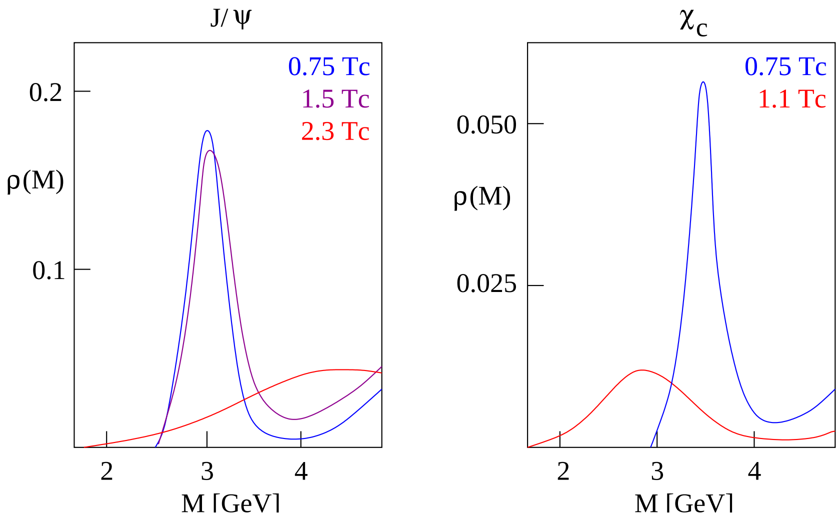
- interaction range (from string breaking) drops sharply as $T \to T_c$



from $r \simeq 1.5$ fm to $r \simeq 0.3$ fm

$\Rightarrow$ colour screening

- **consequence: charmonium suppression**



J/ψ survives until 1.5–2.0 T_c

χ_c suppressed essentially at T_c

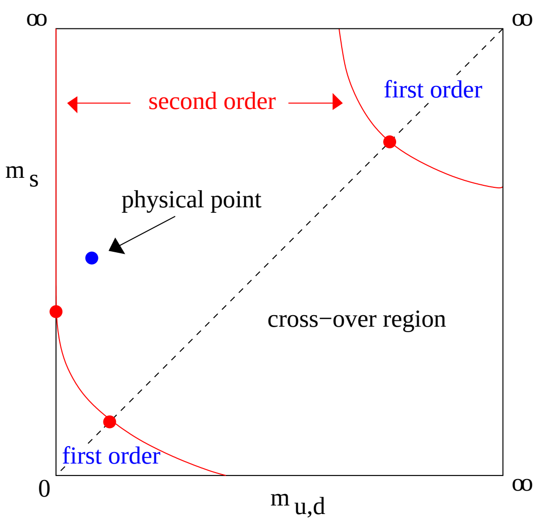
NB: equilibrium QCD thermodynamics

- **nature of transition**

depends on N_f and m_q:

continuous, first order, cross-over (percolation)

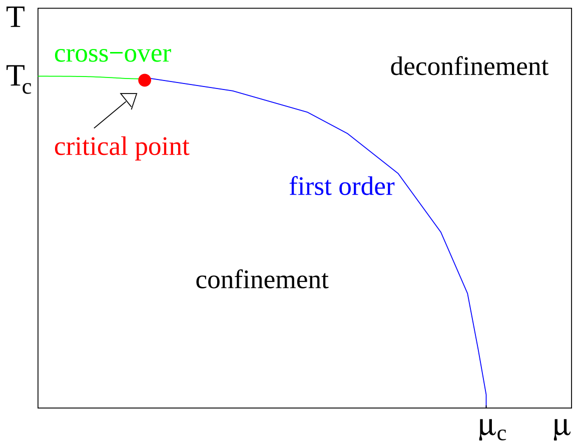
structure for $\mu = 0$



• <u>non-zero net baryon density</u> ($\mu \neq 0, N_b > N_{\bar{b}}$),

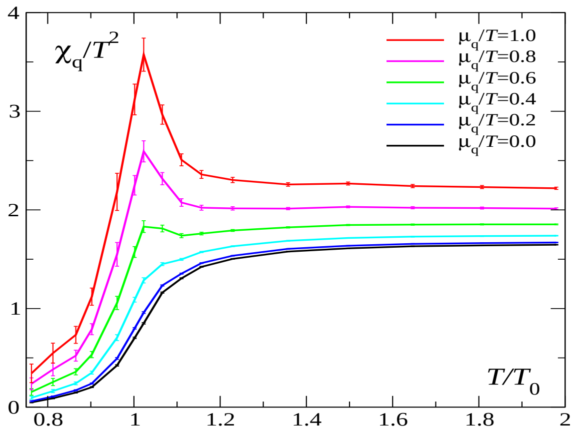
computer algorithms break down, power series...

<u>conjecture for $\mu \neq 0,\ N_f = 2+1$</u>



<u>critical point</u> in $T - \mu$ plane depends on position of <u>physical point</u> in $m_s - m_{u,d}$ plane

preliminary results (m_q, power series, ...)



net baryon density fluctuations increase with μ,

$\rightarrow$ approach to critical point $\mu_c \simeq 0.3 - 0.7$ GeV

- conclude:

  in QCD, ∃ critical temperature T_c

  at which

  – deconfinement sets in

  – chiral symmetry is restored

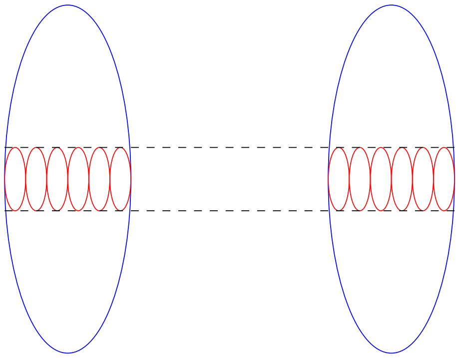
  – latent heat of deconfinement increases energy density

  – colour screening reduces interaction range

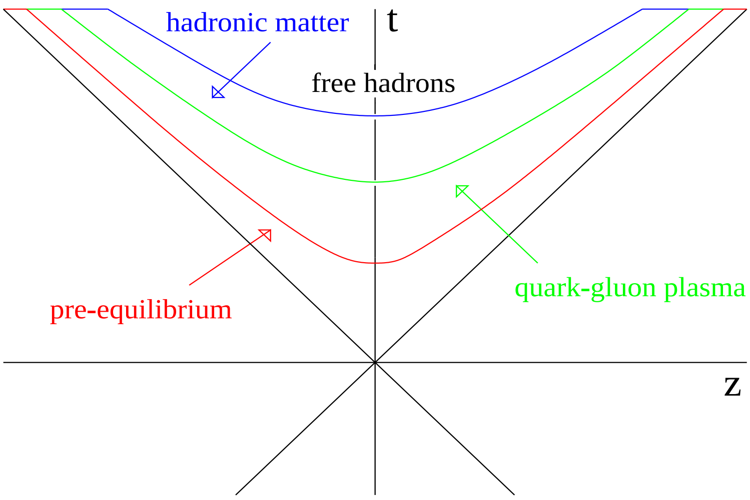
Can all this be tested in the laboratory?

2. High Energy Nuclear Collisions

High energy $A-A$ collisions produce many nucleon-nucleon collisions in same space time region



Canonical view of high enery heavy ion collision



Assume:

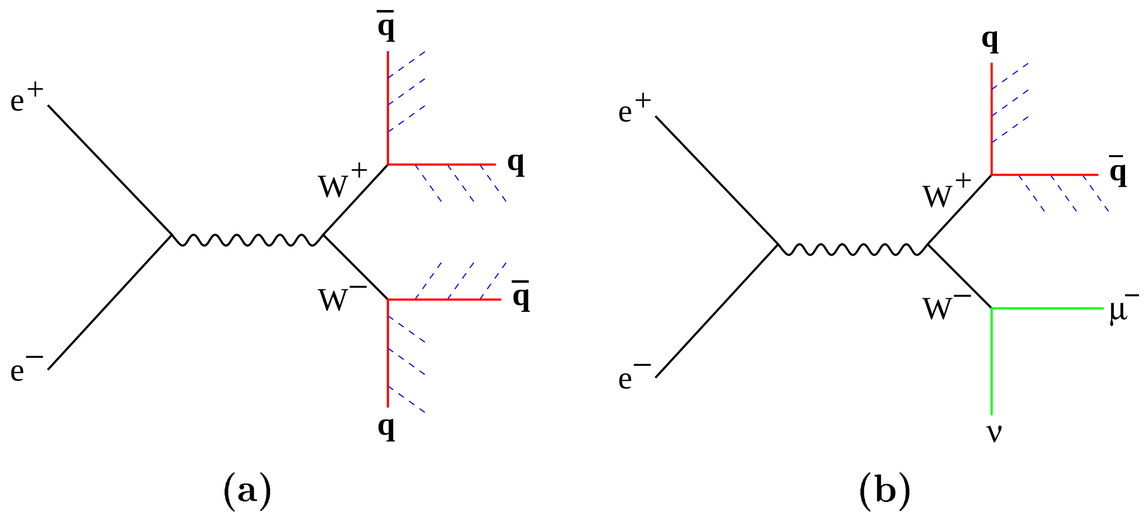
multiple parton interactions → thermalization, hot thermal medium: quark-gluon plasma, thermal deconfinement/confinement transition, emission of hadrons

conditions for thermalization?

prerequisite :

∃ communication ('cross talk', 'colour connection') between partons from different nucleon interactions

counterexample : hadron production at LEP



consider hadron multiplicity from jet decay of W's

– cross talk:

$\Rightarrow N_h(a) < 2N_h(b)$

– no cross talk:

$\Rightarrow N_h(a) = 2N_h(b)$ $\Leftarrow$ 3 LEP expts.

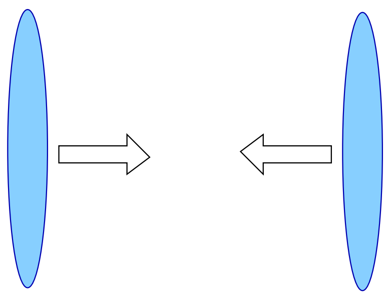
same space-time region, but no cross talk

$\Rightarrow$ pre-equilibrium initial state conditions crucial for final state of high energy nuclear collisions

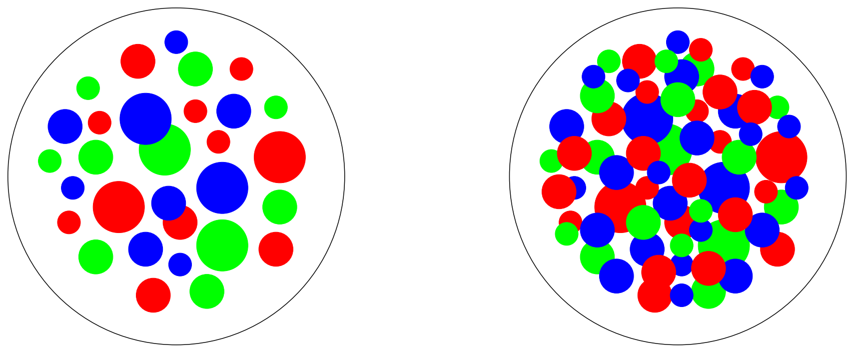
$\Rightarrow$ parton percolation, colour glass condensate

Consider partons in nuclear collisions:

Lorentz-contracted nuclei ($A - A$)



superposition of partons: parton density in transverse plane increases with A, $\sqrt{s}$



with increasing density:

partons overlap $\rightarrow$ clusters in transverse plane; within a cluster, partons communicate

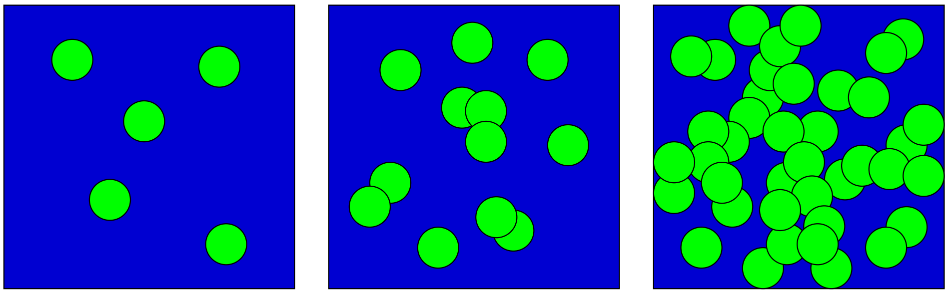
- **how does cluster size grow with parton density?**
- **when does partonic cluster size $\sim$ system size ($\rightarrow$ parton network, global cross-talk)?**

$\Rightarrow$ Short Interlude: Percolation Theory $\Leftarrow$

Percolation $\sim$ formation of infinite cluster, network

example: 2-d disk percolation (lilies on a pond)

distribute small disks of area $a = \pi r^2$ randomly on large area $F = L^2$, $L \gg r$, with overlap allowed



isolated disks **clusters** **percolation (network)**

for N disks, disk density $n = N/F$

average cluster size $S(n)$ increases with increasing density n

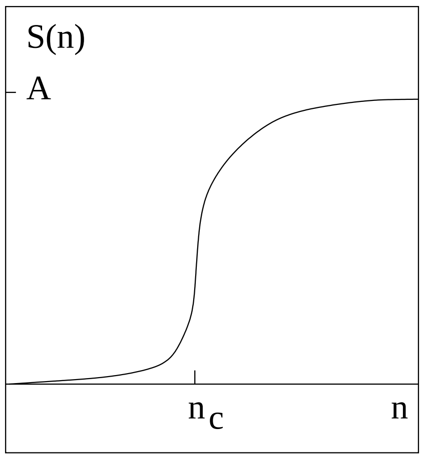
$\exists$ critical density: for

$$n \to n_c = 1.13/a$$

$S(n)$ spans area F: $S \sim F$

for $N \to \infty, F \to \infty$:

$S(n_c)$ and $(dS(n)/dn)_{n=n_c}$ diverge: $\Rightarrow$ percolation



probability $P(n)$ that given disk in infinite cluster

$$P(n) \begin{cases} = 0 & \forall\ n < n_c \\ \sim (n - n_c)^{\beta} & \text{for } n \to n_c \text{ from above} \end{cases}$$

$\Rightarrow$ order parameter for percolation

average cluster size diverges

$$\tilde{S}(n) \simeq |n - n_c|^{-\gamma}$$

so do other observables: singular behaviour as function of density n

$\Rightarrow$ critical exponents, universality classes

Why is there singular behaviour?

$\Rightarrow$ spontaneous global connection

connected or disconnected, not "gradual"

$\Rightarrow$ Geometric Critical Behaviour $\Leftarrow$

- onset of infinite cluster/network formation
- singular behaviour of geometric observables

- Thermodynamic critical behaviour:

spontaneous symmetry breaking as function of T

- Geometric critical behaviour:

spontaneous global connection as function of n

geometric critical behaviour can occur even if the partition function is analytic

$\Rightarrow$ geometric without thermodynamic criticality

(spin systems in external magnetic field)

$\Rightarrow$ End of Interlude $\Leftarrow$

To study percolation in (central) $A-A$ collisions:

- **number of partons per nucleon**

  - deep inelastic lepton-nucleon scattering gives parton distributions/nucleon, determines parton number at resolution scale Q:

$$\left(\frac{dN}{dy}\right)_{y=0} = x\{g(x,Q) + \sum_i [q_i(x,Q) + \bar{q}_i(x,Q)]\}$$

  with $x = Q/\sqrt{s}$ at $y = 0$.

  - in nucleon-nucleon collisions, resolution scale $Q \sim k_T$ defined by transverse parton size

- **number of parton sources per nucleus**

$$\left(\frac{dN}{dy}\right)^A_{y=0} = A\left(\frac{dN}{dy}\right)_{y=0}$$

- **transverse size of nucleus πR_A^2**

- **transverse size of parton**

$$\pi r^2 \simeq \pi/\langle k_T^2\rangle = \pi/Q^2$$

  intrinsic transverse momentum

Combine to get parton percolation condition for central $A-A$ collisions

$$\frac{2A}{\pi A^{2/3}}\left(\frac{dN(\sqrt{s},Q)}{dy}\right)_{y=0} = n_c = \frac{1.13}{\pi Q^{-2}}$$

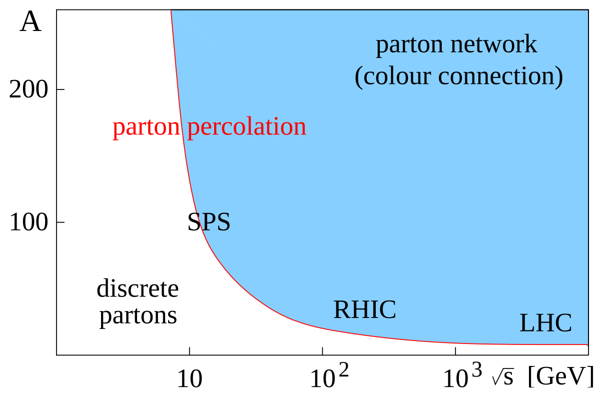
specifies A_s, Q_s, so that given $\sqrt{s}$, for $A \geq A_c$ and for parton scale $Q \leq Q_s$

$\exists$ parton percolation

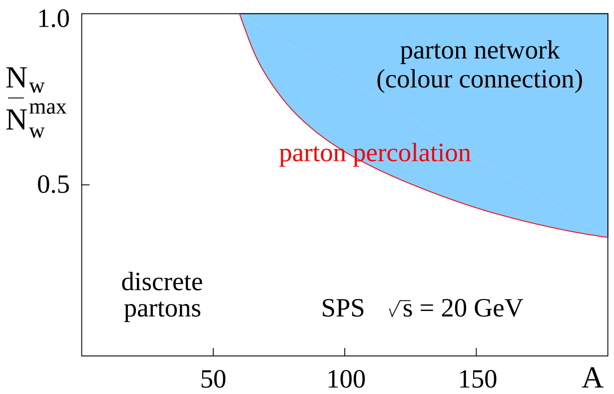
In general:

$\Rightarrow$ n_c depends on A, centrality, collision energy

schematic:
central $A-A$ collisions
vs. A and $\sqrt{s}$



schematic:
$Pb-Pb$ collisions
vs. centrality
SPS, $\sqrt{s} = 20$ GeV



parton network:

- partons of all scales $k_T \leq Q$
- interconnected and interacting
- geometric deconfinement
- no thermalization, but:

initial state fulfills prerequisite for thermalization
necessary, but not necessarily sufficient

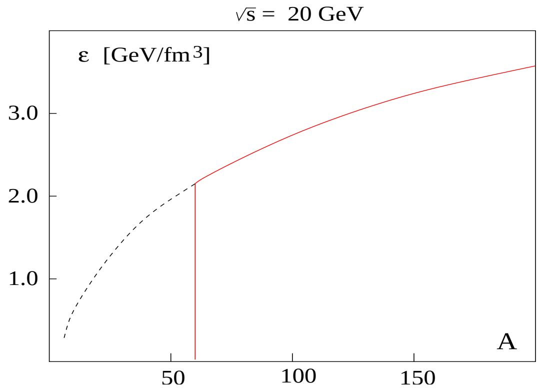
assume: parton network thermalizes $\rightarrow$ QGP energy density of QGP [Bjorken estimate]

$$\epsilon_0 \simeq \frac{p_0}{\pi R_A^2 \tau_0} \left(\frac{dN_h^{AA}}{dy} \right)_{y=0} \simeq \frac{p_0}{\pi \tau_0} A^{0.43} \ln(\sqrt{s}/2)$$

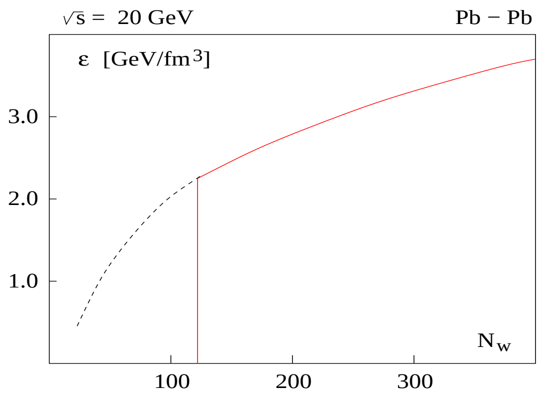
τ_0: time needed to reach thermalization

if partons do not form network, they cannot thermalize, $\tau_0 = \infty$

schematic:
central collisions
energy density
vs. A
for $\sqrt{s} = 20$ GeV



schematic:
$Pb-Pb$ collisions
energy density
vs. centrality
for $\sqrt{s} = 20$ GeV



$\Rightarrow$ hot QGP, well above deconfinement

$[\ \epsilon(T_c) \simeq 0.5 - 1.0\ \mathrm{GeV/fm^3}]$

experimental consequences?

3. Experimental Signatures

Initial state parton structure ⇒ geometric critical behavior ⇒ parton network

Parton network thermalizes ⇒ QGP ⇒ thermal critical behavior ⇒ hadronization

- how to probe and distinguish geometric and thermal critical behavior?
- what observable features follow already from parton percolation, parton network?
- do present data provide any evidence for (or against) thermalization?

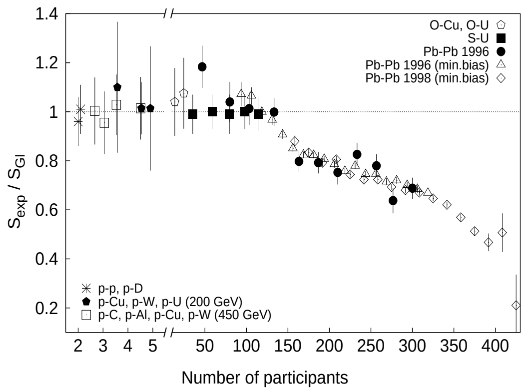
Consider as illustration

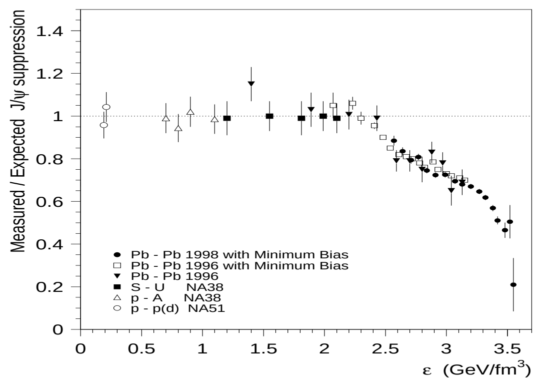
J/ψ Suppression

- charmonium states survive in confined matter, dissolve in hot enough QGP (different dissociation temperatures for different states).
- resolution scale in parton network at SPS ($\sqrt{s} = 20$ GeV, $Q \simeq 0.7$ GeV) allows χ_c break-up at and above percolation point; J/ψ?
- Feed-down J/ψ production in hadronic collisions: 60 % direct 1S, 30 % χ_c decay, 10 % ψ' decay; different dissociation points ⇒ step-wise J/ψ suppression.

- **Pre-resonance absorption in nuclei ⇒ reduced J/ψ production in pA collisions, <u>normal</u> J/ψ suppression.**

- **NA50 observes further <u>anomalous</u> J/ψ suppression in <u>stepwise</u> form.**





- **What does it mean?**
  - **geometric deconfinement**

    'step' at $N_{part} \simeq$ 125: onset of colour connection, formation of parton network; perhaps also at $\sim$ 250, when resolution scale in parton network reaches J/ψ scale.
  - **formation of hot QGP:**

    nothing happens at $\epsilon(T_c) \simeq 0.5 - 1.0$ GeV/fm^3: no parton connection, no QGP;
    at parton percolation, QGP possible; there $\epsilon \simeq$ 2.3 GeV/fm^3, and ∃ step in data

⇒ observed J/ψ suppression pattern may be due to initial state parton percolation or to subsequent thermal QGP formation

Conclude:

- **matter in equilibrium: statistical QCD**
  $\Rightarrow$ thermal deconfinement, quark-gluon plasma

- **nuclear collisions: parton structure**
  $\Rightarrow$ geometric deconfinement, parton network

- **thermalization of parton network, QGP formation in nuclear collisions? Quite possible:**

– the future will tell –