The Quark-Gluon Plasma

Four Lectures

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The Fundamental Problems of Physics

constituents	forces
quarks	strong
leptons	e-m
gluons, photons	weak
vector bosons (Z, $W^{\pm}$)	gravitation
Higgs	unification, TOE

elementary interactions

$\Downarrow$

complex systems

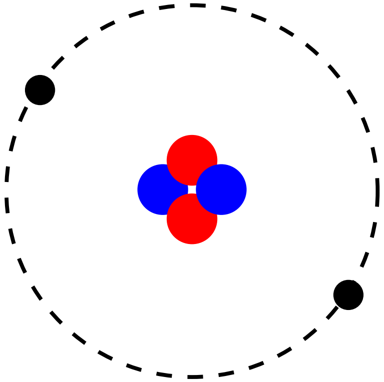
states of matter	transitions
solid, liquid, gas	thermal phase transitions
glass, gelatine	percolation transitions
insulator, conductor	scaling and renormalization
superconductor, ferromagnet	critical exponents
fluid, superfluid	universality classes

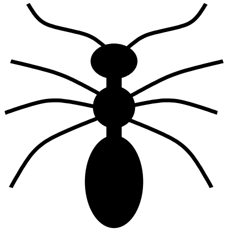
Complex Systems ⇒ New Direction in Physics

- **Given constituents and dynamics of elementary systems, what is the behaviour of complex systems?**
- **What are the possible states of matter and how can they be specified?**
- **How do transitions from one state of matter to another occur?**
- **Is there a general pattern of critical phenomena, independent of specific dynamics?**
- **Conceptually new physics: renormalization, self-similarity, self-organization, emergence, sand piles, swarm intelligence, ...**

Knowing all there is to know about

the helium atom **the ant**

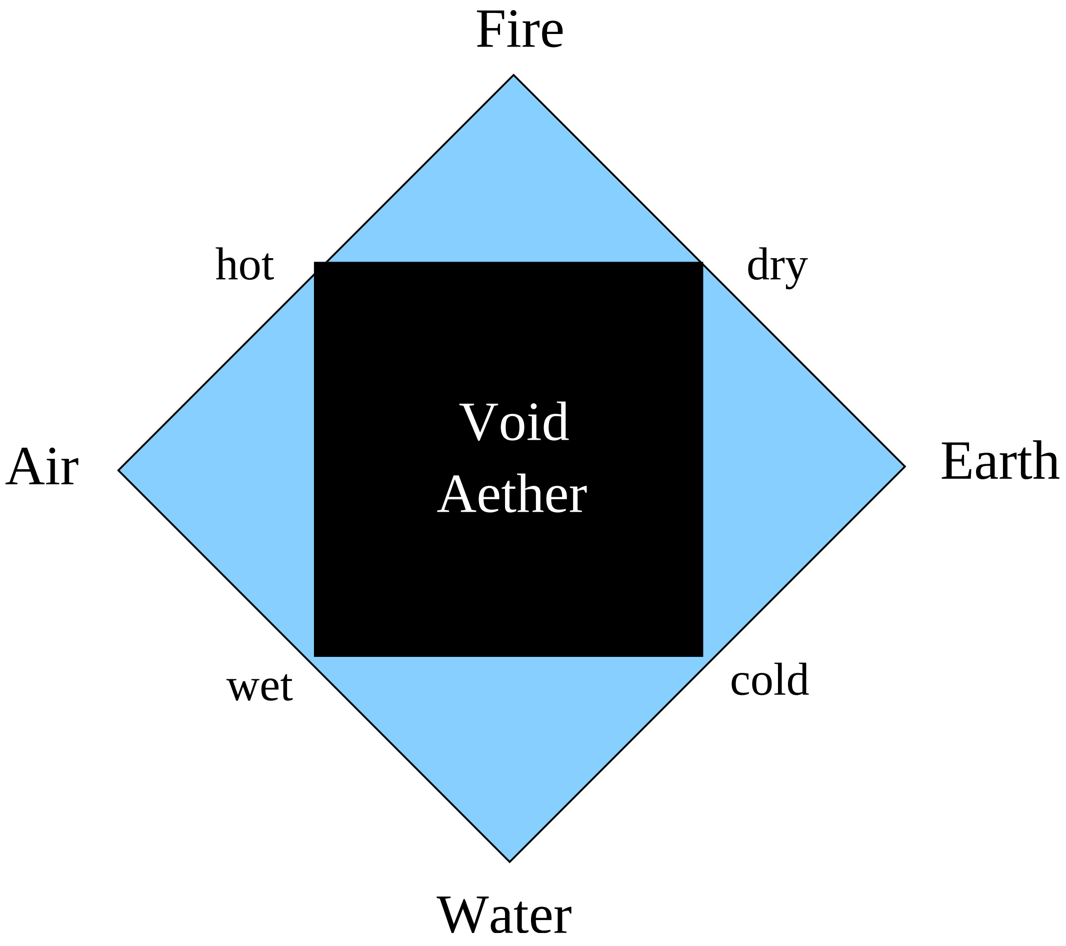




tells you nothing about the behaviour of

liquid helium **a colony of ants**

⇒ even a fully unified fundamental theory does not solve the issue of complex systems, of the states of matter



states of matter in antiquity - and in strong interaction physics?

Four Lectures

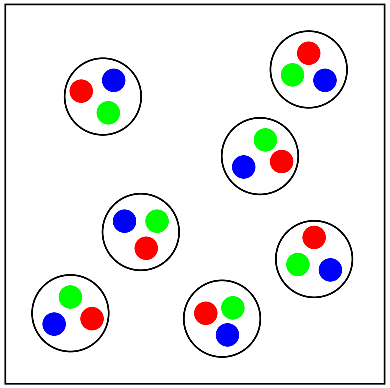
1. The Thermodynamics of Quarks and Gluons
2. Phase Diagram of Strongly Interacting Matter
3. Quarkonia in Deconfined Matter
4. Statistical Hadronization and its Origin

Lecture 1

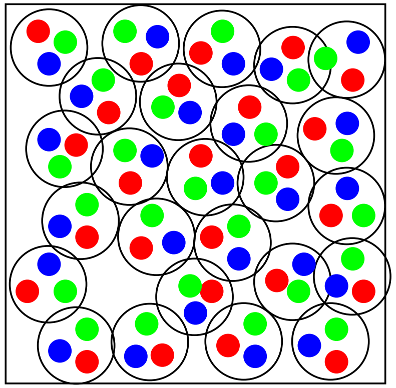
The Thermodynamics of Quarks and Gluons

What is the Quark-Gluon Plasma?

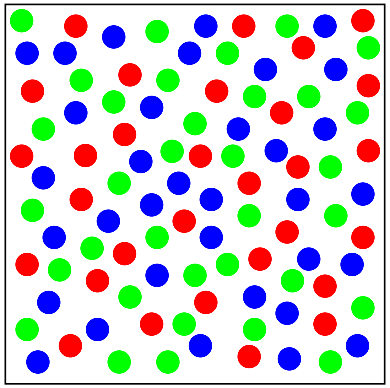
A state of strongly interacting matter, in which the constituents of hadrons, quarks and gluons, are not spatially confined to form color-neutral bound states.



Nucleon Gas



Nuclear Matter



Quark Matter

When many hadrons overlap, quarks cannot identify “their hadron”, the concepts of a hadron and of confinement become meaningless, color screening and high quark density (asymptotic freedom) forbid hadronic scales ⇒ transition to a new state of matter

Confined Matter

- quark-antiquark pairs or three-quark states form color-neutral states of hadronic size $\sim$ 1 fm;
- quarks acquire a dynamically generated "effective" mass of about 300 MeV by gluon dressing $\rightarrow$ spontaneous chiral symmetry breaking;
- mesonic matter: constituents are mesons and baryons, the interaction is resonance-dominanted;
- baryonic matter: constituents are nucleons, the interaction is long-range attraction (1 fm) and short range repulsion (0.5 fm)

increasing the meson density (by increasing T), or increasing the nucleon density (by compressing nuclear matter) leads to hadron overlap and thus deconfinement.

what happens in the deconfinement transition?

Deconfined Matter

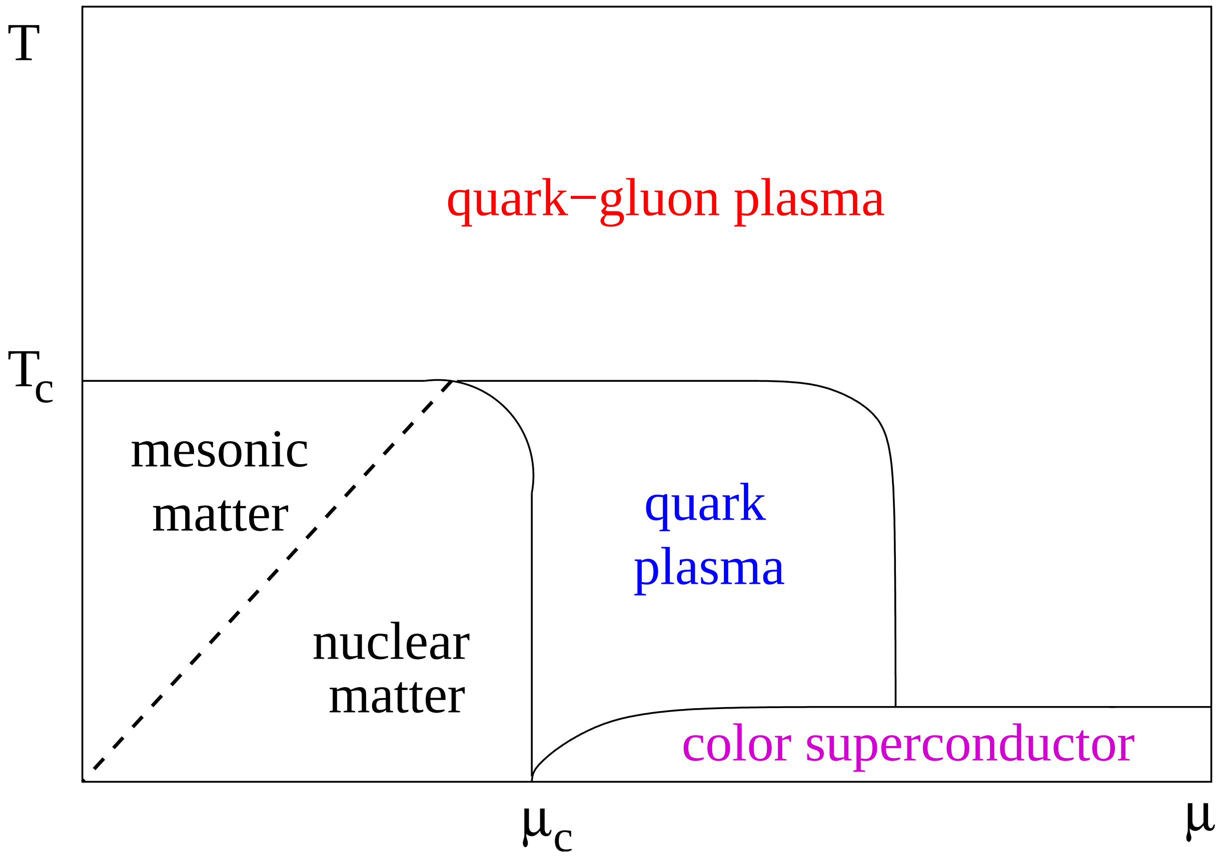
- at deconfinement, bound states are dissolved, constituents are colored quarks; ⇒ insulator-conductor transition of QCD
- the gluon dressing melts, the quark mass drops to Lagrangian mass; ⇒ chiral symmetry restoration.

do the two phenomena coincide?

In general: either yes or first deconfinement, then chiral symmetry restoration [Banks & Casher 1979]

- possible state of deconfined massive colored quarks: quark plasma; lattice studies: at low baryon density, deconfinement and chiral symmetry restoration coincide;
- deconfined quarks (whether massive or not) may still interact; QCD ⇒ quark-quark binding ⇒ colored bosonic diquarks;
- colored diquark bosons at low T can form Bose condensate: color superconductor.

Speculative phase diagram for strongly interacting matter:



NB: in all phases, $\exists$ interactions!

2. From Hadrons to Quarks and Gluons

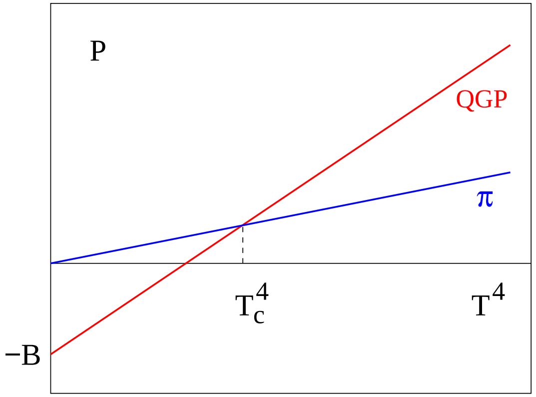
simplest confined matter: ideal pion gas $P_\pi = \frac{\pi^2}{90}\, 3\, T^4 \simeq \frac{1}{3}\, T^4$

simplest deconfined matter: ideal quark-gluon plasma

$$P_{QGP} = \frac{\pi^2}{90} \left\{ 2 \times 8 + \frac{7}{8} \left[2 \times 2 \times 2 \times 3 \right] \right\} T^4 - B \simeq 4\, T^4 - B$$

with bag pressure B for outside/inside vacuum

given $P_\pi(T)$ vs. $P_{QGP}(T)$: nature chooses highest P (lowest F)



phase transition from hadronic matter at low T to QGP at high T

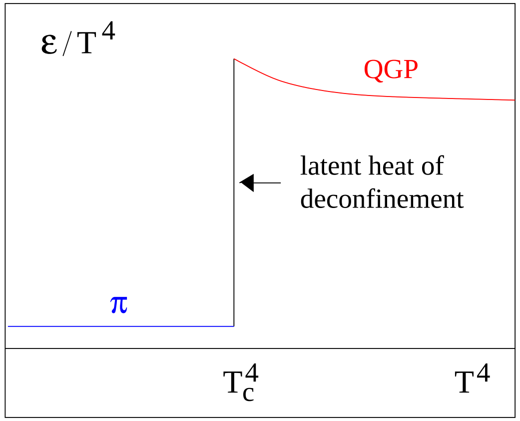
critical temperature:

$$P_\pi = P_{QGP} \longrightarrow T_c^4 \simeq 0.3\ B \simeq 150\ \mathrm{MeV}$$

with $B^{1/4} \simeq 200$ MeV from quarkonium spectroscopy

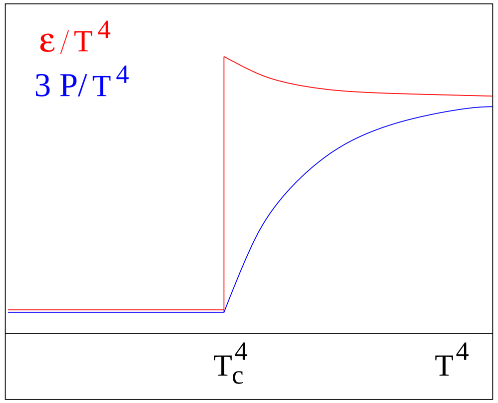
corresponding energy densities

$$\epsilon_\pi \simeq T^4 \longrightarrow \epsilon_{QGP} \simeq 12\ T^4 + B$$



at T_c, energy density changes abruptly by latent heat of deconfinement compare energy density and pressure:

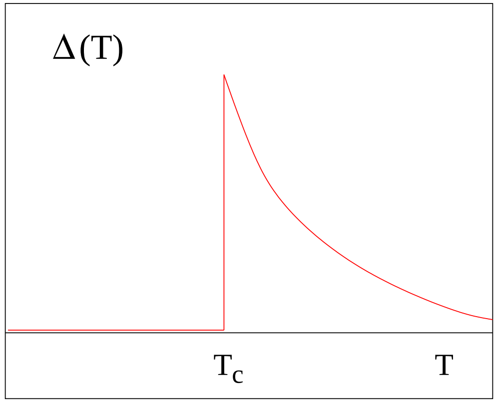
ideal gas $\epsilon = 3P$



here we obtain

and the interaction measure

$$\Delta \equiv \frac{\epsilon - 3P}{T^4} = \frac{4B}{T^4}$$



shows that for $T_c \leq T < 2 - 3\ T_c$

the QGP is <u>strongly interacting</u>

so far, simplistic model; real world?

3. Finite Temperature Lattice QCD

given QCD as dynamics input, calculate resulting thermodynamics, based on QCD partition function

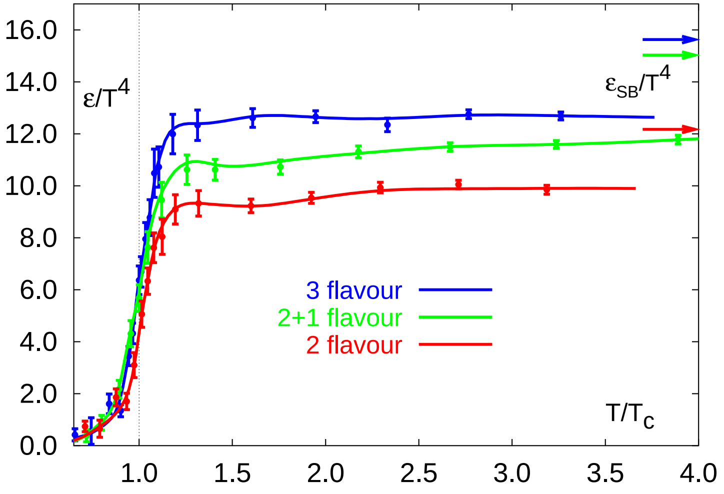
$\Rightarrow$ lattice regularization, computer simulation

- <u>energy density</u>

$\Rightarrow$ latent heat of deconfinement

For $N_f = 2, 2+1$:

$$\boxed{\begin{array}{l} T_c \simeq \ 175 \text{ MeV} \\ \epsilon(T_c) \simeq 0.5 - 1.0 \text{ GeV/fm}^3 \end{array}}$$



explicit relation to deconfinement, chiral symmetry restoration?

$\Rightarrow$ <u>order parameters</u>

- deconfinement $\Rightarrow m_q \to \infty$

  Polyakov loop $L(T) \sim \exp\{-F_{Q\bar{Q}}/T\}$

  $F_{Q\bar{Q}}$: free energy of $Q\bar{Q}$ pair for $r \to \infty$

  $$L(T) \begin{cases} = 0 & T < T_L \text{ confinement} \\ \neq 0 & T > T_L \text{ deconfinement} \end{cases}$$

  variation defines deconfinement temperature T_L

- chiral symmetry restoration $\Rightarrow m_q \to 0$

  chiral condensate $\chi(T) \equiv \langle \bar{\psi}\psi \rangle \sim M_q$

  measures dynamically generated ('constituent') quark mass

  $$\chi(T) \begin{cases} \neq 0 & T < T_\chi \text{ chiral symmetry broken} \\ = 0 & T > T_\chi \text{ chiral symmetry restored} \end{cases}$$

  variation defines chiral symmetry temperature T_χ

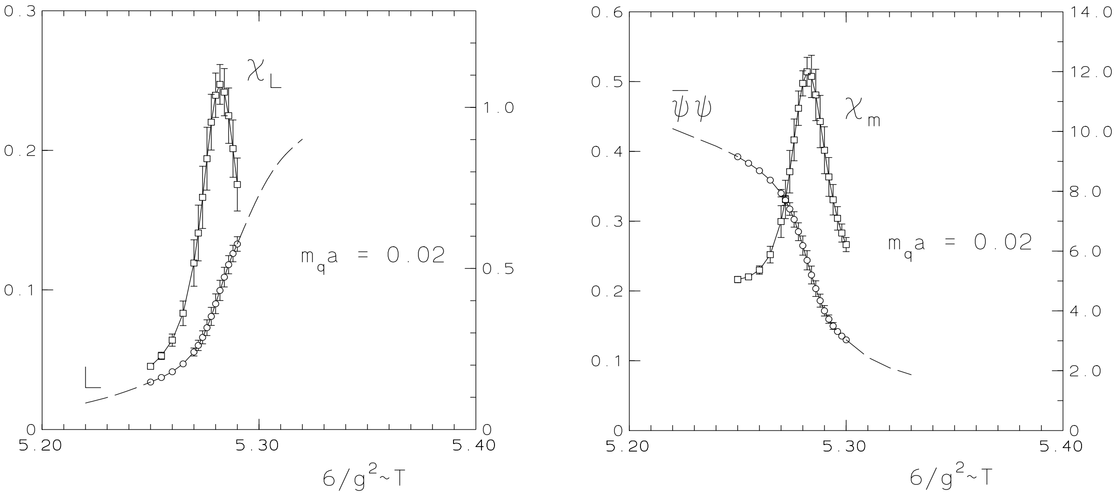
- how are T_L and T_χ related?

$SU(N)$ gauge theory: $\sim$ spontaneous Z_N breaking at T_L

QCD, chiral limit: $\sim$ explicit Z_N breaking by $\chi(T) \longrightarrow 0$ at T_χ

chiral symmetry restoration $\Rightarrow$ deconfinement

lattice results



Polyakov loop & chiral condensate vs. temperature

at $\mu = 0$, $\exists$ one transition hadronic matter $\longrightarrow$ QGP

for $N_f = 2, m_q \longrightarrow 0$ at $T_c = T_L = T_\chi \simeq 175$ MeV

Finite temperature lattice QCD shows:

– $\exists$ transition at $T \sim 0.175 \pm ?$ GeV, where deconfinement & chiral symmetry restoration coincide

– at transition, ϵ increases suddenly by latent heat of deconfinement

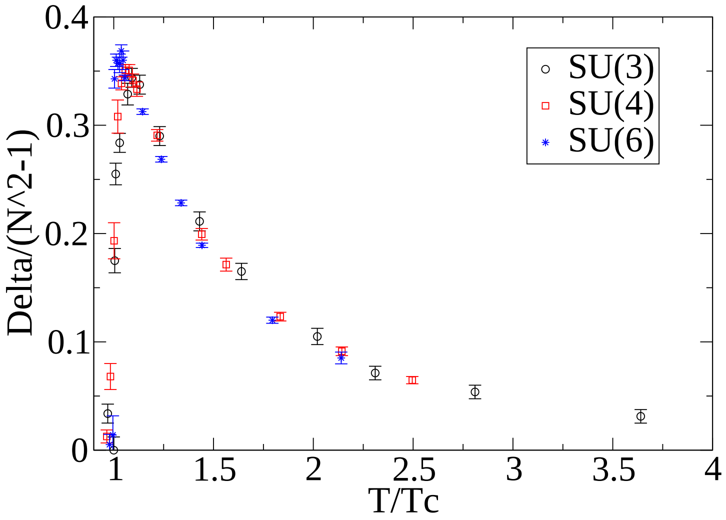
What about interactions in QGP?

<u>interaction measure</u>(trace of energy-momentum tensor)

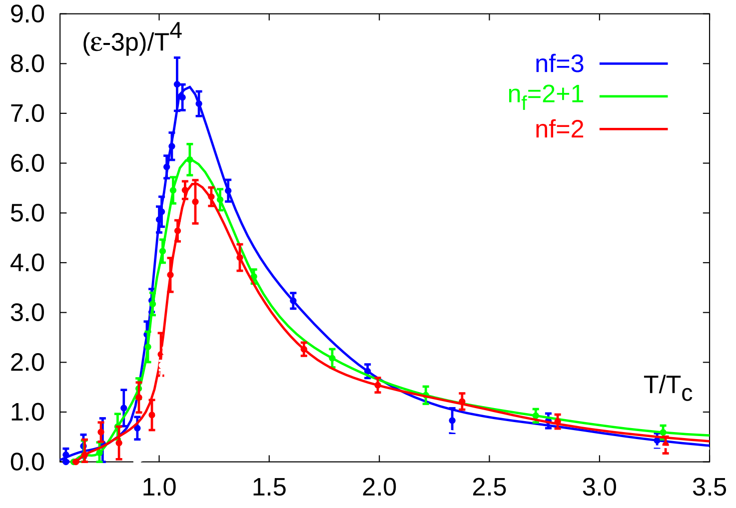
$$\Delta = \frac{\epsilon - 3P}{T^4}$$

vanishes for non-interacting massless constituents

quarks and gluons are (ideally) massless; what $\Delta(T > T_c)$?



Datta & Gupta 2009



Karsch, Laermann & Peikert 2000

4. The Strongly Interacting QGP

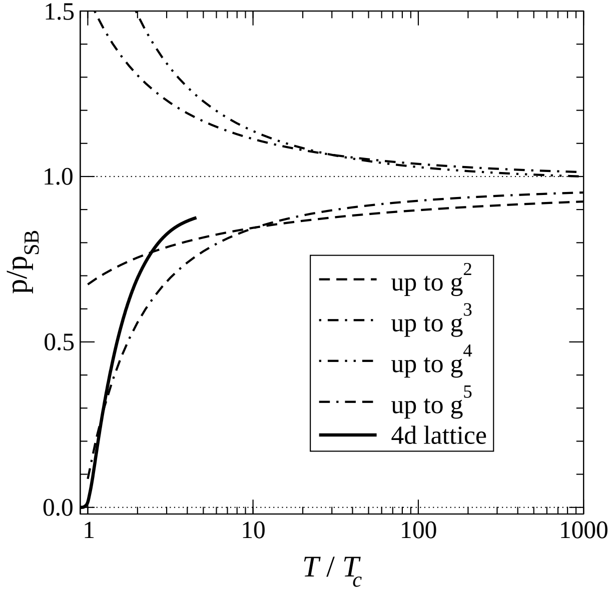
Expect that for high enough T, asymptotic freedom → ideal QGP (perturbation theory)

how high is enough? – consider best known case $SU(3)$ gauge theory

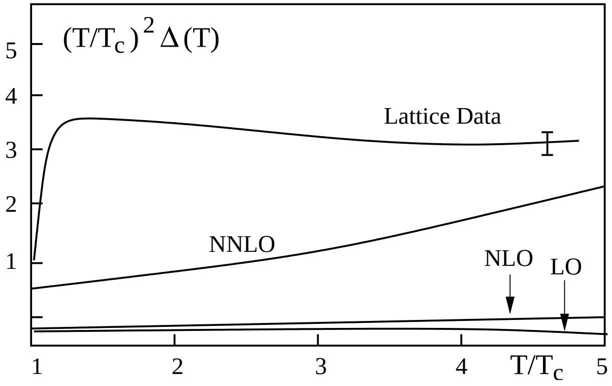
$\exists$ perturbative calculations up to $O(g^5)$

perturbation theory oscillates strongly
does not converge for $T \leq 10\ T_c$

non-pert. extension [Kajantie et al. 2003]:
still qualitatively wrong for $T \leq 5\ T_c$



re-organize perturbation theory
(“re-summed” theory, HTL)
[Andersen, Strickland & Su 2010]

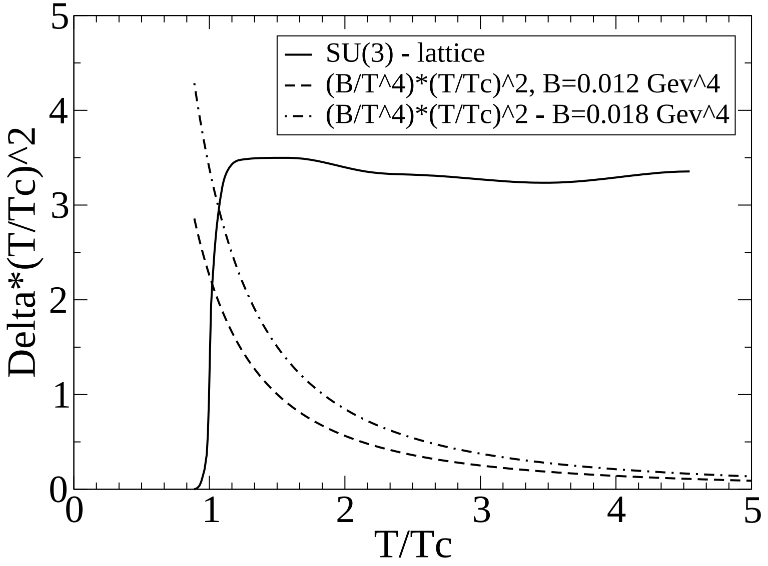


– weak coupling approaches cannot account for QGP at
$T \leq T_c \leq 5\ T_c$: no dip at T_c, wrong (log) T-dependence

Non-perturbative approach: bag model

non-interacting quarks & gluons in “medium” gluon condensate

$$\Delta = \frac{4B}{T^4} = \frac{G_0^2}{T^4}$$



bag pressure $\sim$ gluon condensate at $T = 0$

numerical estimate $G_0^2 \simeq 0.012$ GeV^4
[Shifman,Vainshtein & Zakharov 1979]

Conclude:

- weak coupling: T-dependence too weak, no dip at T_c
- bag model: T-dependence too strong, no dip at T_c

what is QGP for $T_c \leq T \leq 4\ T_c$? ⇒ Quasi-Particle Model

$\exists$ two regions

- critical region as $T \to T_c$, “singular” behavior
- screening region in hot QGP

consider gluons in deconfined medium:
polarization $\longrightarrow$ dressing, effective gluon mass

– as $T \to T_c$ from above, correlation length increases/diverges, so gluon polarizes more & more of medium

– as $T > T_c$ increases, correlation length decreases, so gluon sees less and less of medium

– as $T > T_c$ increases, energy density of medium increases

two competing effects:

consider $SU(2)$ gauge theory [Goloviznin & HS 1993]
$\Rightarrow$ continuous transition, critical exponents

for $T \to T_c$, with $t \equiv (T/T_c)$,

- energy density $\epsilon \sim (t-1)^{1-\alpha}$
- correlation volume $V_{cor} \sim (t-1)^{-2\nu-\eta}$

with (Z_2 universality class) $\alpha = 0.11,\ \nu = 0.69,\ \eta = 0.04$, so that

$$m_{crit}(T) \sim \epsilon\, V_{cor} \sim (t-1)^{1-\alpha-2\nu-\eta} \sim (t-1)^{-0.41}$$

effective gluon mass diverges for $T \to T_c$

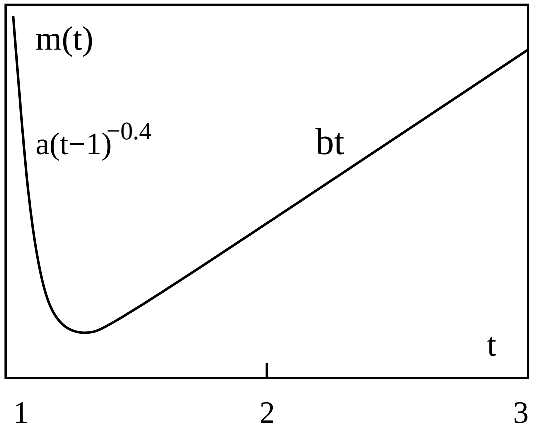
in hot QGP, screening length $r_D \sim 1/T$, hence

- $\epsilon \sim T^4$
- $V_{cor} \sim T^{-3}$
- $m_{crit}(T) \sim \epsilon\, V_{cor} \sim T$

overall behavior of effective gluon mass

$$m(T) = a(t-1)^{-c} + bt$$

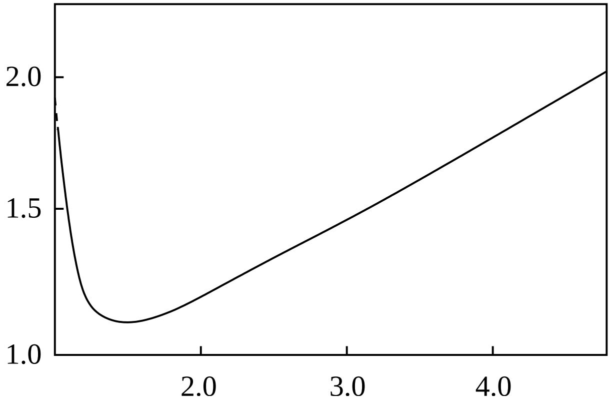
with constants a, b, c; here $c = 0.41$



retain this form in general

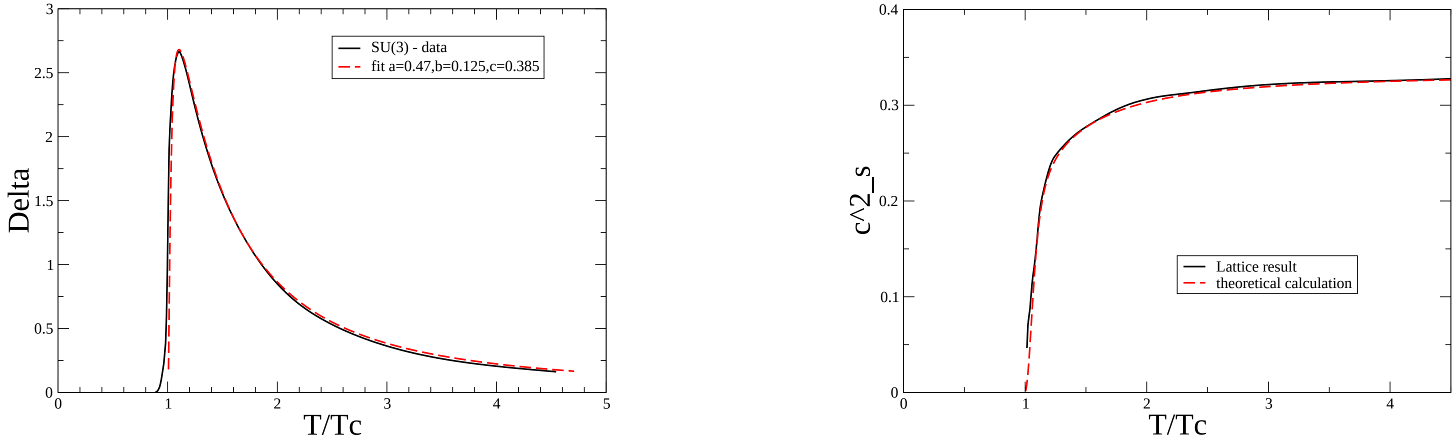
apply to $SU(3)$ gauge theory

[Castorina, Miller & HS 2010]



excellent description of all thermodynamic quantities, including $\Delta(T)$

NB: speed of sound in QGP “vanishes” at T_c, heavy gluons...



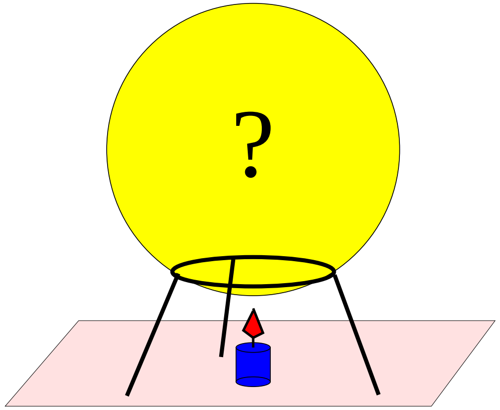
5. Probing the Quark-Gluon Plasma

At high temperatures and/or densities, strongly interacting matter becomes a QGP;

how can we probe its properties and its behaviour as function of temperature and density?

Given a volume of strongly interacting matter and an energy source, how can we determine its state at different temperatures?

NB:
equilibrium thermodynamics, no collision effects, time dependence, equilibration, etc.



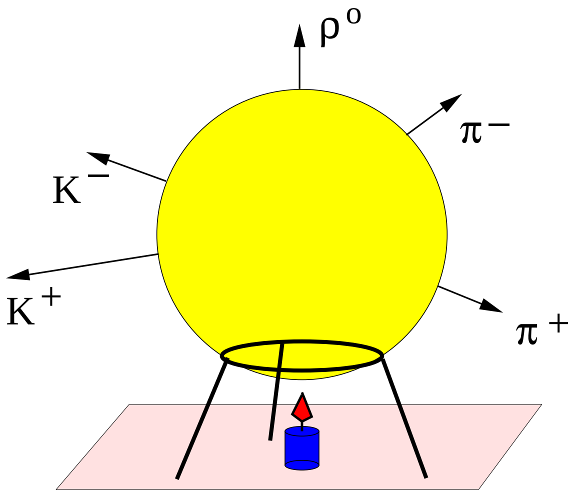
Possible probes:

- hadron radiation
- electromagnetic radiation
- dissociation of quarkonium states
- energy loss of parton beams

Here, just a brief first look....

The medium is hotter than its environment (vacuum) and hence emits

- Hadron Radiation



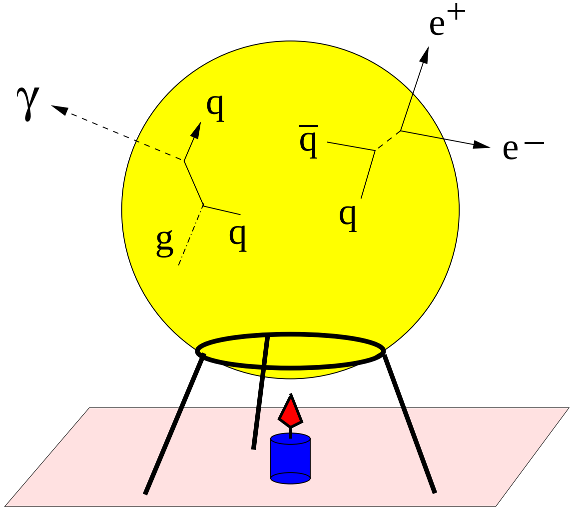
emission of light hadrons
(made of u, d, s quarks)
scale $\sim$ 1 fm $\simeq 1/(200$ MeV)

cannot exist in hot interior
emission at surface of $T \simeq T_c$
information about hadronization stage

⇒ same relative abundances for different initial energy densities

In the interior of the medium, quark-gluon interactions or quark-antiquark annihilation leads to

- Electromagnetic Radiation



produced photons and dileptons
leave medium without further interaction

provide information about the medium
at the time of their production:
probe of hot QGP

problem:
they can be formed anywhere & at any time
even at the surface or by the emitted hadrons
task: identify hot thermal radiation

hadronic and e-m radiation: emitted by the medium itself
provide information about the medium at the time of production

other possibility: “outside” probes

- Quarkonium Suppression

quarkonia: bound states of heavy quarks ($c\bar{c}, b\bar{b}$)

smaller than usual hadrons ($r_Q \ll r_h \simeq 1$ fm),
binding energies 0.5 – 1.0 GeV

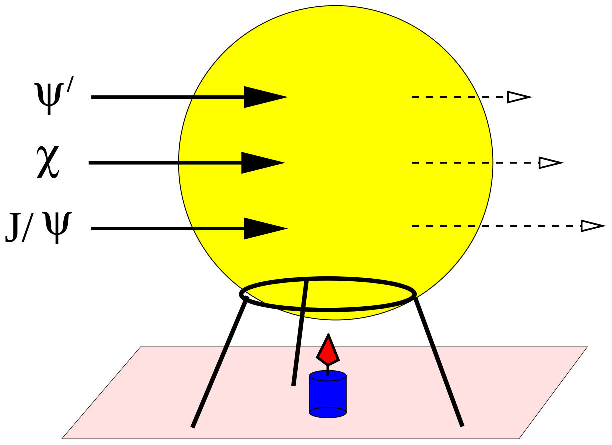
$\Rightarrow$ can survive in QGP
in some temperature range $T > T_c$

Example: charmonium states

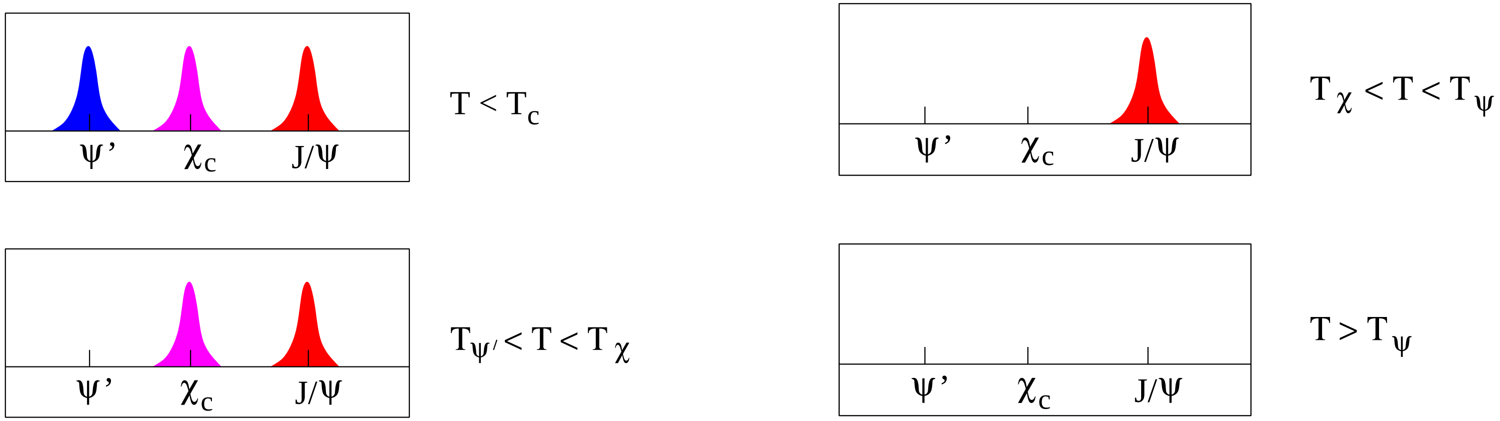
J/ψ(1S) – $r_{J/\psi} \simeq 0.2$ fm
χ_c(1P) – $r_\chi \simeq 0.3$ fm
ψ'(2S) – $r_{\psi'} \simeq 0.4$ fm

different charmonia "melt" in QGP at different temperatures

potential & lattice studies: $T_{\psi'} \simeq T_\chi \simeq 1 - 1.1,\ T_{J/\psi} \simeq 1.5 - 2\ T_c$
$\epsilon_{\psi'} \simeq \epsilon_\chi \simeq 1 - 1.5,\ \epsilon_{J/\psi} \simeq 8 - 12\ \mathrm{GeV/fm^3}$



⇒ “seqential charmonium melting”
as quantitatively predicted
property of QGP

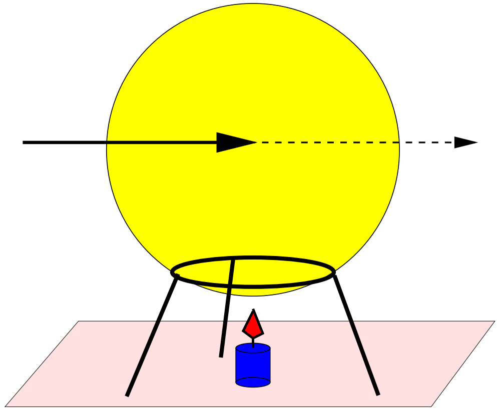


similar to solar spectra as thermometer of sun

- **Jet Quenching**

shoot an energetic parton beam
(quarks or gluons) into QGP,
measure energy of outgoing beam

attenuation ("quenching")
determined by density of medium
increases with temperature



NB: how to get "external" probes in nuclear collision experiments?

- **Hard Probes:**

quarkonia, open charm/beauty, jets, energetic photons & dileptons
– formed very early in the collision, are present when QGP appears
– can be predicted (to large extent) by perturbative QCD
– can be "gauged" in *pp* and *pA* collisions

Summary

In strong interaction thermodynamics $\exists$ a well-defined transition at which

- deconfinement sets in & chiral symmetry is restored
- latent heat increases energy density
- transition temperature $T_c \simeq 160 - 190$ MeV.

For $T > T_c$, the state of matter is a plasma of deconfined quarks and gluons which can be probed by

- electromagnetic radiation
- quarkonium spectra
- jet quenching

In addition, decisive information on confinement transition from

- hadron production