H. Satz ITP, April 2002

PROBING THE STATES OF MATTER IN QCD

1. Introduction
2. Statistical QCD
3. Dileptons & Photons

— Invasive Probes —

4. Quarkonia
5. Jets
6. Outlook

1. Introduction

High energy nuclear collisions:

Study experimentally the states of matter and transitions predicted by QCD.

∴ must identify suitable probes.

∃ additional (unwanted) problems, caused by nuclear collision pattern:

- can non-thermal initial state produce a secondary thermal medium?
- nuclear geometry, profile produce non-uniform medium.
- evolution (expansion & cooling) leads to superposition of information from different conditions.

Probes must be produced by collision:

- nuclear matter modifies probe production, incident partons suffer shadowing, multiple scattering, energy loss.

-2-

- produced probes interact with nuclear matter: "normal" J/ψ suppression, jet quenching in cold nuclear matter.

∴ extraneous effects obscure the essential problem:
identify state of QCD matter, transition.

∴ simplify.

Gedankenexperiment

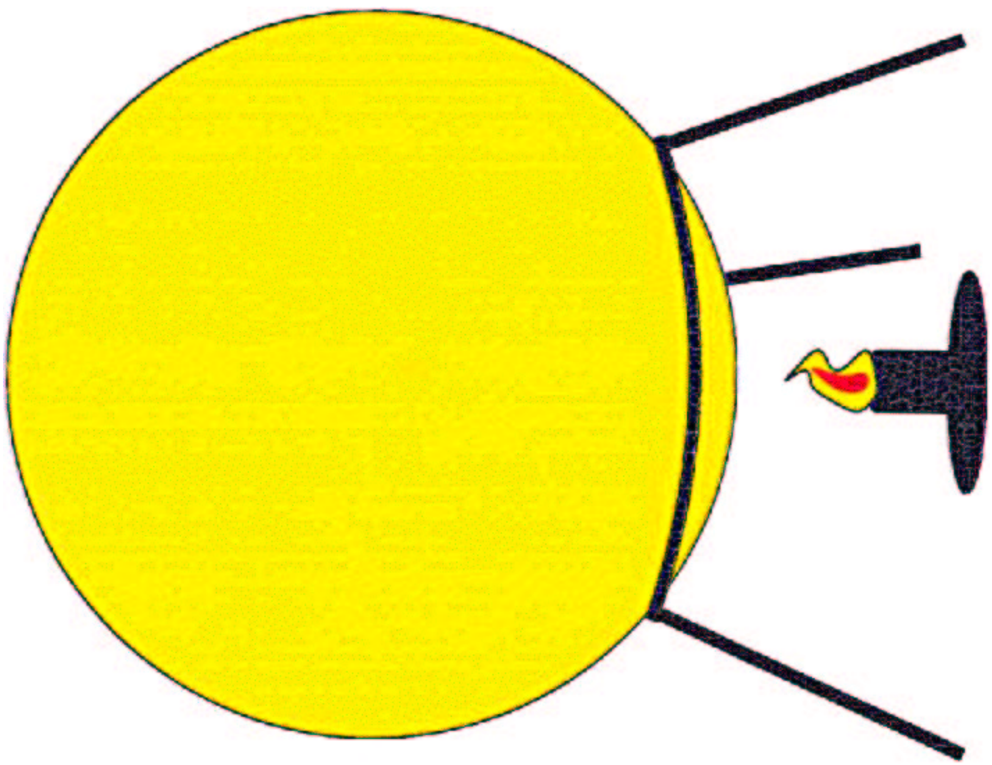
Given:
- fixed volume $V_0 \sim 10^3\ \mathrm{fm}^3$ filled uniformly with QCD matter in thermal & chemical equilibrium,
- a device to adiabatically add or remove energy E.

Can we then for each value of $\varepsilon = E/V_0$ identify the state of matter and any transition between states?

If we can solve this problem, perhaps some hints for the real world, which remains difficult enough...
If we can't: forget it...

Everything should be made as simple as possible, but not simpler.

Albert Einstein

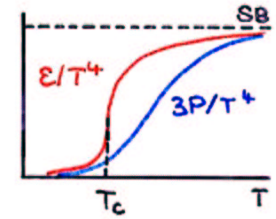


2. Statistical QCD

Basis for Gedankenexperiment:
finite temperature lattice QCD

- equation of state

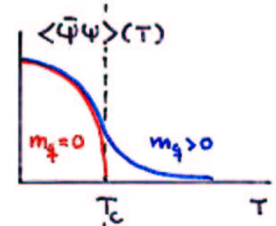
$N_f = 2;\ m_q \simeq 0$



- order parameters

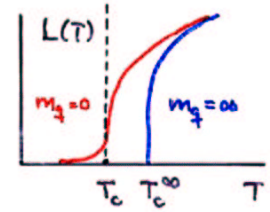
chiral condensate

for $m_q = 0$, chiral symm. restoration at $T = T_c$



Polyakov loop

for $m_q = \infty$ (pure gauge theory), spontaneous Z_N symmetry breaking at $T = T_c^\infty$

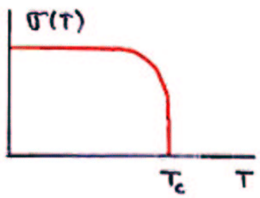


for $m_q = 0$, explicit Z_N symmetry breaking by
$H \sim 1/\langle\bar\psi\psi\rangle$

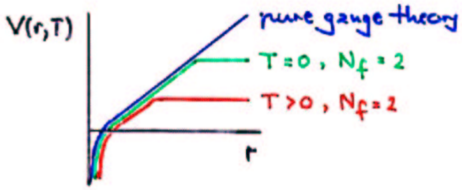
- potentials from Polyakov loop correlations

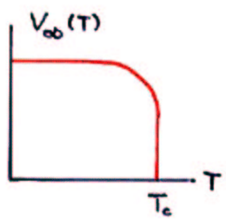
string tension

pure SU(N) gauge theory



heavy quark potential ~ string breaking





$V_\infty(T) \equiv \lim_{r\to\infty} V(r,T)$

$\sim Q\bar{Q} \to Q\bar{q} + \bar{Q}q$

- scales

$T < T_c$: ∃ intrinsic hadronic scale:
$\sigma, \langle\bar{\psi}\psi\rangle, m_h, r_h, \dots$

$T > T_c$: temperature T is the scale
[NB: $g(T/\Lambda)$]

- thermodynamic variables

thermodynamics	temperature T energy / ° freedom
percolation	density n # constituents / volume
(Gedanken-) experiment	energy density ε energy / volume

NB: energy density varies rapidly with T
$\varepsilon(1.1\,T_c)/\varepsilon(0.9\,T_c) \simeq 10$!
T_c easier to specify than $\varepsilon_c \equiv \varepsilon(T_c)$

∴ try to identify thermometer

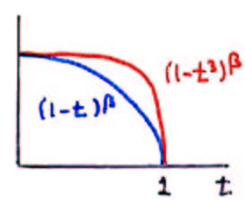
- why "late criticality" $A(T) \sim \Theta(T-T_c)$?
$\varepsilon(T), \langle\bar{\psi}\psi\rangle(T), \dots$

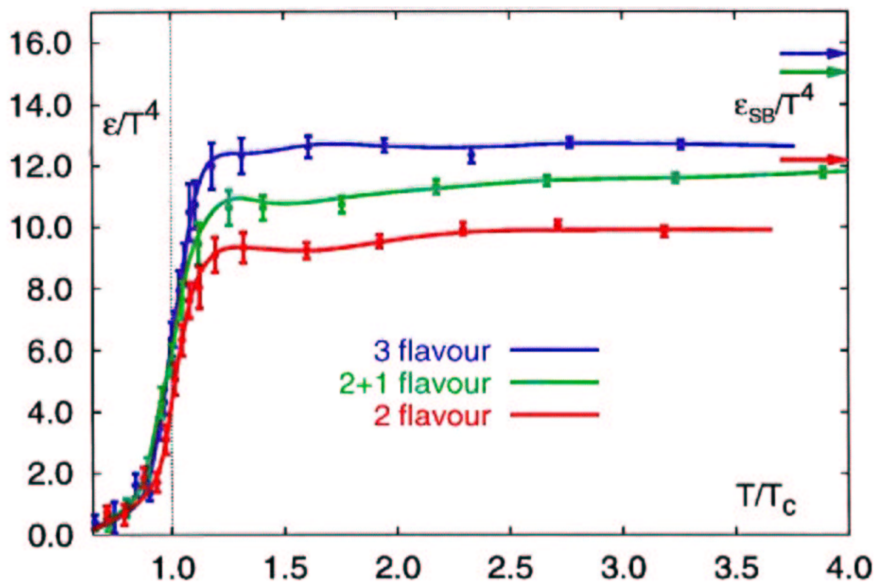
hint for underlying mechanism, "correct variable"?

e.g. magnetisation $m(T) \sim (T_c - T)^\beta$ $T < T_c$
percolation $P(T) \sim (n - n_c)^\beta$ $n > n_c$

for $n(T) \sim T^3$, same critical exponents ($t \equiv T/T_c$):
$\lim_{t\to 1} (1-t^3)^\beta \sim 3 \lim_{t\to 1} (1-t)^\beta$

but "retarded onset"





Bielefeld Lattice Group

- information wanted

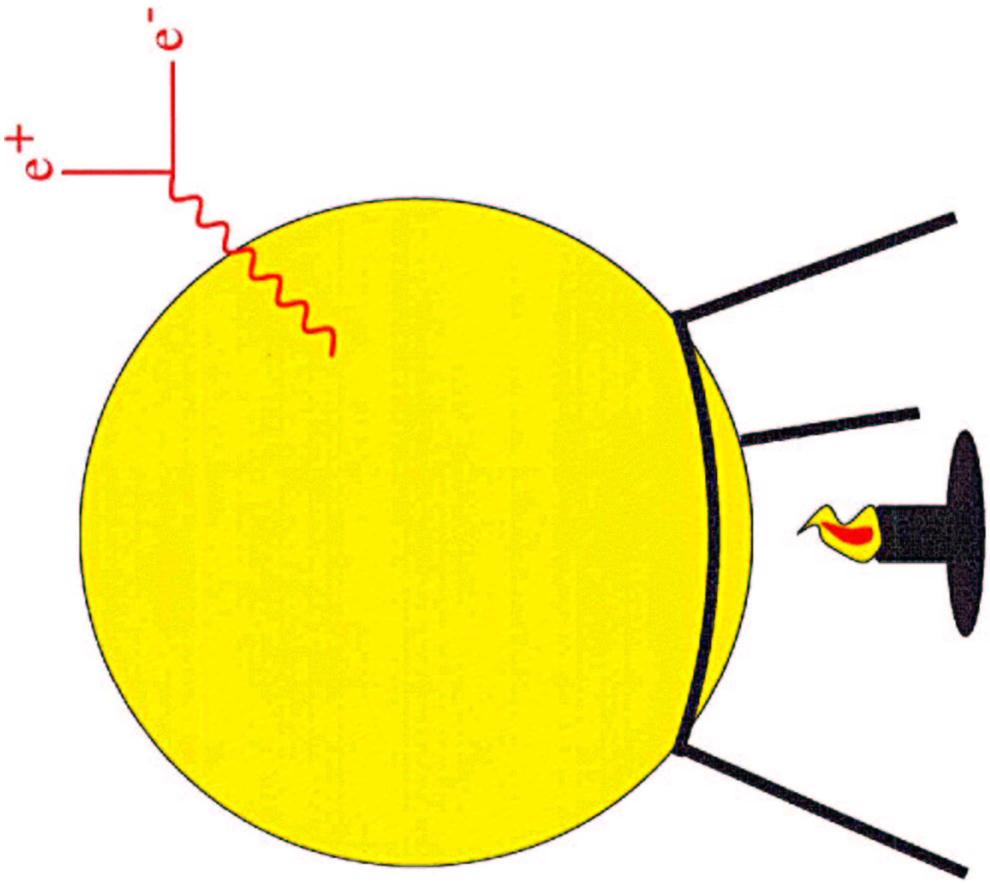
  - thermometer
  - nature of medium (confined/deconfined)
  - deconfinement/chiral transition
  - in-medium modifications of light hadrons, quarkonia
  - hot QGP properties

- direct probes

non-invasive:
e-m radiation emitted by medium
dileptons & photons

invasive (but painless):
hard external probes traversing medium
quarkonium beams
hard jets

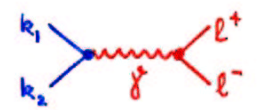
what information do probes provide in Gedankenexperiment?



3. Dileptons & Photons

A. Dileptons

Constituents of medium annihilate to form $\ell^+\ell^-$, leave medium without further interaction



measure dilepton mass ($M \equiv M_{\ell^+\ell^-}$) distribution at fixed dilepton rapidity y:

$$\frac{dN}{dy\,dM^2} \sim \int d^3k_1 \int d^3k_2\, f(k_1/T)\, f(k_2/T)\, \sigma(k_1+k_2) \times \delta^{(4)}(k_1+k_2-P)$$

$$P^2 = M^2$$

thermal distribution of constituents $f(k/T) \sim e^{-k/T}$; annihilation $\emptyset$ $\sigma(k_1+k_2)$

- confined state

VMD: ρ-pole $\quad \sigma \sim 1/[(M-M_\rho(T))^2 + \Gamma_\rho(T)^2]$

$$\Rightarrow \frac{dN}{dy\,dM^2} \sim \frac{1}{(M-M_\rho(T))^2 + \Gamma_\rho(T)^2}\, e^{-M/T}$$

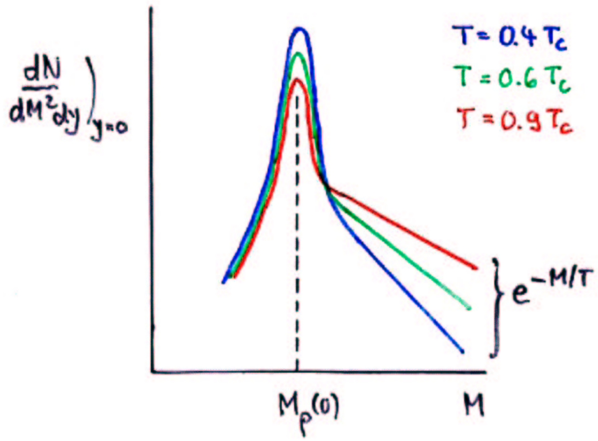
+ other vector mesons, Dalitz decays, ... ignore here!

∴ expect ρ-peak, exponential M/T tail

unknowns $M_\rho(T)$, $\Gamma_\rho(T)$

- data from Gedankenexperiment

quenched lattice QCD [Karsch ~ BLG]



$M_\rho(T) \simeq M_\rho(0)$ for $T \leq 0.9\,T_c$
$\Gamma_\rho(T)$?
Large M behavior specifies T

$M_\rho(T)$ in unquenched QCD ?

- deconfined state

$q\bar{q}$ annihilation $\sigma(k_1+k_2) \sim \alpha^2/(k_1+k_2)^2$

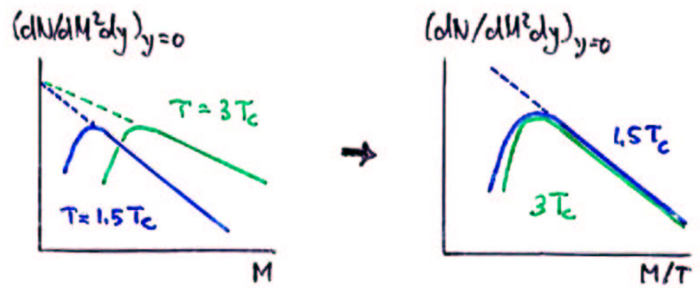
⇒ Born term

$(dN/dM^2dy)_{y=0} \sim \alpha^2 e^{-M/T}$

HTL: low mass excess

- data from Gedankenexperiment

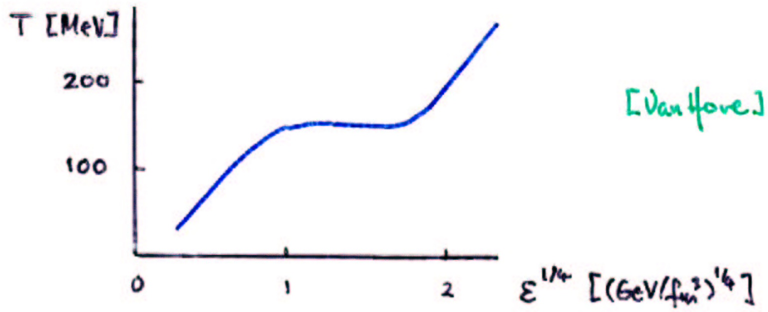
quenched lattice QCD [Karsch ~ BLG]



~ scaling in M/T
low mass depletion, thermal quark mass $m_q(T) \sim T$?
large M behavior specifies T

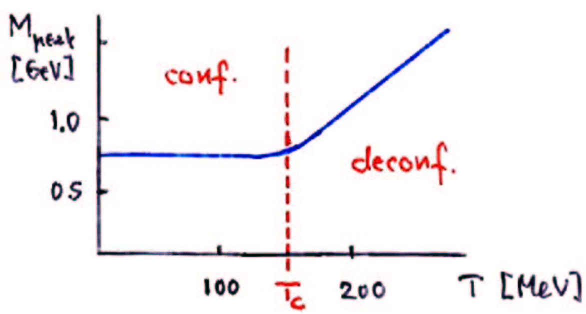
Dilepton Results of Qcd-Ex

- measure $T(\varepsilon)$ from large M behavior



[Van Hove]

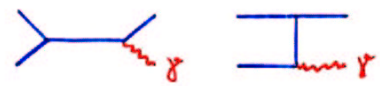
- given $T(\varepsilon)$, measure $M_{peak}(T)$



- conclusions on dileptons
  - large M behavior identifies T correctly in confined & deconfined regions.
    NB: in lattice QCD, T is known!
  - T-independent peak at $M_\rho(0)$ is signature of confinement, peak position scaling with T of deconfinement; origin of peak for $T > T_c$? thermal quark mass ?

B. Photons

expect:



$dN/dk_\gamma \sim e^{-k_\gamma/T}$

provides thermometer for all T, in confined & deconfined regions

confined: hadron decays for small k $\pi^0 \to 2\gamma$ ...

deconfined: thermal parton masses ?

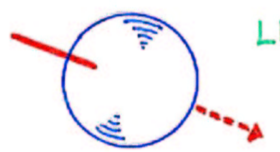
so far, no data from finite T lattice QCD.

-10a-

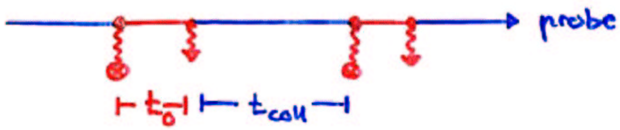
Interlude: Invasive Probes

Crucial feature:

probe interacts with constituents of medium



∴ two inherent time scales:



t_{coll} : time between successive collisions

$$t_{coll} \sim \lambda/v \sim \lambda \sim 1/n\sigma$$

mean free path

determined by density n of medium and cross section σ for interaction of probe with a constituent of medium

t_0 : time for probe to recover from the interaction, get back on-shell, ... probe specific.

∴ two distinct regimes

-10b-

1) $t_0 \ll t_{coll}$ incoherent interactions of the probe with the constituents of the medium

"kinetic" or "probabilistic" regime: total effect = sum of individual scatterings

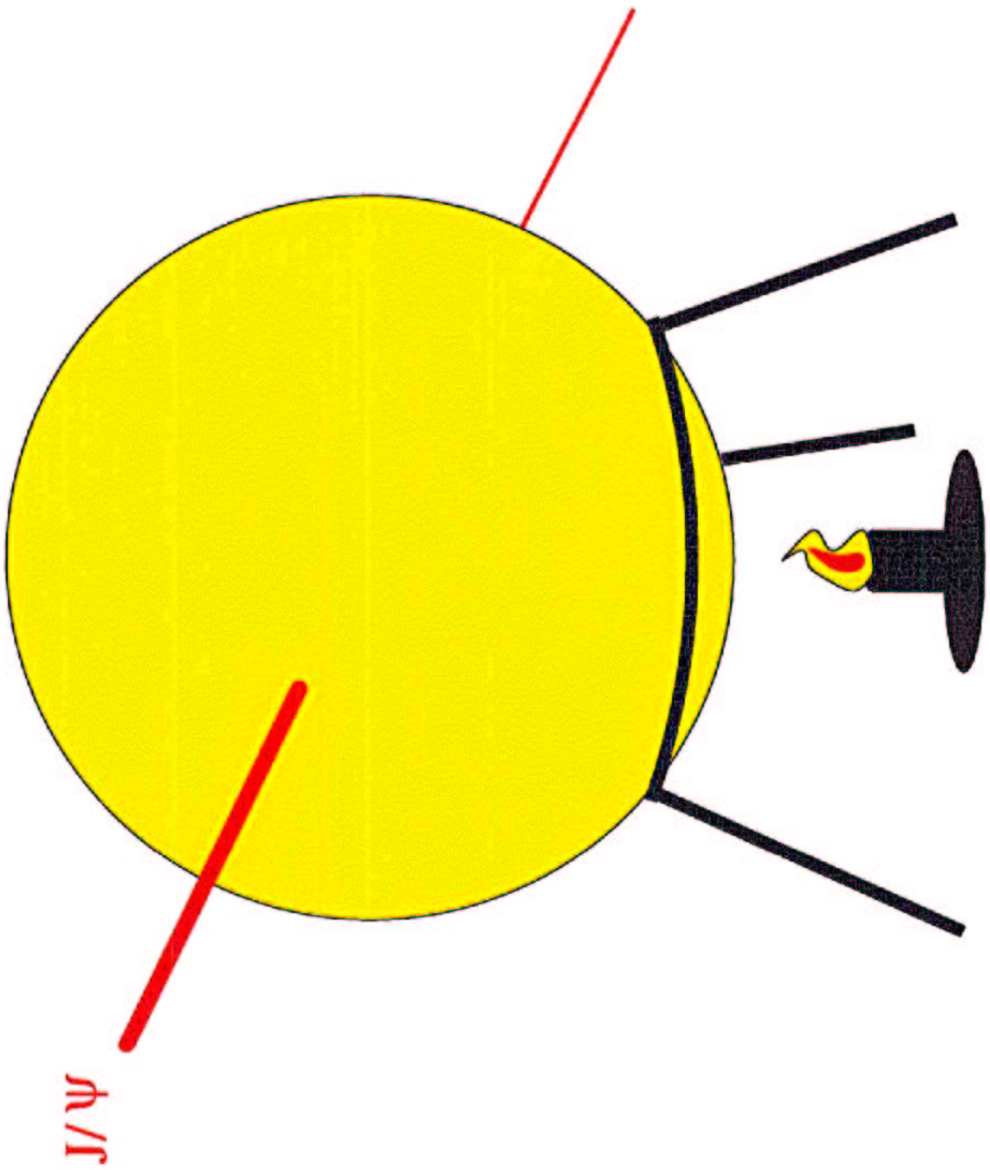
$$|\sum_i A_i|^2 = \sum_i |A_i|^2$$

2) $t_0 \gg t_{coll}$ coherent regime: probe in time t_0 interacts with several constituents of medium; coherence length $z_0 \sim t_0$ is larger than mean free path λ

LPM regime: ∃ destructive or constructive interference

$$|\sum A_i|^2 \neq \sum_i |A_i|^2$$

- essential tasks for each probe:
  - determine σ: constituent-probe
  - determine z_c: medium
- statistical QCD: $n(T)$



-11-

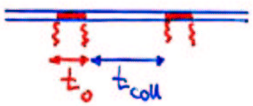
4. Quarkonia

Basis: different binding & dissociation patterns in confined & deconfined media.

Start: in QGP, color screening dissolves $J/\psi, \Upsilon, \dots$ MS

- in confined media?
- screening vs. collision dissociation?

J/Ψ traverses medium:



compare $t_{coll} \sim 1/n\sigma$ with $t_0 \sim 1/\Delta E_\psi \sim r_\psi$:

- $t_0 \ll t_{coll}$: collision regime
- $t_0 \gg t_{coll}$: collective regime

∴ must know:

- in-medium binding energy $\Delta E_\psi(T)$,
- in-medium J/Ψ-constituent cross section $\sigma(T)$,
- density $n(T)$ and screening radius $\mu^{-1}(T)$ of medium.

-12-

- binding energy $\Delta E_\psi \equiv 2M_D - M_\psi$

$T = 0$ $\Delta E_\psi \simeq 650$ MeV

$T \neq 0$ $2M_D(T)$ from Polyakov loop correl'ns in unquenched lattice QCD

$M_{J/\psi}(T)$ from Schrödinger eq'n

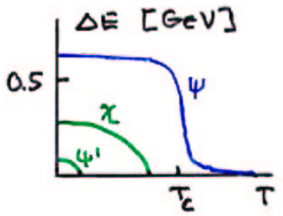
$$\left[2m_c - \frac{1}{m_c}\nabla^2 + V(r,T)\right]\Phi_\psi = M_\psi(T)\,\Phi_\psi$$

$$V(r,T) = \sigma(T)\,r - \alpha(T)/r \qquad T < T_c$$

$$V(r,T) = [\alpha(T)/r]\,e^{-\mu(T)\,r} \qquad T > T_c$$

with $\sigma(T)$, $\alpha(T)$, $\mu(T)$ from lattice QCD
NB: $\sigma(T) = 0$ for $T \gtrsim T_c \Rightarrow J/\psi$ is bound state in screened Coulomb potential.

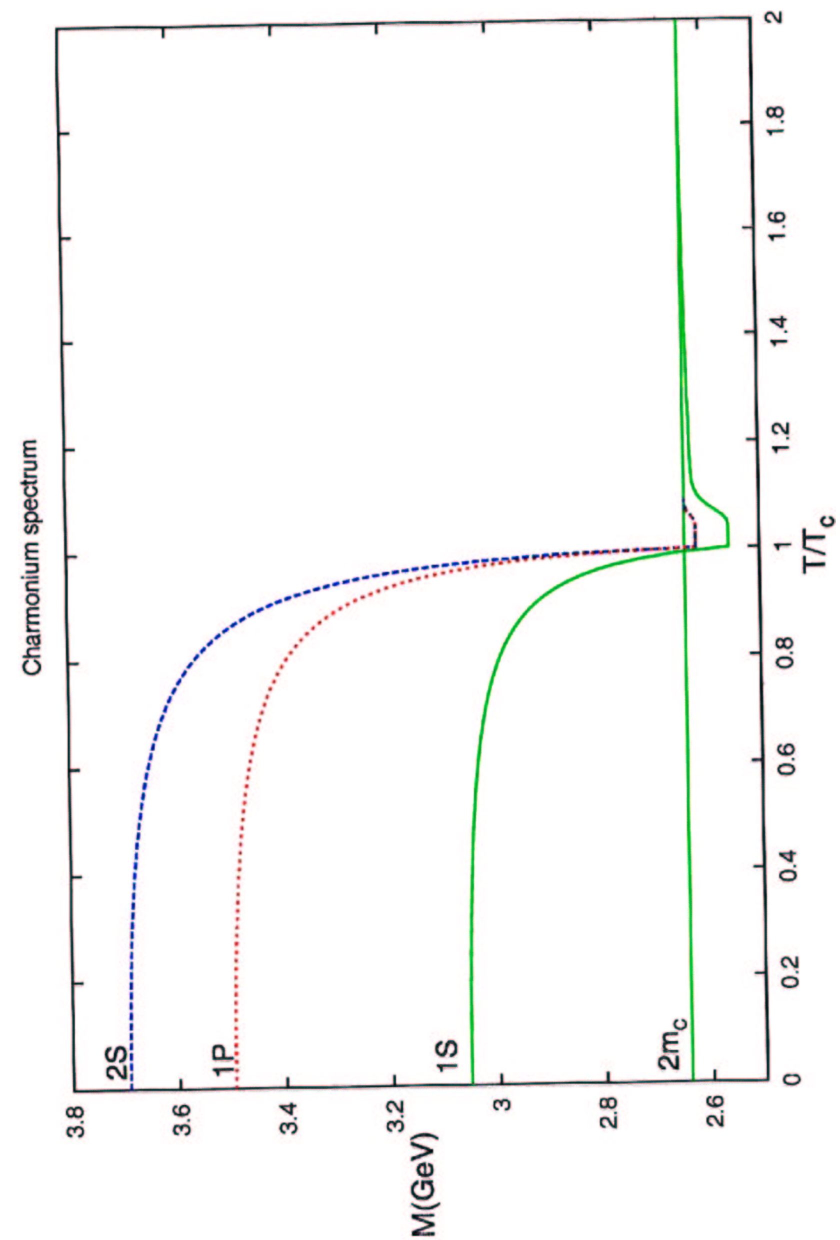
compare $2M_D(T)$ to $M_\psi(T)$ to get $\Delta E_\psi(T)$.

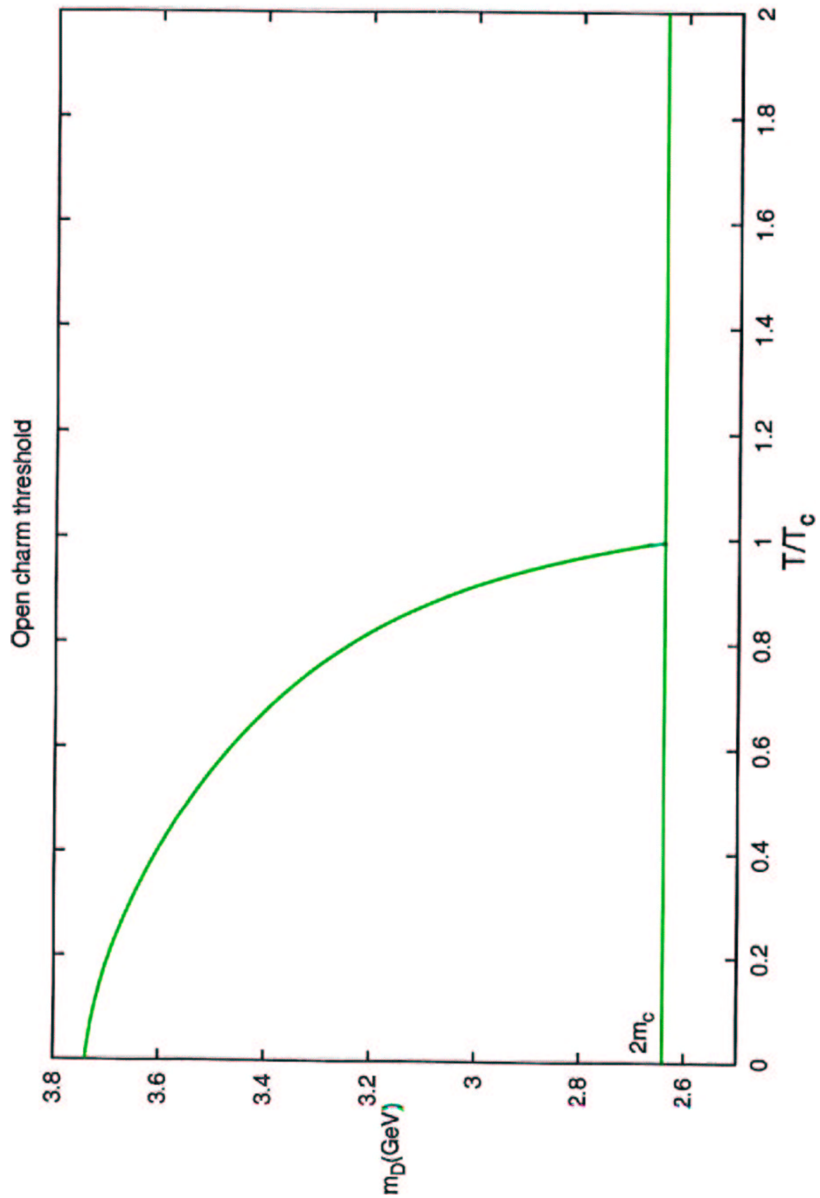


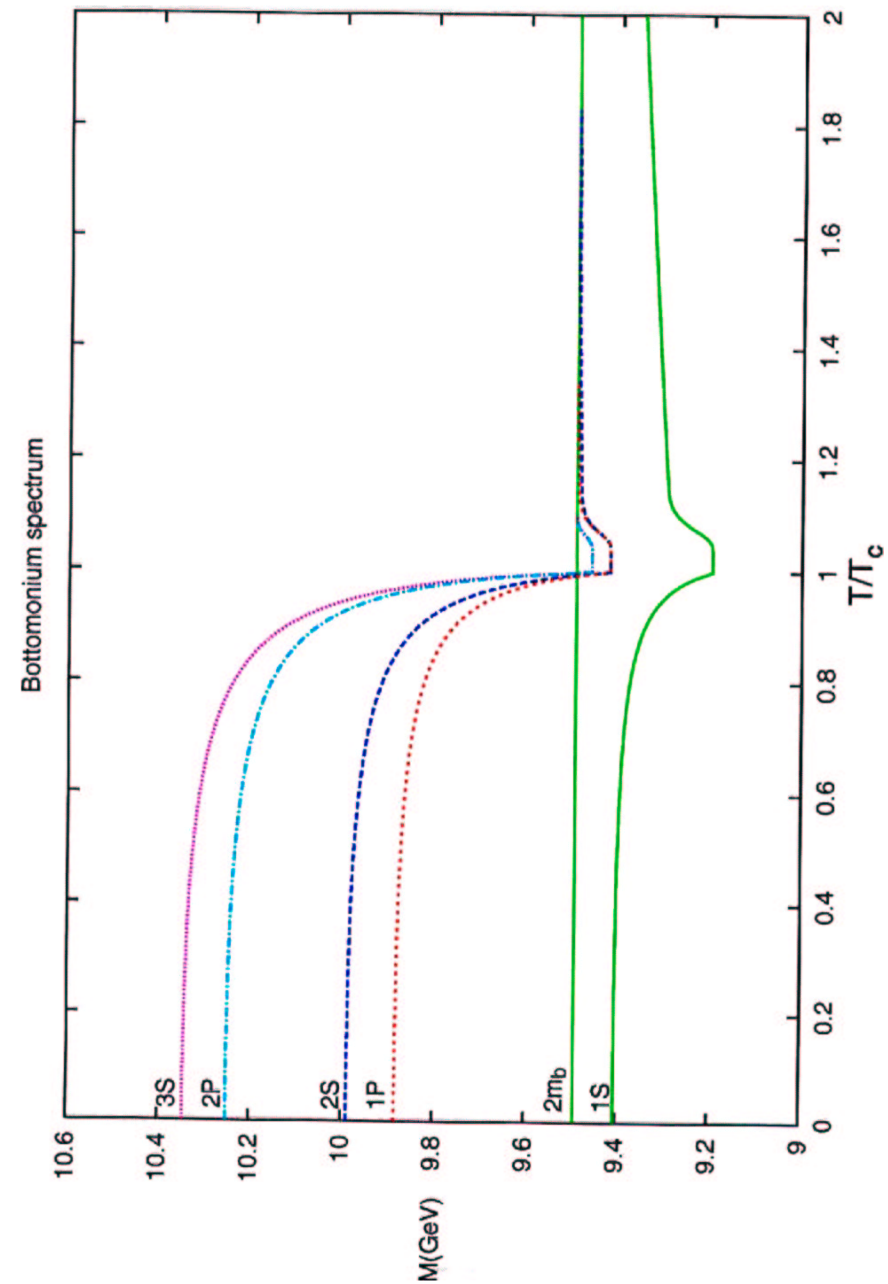
↷ for χ, ψ'

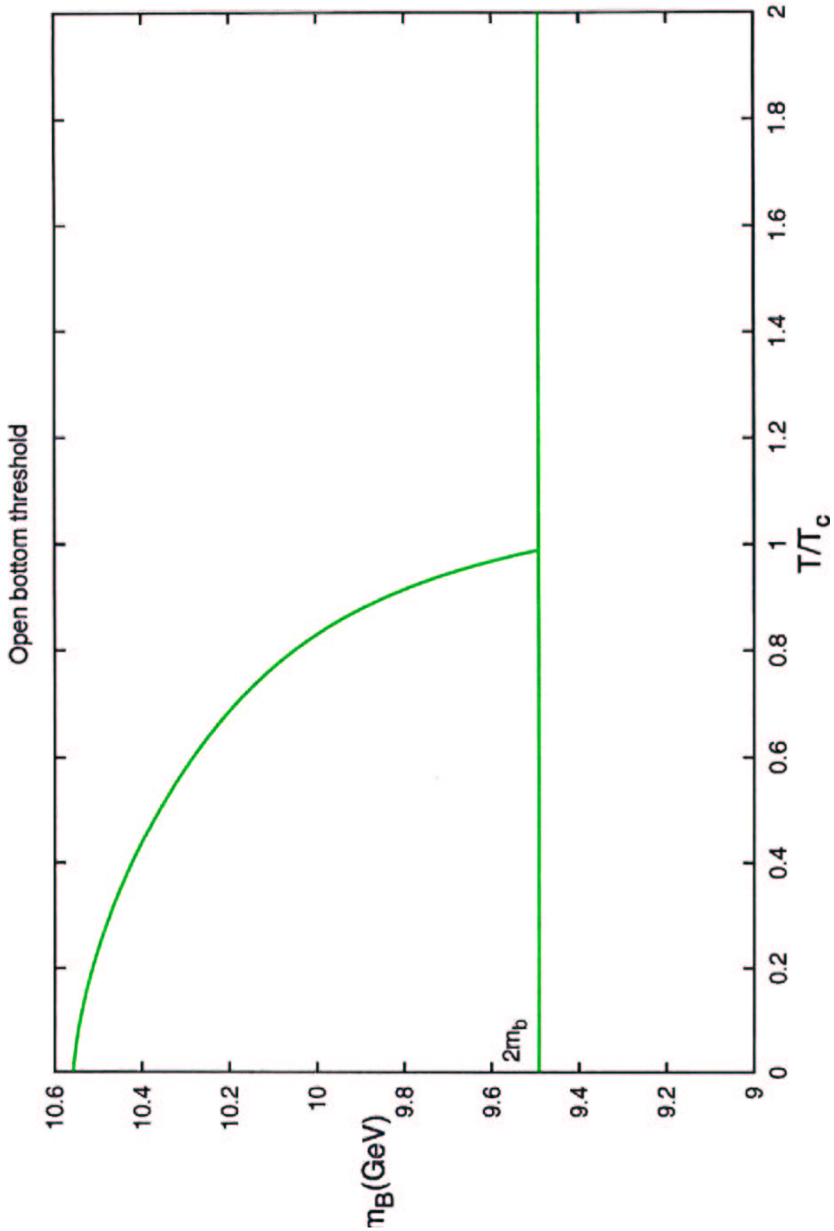
∴ χ & $\psi' \to 2M_D$ below T_c

↷ for bottomonium states Υ, χ_b, Υ', χ_b', Υ''




Open charm threshold
m_D(GeV)
T/T_c
2m_c
3.8
3.6
3.4
3.2
3
2.8
2.6
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


Bottomonium spectrum
M(GeV)
T/T_c
3S
2P
2S
1P
2m_b
1S
10.6
10.4
10.2
10
9.8
9.6
9.4
9.2
9
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2



- cross sections & densities

$T < T_c$, $\sigma^{dis}_{h-\psi} \lesssim 10^{-1}$ mb $\leftrightarrow$ soft hadronic gluons KS

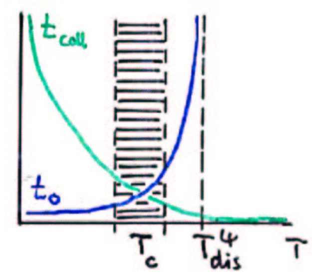
$T > T_c$, $\sigma^{dis}_{g-\psi} \simeq 2$ mb $[\sim \pi \mu^{-2}]$

$n(T)$? $\sim 0.5 \to 2\ \mathrm{fm}^{-3}$ crossing T_c
from $P(T)$ lattice data

- time scales $t_0(T) \sim 1/\Delta E(T)$ vs
$t_{coll}(T) \sim 1/n(T)\sigma^{dis}(T)$ } for J/ψ

$T \lesssim T_c$: J/ψ collision regime

$T \gtrsim T_c$: J/ψ collective regime



- J/ψ survival

$T \lesssim T_c$ $S_{coll} \simeq e^{-n\sigma\tau} \gtrsim 0.95$

NB: thermal activation?
No, $S_{act} \gtrsim 0.9$

$\therefore$ J/ψ survives $\sim$ up to T_c

$T \gtrsim T_c$ collective regime for J/ψ dissociation

color screening dissolves Coulomb binding for $T \geq T_{dis} \simeq 1.5\, T_c$, with $r_\psi(T_{dis}) = \infty$

what happens for $T_c \leq T \leq T_{dis}$?

thermal activation for $\Delta E_\psi \ll T$

$$R_{act} \simeq \frac{4}{r_\psi}\left[\frac{T}{2\pi M_\psi}\right]^{1/2} \gtrsim 0.5\ \text{fm}^{-1}$$

$$\Rightarrow S_{act}(T>T_c) \leq 10^{-2}$$

Coulombic J/ψ is thermally dissociated

∴ J/ψ suppression indicates $T \gtrsim T_c$

- higher $c\bar{c}$ excitations χ_c & ψ' suppressed by hadronic decay $\to 2M_D$ for $T < T_c$;

quantitative details? extract V_1 from $\bar{V}$ for $T < T_c$; possible increase of $2M_D(T)$

for final answer, need charmonium masses $M_\psi(T)$, $M_\chi(T)$, $M_{\psi'}(T)$ directly from lattice QCD

- bottomonia?

can Coulombic Υ survive for $T > T_c$?

present status

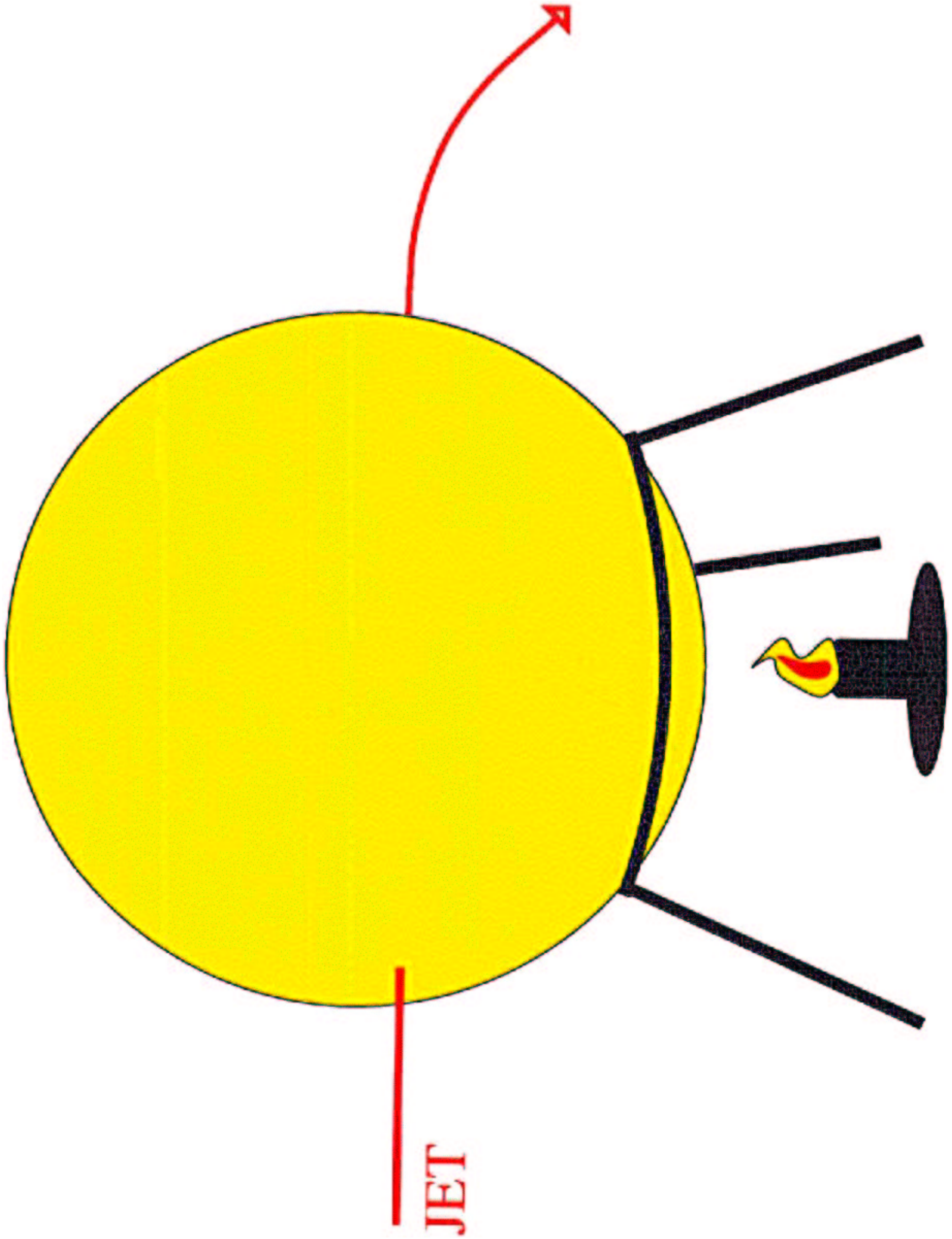
$T_{\psi'}$	T_{χ_c} $T_{\Upsilon''}$ $T_{\chi_b'}$	T_ψ $T_{\Upsilon'}$ T_{χ_b}	T_Υ
$\ll T_c$	$\sim T_c(1-\delta)$	$\sim T_c$	$\sim T_c(1+\bar{\delta})$

with $\delta, \bar{\delta} \lesssim$ 20-30 %, decreasing.

- quarkonium suppression occurs in narrow band around T_c

∴ quarkonia ~ microscope for transition

NB: interval $T_c - \delta \leq T \leq T_c + \bar{\delta}$ strongly amplified as $f(\varepsilon)$

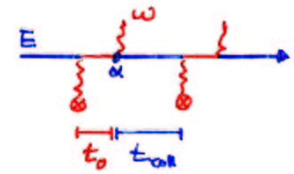


-16-

5. Jets

energy loss through gluon radiation in traversal of medium?

- incoherent regime



$t_0 \ll t_{coll}$

energy loss $-\Delta E = \nu\omega$

└ gluon energy $\omega \sim \alpha E$

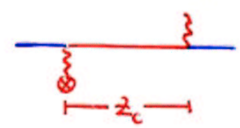
└ no. of collisions

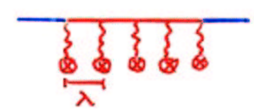
$\therefore \quad -dE/dz = [\frac{\omega}{\lambda}]$

$\int_0^L dz\,(dE/dz) = -\omega\,[\frac{L}{\lambda} = \nu]$

- coherent regime [Bzier ~ BDMPS]

$t_0 \gg t_{coll} \Rightarrow z_0 \gg \lambda$





$(z_c/\lambda) > 1$ interactions interfere destructively

$\therefore \quad -dE/dz = \frac{\omega}{\lambda}\underbrace{[\frac{\lambda}{z_c}]}_{<1}$ reduced energy loss

-17-

- calculate coherence length $z_0(E, \text{medium})$

$$-dE/dz = \text{const.}\ \underbrace{\frac{\mu^2}{\lambda}} \times \begin{cases} z_0 & L > z_c \\ L & L < z_c \end{cases}$$

$\equiv$ transport coefficient $\hat{q}$

coherence length $z_0 \sim (E/\hat{q})^{1/2}$

NB: α's ..

average p_T-kick / scattering

$$\mu^2 = \frac{1}{\sigma}\int dq_T^2\, q_T^2\, \frac{d\sigma}{dq_T^2}$$

$\therefore$ $\hat{q} = \underbrace{n(T)}_{\text{density of medium}} \underbrace{\int dq_T^2\, q_T^2\, d\sigma/dq_T^2}_{\text{scattering strength}}$

determines jet quenching

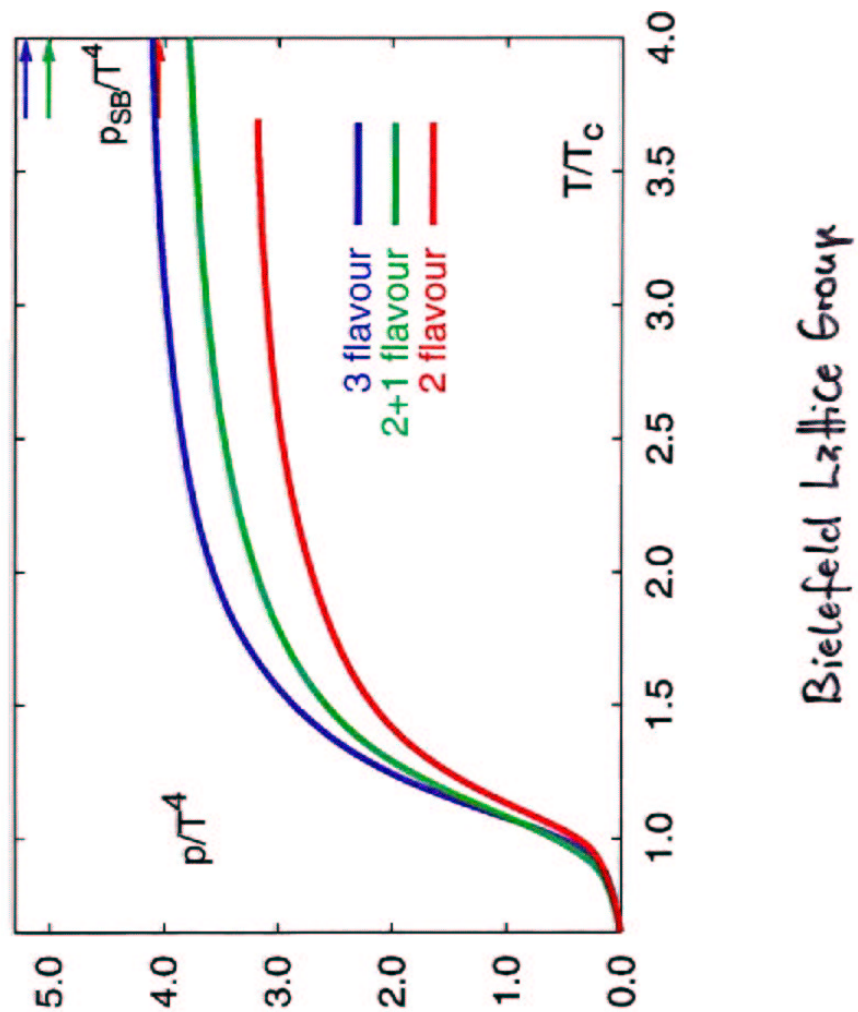
- scattering strength

$d\sigma/dq_T^2$: high energy limit for scattering of jet on constituents

$T < T_c$: hadrons, σ_h

$T > T_c$: partons, σ_p

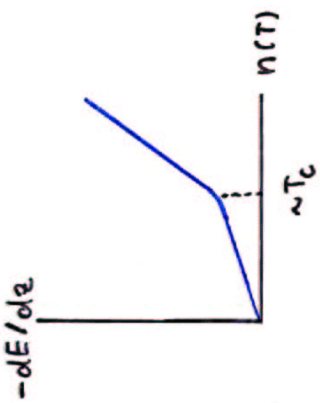
$r_i \equiv \int dq_T^2\, q_T^2\, d\sigma_i/dq_T^2$; i = hadron, parton



-18-

∴ with constants r_h, r_p

$$\hat{q}(T) = \begin{cases} r_h\, n_h(T) & T < T_c \\ r_p\, n_p(T) & T > T_c \end{cases}$$



∴ deconfinement ⇒ slope change for jet quenching as f(density)

identify T_c?

with $n(T) \sim P(T)/T$, behavior of $\hat{q}/T^3$ similar to that of P/T^4

- quantitative predictions for dE/dz in very hot QGP?

-19-

6. Outlook

- Gedankenexperiment conclusive
- nuclear collision "complications"?
- is equilibration necessary for confinement/deconfinement?

confinement binds partons into hadronic p.d.f.'s $g(x)$, $q(x)$, $\bar{q}(x)$

this uses some of collision energy:
∴ decoufined partons are harder

e.g.: for J/Ψ dissociation, this is enough, equilibration not needed

- is color glas "pre-deconfined matter"?

parton saturation ~ percolation
= critical behavior

relation to deconfinement?

Gedankenexperiment : Summary

- temperature : large mass dilepton spectrum
- state of medium :
  peak P(T) in dilepton spectrum
  J/Ψ survival / suppression
- transition details :
  sequential quarkonium suppression
- in-medium hadrons :
  light - dileptons
  quarkonia - J/Ψ vs Υ
- warm QGP : origin of dilepton peak, $T > T_c$
  J/Ψ vs Υ
- hot QGP : Large mass dileptons
  jets