Lecture 2:

Heavy quarks & Quarkonia

Heavy Quark Potentials and Quarkonium

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International School on

Quark Gluon Plasma and Heavy Ion Collisions

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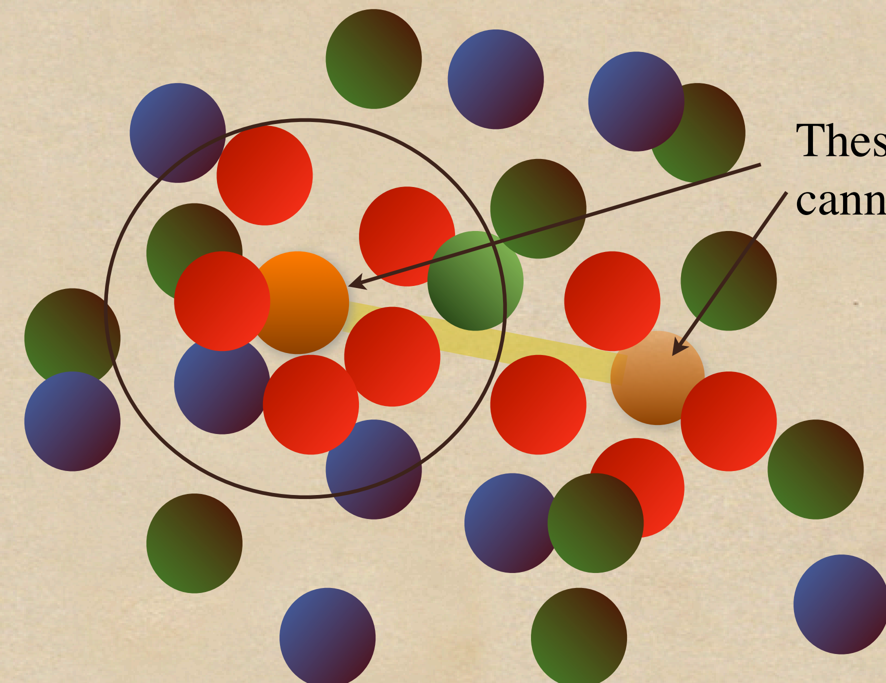
The menu

- Refresher from lecture 1
- Heavy quark free energy from lattice
- Direct/indirect lattice quarkonium

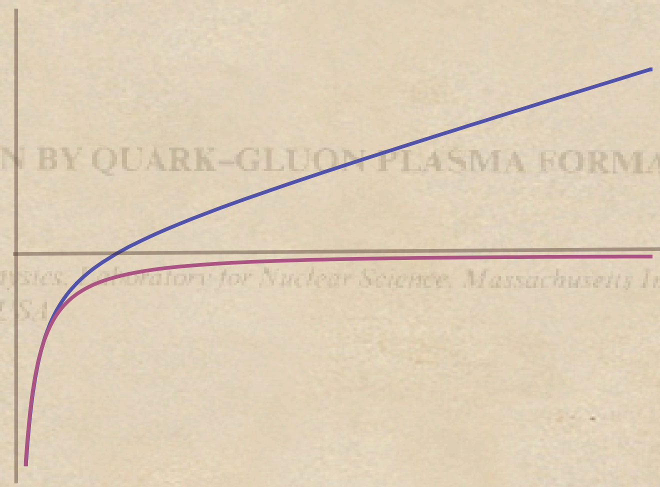
Quarkonium at T≠0



- rearrangement of color around Q
- effective charge of Q reduced (screened)
- assume potential interaction at finite T

Matsui-Satz argument

Volume 178, number 4 PHYSICS LETTERS B 9 October 1986



$$V(r) = -\frac{\alpha_{eff}}{r} + \sigma r$$

$$V(r,T) = -\frac{\alpha_{eff}}{r} e^{-r/r_D(T)}$$

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

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Received 17 July 1986

Yukawa potential can still hold bound states

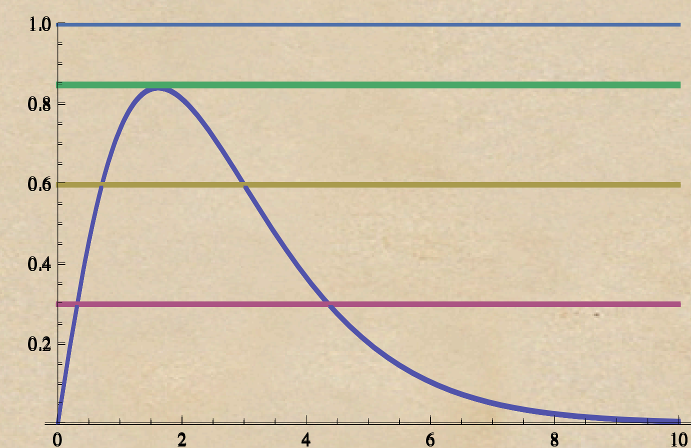
If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents c̄c binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

Matsui-Satz argument

back to semi-classical approximation

$$\frac{dE_{Q\bar{Q}}(r, r_D(T))}{dr} = 0$$

$x(1+x)e^{-x}$



$$x(1+x)e^{-x} = \frac{1}{m_Q \alpha_{eff} r_D(T)}$$

$$x = r / r_D$$

$$\frac{1}{m_Q \alpha_{eff} r_D(T)}$$

at some $r_D(T)$ no solution exists, i.e. no bound state

$$r_D < r_{Bohr} \approx 1/m\alpha_{eff}$$

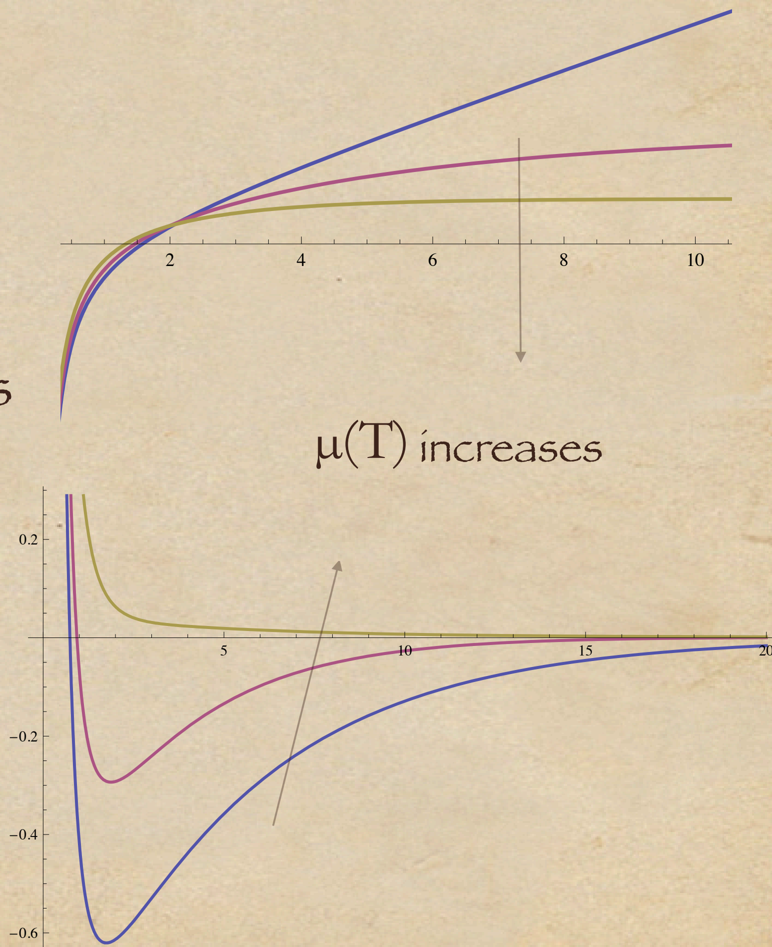
KMS potential

- Screened Cornell potential

$$V(r,T) = -\frac{\alpha_{eff}}{r} e^{-\mu(T)r} + \frac{\sigma}{\mu(T)}\left(1 - e^{-\mu(T)r}\right)$$

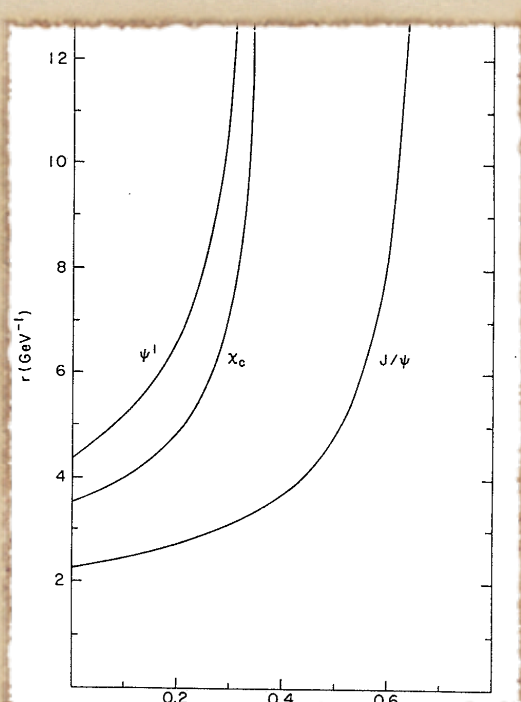
- As the screening μ(T) increases with T the potential becomes less effective

- Effective binding potential
  Large μ(T) no bound state



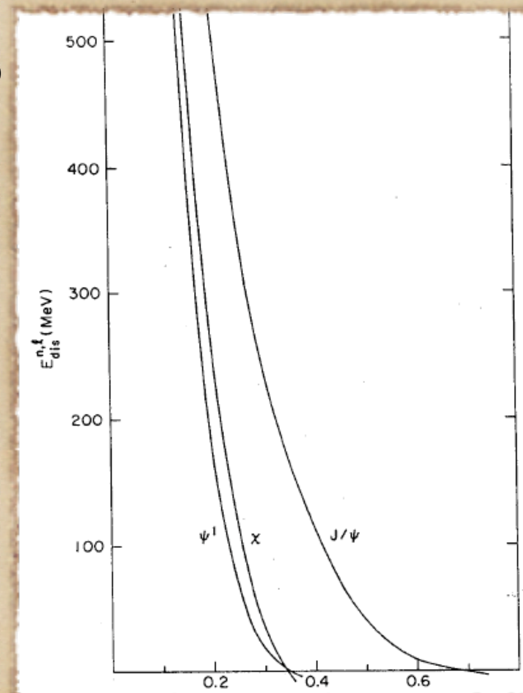
Quarkonium properties

Radii $\langle r^2 \rangle = \int d^3 r r^2 |\psi(r)|^2$



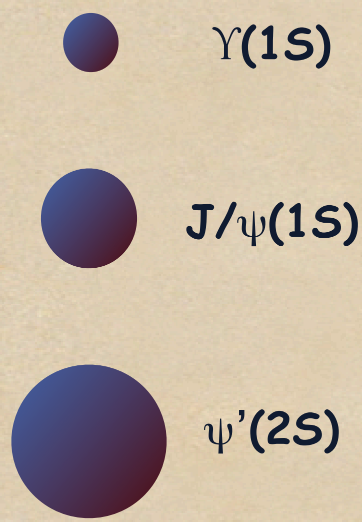
Vanishing of the states has been looked at in terms of dissociation energy

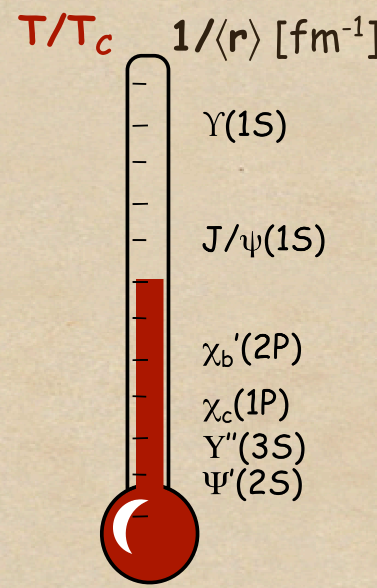
$$E_{diss}(\mu) = 2m_Q + \frac{\sigma}{\mu} - E_{Q\bar{Q}}(\mu)$$



Need to know how the screening changes with T !

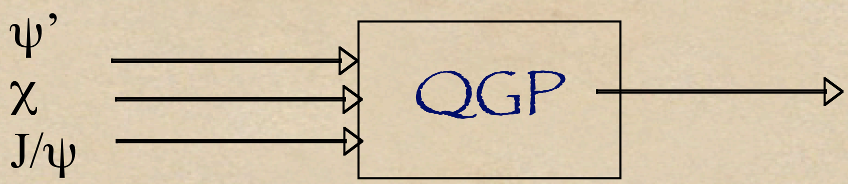
Sequential dissociation





QGP thermometer

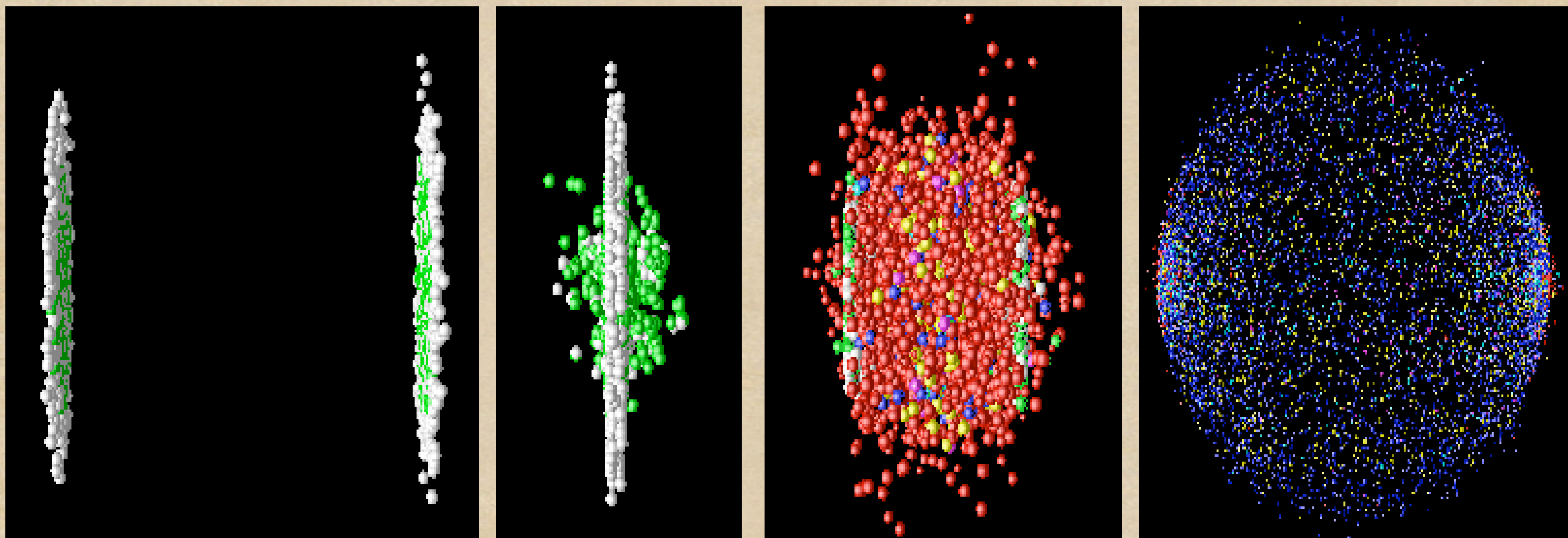
shine 3 beams onto a black box



1) If ψ' is absorbed and χ, J/ψ get through
   => strongly interacting matter < T_c, i.e. hadrons
2) If ψ', χ are absorbed, J/ψ gets through
   => matter near T_c
3) If nothing gets through
   => QGP above T_c

but we don't have a box full of QGP or quarkonium beams
and bound states likely not form before the hot medium

collision evolution

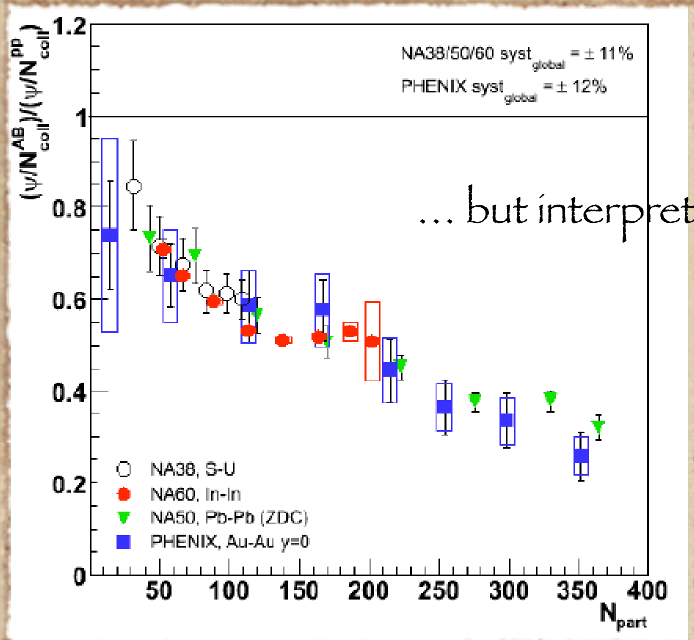


J/Ψ - is a problem of scales

c-$\bar{c}$ production time, bound state formation time,

plasma, glasma formation time, plasma life time, ...

experimental observation



… but interpretation not understood

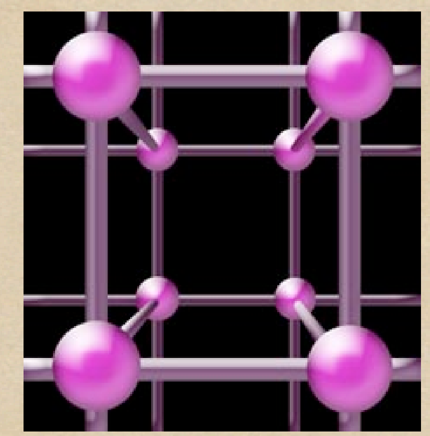
Hot medium effects - screening?

Cold nuclear matter effects ?

Recombination?

- Need to know how quarkonium properties are modified in the plasma
- Is there a rigorous way to study the modification with temperature of interquark forces ? this is a much more generic question (how the confining force is changing)

Lattice QCD

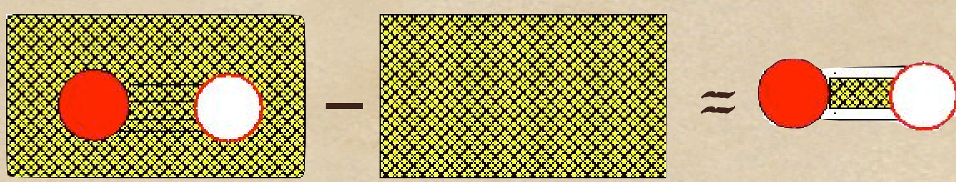


- ab initio (1st principles) Monte-Carlo simulations of QCD on a 4D grid (need a lot for operations to complete)

- supercomputers
  1 Tflop = 10^{12} operation/s

Static quark free energy

- Lattice studies the difference in the free energy of the system with static Q-Q̄ pair and the same system without static charges

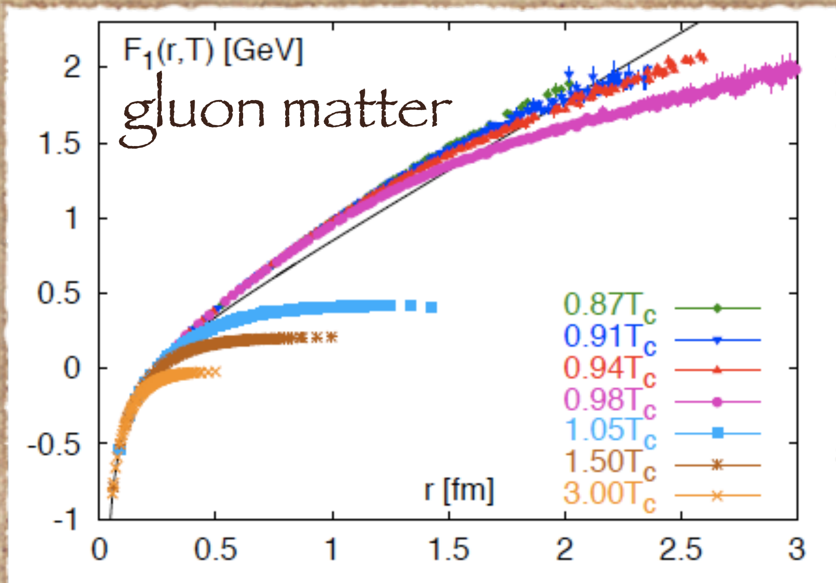


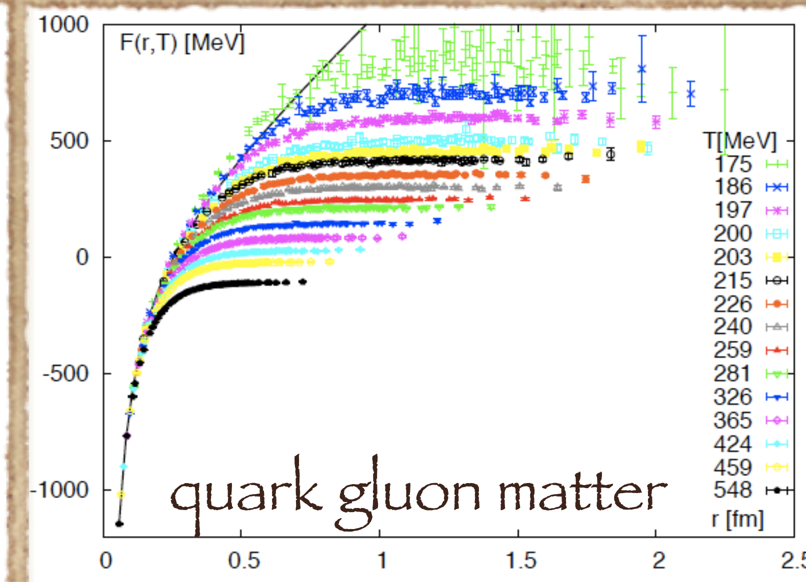
$$\exp(-F_1(r,T)/T) = \frac{1}{Z(T)}\frac{\mathrm{Tr}P_1 Z_{Q\bar{Q}}(r,T)}{\mathrm{TrP}_1} = \frac{1}{3}\mathrm{Tr}\langle W(r)W^\dagger(0)\rangle$$

$$-\frac{4}{3}\frac{\alpha_s}{r}\exp(-m_D \cdot r)$$

McLerran, Svetitsky, Phys lett B 98, 195 (1981)

Quenched & Full QCD





$N_f = 0$:
$32^3 \times 4, 8, 16$-lattices
(*Symanzik*)

O. Kaczmarek, F. Karsch, P. Petreczky, F. Zantow (2002, 2004)

$N_f = 2$:
$16^3 \times 4$-lattices
(*Symanzik, p4-stagg.*)
hybrid-R

$m_\pi/m_\rho \simeq 0.7$ $(m/T = 0.4)$

O. Kaczmarek, F. Zantow (2005), O. Kaczmarek et al. (2003)

$N_f = 3$:
$16^3 \times 4$-lattices
(*stagg., Asqtad*)
hybrid-R

$m_\pi/m_\rho \simeq 0.4$

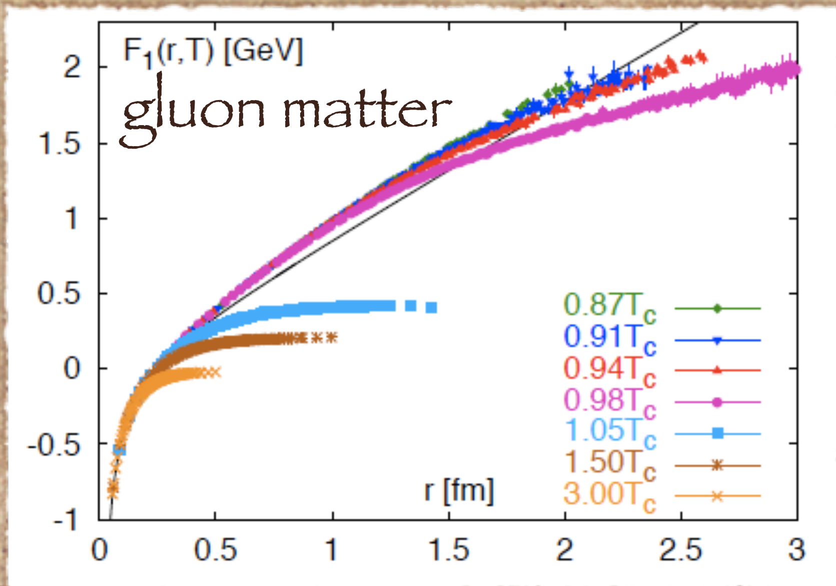
P. Petreczky, K. Petrov (2004)

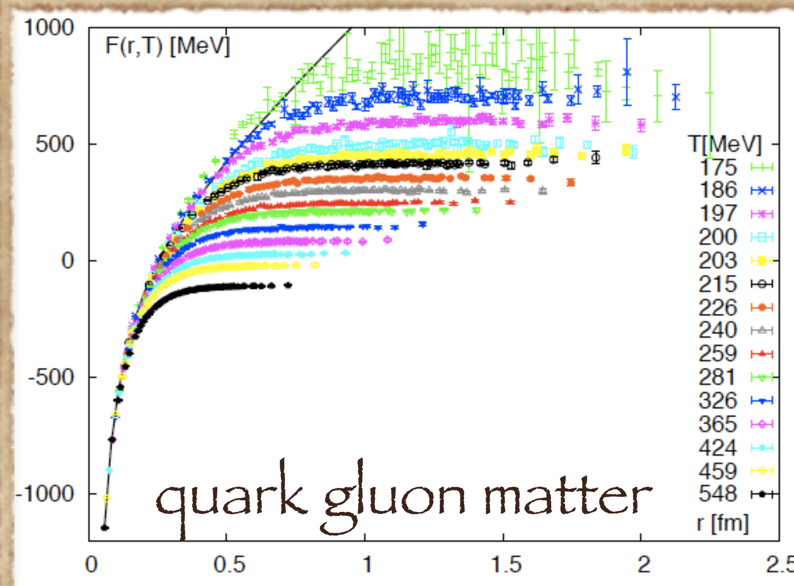
$N_f = 2+1$:
$24^4 \times 6$-lattices
(*Symanzik, p4fat3*)
RHMC

$m_\pi \simeq$ **220 MeV, phys.** m_s

O. Kaczmarek (2007), RBC-Bielefeld (2008)

Quenched & Full QCD



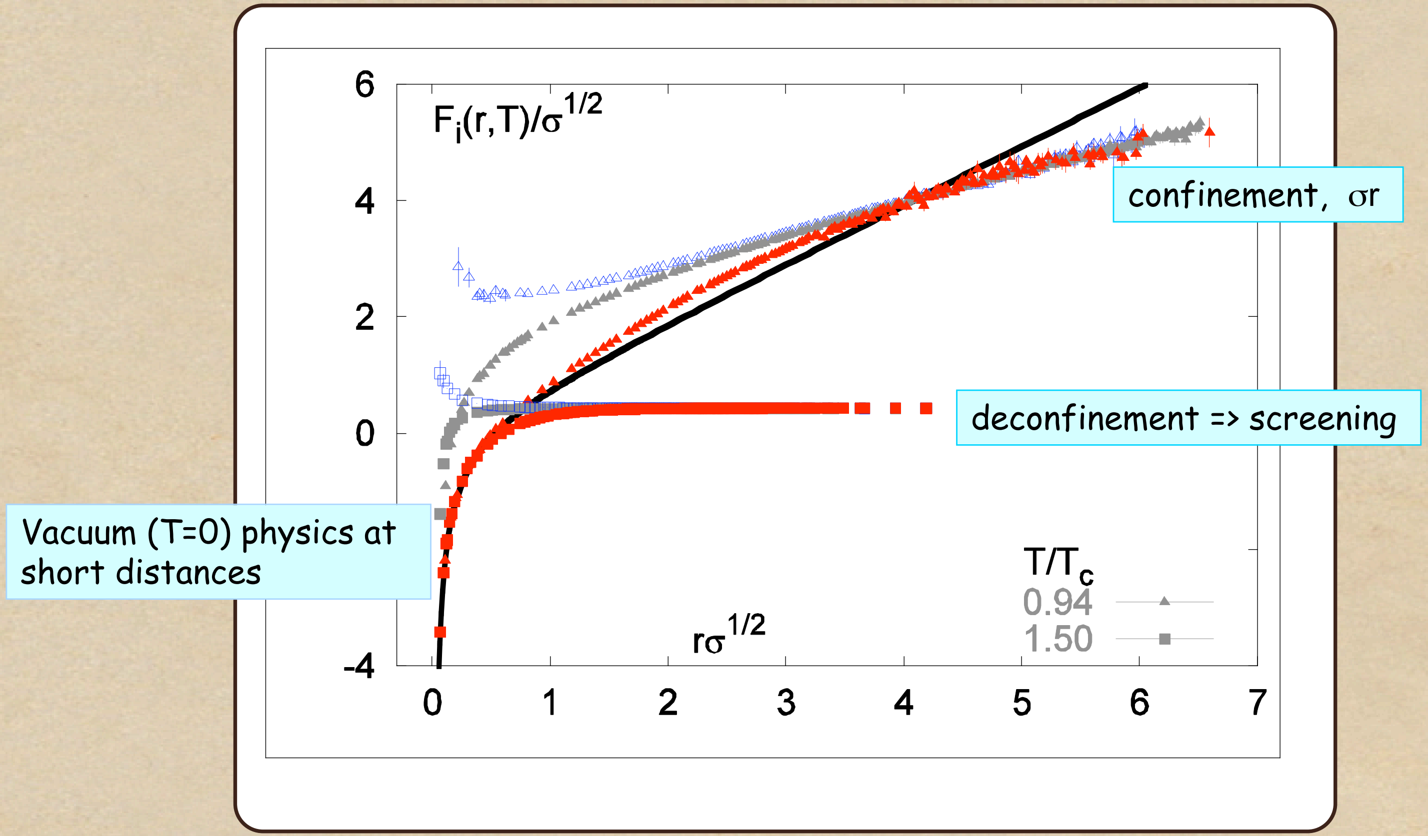


T<Tc : linear rise — string breaking

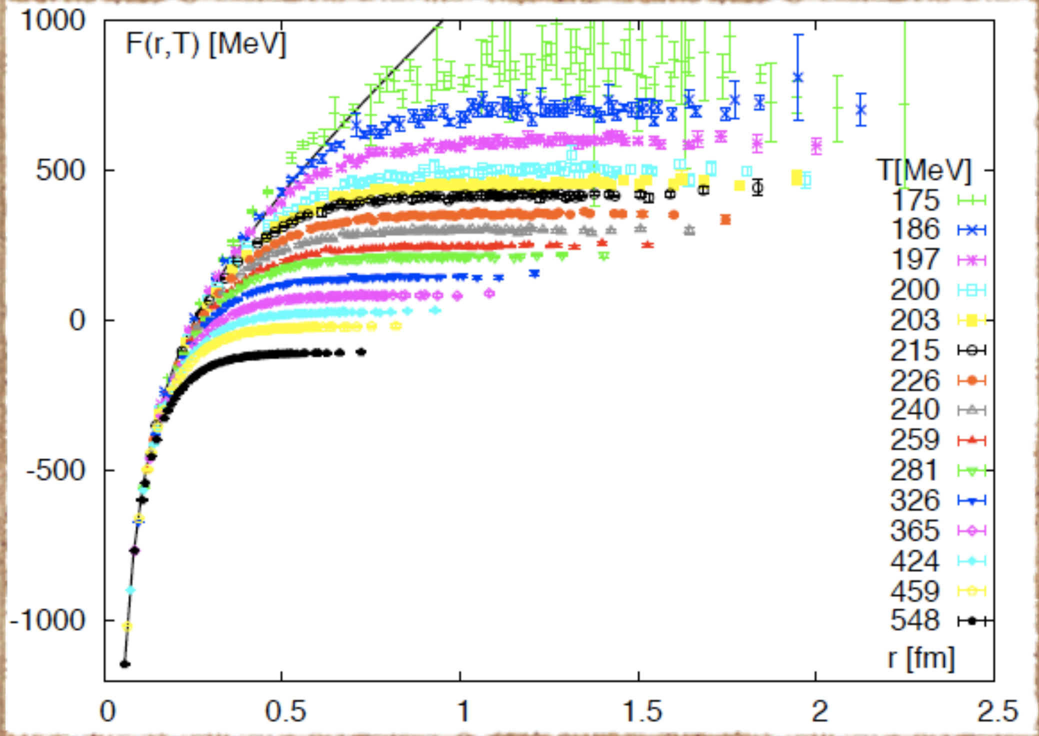
$F_1(r \to \infty) \to \infty$ — $F_1(r \to \infty) \to$ constant

qualitatively different behavior at large distances

Free energy - quenched



Free energy - full QCD



short

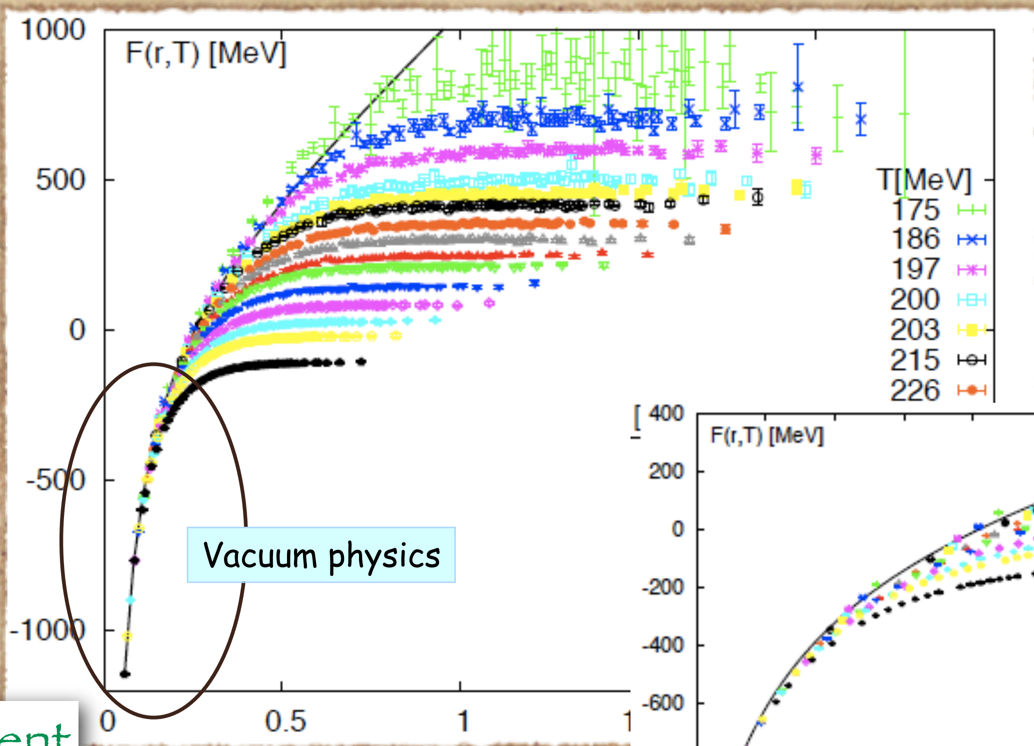
intermediate

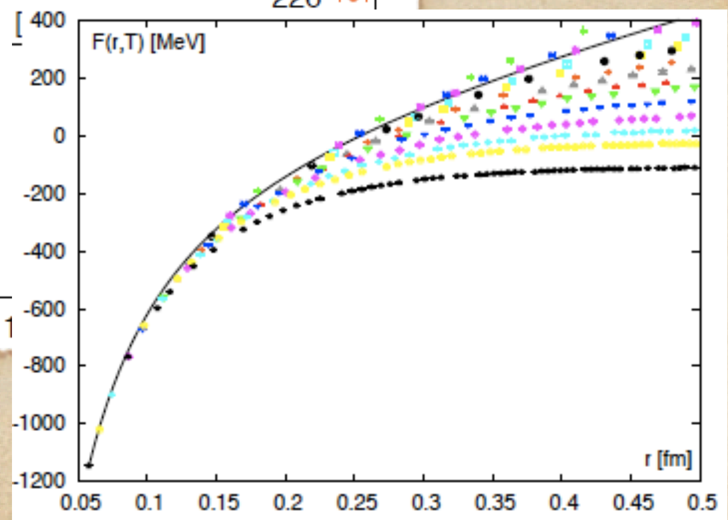
large distances

Free energy - full QCD

$r < r_{med}(T)$

$F(r,T) \approx F(r)$





T-independent

$F(r,T) \sim g^2(r)/r$

Free energy full QC

String breaking

$T<T_c$

$F(\infty,T)<\infty$

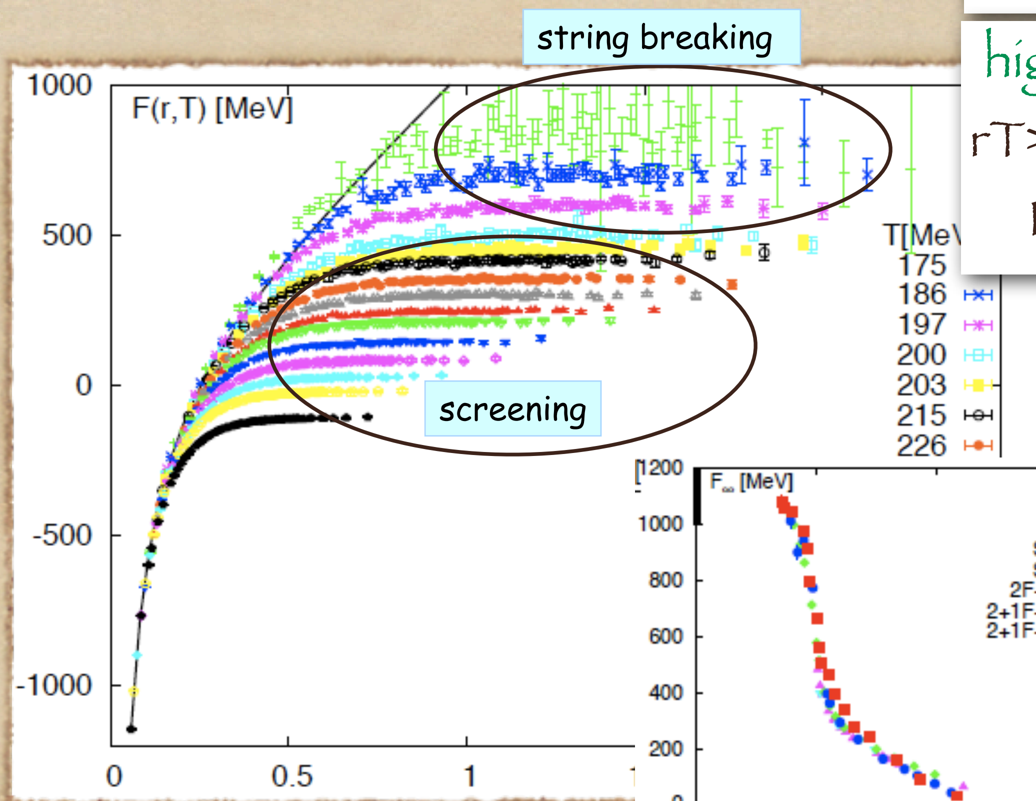
high T physics

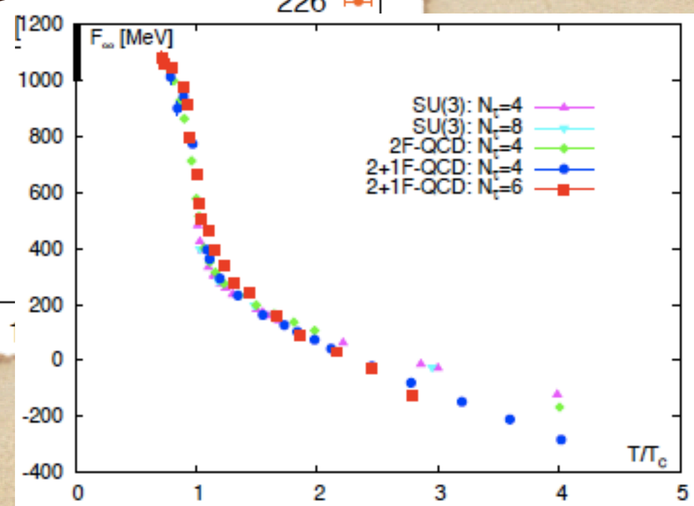
$rT>>1$ screening

$F(\infty,T)\sim -T$

$r > r_{scr}(T)$

$F(r,T) \approx F(T)$



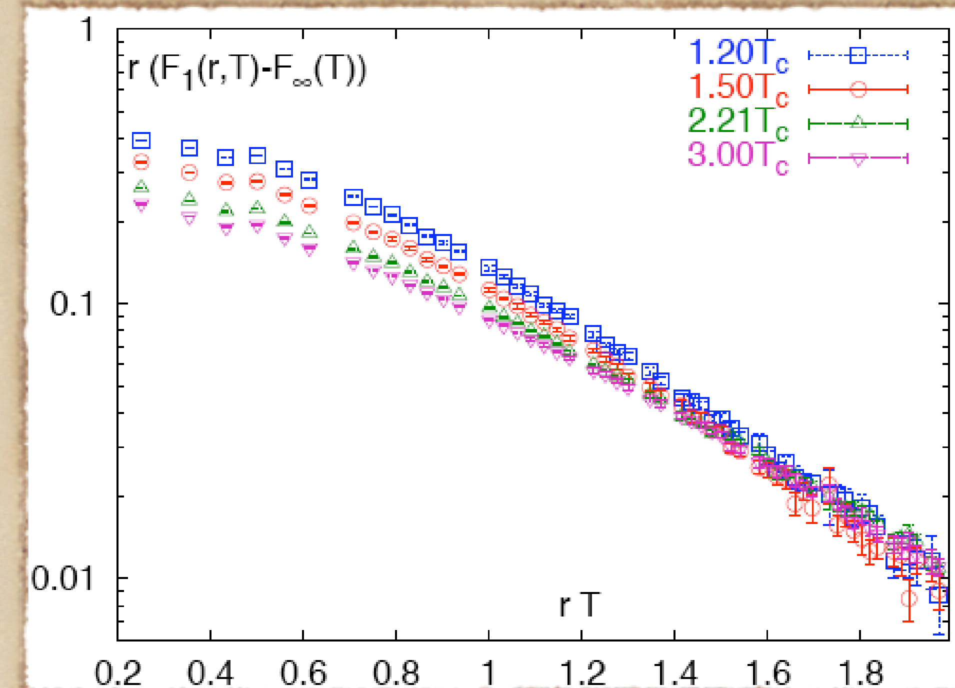


Screening

exponential falloff of the color singlet free energy at large distances

rT > 0.8-1 full QCD

rT > 1.25 quenched



$$F_1(r,T) - F_1(r=\infty,T) = -\frac{4\alpha(T)}{3r} e^{-m_D(T)r}$$

Screening mass

Screening masses obtained from fits to:

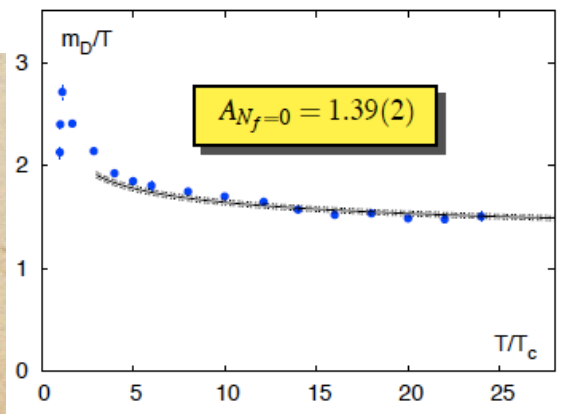
$$F_1(r,T) - F_1(r=\infty,T) = -\frac{4\alpha(T)}{3r} e^{-m_D(T)r}$$

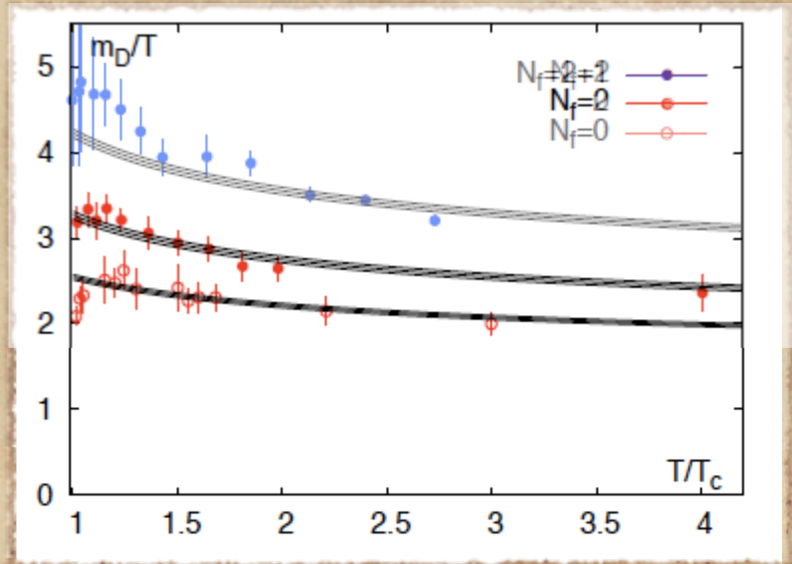
at large distances $rT \gtrsim 1$

leading order perturbation theory:

$$\frac{m_D(T)}{T} = A\left(1+\frac{N_f}{6}\right)^{1/2} g(T)$$

perturbative limit reached very slowly





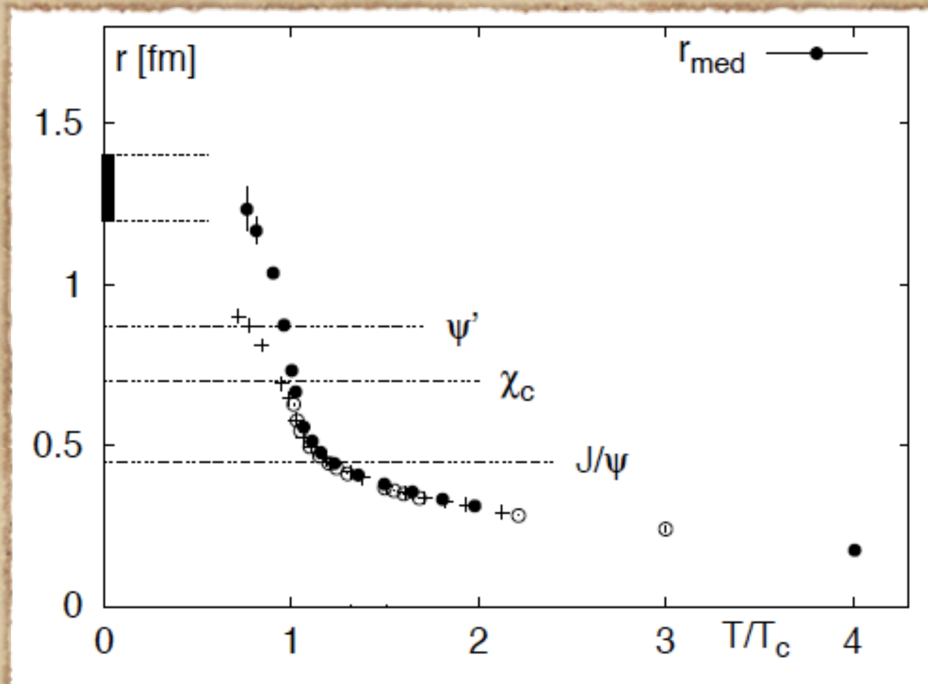
T depencence qualitatively described by perturbation theory

But $A \approx 1.4$ - 1.5 $\Longrightarrow$ non-perturbative effects

$A \to 1$ in the (very) high temperature limit

Medium effects

$r_{med}(T)$ characterizes the onset of medium modifications of the Q-$\bar{Q}$ free energy

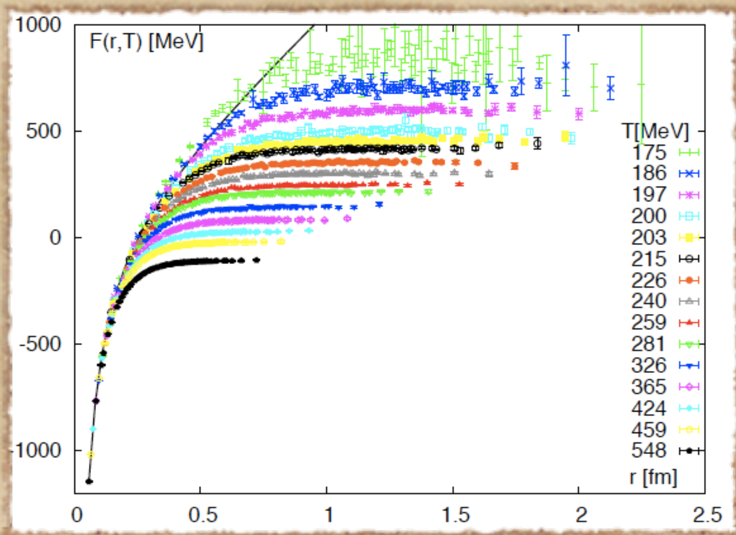


Digal, Petreczky, Satz, PRD 64 (2001)

Matsui-Satz:

quarkonium dissociates when the screening radius becomes smaller than the size of the state $r_{med} < r_{Q\bar{Q}}$

Free energy as potential



$q\bar{q}$	T/T_c
J/Ψ	1.10
$\chi_c(1P)$	0.74
$\psi(2S)$	0.1–0.2
$\Upsilon(1S)$	2.31
$\chi_b(1P)$	1.13
$\Upsilon(2S)$	1.10
$\chi_b(2P)$	0.83
$\Upsilon(3S)$	0.75

Digal, Petreczky, Satz, PRD 64 (2001)

Why F_1 not equal V?

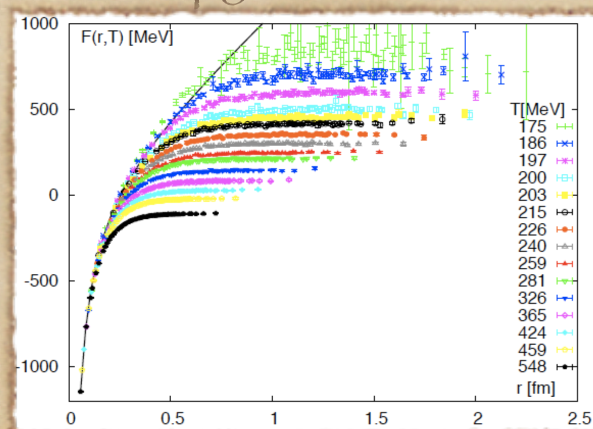
Recall pQCD $$V(r) = -\frac{4}{3} g^2 \int \frac{d^3k}{(2\pi)^3} e^{i\mathbf{k}\cdot\mathbf{r}} D_{00}(\mathbf{k}) = -\frac{4}{3}\frac{g^2}{r} e^{-m_D r}$$

Singlet free energy $$F_1 = -\ln\left(T \frac{Z_{QQ}(r,T)}{Z(T)} \right)$$

LO pQCD: $$F_1 = -\frac{4}{3}\frac{g^2}{r} e^{-m_D r} = V$$

NLO pQCD: $$F_1 = -\frac{4}{3}\frac{g^2}{r} e^{-m_D r} - \frac{g^2 m_D}{3\pi} \neq V$$

entropy contribution



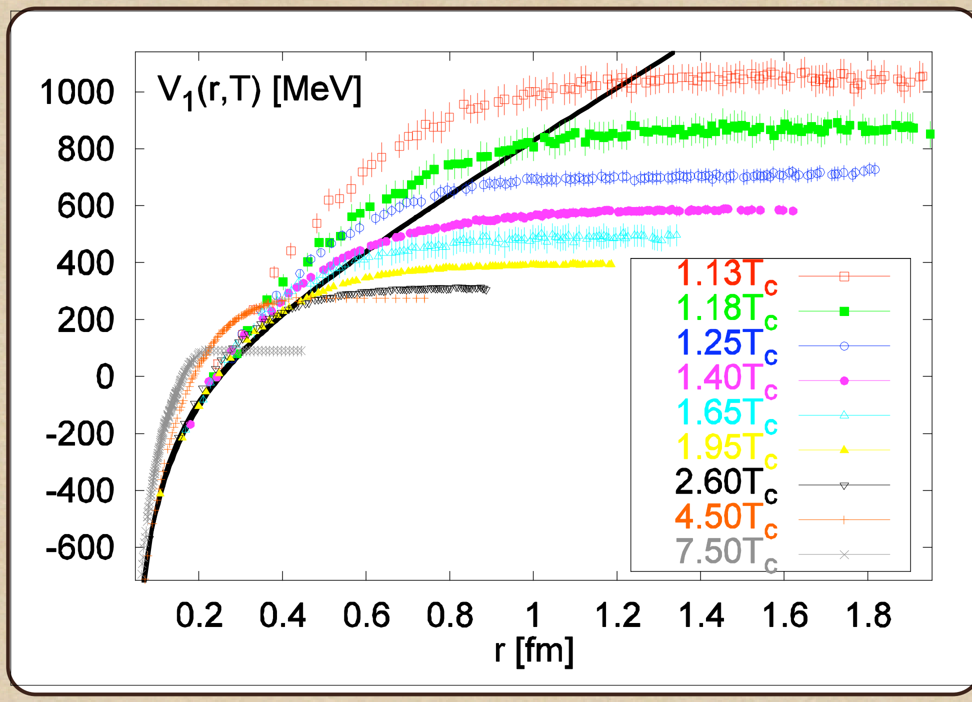
$$S = -\frac{\partial F}{\partial T} = -\frac{g^2 m_D}{3\pi T}\left(1 - e^{-m_D r}\right) \to -\frac{g^2 m_D}{3\pi T} \quad \text{for large r}$$

$$\to 0 \quad \text{for r ->0}$$

$$F_\infty(T) = -\frac{g^2 m_D}{3\pi} \cong O(g^3) \to -\infty$$

Entropy plays a role at finite T

Internal energy



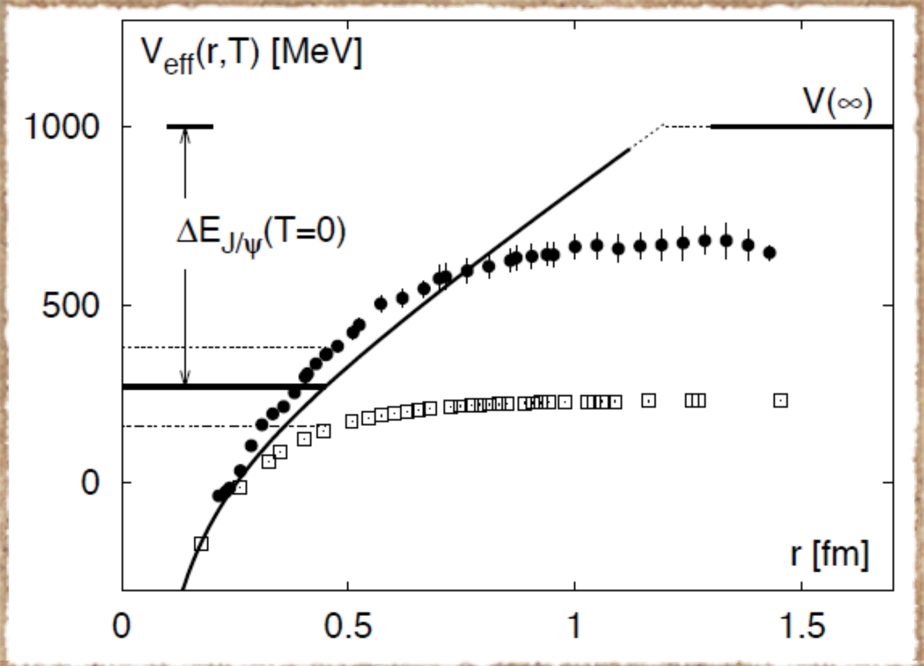
$$U_i(r,T) = T^2 \frac{\partial}{\partial T} \ln\left(\frac{Z^i_{Q\bar{Q}}(r,T)}{Z(T)}\right)$$
$$= F_i(r,T) + TS_i(r,T),$$
$$i = 1, 8, av.$$

$$S_i(r,T) = \frac{\partial}{\partial T} \ln\left(T\frac{Z^i_{Q\bar{Q}}(r,T)}{Z(T)}\right) = -\frac{\partial F_i(r,T)}{\partial T}$$

Internal energy as potential

Entropy contributions vanish in the limit $r \to 0$

$$F_1(r \ll 1, T) = U_1(r \ll 1, T) \equiv V_1(r)$$



Kaczmarek (2005)

steeper slope of $V_{eff}(r,T) = U_1(r,T)$

$\Longrightarrow$ J/ψ stronger bound using $V_{eff} = U_1(r,T)$

$\Longrightarrow$ dissociation at higher temperatures compared to $V_{eff}(r,T) = F_1(r,T)$

Internal energy as potential

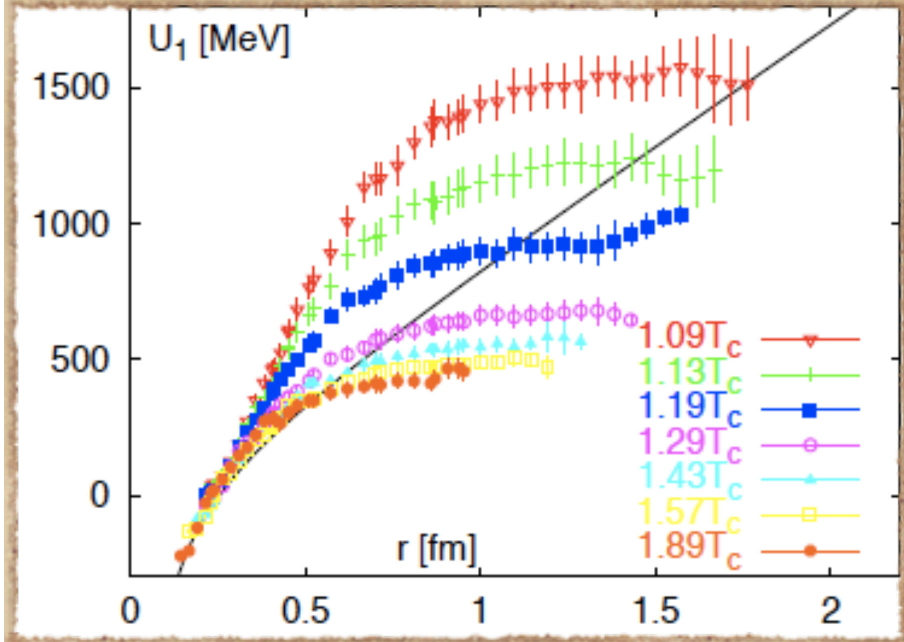
TABLE I. Summary of masses and binding energies (in [GeV]) for *S*-wave quarkonia in the QGP as extracted from the finite-temperature *T*-matrix determinant, Eq. (7).

T/T_c	1.1	1.5	2.0	2.5	3.0	3.3
$M[J/\psi, \eta_c]$	2.99	3.13	3.25	3.34	≈3.40	⋯
$E_B[J/\psi, \eta_c]$	0.41	0.27	0.15	0.06	≈0	⋯
$M[\psi(2S)]$	≈3.40	⋯	⋯	⋯	⋯	⋯
$E_B[\psi(2S)]$	≈0	⋯	⋯	⋯	⋯	⋯

T/T_c	1.1	1.5	1.8	2.1	2.7	3.5
$M[\Upsilon, \eta_b]$	9.35	9.47	9.59	9.70	9.81	9.86
$E_B[\Upsilon, \eta_b]$	0.95	0.83	0.71	0.60	0.49	0.44
$M[\Upsilon(2S)]$	10.05	10.18	10.28	⋯	⋯	⋯
$E_B[\Upsilon(2S)]$	0.25	0.12	≈0	⋯	⋯	⋯
$M[\Upsilon(3S)]$	≈10.30	⋯	⋯	⋯	⋯	⋯
$E_B[\Upsilon(3S)]$	≈0	⋯	⋯	⋯	⋯	⋯

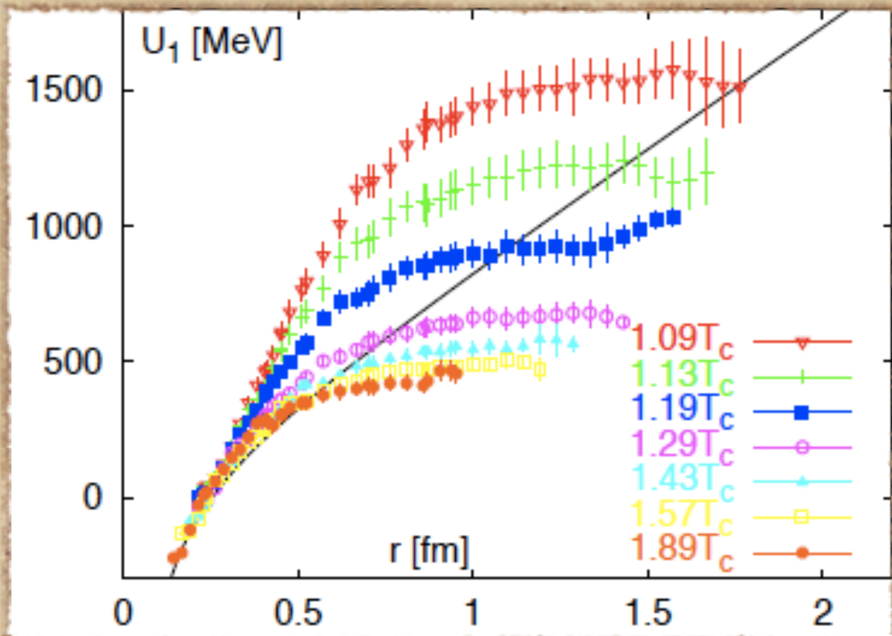
TABLE II. Same as in Table I for *P*-wave quarkonia.

T/T_c	1.1	1.3	1.5	2	2.3
$M[\chi_c(1P)]$	3.38	⋯	⋯	⋯	⋯
$E_B[\chi_c(1P)]$	≈0	⋯	⋯	⋯	⋯
$M[\chi_b(1P)]$	9.95	10.05	10.11	10.23	10.30
$E_B[\chi_b(1P)]$	0.35	0.25	0.19	0.07	≈0
$M[\chi_b(2P)]$	10.25	10.30	⋯	⋯	⋯
$E_B[\chi_b(2P)]$	0.05	≈0	⋯	⋯	⋯



Wong, PRC (2005)

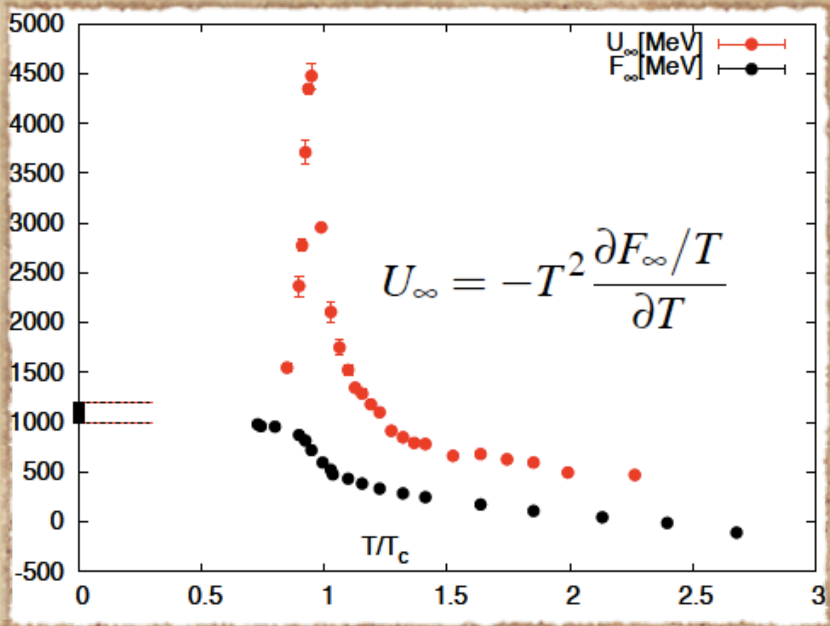
Why U_1 not equal V?



There is a large increase in the strength, well above the T=0 potential

Implications on heavy quark bound states

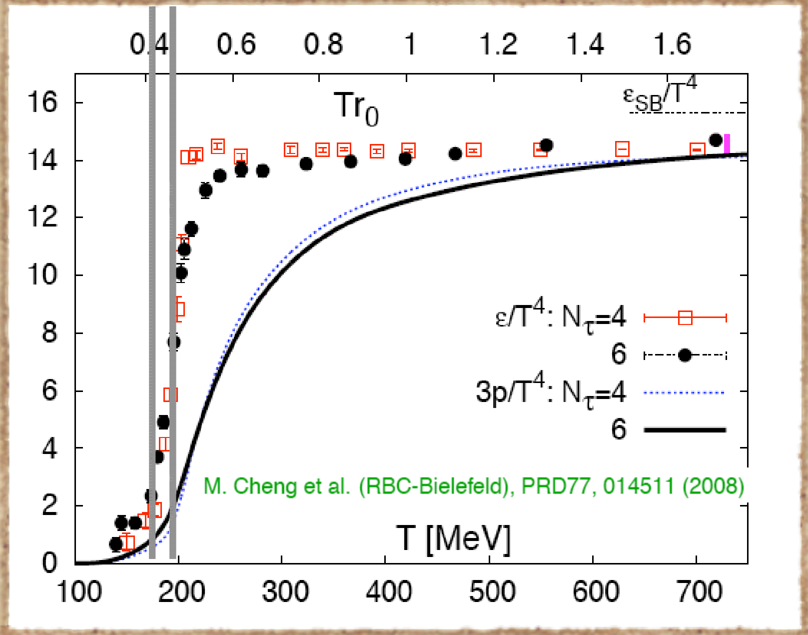
Why U_1 not equal V?



There is a large increase in the entropy and internal energy at the transition temperature !

Adding an extra static meson increases the entropy and the internal energy like in the production of extra hadrons in resonance gas model. This increase is not related to the increase of the strength of interaction between the q-$\bar{q}$ pair.

- the strong screening seen is in accordance with the liberation of a large number of degrees of freedom



energy density~ # dof

- The question has become which potential to use in potential models
- we'll discuss this in lecture 3

Quarkonium correlators

- In lattice QCD correlation function of mesonic currents are directly calculated in Euclidean time

$$G(\tau,\vec{p},T) = \int d^3x e^{i\vec{p}\vec{x}} \left\langle j_H(\tau,\vec{x}) j_H^+(0,\vec{0}) \right\rangle$$

- meson current in different channels

$$j = \begin{array}{lll} \bar{q}q & \text{scalar} & \chi_{c0}\ \chi_{b0} \\ \bar{q}\gamma_5 q & \text{pseudoscalar} & \eta_c\ \eta_b \\ \bar{q}\gamma_\mu q & \text{vector} & J/\psi\ \Upsilon \\ \bar{q}\gamma_\mu\gamma_5 q & \text{axialvector} & \chi_{c1}\ \chi_{b1} \end{array}$$

- Meson correlator is related to the spectral function $G(\tau,T) = \int_0^\infty d\omega \sigma(\omega,T) \frac{\cosh(\omega(\tau - 1/(2T))}{\sinh(\omega/(2T))}$
- We can learn about the spectral function at finite temperature in two ways: look at either the spectral function directly or the ratio of correlators

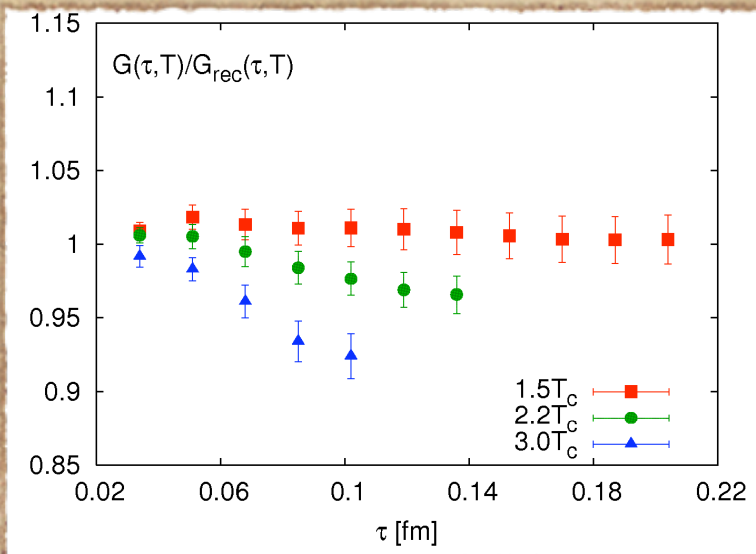
$$\frac{G(\tau,T) = \int \sigma(\omega,T) K(\tau,\omega,T) d\omega}{G_{rec}(\tau,T) = \int \sigma(\omega,T=0) K(\tau,\omega,T) d\omega}$$

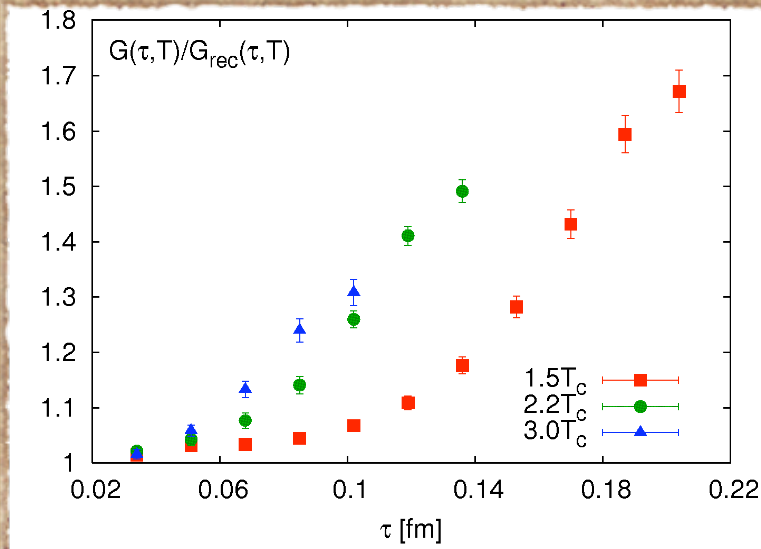
Initial interpretation

$$\frac{G(\tau,T) = \int \sigma(\omega,T)K(\tau,\omega,T)d\omega}{G_{rec}(\tau,T) = \int \sigma(\omega,T=0)K(\tau,\omega,T)d\omega}$$

- G/Grec ≈ 1 means spectral function unchanged, state survives
- G/Grec ≠ 1 means spectral function modified, state dissociated

Charmonium correlators



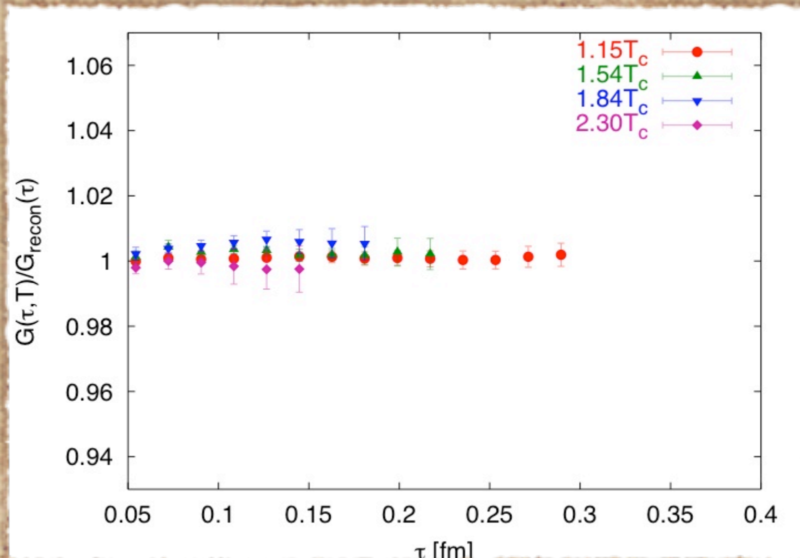


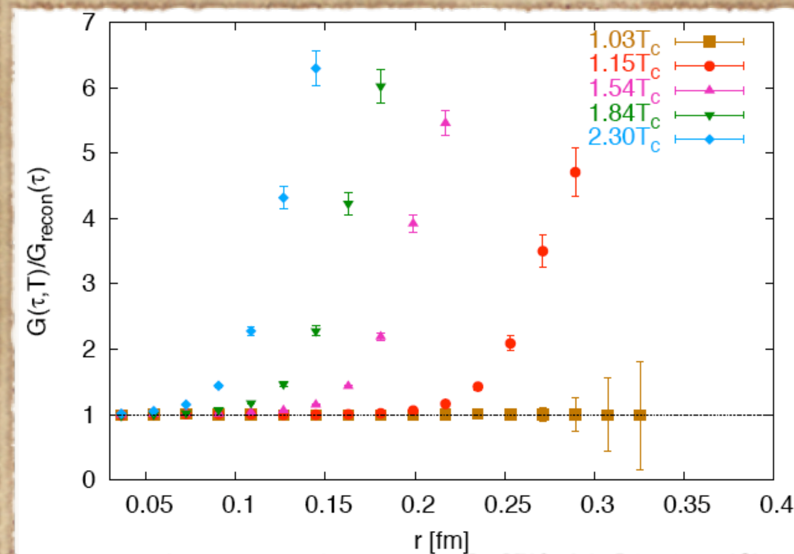
Jakovac et al, PRD 75 (2007)

Initial interpretation

$J/\psi(\eta_c)$ survives up to 1.5-2T_c AND χ_c melts by 1.1 T_c

Bottomonium correlators





Jakovac et al, PRD 75 (2007)

Initial interpretation

Υ and η_b survive well above 2T_c

χ_b melts by 1.1 T_c

χ_b same size as the J/ψ, so why are the χ_b and J/ψ correlators so different ?

Spectral function

$$G(\tau,T) = \int \sigma(\omega,T) K(\tau,\omega,T) d\omega$$

Correlator
MEASURED

Spectral Function
EXTRACTED **with MEM**

Kernel
cosh[ω(τ-1/2T)]/sinh[ω/2T]

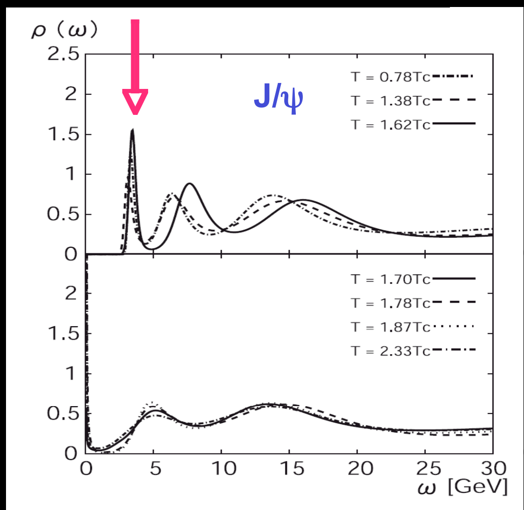
$G(\tau, \vec{p}, T)$ ➡ MEM ➡ $\sigma(\omega, \vec{p}, T)$

- Looking for the spectral function which maximizes the conditional probability P[sigma|DH] of having the spectral function sigma given the data D and some prior knowledge H

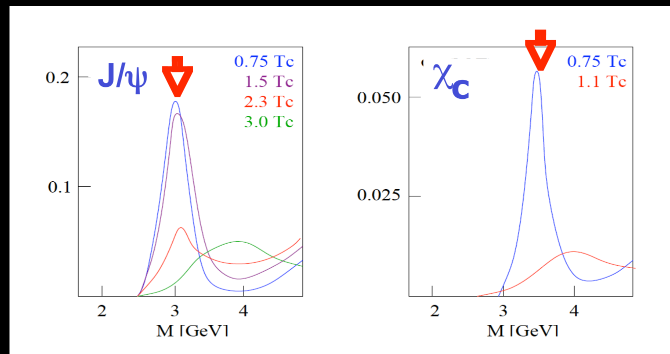
- prior knowledge is the positivity of the spf, given by Shannon-Janes entropy (has a default model as input)

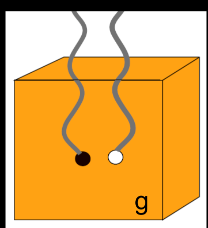
Spectral function SPLASH

anisotropic lattice, 32^3 x (96-32)
ξ=4.0, a_t=0.01 fm, (L_s=1.25fm)
Asakawa & Hatsuda, hep-lat/0308034

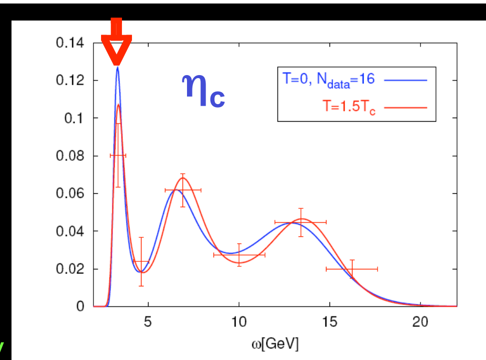


isotropic lattice, 48^3 x(24-12),
a=0.04 fm (L_s=1.9 fm)
Datta, Karsch, Petreczky & Wetzorke,
hep-lat/0312034





anisotropic lattice, 24^3 x (160-34)
ξ=4.0, a_t=0.056 fm, (L_s=1.34 fm)
Jakovac, Petreczky, Petrov & Velytsky
hep-lat/0611017



Summary of Lecture 2

- Static Q-$\bar{Q}$ free energy from the lattice shows strong modification of interquark forces, screening above deconfinement
- Lattice correlators/spectral functions - in the next lecture - what we make of all this

Would the J/Ψ survive unaffected in the QGP up to 1.5-2T_c even though strong screening is seen the plasma?