Charmonium dissociation and heavy quark screening from lattice QCD

- Deconfinement, screening and asymptotic freedom
  - Heavy quark free energies: $\bar{q}q$ and qq systems
  - screening vs. string breaking
- Potential models for quarkonium
  - input from LGT: energy vs. free energy
  - sequential suppression pattern?
- Spectral functions
  - (directly produced) J/ψ exist well above T_c
- Charmonium in heavy ion collisions
  - sequential suppression pattern may be the smoking gun

Heavy quark free energies: Testing $\bar{q}q$ interactions in matter

- Static quark and anti-quark sources in a thermal heat bath

  ⇒ change in free energy due to presence of external sources

  L.G. McLerran, B. Svetitsky, Phys. Rev. D24 (1981) 450

$$\mathrm{e}^{-F_{\bar{q}q}(r,T)/T} = \frac{1}{9}\langle \mathrm{Tr} L_{\vec{x}} \mathrm{Tr} L^{\dagger}_{\vec{0}} \rangle$$

- asymptotic freedom, screening, string breaking

singlet free energy

in 2-flavor QCD

$(m_q/T = 0.4)$

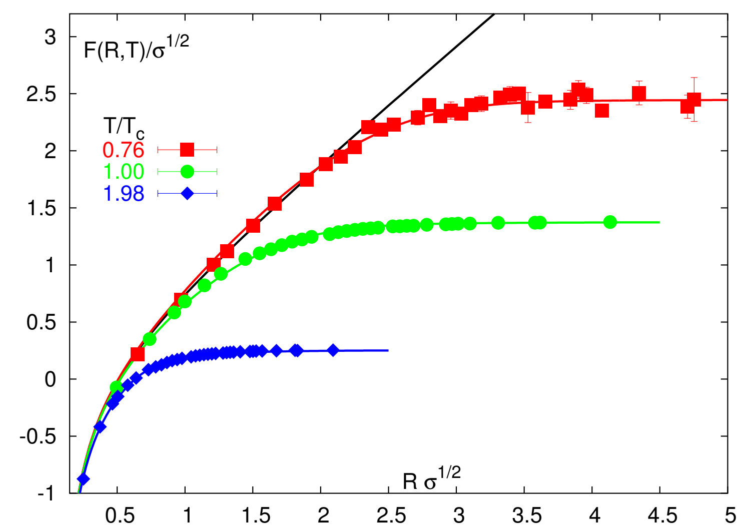
O.Kaczmarek, F. Zantow;

hep-lat/0503017

similar:

P.Petreczky, K. Petrov

hep-lat/0405009



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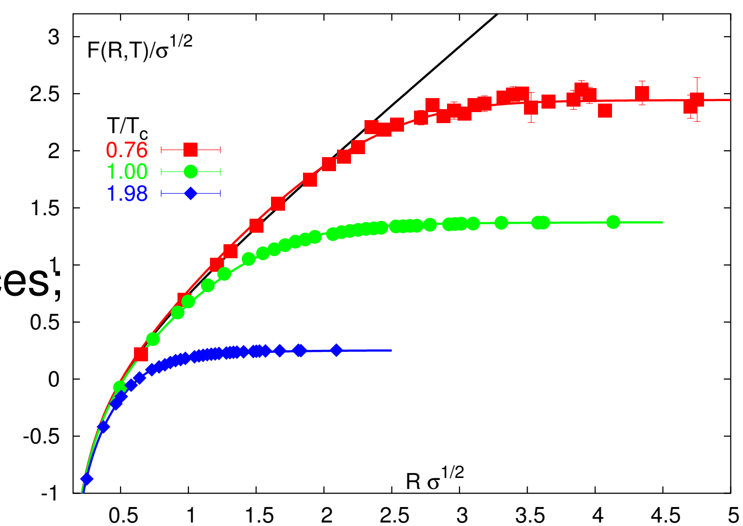
asymptotic freedom;
screening at short distances;
$F(r,T) \sim const.$
for $r \lesssim r_{af}$, $T \gtrsim 2T_c$



$T \lesssim 0.75\ T_c$:
string breaking
$F(r,T) \simeq V(r,T=0)$

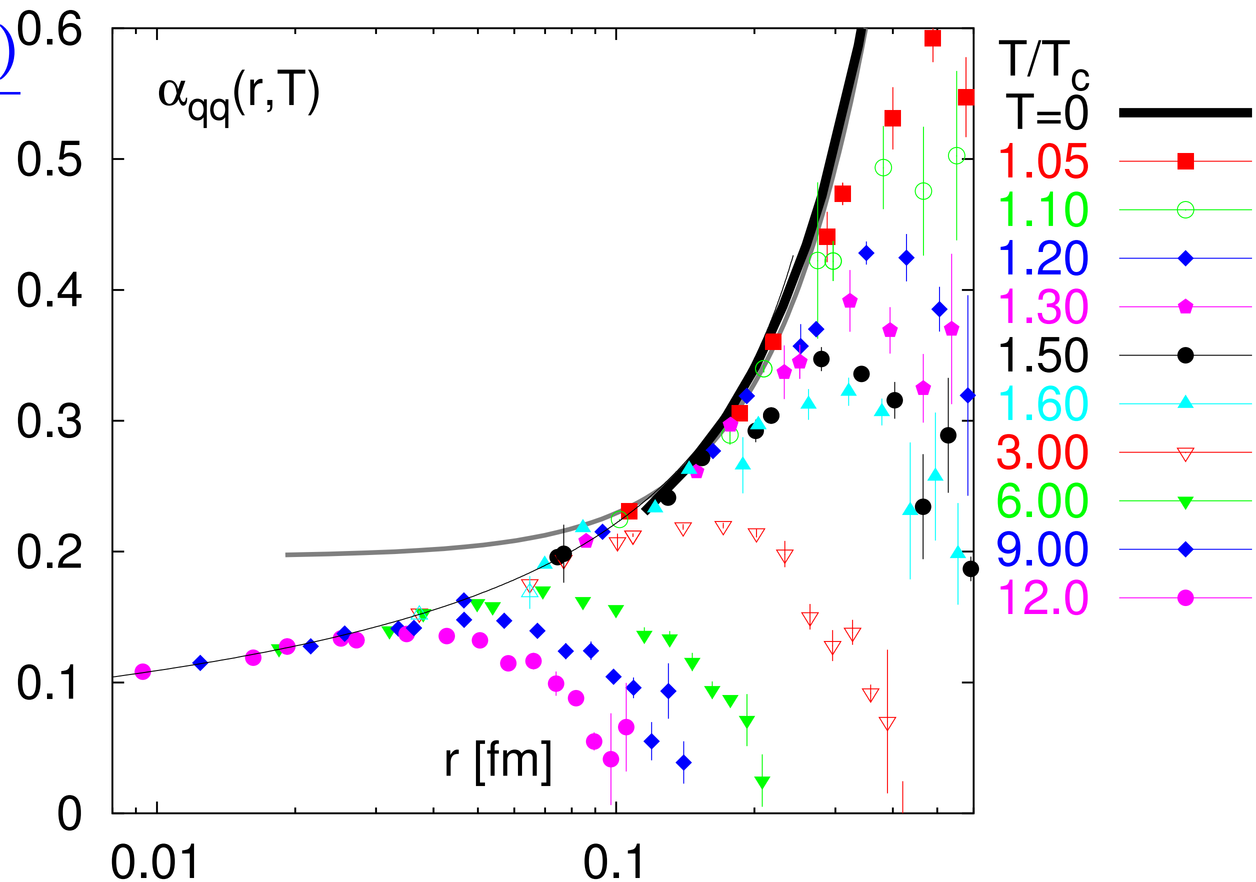
$T \simeq T_c$:
screening sets in at
$r \simeq 0.3$ fm;
significant r-dep. upto
$r \simeq 1$ fm $T \gtrsim 2\ T_c$:

Singlet free energy and asymptotic freedom

pure gauge: O.Kaczmarek, FK, P. Petreczky, F. Zantow, PRD70 (2005) 074505
2-flavor QCD: O.Kaczmarek, F. Zantow, Phys. Rev. D71 (2005) 114510

- singlet free energy defines a running coupling:

$$\alpha_{\text{eff}} = \frac{3r^2}{4}\,\frac{\mathrm{d}F_1(r,T)}{\mathrm{d}r}$$



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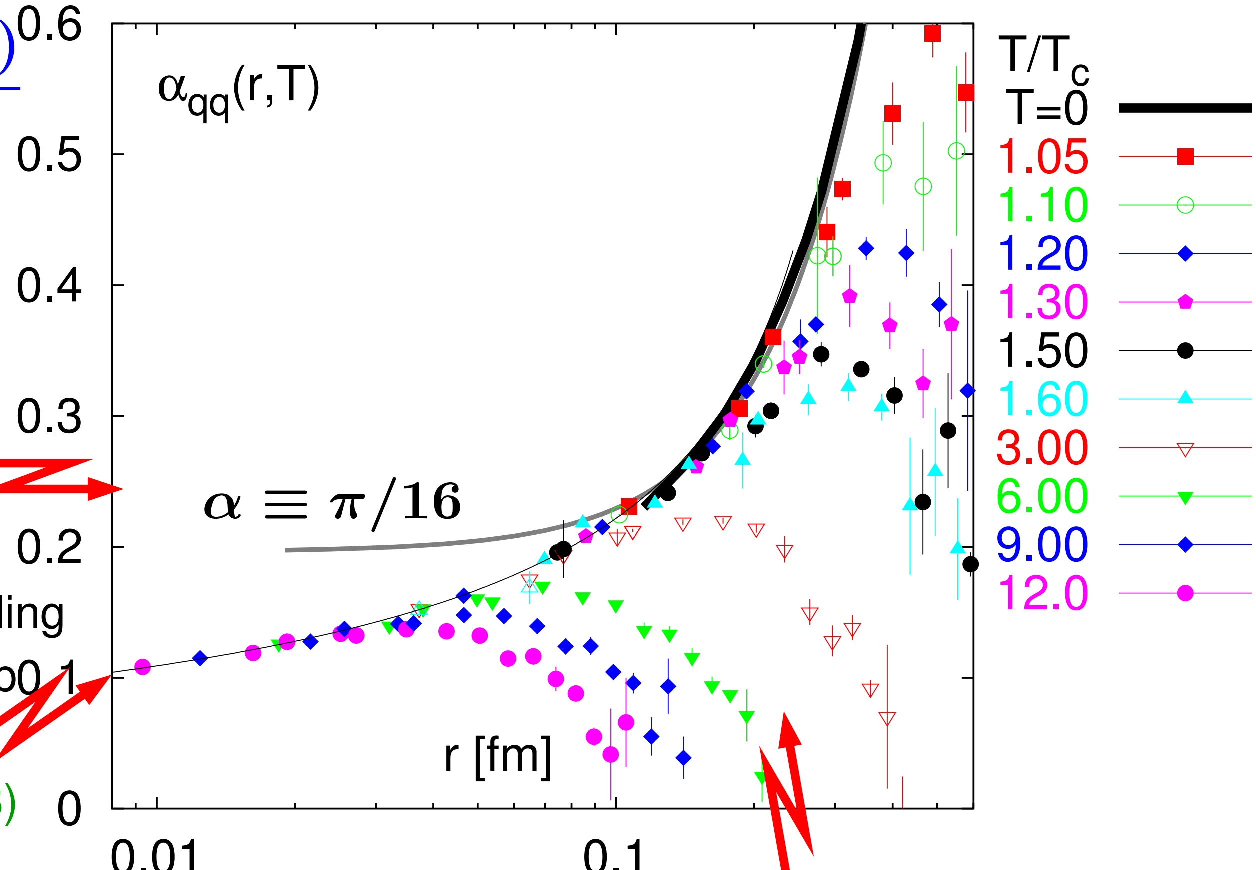

large distance: constant
Coulomb term (string model)

short distance: running coupling
$\alpha(r)$ from $(T=0)$, 3-loop
(S. Necco, R. Sommer,
Nucl. Phys. B622 (2002) 328)

T-dependence starts in non-perturbative regime for $T \lesssim 3\ T_c$

- short distance physics $\Leftrightarrow$ vacuum physics

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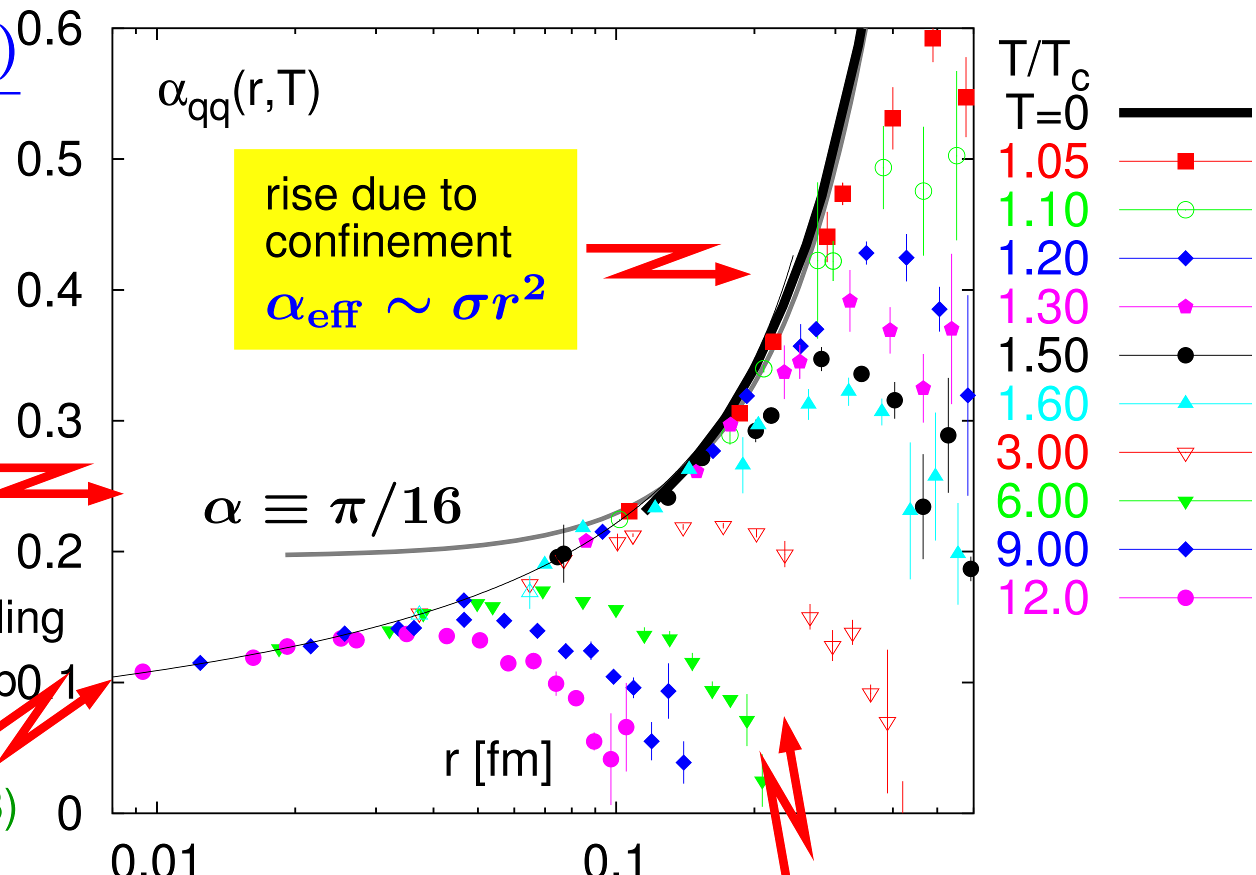

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String breaking and screening
Does a heavy quark bind a light (anti) quark?

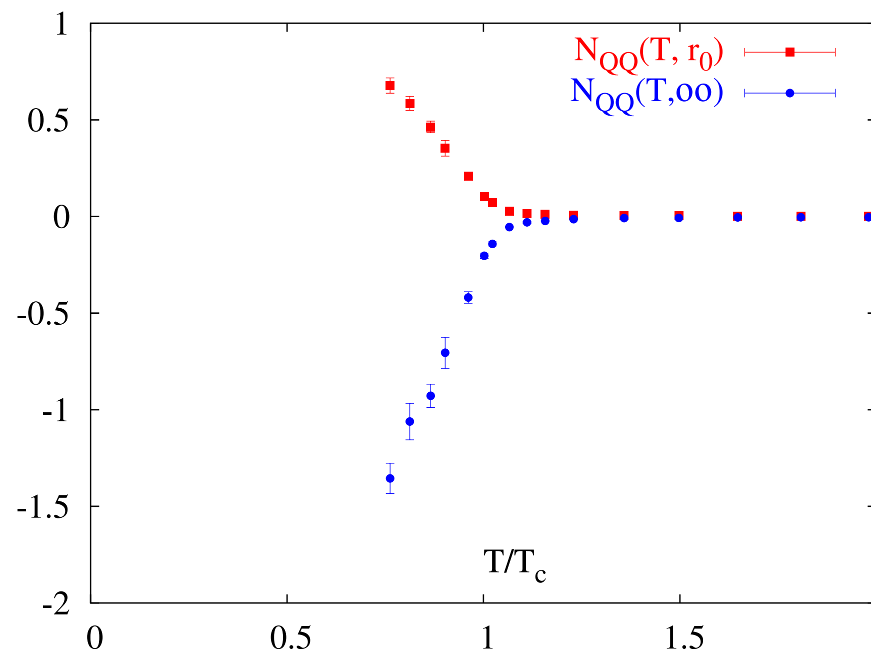
- Static quark-quark source in a thermal heat bath

  triality = 0: medium provides additional quark or 2 anti-quarks

- average quark number in the presence of two static quark sources

$$Z_{qq}(T,\mu,r) = \int \mathrm{d}U \; \mathrm{TrL_0 Tr}L_r \; \det \mathrm{Q}(m_q,\mu) \; \mathrm{e}^{-\beta S_G}$$

$$N_{qq}(T,r) = \left. \frac{\partial \ln Z_{qq}(T,\mu,r)}{\partial \mu / T} \right|_{\mu=0}$$



M. Döring, PhD thesis, in preparation

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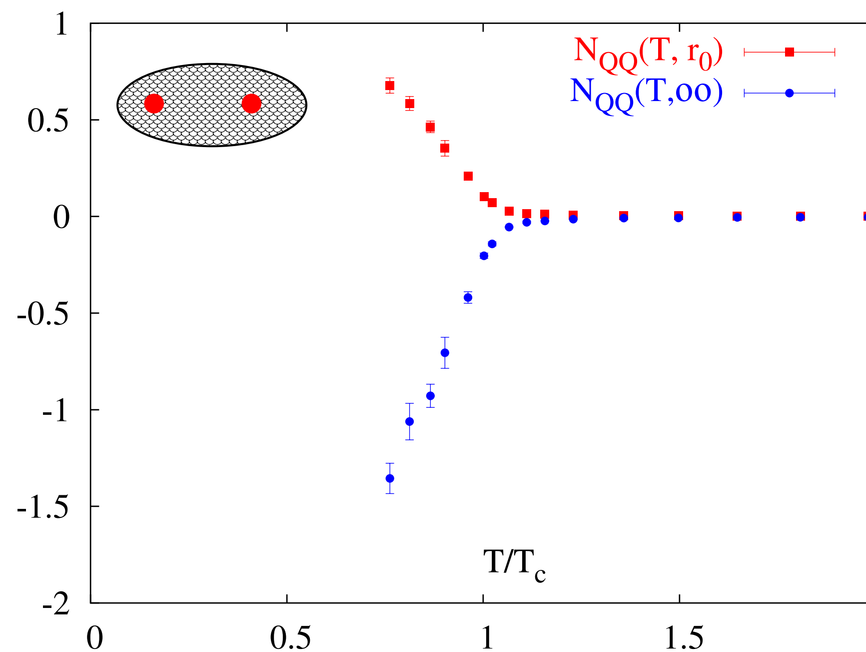

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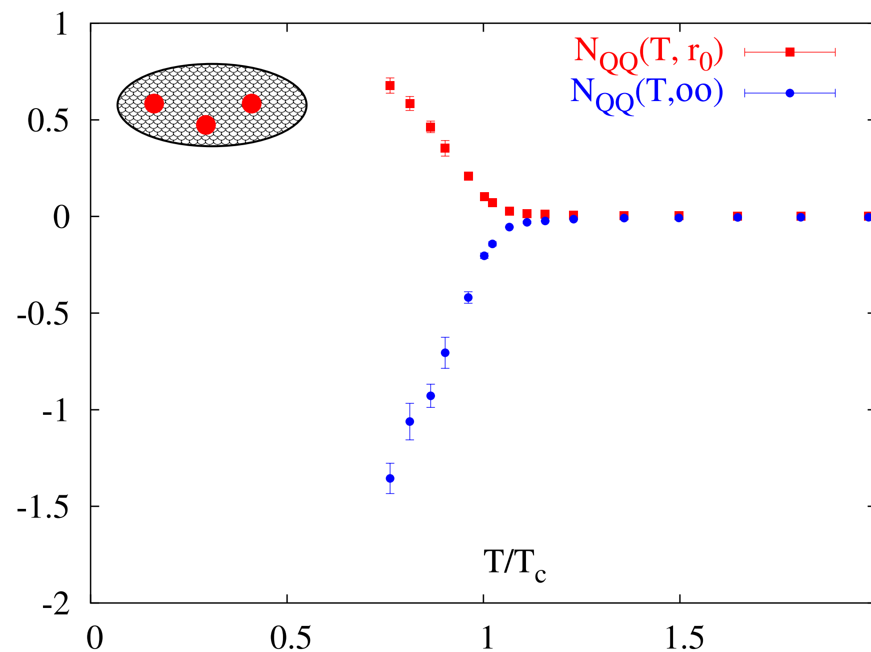

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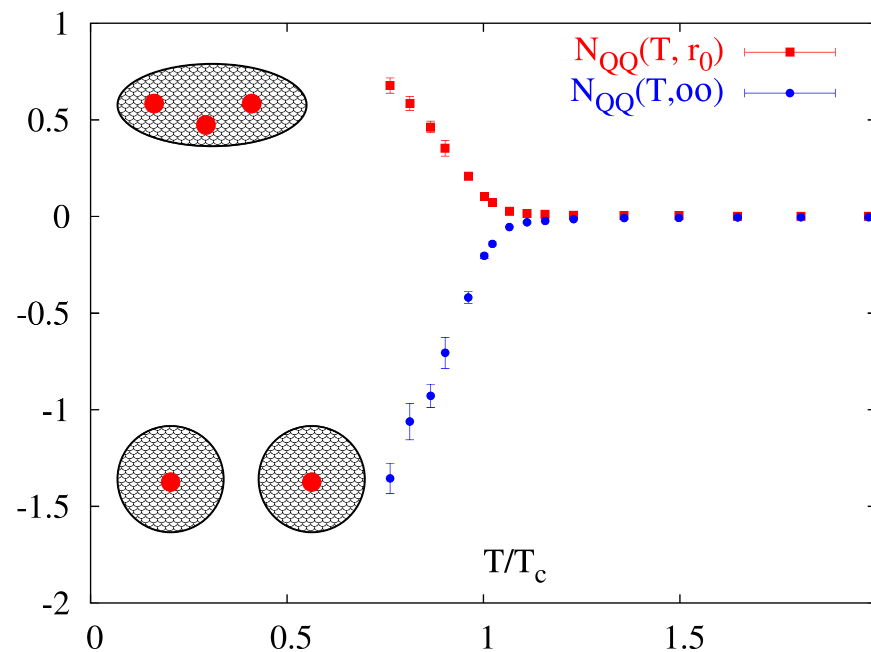

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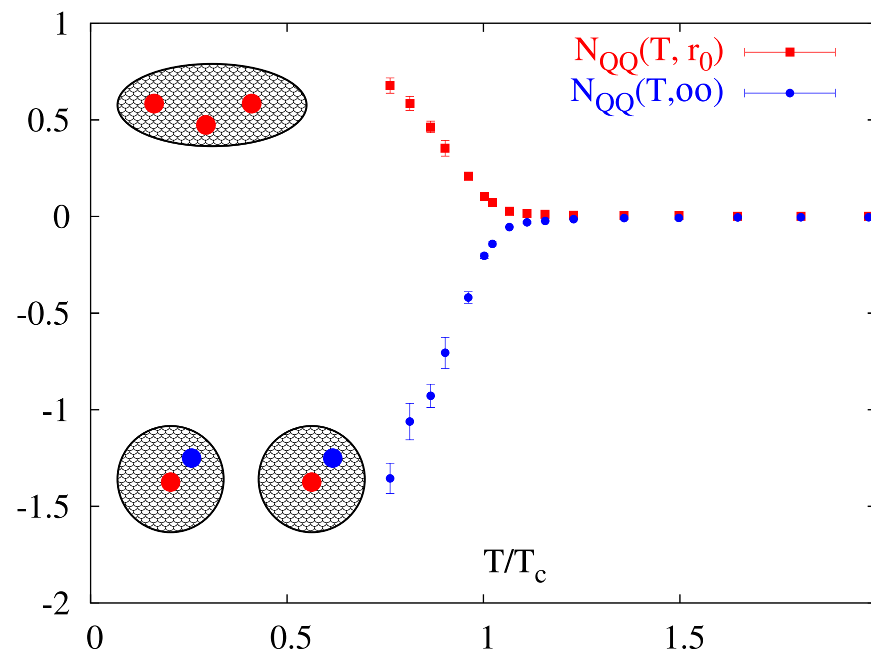

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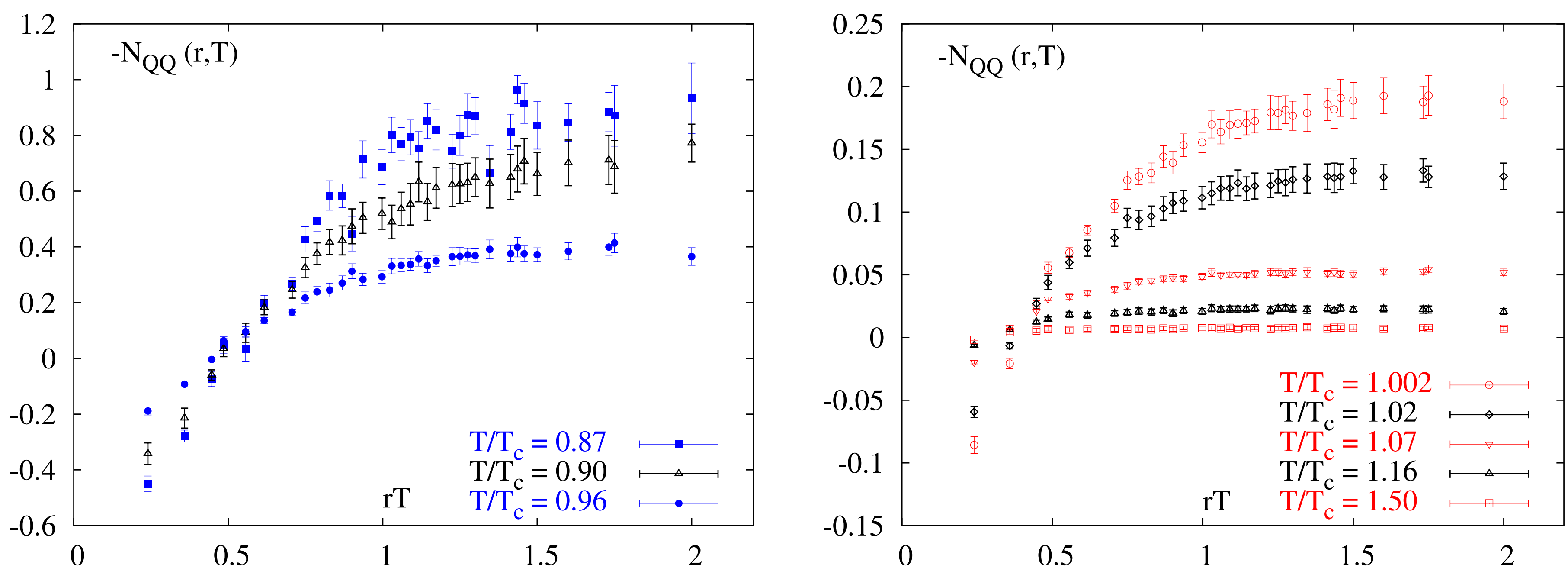
String breaking and screening
Does a heavy quark bind a light (anti) quark?

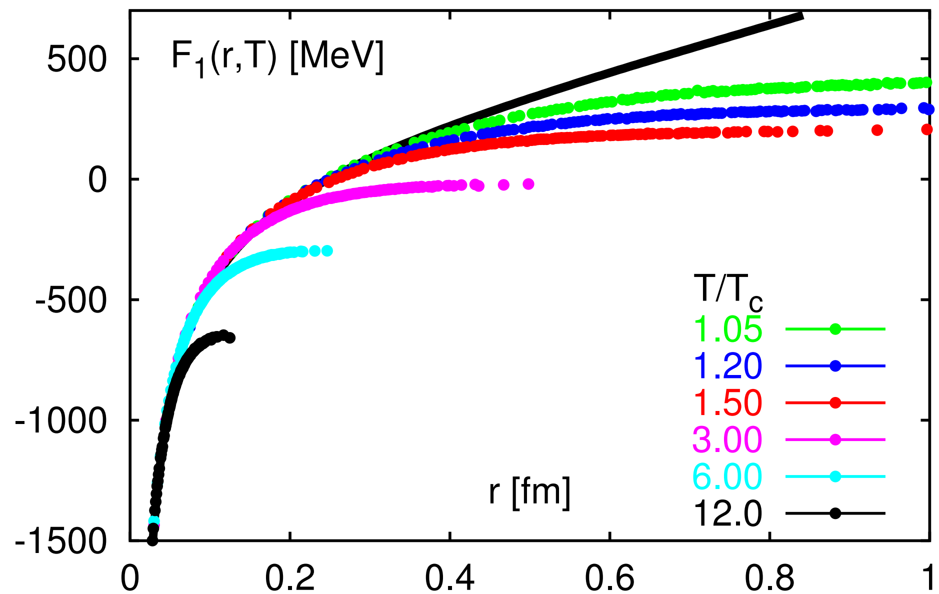
- $N_{qq}(r,T)$ depends on separation between static quark-quark source
- $r = r_{b/s} \simeq 0.5/T$:
  screening changes from q-dominated to $\bar{q}\bar{q}$-dominated
- $T \gtrsim 1.1 T_c$: presence of q or $\bar{q}\bar{q}$ not important for screening



From heavy quark free energies to heavy quark potentials

$$\lim_{T\to\infty} F(r,T) = -\infty \text{ !!}$$

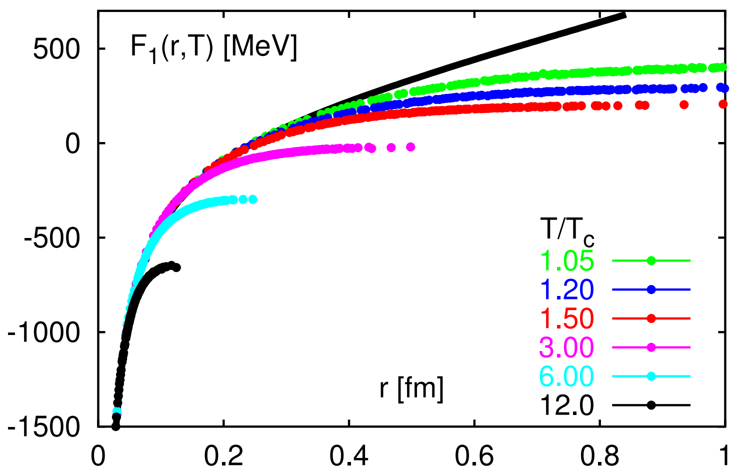
$$F = U - T \cdot S$$



$$U(r,T) = -T^2 \frac{\partial\, F(r,T)/T}{\partial\, T} \quad , \quad S(r,T) = -\frac{\partial\, F(r,T)}{\partial\, T}$$

- reconstruct energies from free energies;
- approximate derivatives through finite differences at $T_1,\ T_2$ and fixed r
- requires good control over scaling behaviour of the cut-off ”a” (complicated!)

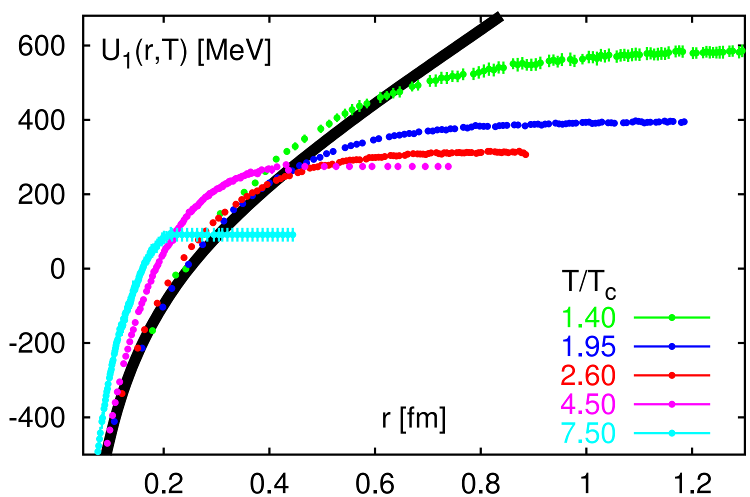
From heavy quark free energies to heavy quark potentials



i) singlet free energy

$$\exp(-F_1(r,T)/T) = \frac{1}{3}\langle \mathrm{Tr} L_{\vec{x}} L^{\dagger}_{\vec{0}} \rangle$$

(Coulomb gauge)

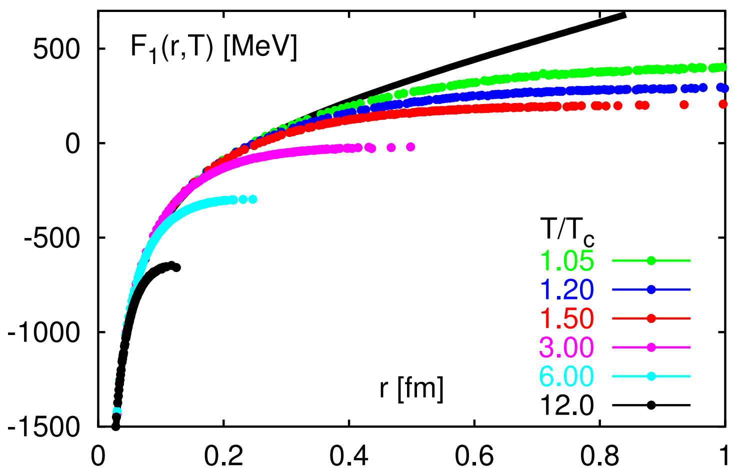


ii) singlet energy ⇔ "potential" energy

$$U_1(r,T) \equiv -T^2 \frac{\partial F_1(r,T)/T}{\partial T}$$

- potential is "deeper": $U(r,T) > F(r,T)$
- potential "barrier" high also well above T_c
- "potential" screened at short distances

From heavy quark free energies to heavy quark potentials

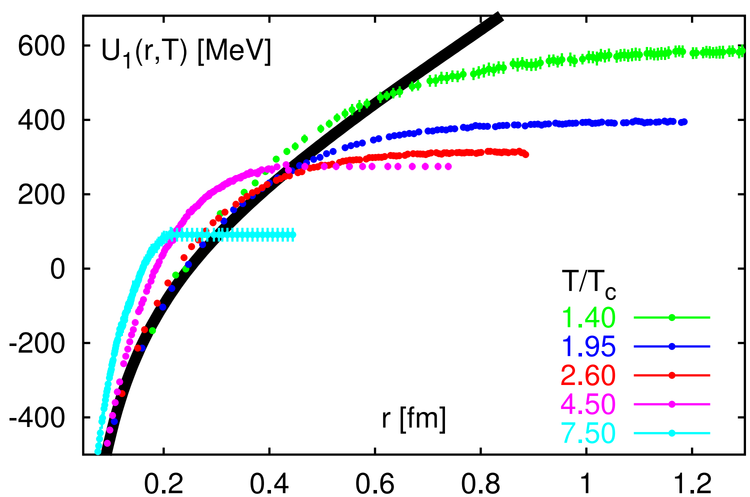


i) singlet free energy

NOTE:

$F_{\bar{q}q}(r,T)$ decreases with increasing T and fixed r $\Rightarrow$ positive entropy

$$S = -\left(\frac{\partial F}{\partial T}\right)_V \geq 0$$



ii) singlet energy $\Leftrightarrow$ "potential" energy

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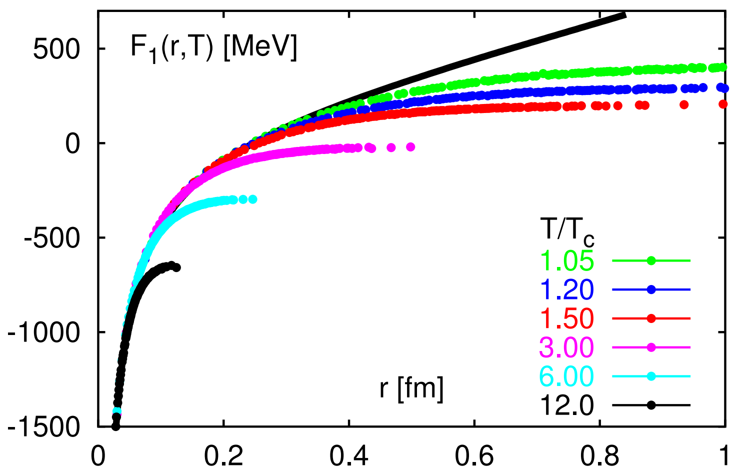

i) singlet free energy

NOTE:

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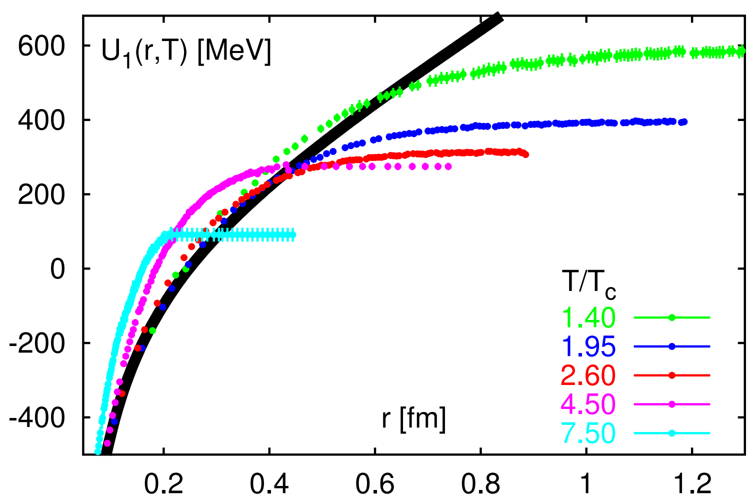
$$F_1(\infty, 1.4T_c) \simeq 200 \text{ MeV}$$

$$U_1(\infty, 1.4T_c) \simeq 600 \text{ MeV}$$



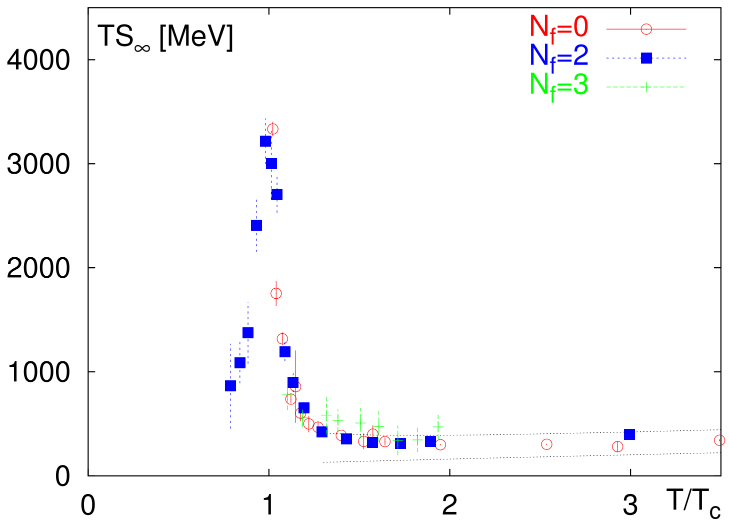
ii) singlet energy $\Leftrightarrow$ "potential" energy

When do heavy quark bound states really disappear?

i) neither U_1 nor F_1 are "potentials"

ii) potential models are MODELS!

Screening of heavy quark free energies at large distance

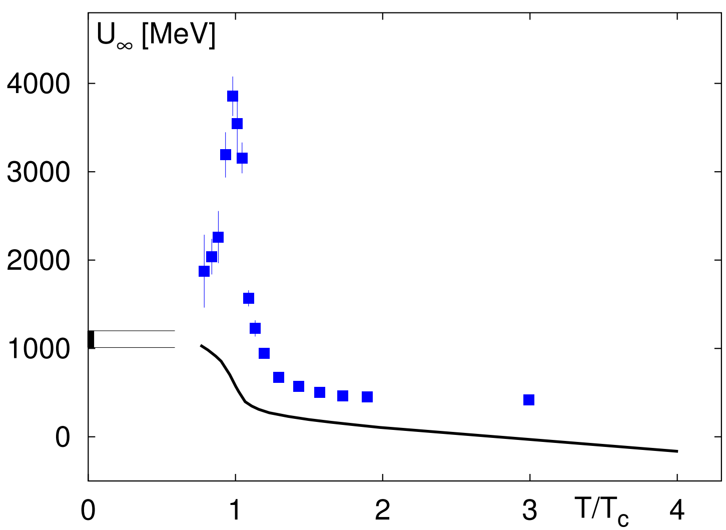


Excess entropy at $r \to \infty$

It's all in the glue:

$$T \lesssim T_c:\ S_{\bar q q}^{nf=2}(\infty, T) \simeq S_{\bar q q}^{nf=0}(\infty, T)$$

Δ(Entropy)/Quark $\sim$ 15



Energy needed to screen 2 quarks

Large increase of energy close to T_c

Why not simply create another $\bar q q$ pair?

large entropy in the glue rearrangement

compensates for higher energy!!

Heavy quark bound states from Schrödinger-Equation

- Schrödinger equation for heavy quarks:

$$\left[2m_a + \frac{1}{m_a}\nabla^2 + V_1(r,T)\right]\Phi_i^a = M_i^a(T)\,\Phi_i^a \quad , \quad a = \text{charm, bottom}$$

  - T-dependent color singlet heavy quark potential mimics in-medium modification of $q\bar{q}$ interaction
  - reduction to 2-particle interaction clearly too simple, in particular close to T_c

- recent analyses:

  using F_1: S. Digal, P. Petreczky, H. Satz, Phys. Lett. B514 (2001) 57;

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state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ”
E_s^i [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
T_d/T_c	1.1	0.74	0.1 - 0.2	2.31	1.13	1.1	0.83	0.74
T_d/T_c	$\sim$ 2.0	$\sim$ 1.1	$\sim$ 1.1	$\sim$ 4.5	$\sim$ 2.0	$\sim$ 2.0	–	–

U_1 leads to dissociation temperatures consistent with spectral function analysis

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> - Schrödinger-eq. yields $T_\chi \;>\; T_{\psi'}$
> - collision with thermal gluons, $\langle p\rangle \sim 3\,T$ can lead to earlier dissociation: $\mathrm{d}n_{J/\psi}/\mathrm{d}t = -n_g\,\langle\sigma_{dis}\rangle$

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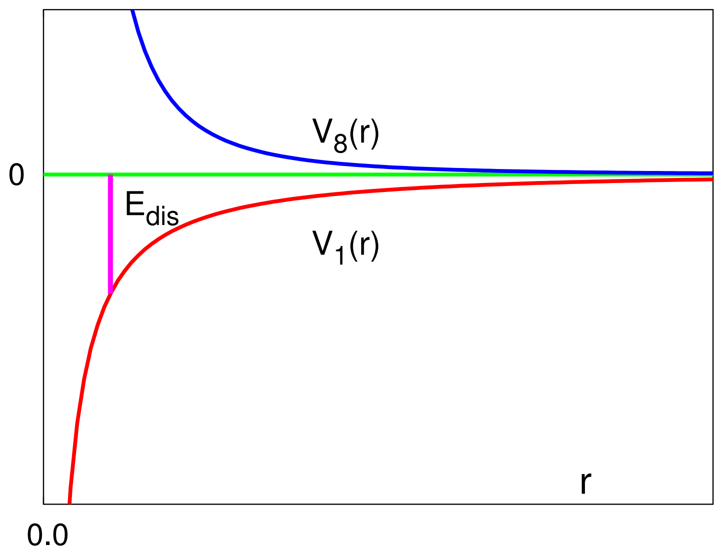

collisional dissociation

D. Kharzeev, H. Satz, PL B334 (1994) 155

$$J/\psi \; + \; g \quad \rightarrow \quad c \; + \; \bar{c}$$

$$T \;=\; 1.1\, T_c : \quad E_{dis,\chi} \simeq 50 \text{ MeV}$$

$$E_{dis,J\psi} \simeq 500 \text{ MeV}$$

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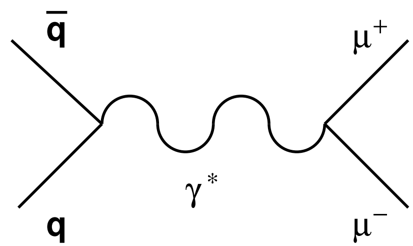
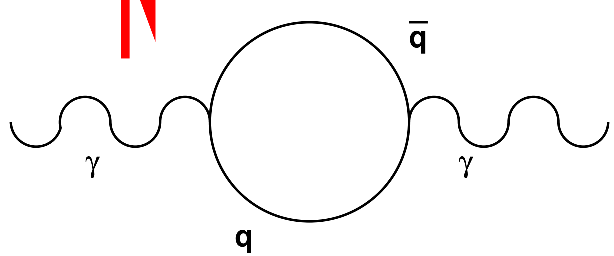
Spectral functions and Dilepton rates

Thermal dilepton rate and vector spectral function



L.D. McLerran, T. Toimela, PR D31 (85) 545.

rate $\sim |q\bar{q} \longrightarrow \gamma^*|^2 \cdot |l^+ l^- \longrightarrow \gamma^*|^2$



photon self-energy

$\Updownarrow$

propagation of a $q\bar{q}$-pair with
the quantum numbers of a vector meson

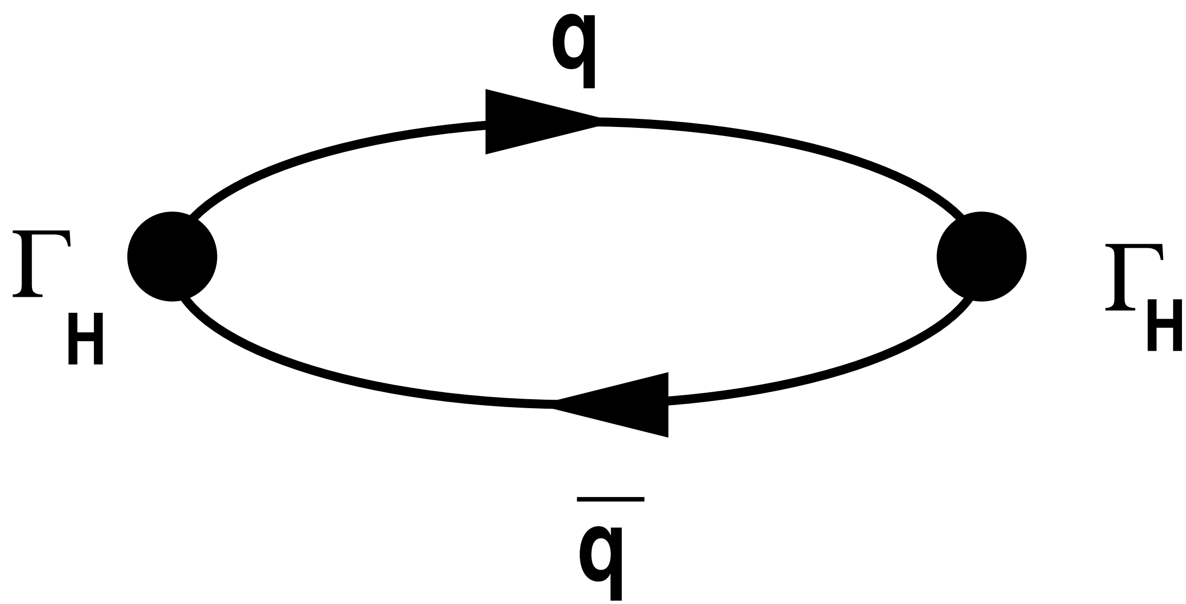
spectral representation of dilepton rate

$$\frac{\mathrm{d}W}{\mathrm{d}\omega \mathrm{d}^3 p} = \frac{5\alpha^2}{27\pi^2} \frac{1}{\omega^2 (\mathrm{e}^{\omega/T} - 1)} \sigma_V(\omega, \vec{p}, T)$$

Thermal meson correlation functions and spectral functions

Thermal correlation functions: 2-point functions which describe propagation of a $\bar{q}q$-pair

spectral representation of correlator $\Rightarrow$ in-medium properties of hadrons;
thermal dilepton (photon) rates



$$G_H^\beta(\tau,\vec{r}) \ = \ \langle J_H(\tau,\vec{r}) J_H^\dagger(0,\vec{0})\rangle \ ; \quad J_H(\tau,\vec{r}) = \bar{q}(\tau,\vec{r})\Gamma_H q(\tau,\vec{r})$$

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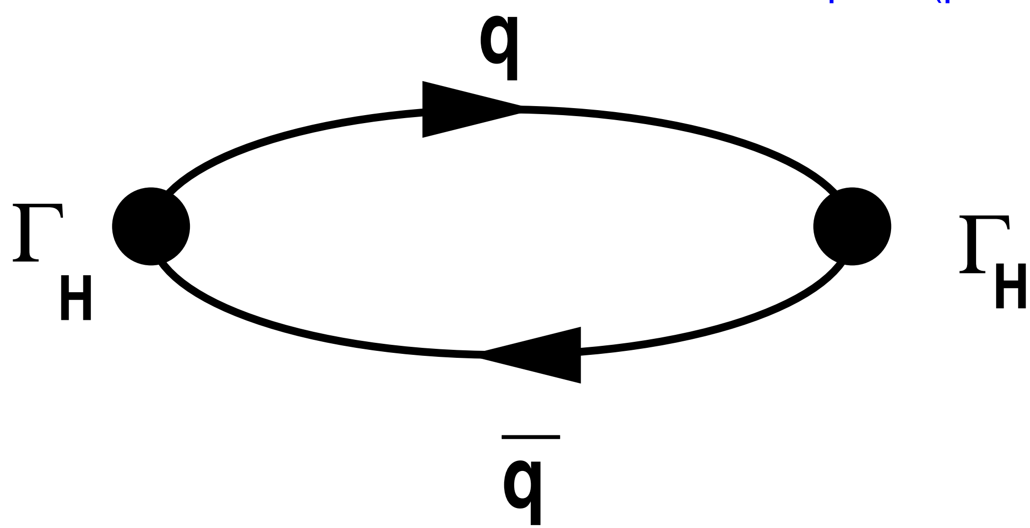

spectral representation of

Euclidean correlation functions

$$G_H^\beta(\tau,\vec{r}) = \int_0^\infty \mathrm{d}\omega \int \frac{\mathrm{d}^3\vec{p}}{(2\pi)^3}\, \sigma_H(\omega,\vec{p},T)\, \mathrm{e}^{i\vec{p}\vec{r}}\, \frac{\cosh(\omega(\tau-1/2T))}{\sinh(\omega/2T)}$$

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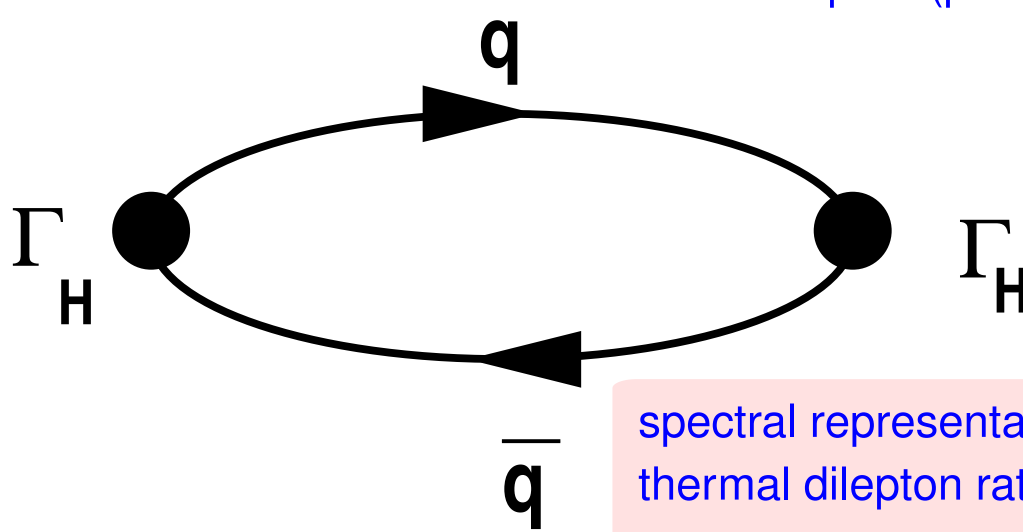

spectral representation of
thermal dilepton rate

$$\frac{\mathrm{d}W}{\mathrm{d}\omega \mathrm{d}^3p} = \frac{5\alpha^2}{27\pi^2} \frac{\sigma_V(\omega, \vec{p}, T)}{\omega^2(\mathrm{e}^{\omega/T} - 1)}$$

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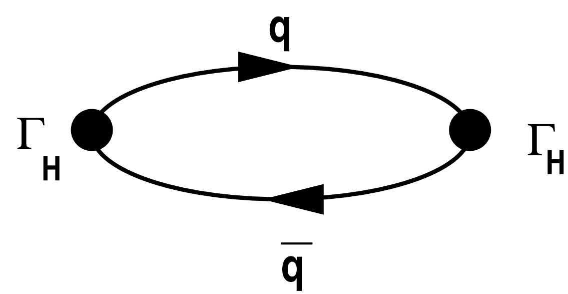
Thermal correlation functions for hadronic excitations in QCD

thermal modifications of the hadron spectrum is encoded in finite temperature

Euclidean correlation functions

- hadronic (mesonic) currents, composite $q\bar{q}$-operators

$$J_H = \bar{\psi}(\tau,\vec{r})\ \Gamma_H\ \psi(\tau,\vec{r})$$



- $G_H^\beta(\tau,\vec{r}) \ \equiv\ \langle J_H(\tau,\vec{r}) J_H^\dagger(0,\vec{0})\rangle_\beta$
- quantum numbers (H) fixed through Γ_H:

state		J^{PC}	Γ_H	(u,d)-states	$c\bar{c}$-states	$b\bar{b}$-states
scalar	$^3P_0$	0^{++}	1	σ	χ_{c0}	χ_{b0}
pseudo-scalar	$^1S_0$	0^{-+}	γ_5	π	η_c	η_b
vector	$^3S_1$	1^{--}	γ_μ	ρ	J/ψ	Υ
axial-vector	$^3P_1$	1^{++}	$\gamma_\mu\gamma_5$	δ	χ_{c1}	χ_{b1}

- so far all studies have been performed in quenched QCD (reasonable) with Wilson fermions (poor resolution at high energies)

Euclidean two-point functions: T > 0

thermal averages over states

- Hamiltonian $\hat{H}$; temperature $T \equiv \beta^{-1}$;

  partition function $Z(\beta) = \mathrm{Tr}\ \mathrm{e}^{-\beta \hat{H}}$; expectation values $\langle O \rangle_\beta = \frac{1}{Z(\beta)}\ \mathrm{Tr}\ O\ \mathrm{e}^{-\beta \hat{H}}$

$$
\begin{aligned}
G_\phi^\beta(\tau) &\equiv \langle 0 | \hat{\phi}^\dagger(\tau) \hat{\phi}(0) | 0 \rangle_\beta \\
&= \frac{1}{Z(\beta)} \sum_{k,l} |\langle l | \hat{\phi} | k \rangle|^2\ \mathrm{e}^{-\beta E_k}\ \mathrm{e}^{-\tau(E_l - E_k)} \\
&= \int_{-\infty}^{\infty} \frac{\mathrm{d}\omega}{2\pi} \sigma_\phi(\omega, T)\ \frac{\cosh(\omega(\tau - 1/2T))}{\sinh(\omega/2T)}
\end{aligned}
$$

with spectral function

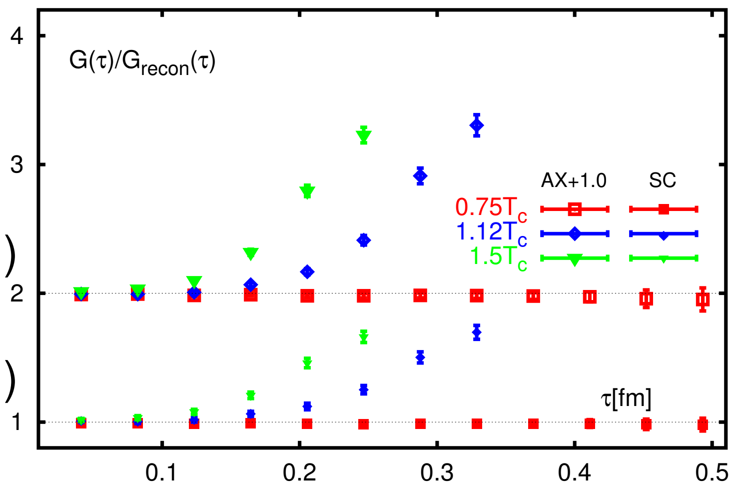
$$
\sigma_\phi(\omega, T) = \frac{2\pi}{Z(\beta)} \sum_{k,l} |\langle k | \hat{\phi} | l \rangle|^2\ \mathrm{e}^{-\beta E_k}\ \left(1 - \mathrm{e}^{-\beta\omega}\right) \delta\left(\omega - (E_k - E_l)\right)
$$

Heavy quark spectral functions and correlation functions

data for $G_H(\tau, T)$ over reconstructed correlation functions at T from data below T_c

(χ_{c1})

(χ_{c0})



scalar and axial-vector correlation functions:

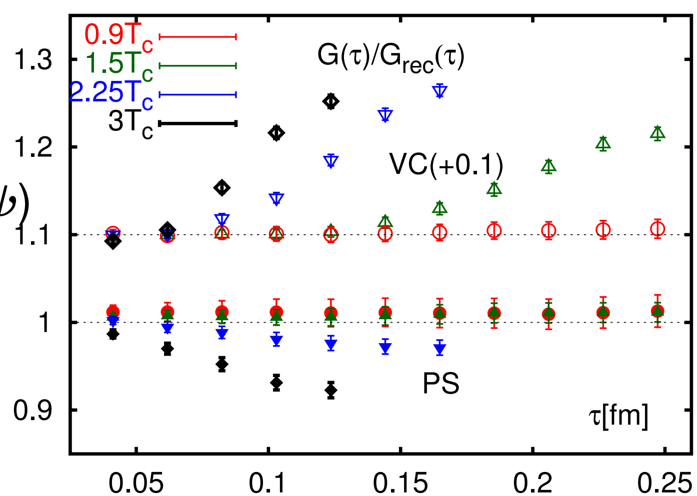
strong temperature dependence just above T_c for χ_c states

(normalized at $T < T_c$)

$(48^3 \times N_\tau,\ N_\tau = 12,\ 16,\ 24,\ a = 0.04$ fm)

(J/ψ)

(η_c)



vector and pseudoscalar correlation functions:

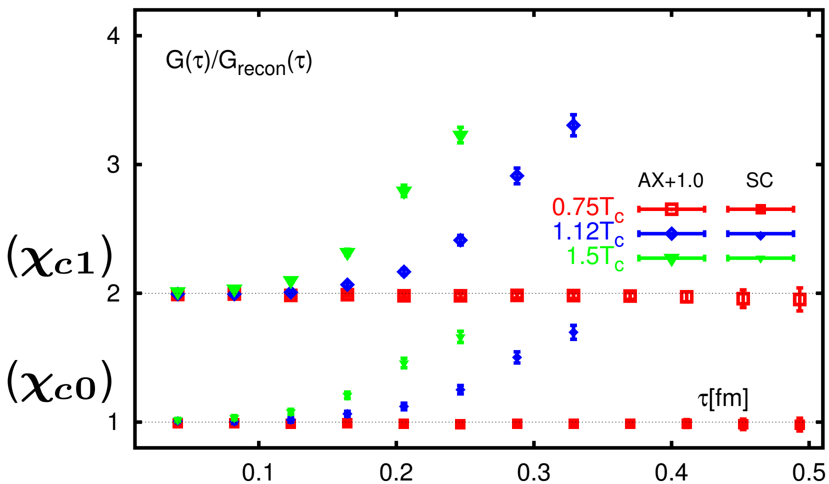
no temperature dependence for η_c up to $1.5\ T_c$; only mild but systematic temperature dependence of J/ψ

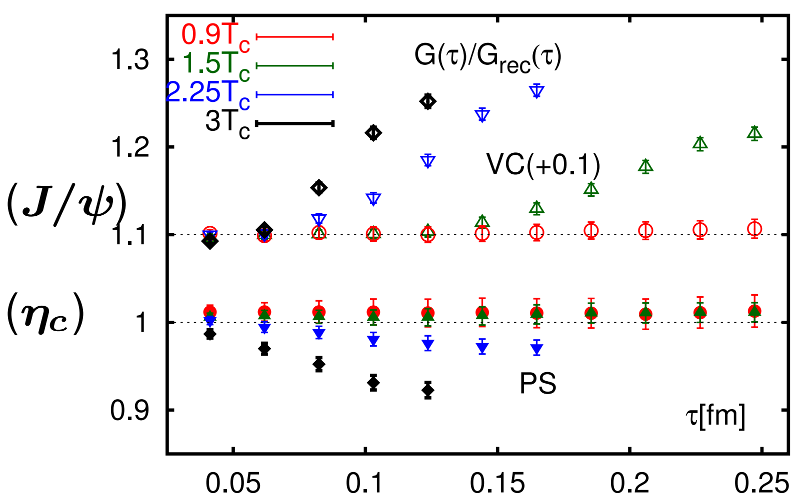
(normalized at $T < T_c$)

$(N_\sigma = 40,\ 48,\ 64,$
$N_\tau = 12,\ 16,\ 24,\ 40,\ a = 0.02$ fm)

S. Datta et al., Phys. Rev. D69 (2004) 094507

Heavy quark spectral functions and correlation functions





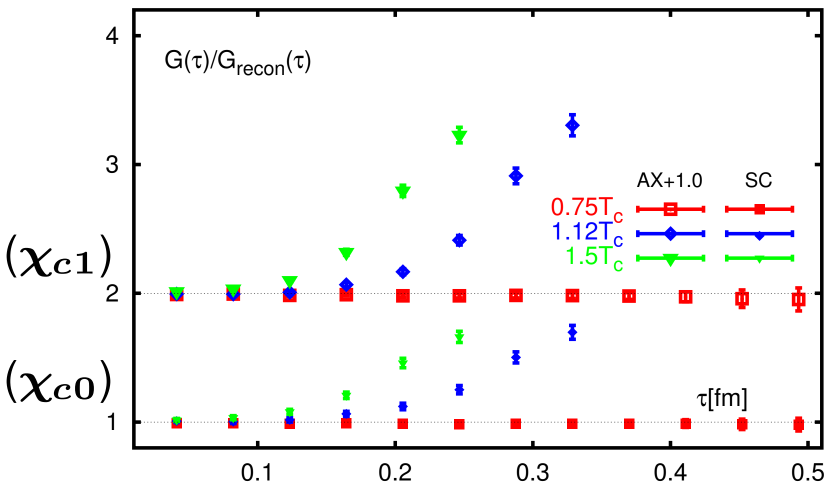
S. Datta et al., Phys. Rev. D69 (2004) 094507

pattern seen in correlation functions also visible in spectral functions

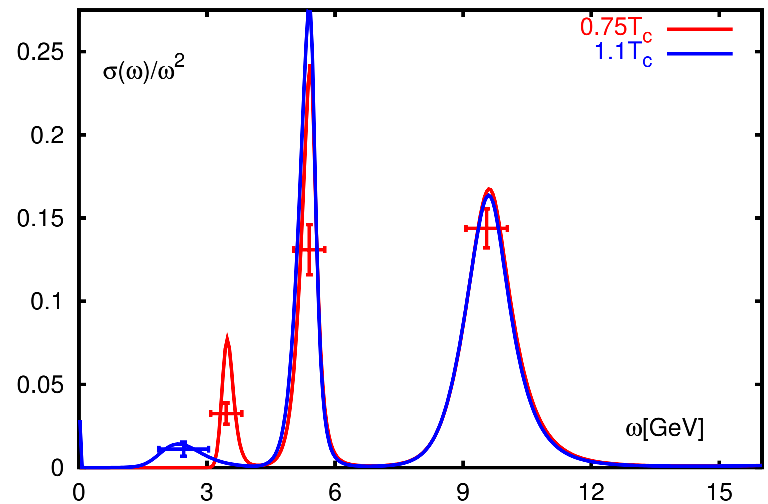
similar results:

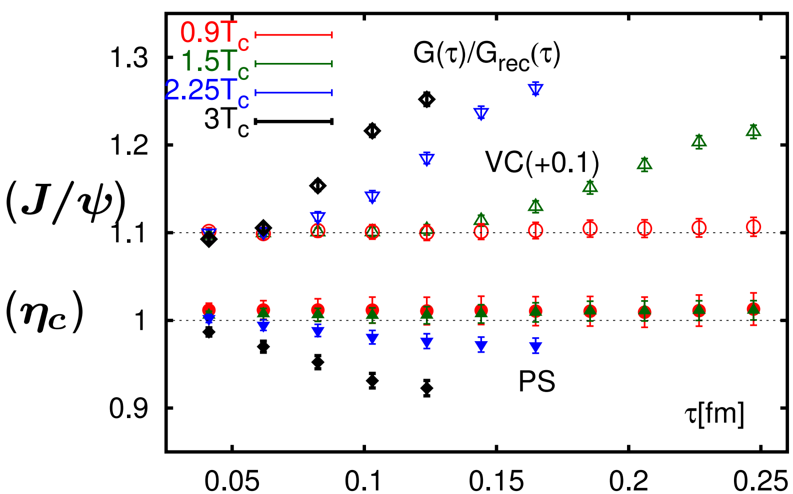
M. Asakawa, T. Hatsuda, PRL 92 (2004) 012001

Heavy quark spectral functions and correlation functions

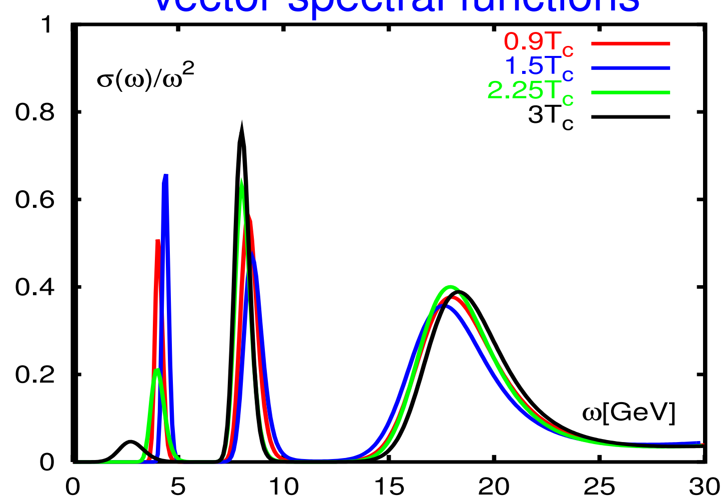


scalar spectral functions



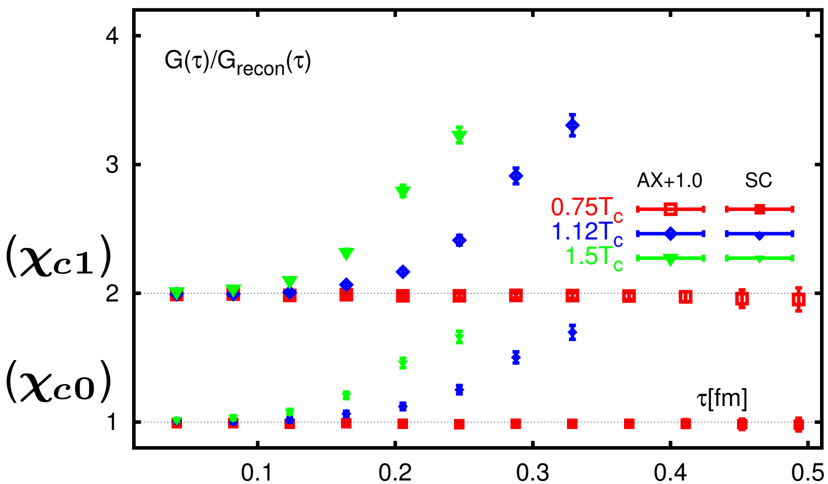


vector spectral functions

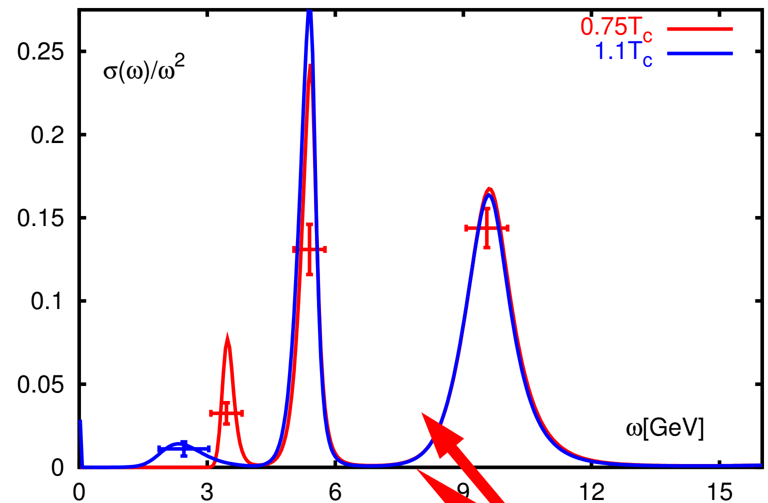


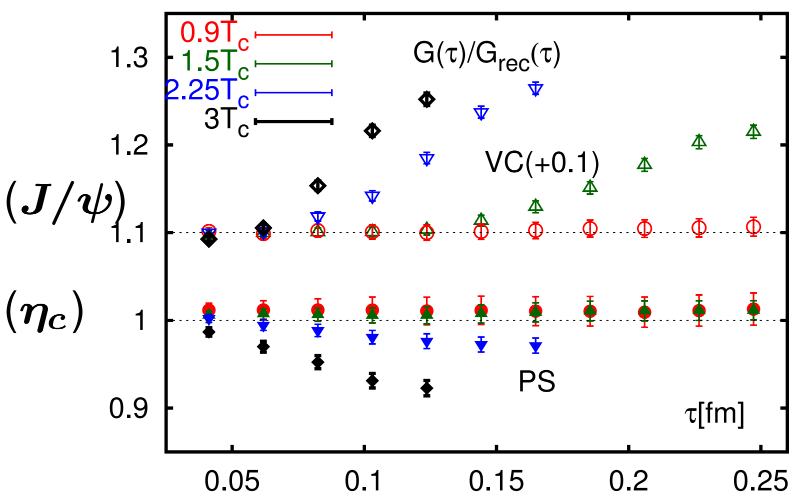
S. Datta et al., Phys. Rev. D69 (2004) 094507

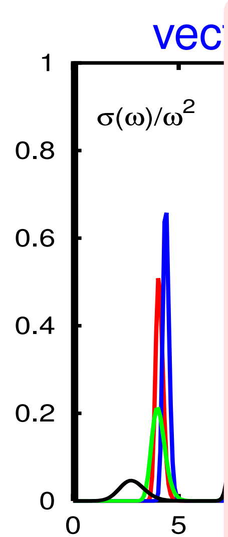
Heavy quark spectral functions and correlation functions



scalar spectral functions







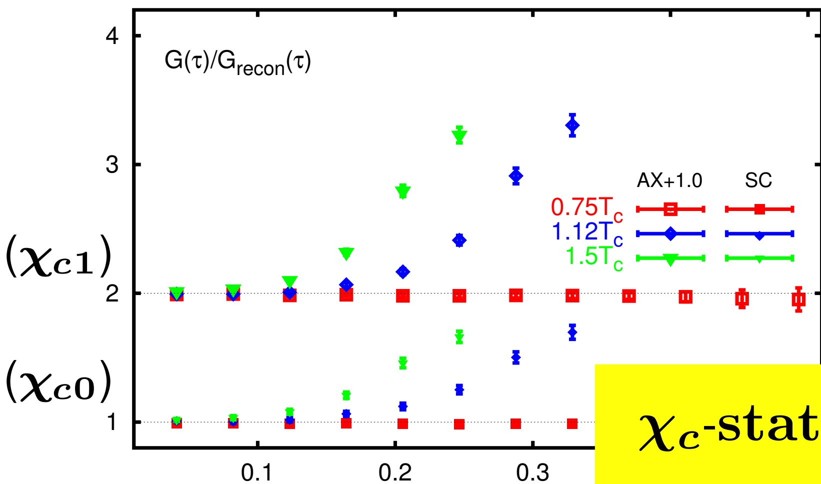
ultra-violet cut-off effects:
Wilson-doubler;
finite Brillouin zone;

need to get better control
over lattice cut-off effects

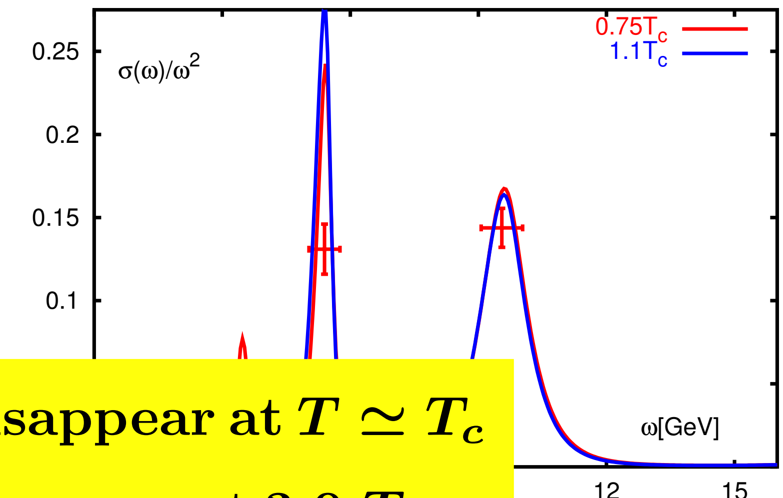
resolution statistics limitted

S. Datta et al., Phys. Rev. D69 (2004) 094507

Heavy quark spectral functions and correlation functions

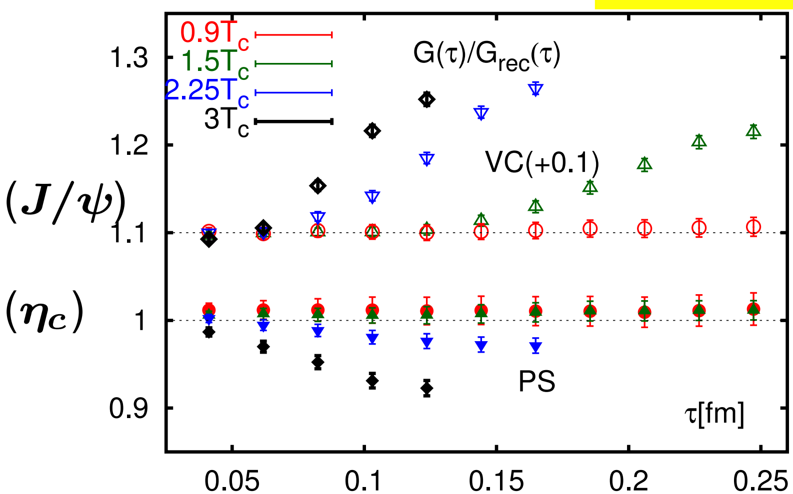


scalar spectral functions

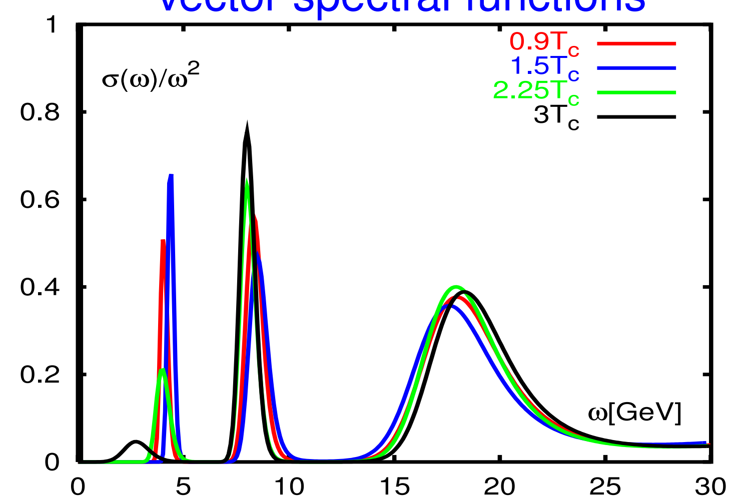


χ_c**-states disappear at** $T \simeq T_c$

J/ψ **and** η_c **gone at 3.0** T_c



vector spectral functions



S. Datta et al., Phys. Rev. D69 (2004) 094507

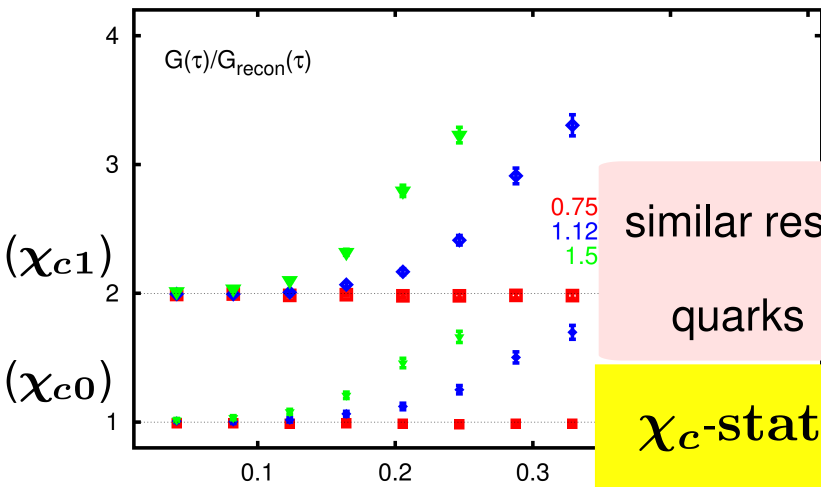
Heavy quark spectral functions and correlation functions

similar results for QCD with dynamical quarks R. Morrin et al., Lattice 2005

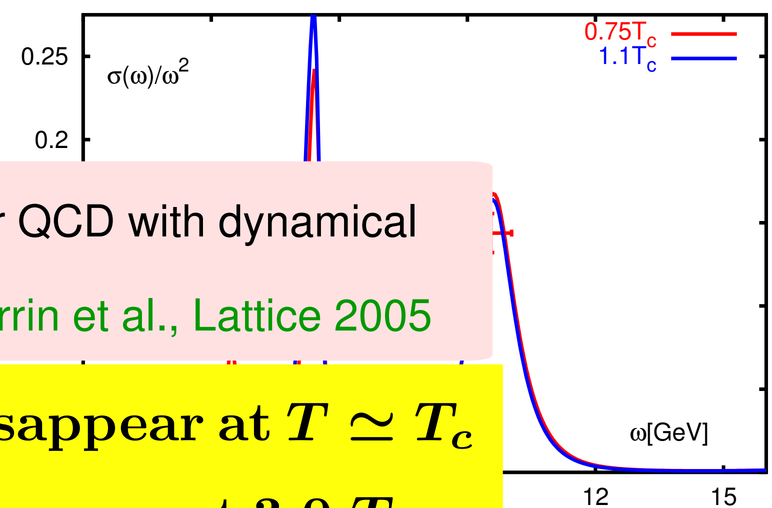
χ_c-states disappear at $T \simeq T_c$

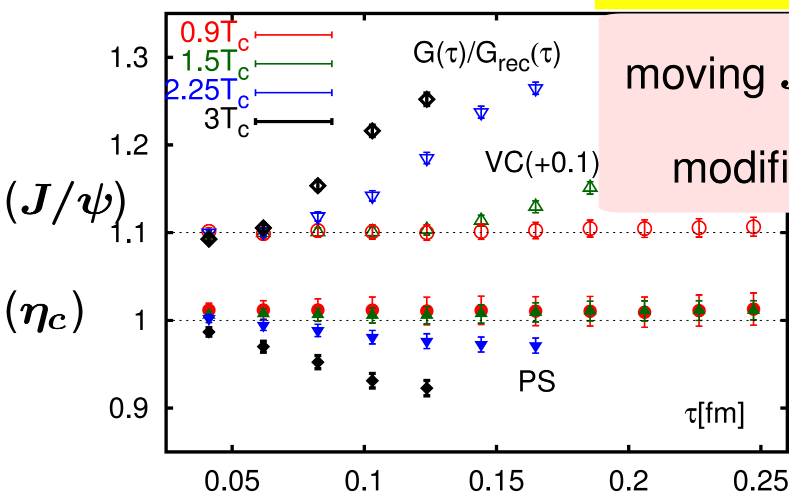
J/ψ and η_c gone at 3.0 T_c

moving J/ψ shows stronger in-medium modification: S. Datta, PANIC 2005



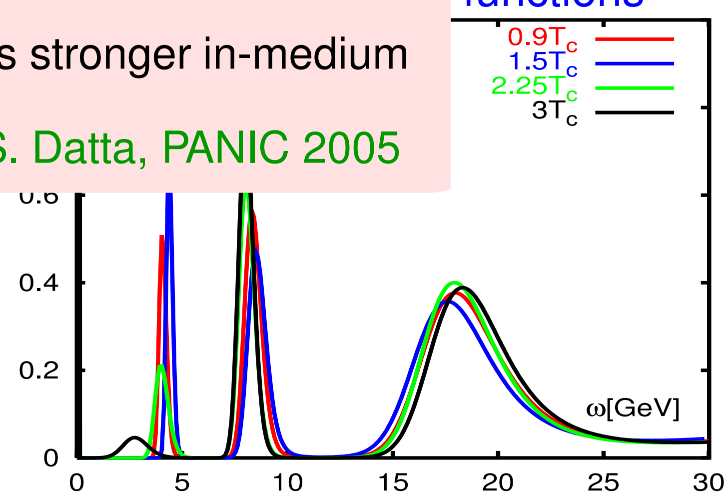
scalar spectral functions





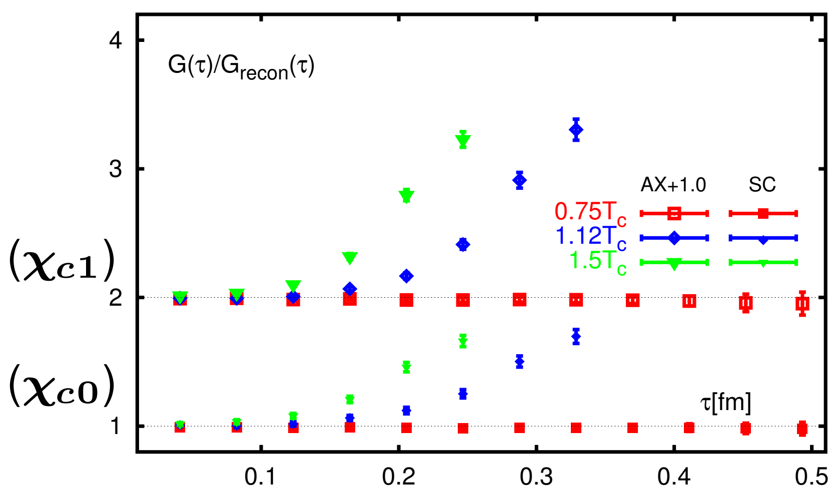
S. Datta et al., Phys. Rev. D69 (2004) 094507

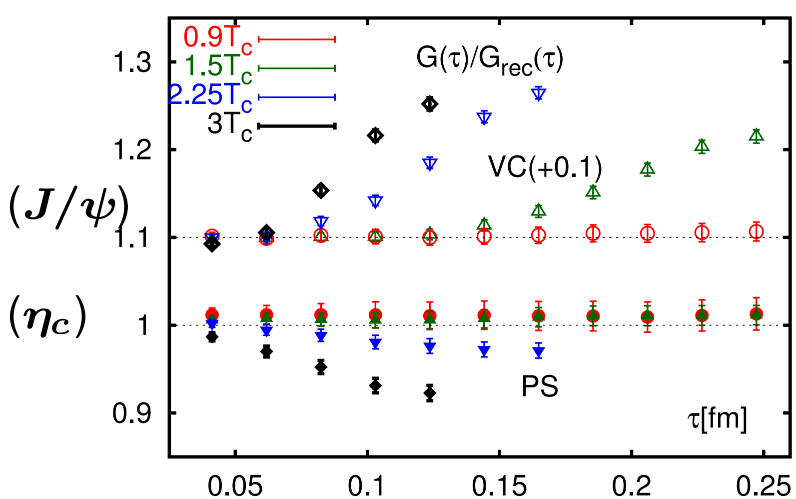
functions



Heavy quark spectral functions and correlation functions

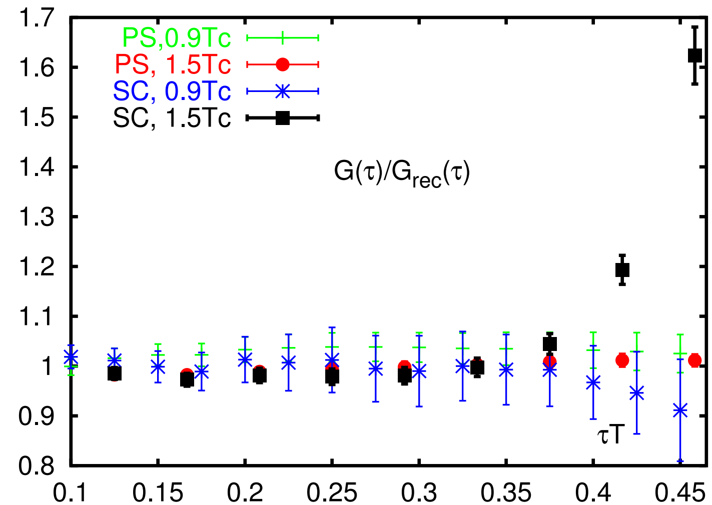
charm





S. Datta et al., Phys. Rev. D69 (2004) 094507

bottom – is coming up



first results on bottomonium at high T

(more difficult, finer lattices needed)

K. Petrov et al., hep-lat/0509138

S. Datta, PANIC 2005

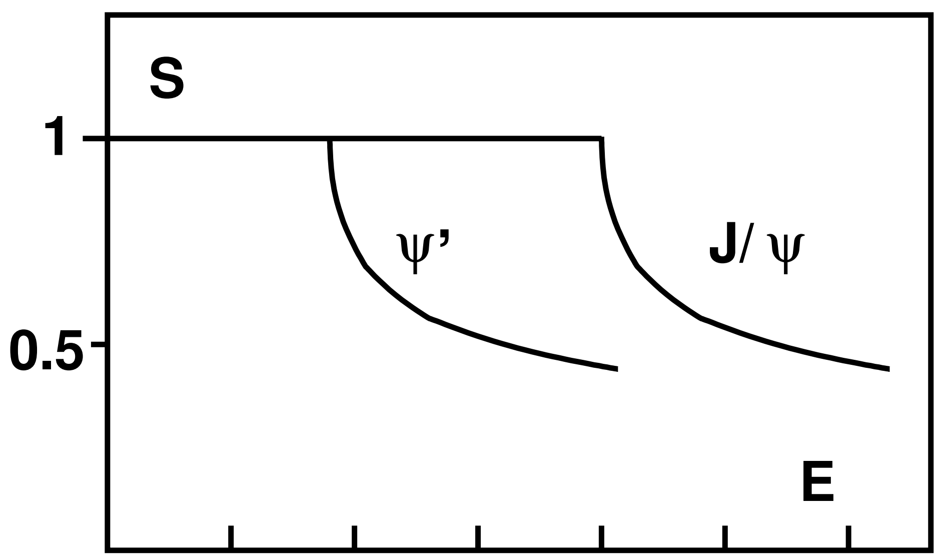
χ_b modified at $1.5\ T_c$

η_b unmodified at $1.5\ T_c$

Lattice QCD and Quarkonium Suppression in HI Collisions

- the original Matsui-Satz concept:
  - check whether medium supports existence of bound states under given thermal conditions: yes/no decision
  - fold with nuclear density and T(τ) cooling profile

$\Rightarrow$ ”abnormal” suppression pattern



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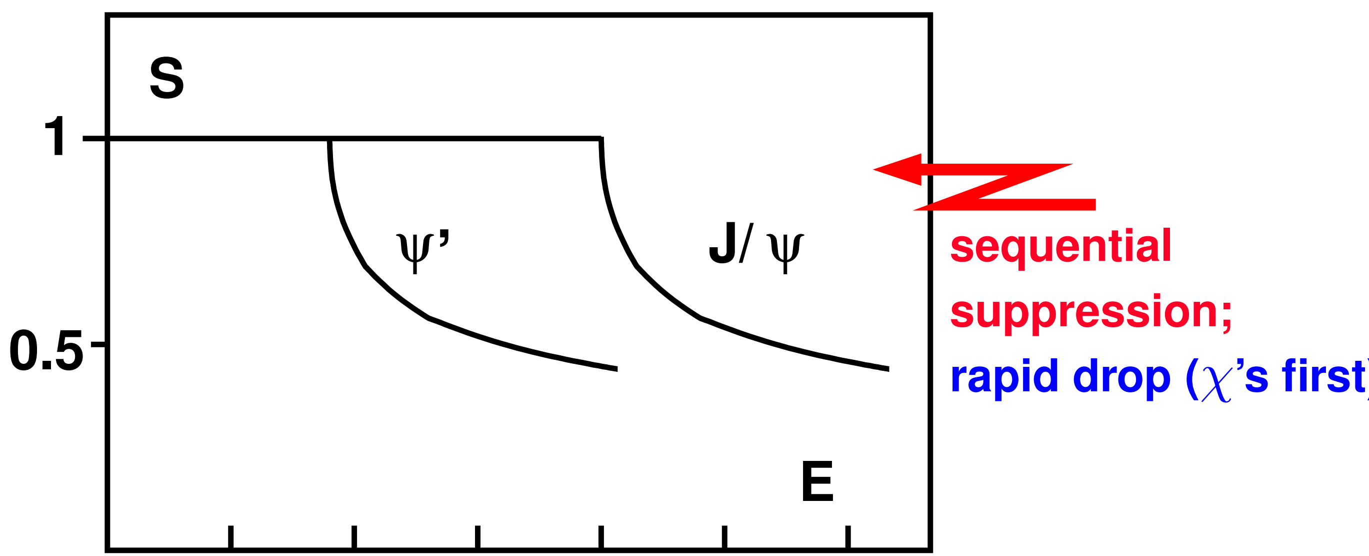

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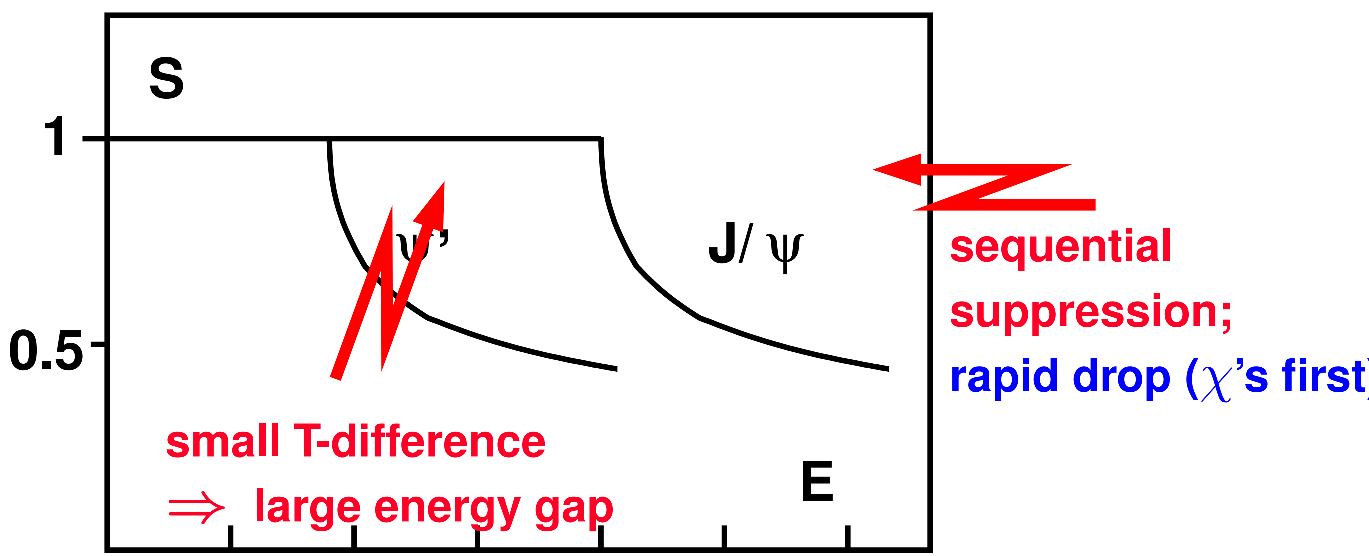
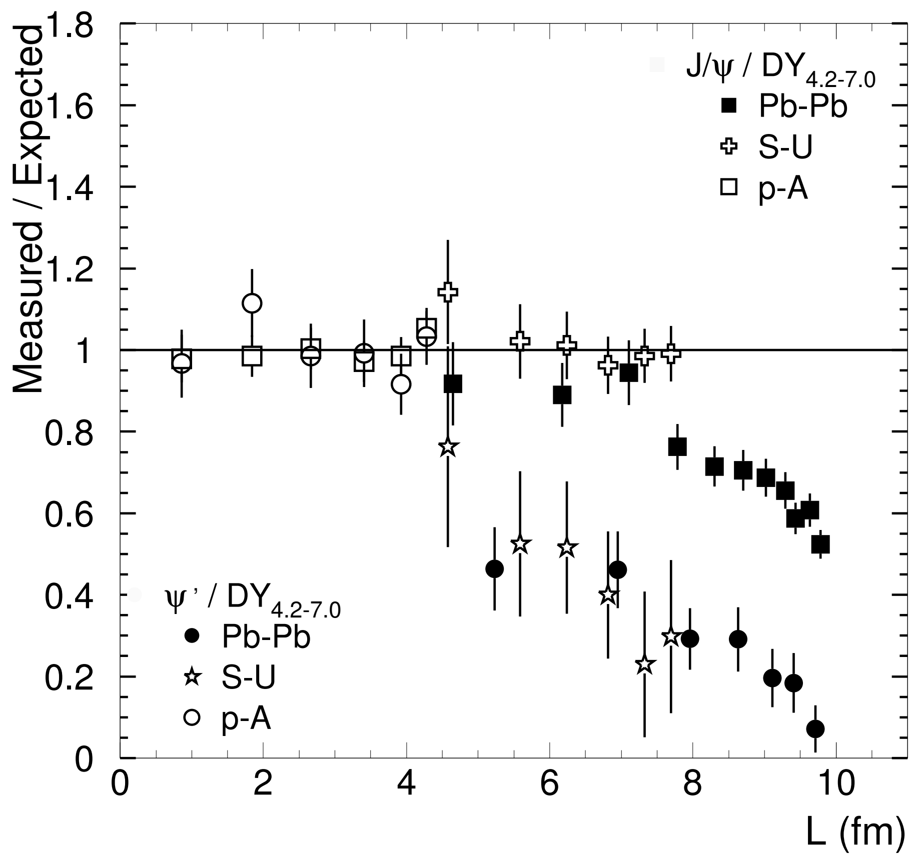


Quarkonium suppression in HI collisions

- SPS data on charmonium suppression:

NA50, hep-ex/0405056

  - may support sequential suppression pattern (or not)



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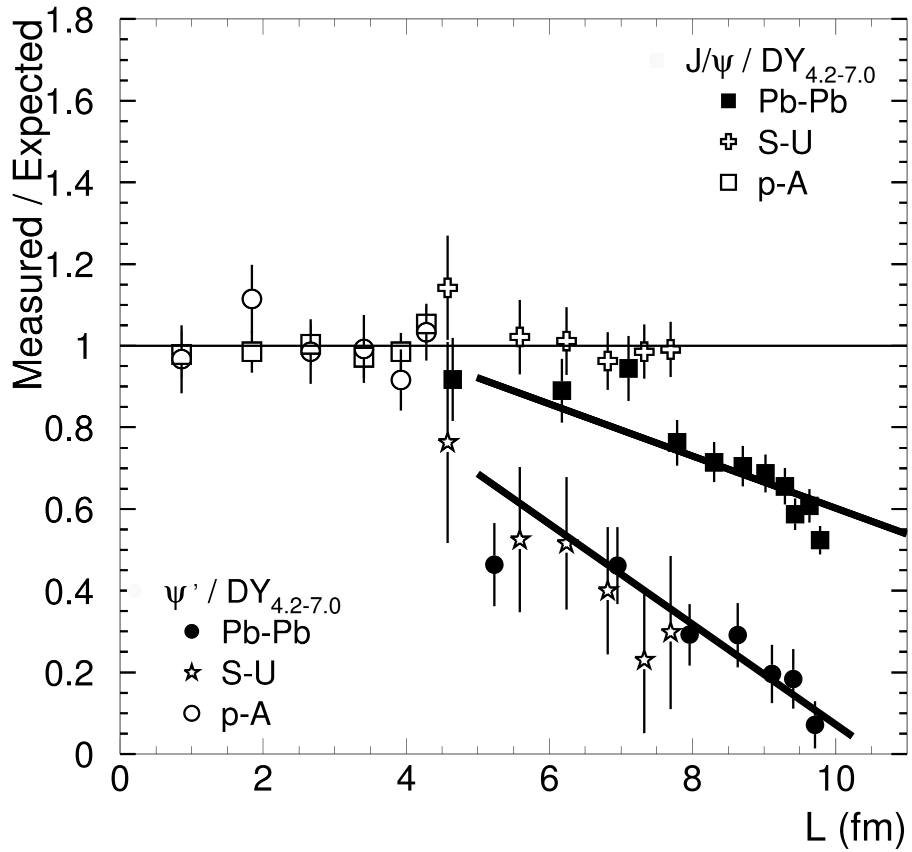

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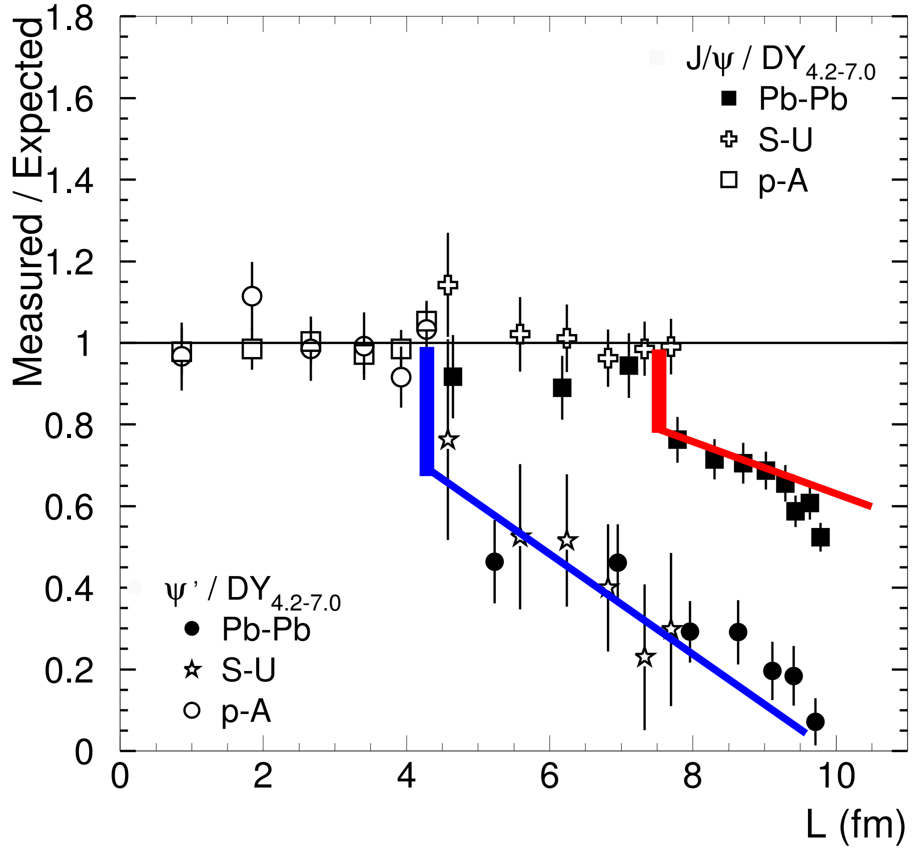

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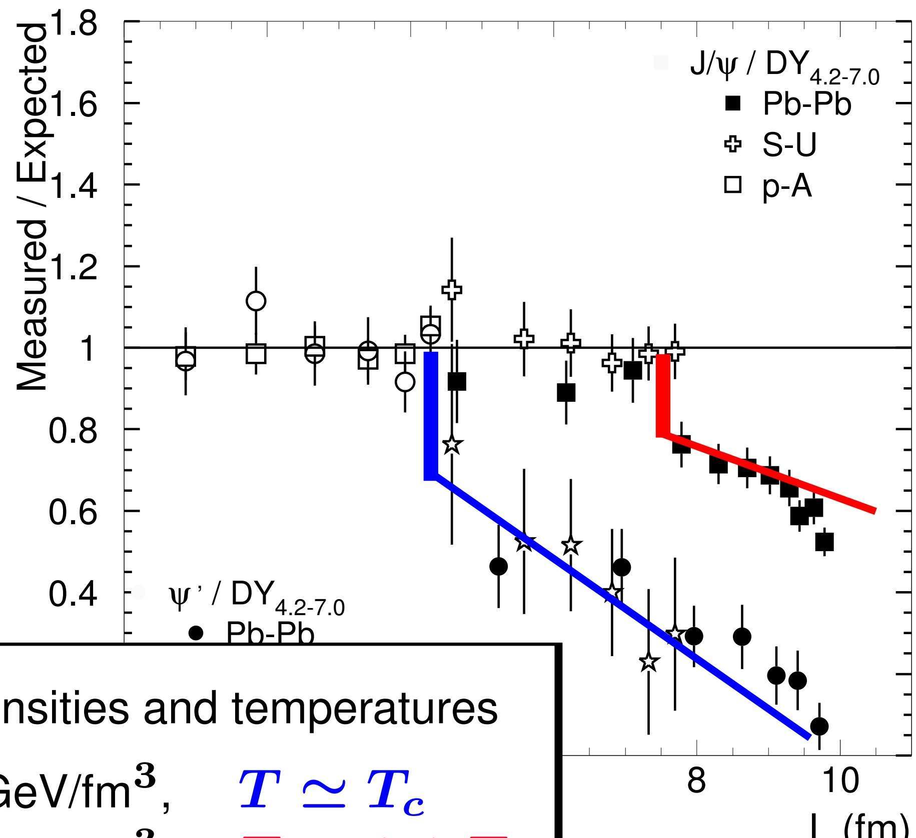


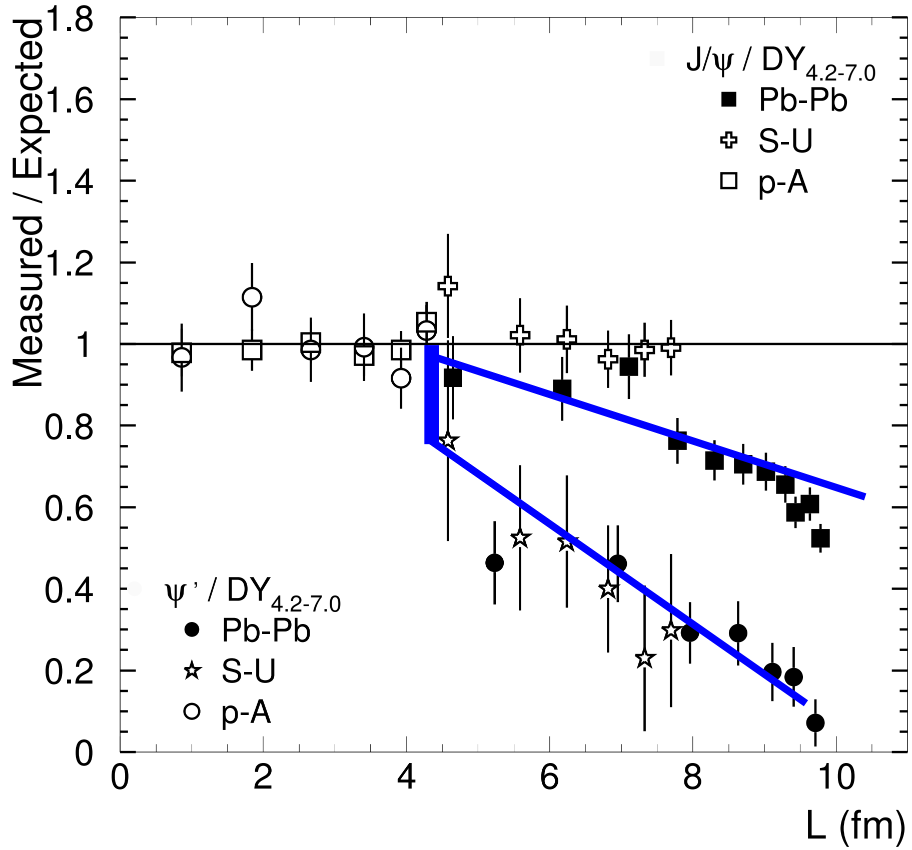
”critical” energy densities and temperatures

L=4 fm: $\epsilon \simeq$ 1.1 GeV/fm^3, $T \simeq T_c$

L=8 fm: $\epsilon \simeq$ 2.2 GeV/fm^3, $T \simeq 1.1\, T_c$

Quarkonium suppression in HI collisions

- SPS data on charmonium suppression:
  - may support sequential suppression pattern OR NOT



Quarkonium suppression in HI collisions

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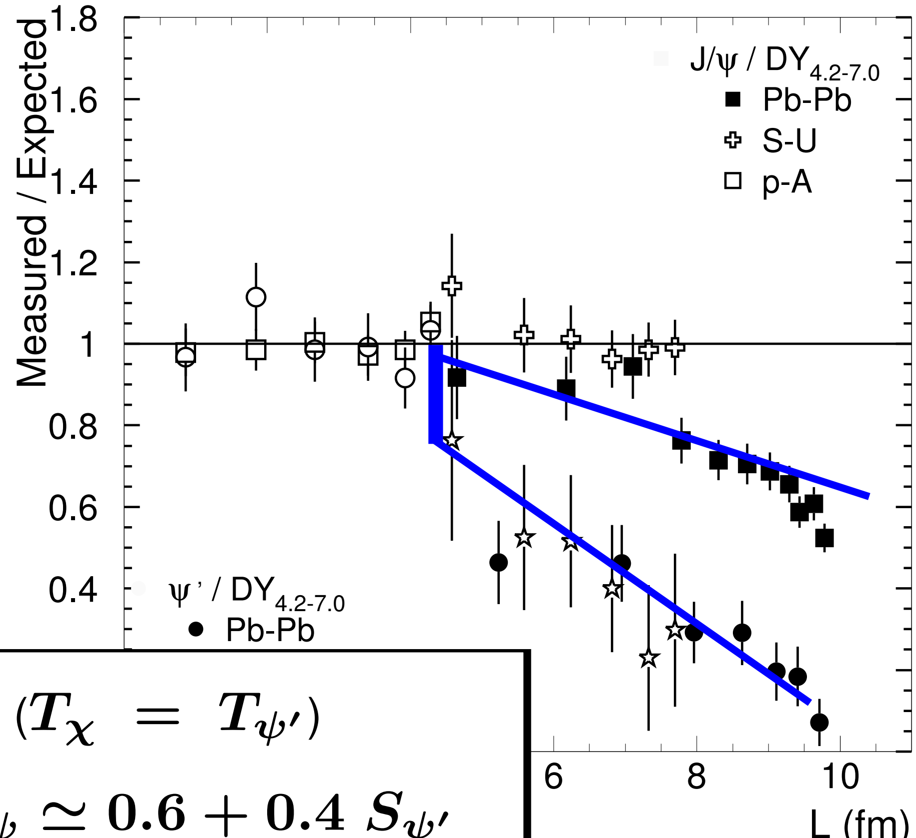

survival probability ($T_\chi = T_{\psi'}$)

$$\epsilon \gtrsim \epsilon_c : \quad S_{J/\psi} \simeq 0.6 + 0.4\ S_{\psi'}$$

Quarkonium suppression in HI collisions

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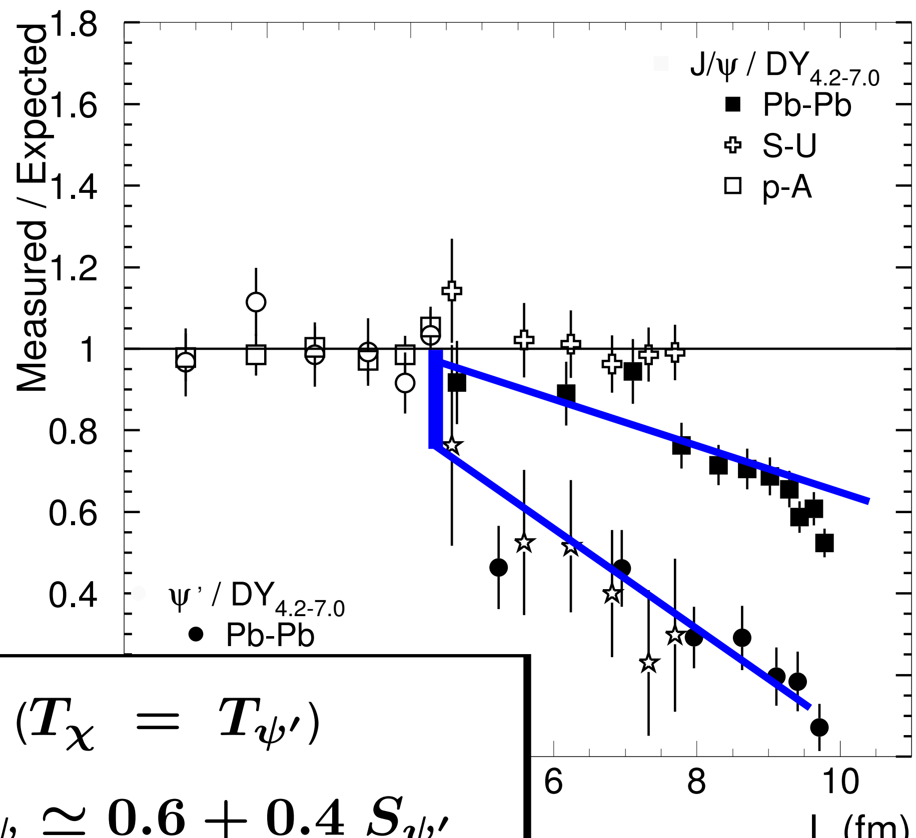
  - may support sequential suppression pattern OR NOT



in conflict
with S-U data

suggests:
only ψ', χ suppression
up to $\epsilon \simeq$ 3.5 GeV/fm^3
or $T \simeq 1.3\ T_c$

survival probability ($T_\chi = T_{\psi'}$)

$$\epsilon \gtrsim \epsilon_c: \quad S_{J/\psi} \simeq 0.6 + 0.4\ S_{\psi'}$$

Quarkonium suppression in HI collisions

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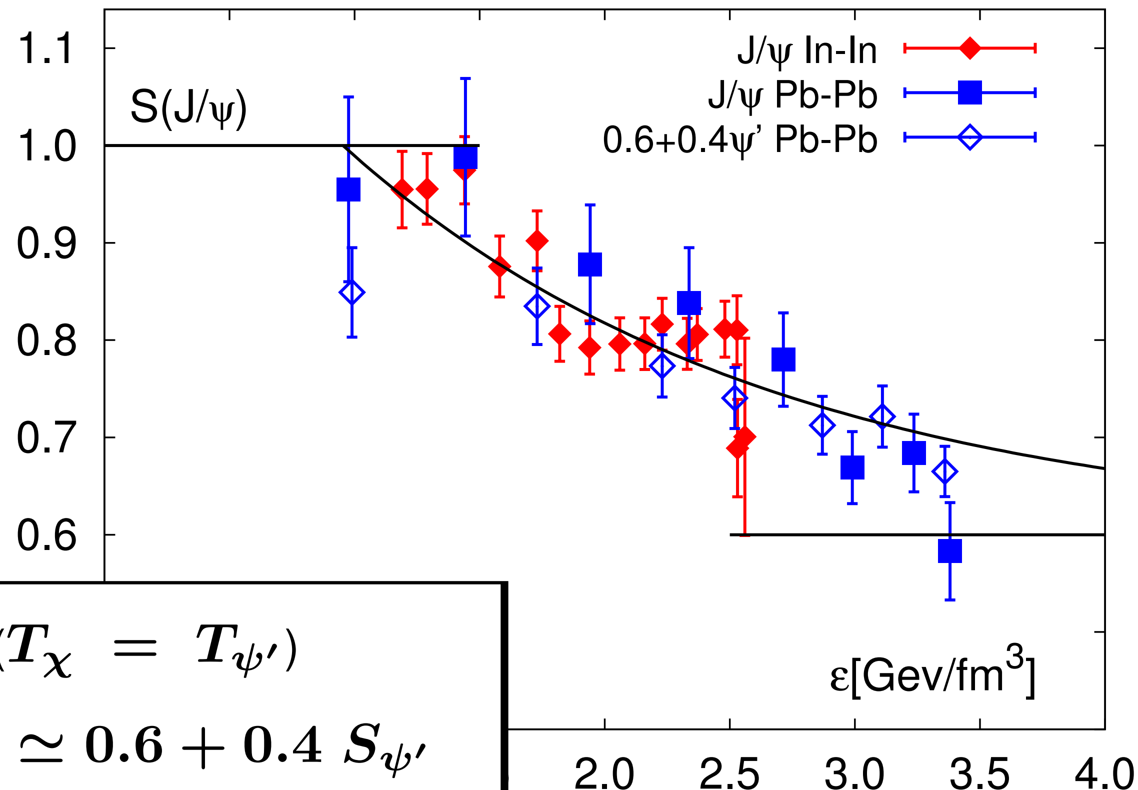

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Lattice EoS: energy density $\Leftrightarrow$ temperature
$\Longrightarrow$ conditions for heavy $q\bar{q}$ bound states

LGT: $T_c \simeq 175$ MeV [maybe 185 MeV]

$T = T_c$: $\epsilon_c/T_c^4 \simeq 6 \;\Rightarrow\; \epsilon_c \simeq 1$ GeV/fm^3

$T \;\geq\; 1.5T_c$: $\epsilon/T^4 \simeq (10-12)$

$T = 1.5T_c$: $\epsilon \simeq 15$ GeV/fm^3

$T = 2.0T_c$: $\epsilon \simeq 45$ GeV/fm^3

$\Downarrow$

observable consequences:

J/ψ suppression

RHIC

$R_{Au} \simeq 7$ fm;

$\tau_0 \simeq 1$ fm

$\langle E_T \rangle \simeq 1$ GeV

$dN/dy \simeq 1000$

$\Downarrow$

$\epsilon_{Bj} \simeq 7$ GeV/fm^3

maybe: $\tau_0 \simeq 0.5$ fm

$\Downarrow$

$\epsilon_{Bj} \simeq 14$ GeV/fm^3

Lattice EoS: energy density $\Leftrightarrow$ temperature $\Rightarrow$ conditions for heavy $q\bar{q}$ bound states

LGT: $T_c \simeq 175$ MeV [maybe 185 MeV]

$T = T_c$: $\epsilon_c/T_c^4 \simeq 6 \;\Rightarrow\; \epsilon_c \simeq 1$ GeV/fm^3

$T \;\geq\; 1.5T_c$: $\epsilon/T^4 \simeq (10-12)$

$T = 1.5T_c$: $\epsilon \simeq 15$ GeV/fm^3

$T = 2.0T_c$: $\epsilon \simeq 45$ GeV/fm^3

$\Downarrow$

χ_c, ψ' suppression at RHIC

direct J/ψ suppression unlikely

$\Downarrow$

$$S(J/\psi) \simeq 0.6 + 0.4S(\chi_c)$$

(assume $S(\chi_c) \simeq S(\psi')$)

RHIC

$R_{Au} \simeq 7$ fm;

$\tau_0 \simeq 1$ fm

$\langle E_T \rangle \simeq 1$ GeV

$dN/dy \simeq 1000$

$\Downarrow$

$\epsilon_{Bj} \simeq 7$ GeV/fm^3

maybe: $\tau_0 \simeq 0.5$ fm

$\Downarrow$

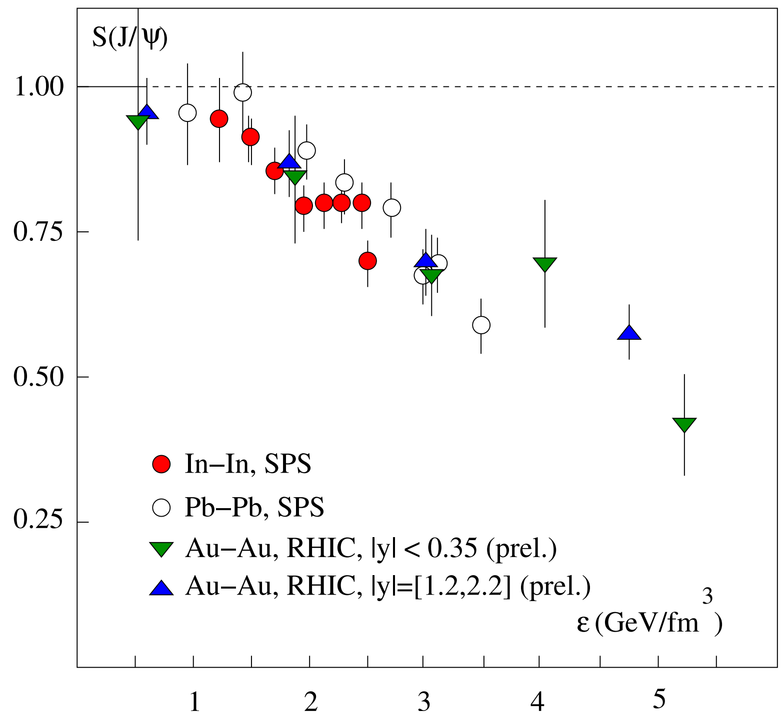
$\epsilon_{Bj} \simeq 14$ GeV/fm^3

Quarkonium suppression at SPS and RHIC

- SPS and RHIC data on charmonium suppression:

  NA50, hep-ex/0405056
  H. Pereira da Costa et al. (PHENIX), Quark Matter 2005

  - RHIC suppression pattern consistent with SPS data
  - energy density at RHIC not yet large enough for direct J/ψ suppression



FK, D. Kharzeev, H. Satz, Phys. Lett. B637 (2006) 75

Conclusions

- Deconfinement, screening and asymptotic freedom
  - string breaking is done by quarks; screening is due to gluons
  - a quark component is needed in screening up to $T \lesssim 1.1 T_c$
- Potential models for quarkonium
  - input from LGT: excess energy $>$ excess free energy
  - increased energy is in gluon cloud
- Spectral functions
  - (directly produced) J/ψ exist well above T_c
- Charmonium in heavy ion collisions
  - sequential suppression pattern may be the smoking gun