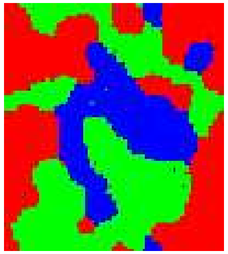
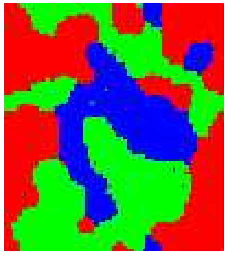


Deconfinement and Quarkonium Suppression

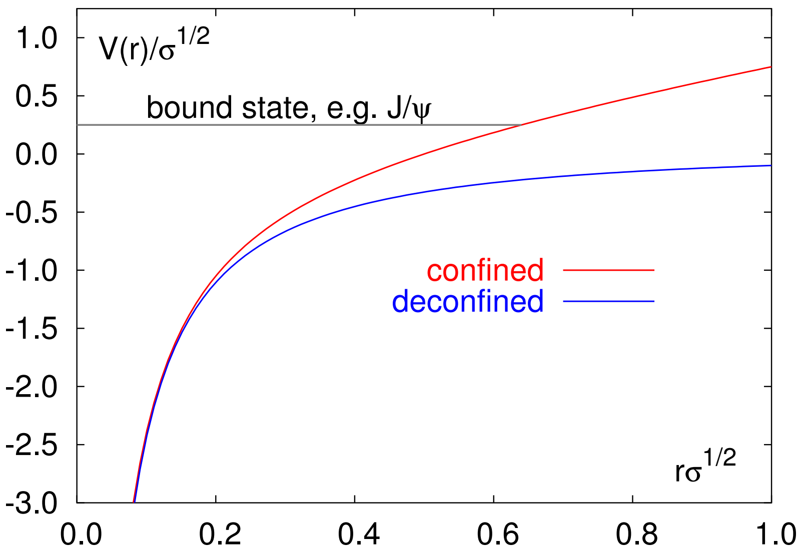
- Deconfinement, screening and asymptotic freedom
  - deconfinement is density driven
- Heavy quark free energies
  - screening sets in at short distances; 1/r still dominant scale
- Potential models for quarkonium
  - dissociation may spoil sequential suppression pattern
- Spectral functions
  - (directly produced) J/ψ exist well above T_c
- Charmonium in heavy ion collisions
  - sequential suppression pattern may be the smoking gun



Deconfinement $\Rightarrow$ screening $\Rightarrow$ quarkonium suppression

The Matsui-Satz argument:

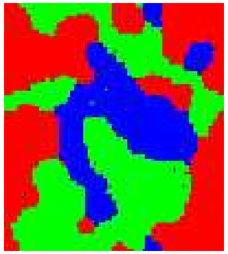
- deconfinement $\Rightarrow$ screening
  $\Rightarrow$ no heavy quark bound states in a QGP



$V_{\bar{q}q}(r,T) \rightarrow \infty$ confinement

$V_{\bar{q}q}(r,T) < \infty$ deconfinement

- heavy $q\bar{q}$-pairs are rare states in a QGP
  $\Rightarrow$ dissolved pairs never recombine



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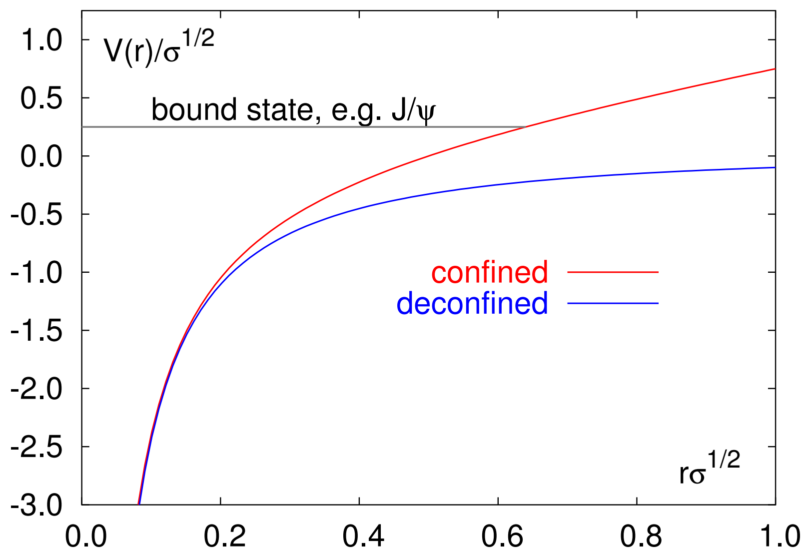

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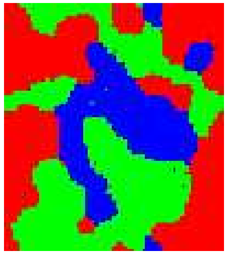


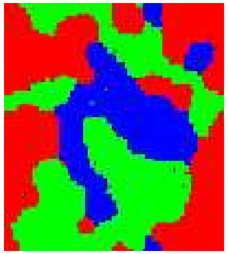
Deconfinement and asymptotic freedom

asymptotic freedom ⇒ deconfinement (the original concept):

- N. Cabibbo, G. Parisi, Exponential Hadronic Spectrum and Quark Liberation, PL B59 (1975) 67;
- J.C. Collins, M.J. Perry, Superdense Matter: Neutrons and asymptotically free quarks? PRL 34 (1975) 1353

- deconfinement is a consequence of asymptotic freedom
- deconfinement ⇔ liberation of many new degrees of freedom, asymptotically free $q\bar{q} + g$ gas
- deconfinement is density driven

⇑ evidence from LGT



Confinement and deconfinement

confinement

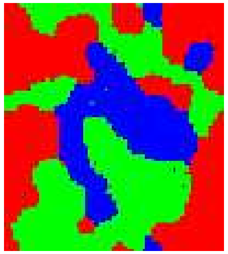
- stick together, find a comfortable separation
- controlled by confinement potential

$$V(r) = -\frac{4}{3}\frac{\alpha(r)}{r} + \sigma r$$

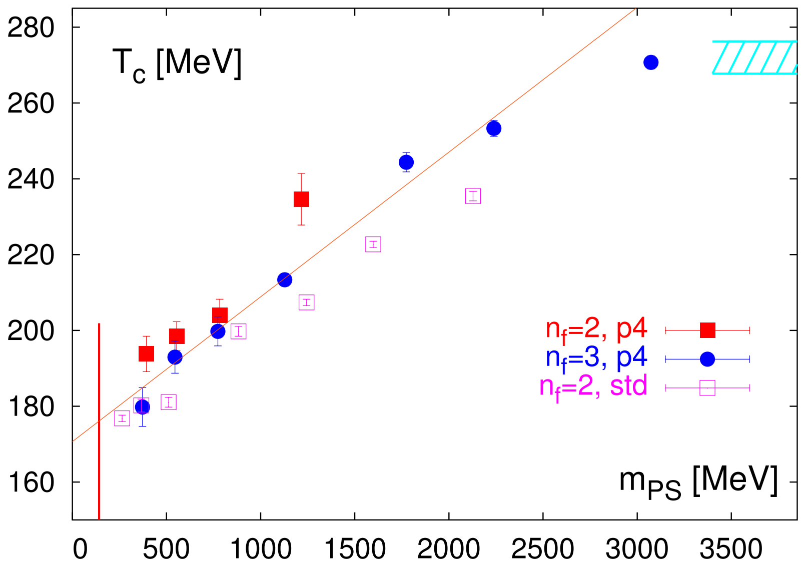
deconfinement

- free floating in the croud
- average distance always smaller than r_{af}:

$$r_{af} = \sqrt{\frac{4}{3}\frac{\alpha(r)}{\sigma}} \simeq 0.25\,\mathrm{fm}$$



Density driven transition: Critical temperature & EoS



$m_{PS} \simeq 140\ MeV:\quad T_c \simeq 175\ MeV$

$m_{GB} \simeq 1.5\ GeV:\quad T_c \simeq 265\ MeV$
$(m_{PS} = \infty)$

lightest masses apparently do

not control the transition

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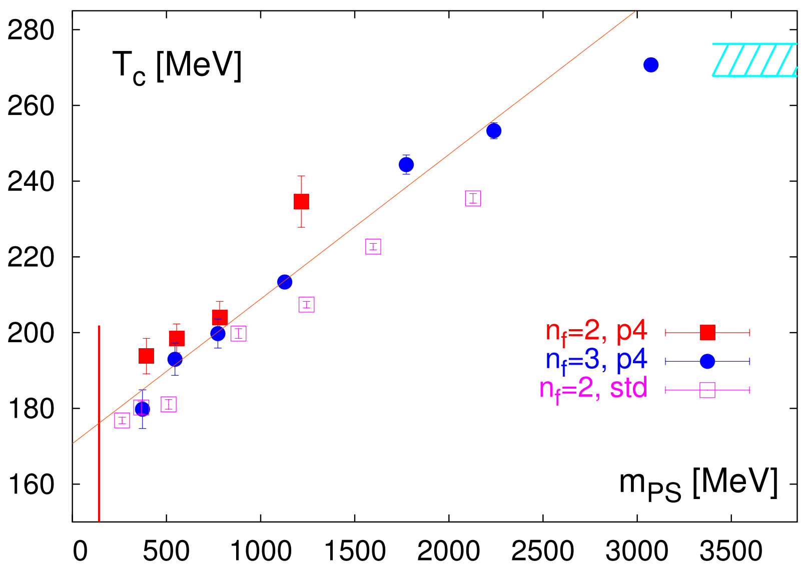

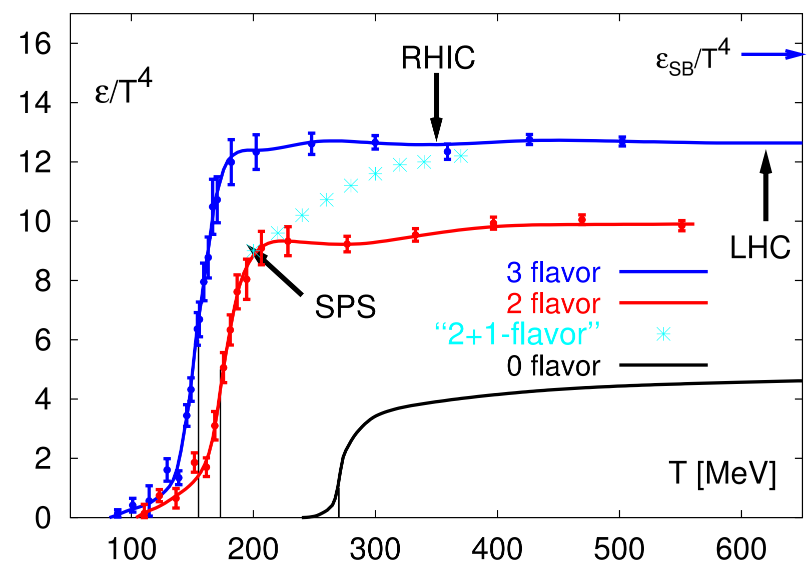

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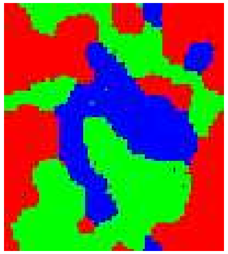
$$n_f = 2: \quad \epsilon_c \simeq (6 \pm 2)\, T_c^4 \simeq (0.3 - 1.3)\ GeV/fm^3$$

$$n_f = 0: \quad \epsilon_c \simeq (0.5 - 1)\, T_c^4 \simeq (0.3 - 0.7)\ GeV/fm^3$$

change in ϵ_c/T_c^4 compensated by shift in T_c
transition sets in at similar energy (or parton) densities $\Rightarrow$ percolation



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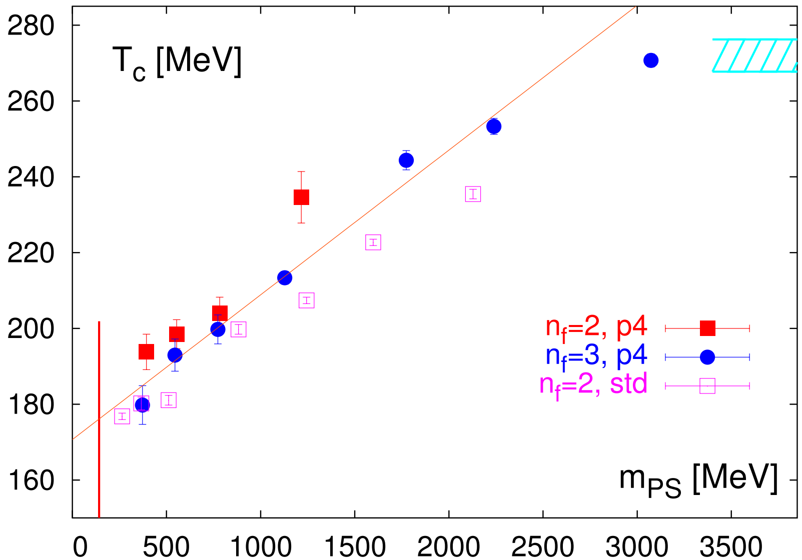
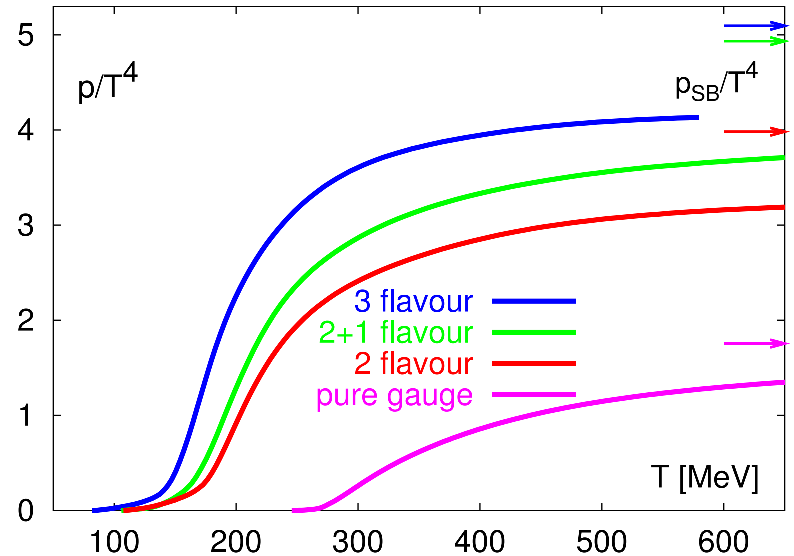




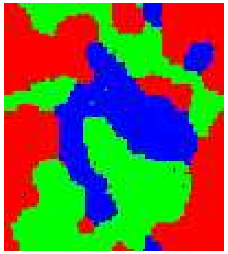
$m_{PS} \simeq 140\ MeV:\quad T_c \simeq 175\ MeV$

parton density (ideal gas): $n \equiv p/T$

Debye screening radius: $r_D \sim 1/g(T)\sqrt{n/T}$

$\sim 1/g\ T$

rapid change across T_c: $r_D/T \sim 1/g(T)\sqrt{p/T^4}$



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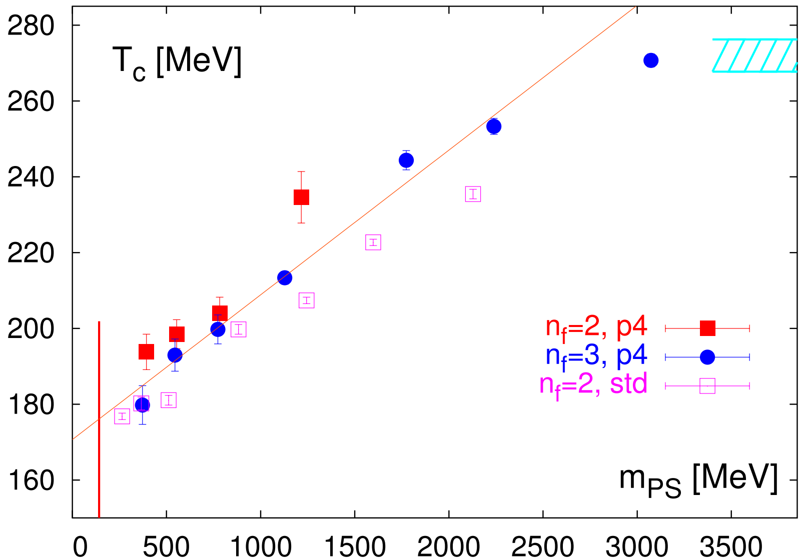

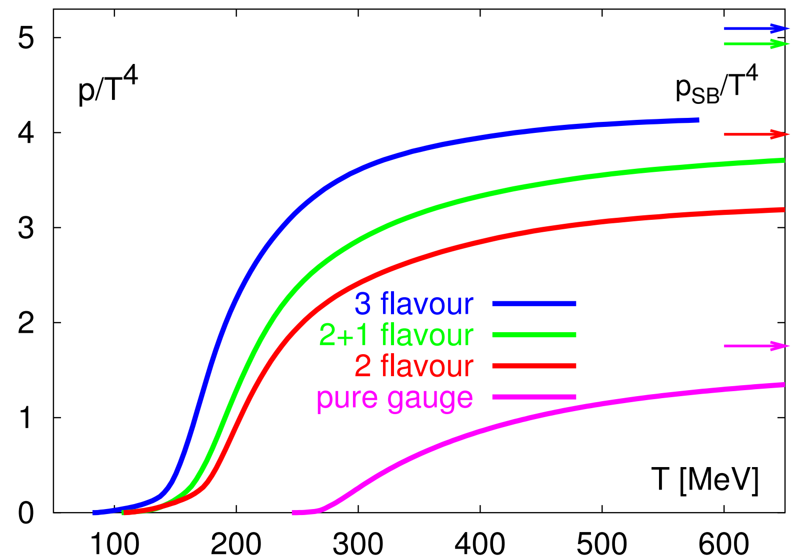

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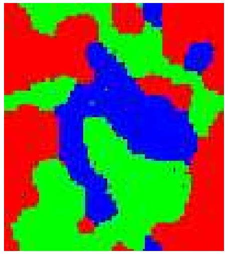
constant parton density in an ideal gas:

$$\frac{T(m_\pi = \infty)}{T(m_\pi = 0)} = \left(1 + \frac{21}{4}\frac{n_f}{N_c^2 - 1}\right)^{1/3} \simeq 1.3 - 1.5$$



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

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

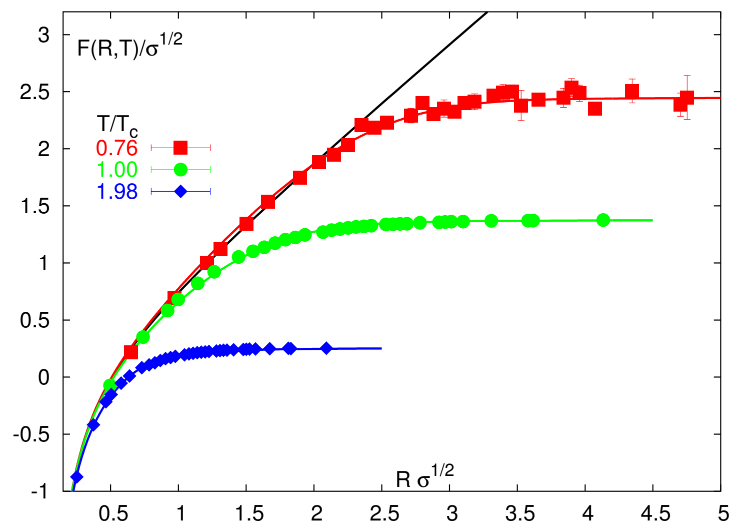
  ⇒ change in free energy due to presence of external sources

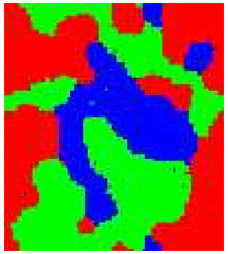
L.G. McLerran, B. Svetitsky, Phys. Rev. D24 (1981) 450

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

- asymptotic freedom, screening, string breaking

singlet free energy
in 2-flavor QCD
$(m_q/T = 0.4)$
O.Kaczmarek, F. Zantow;
similar:
P.Petreczky, K. Petrov





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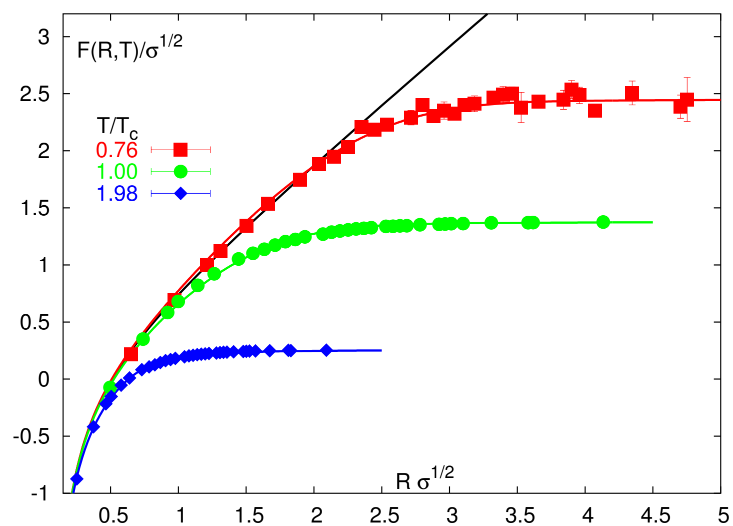
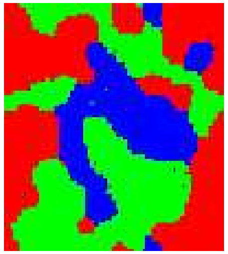


$T \lesssim 0.75\ T_c$:

string breaking

$F(r,T) \simeq V(r, T=0)$



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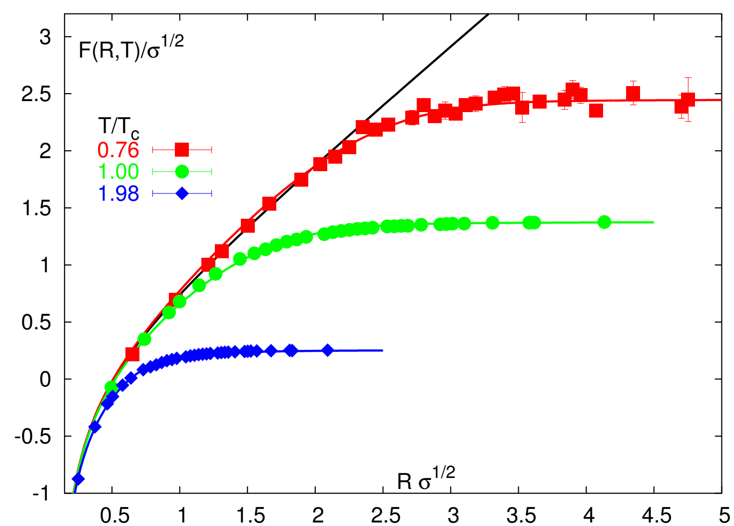

$T \lesssim 0.75\, T_c$: string breaking $F(r,T) \simeq V(r,T=0)$

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

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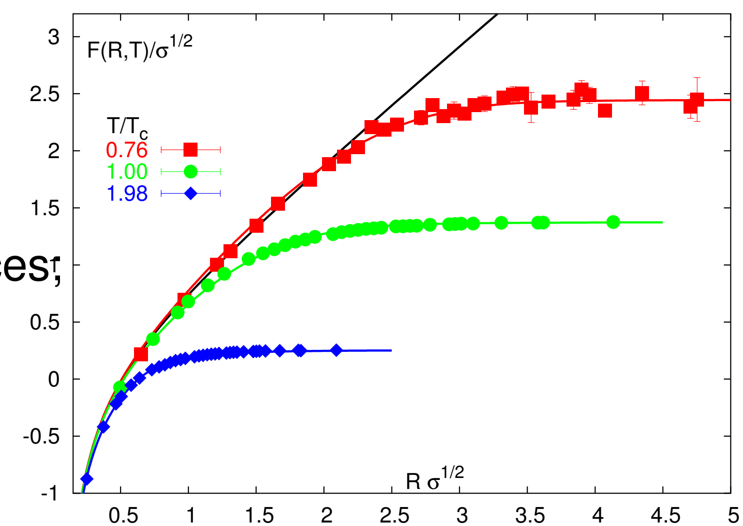
- asymptotic freedom, screening, string breaking

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



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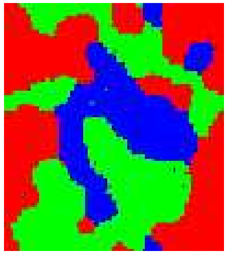

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$$e^{-F_{\bar{q}q}(r,T)/T} = \frac{1}{9}\langle \mathrm{Tr} L_{\vec{x}} \mathrm{Tr} L^\dagger_{\vec{0}} \rangle$$

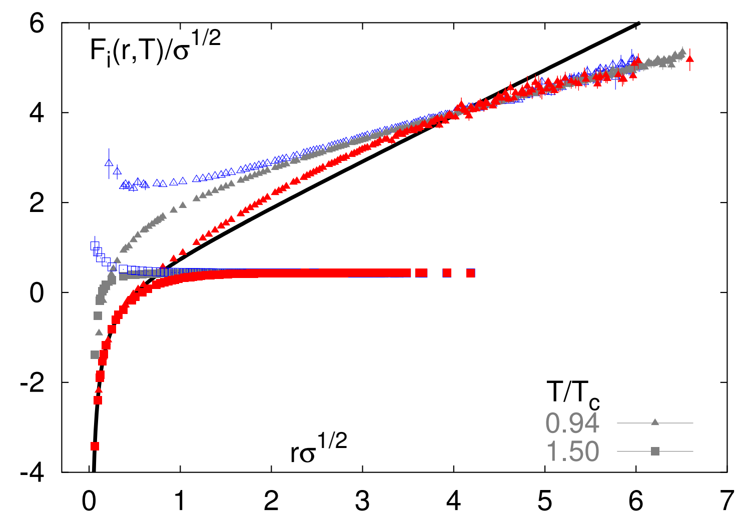
- $3 \times \bar{3} = 1 + 8$; $(q\bar{q})$-pair can be in a singlet or octet state

$$e^{-F_{\bar{q}q}(r,T)/T} = \frac{1}{9}\, e^{-F_1(r,T)/T} + \frac{8}{9}\, e^{-F_8(r,T)/T}$$

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

- $F_1,\ F_8$ require gauge fixing:
  Coulomb gauge; gauge invariant interpretation:
  O. Philipsen, PLB 535 (2002) 138)

$\Rightarrow$ F_1,F_8 are not unique;
BUT: short and large distance behaviour are!!

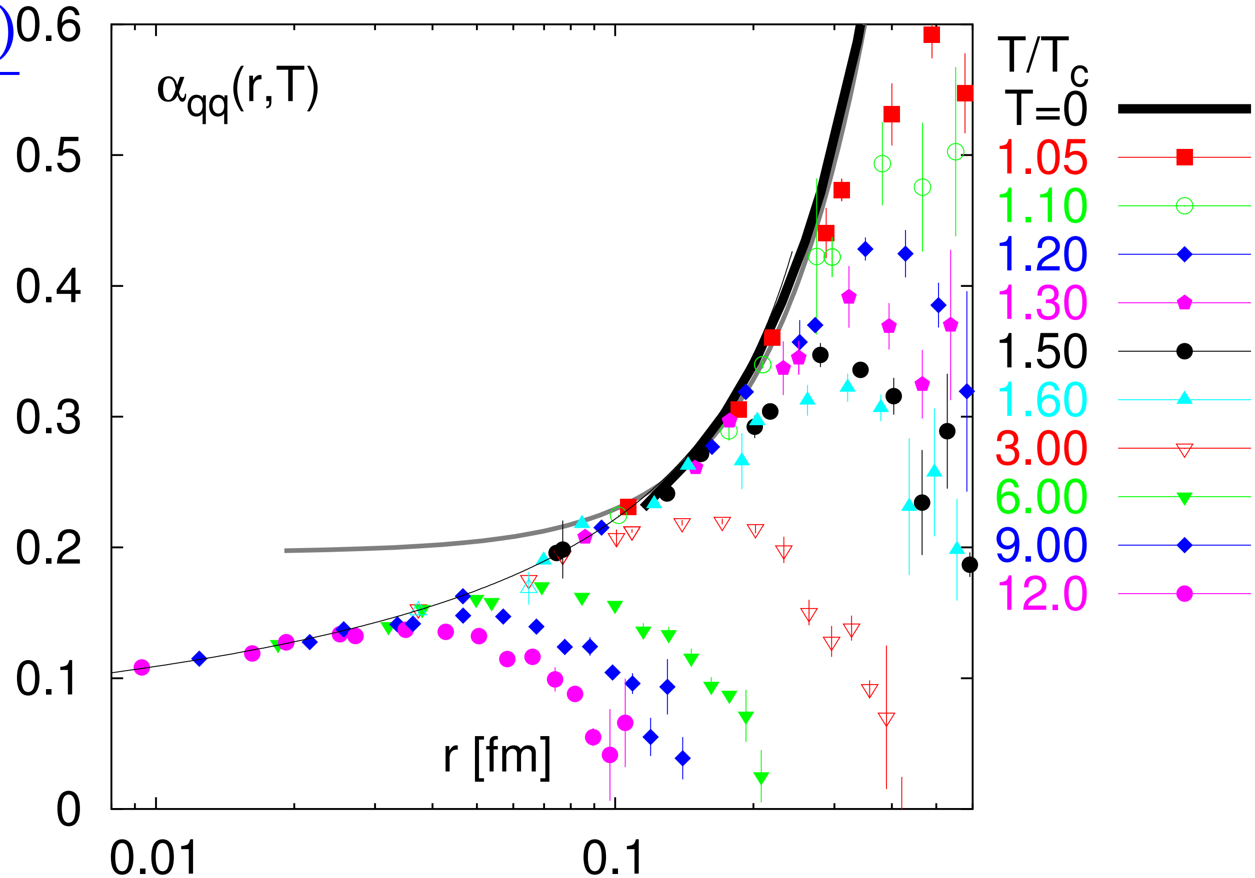


Singlet free energy and asymptotic freedom

O.Kaczmarek, FK, P. Petreczky, F. Zantow (2004)

- 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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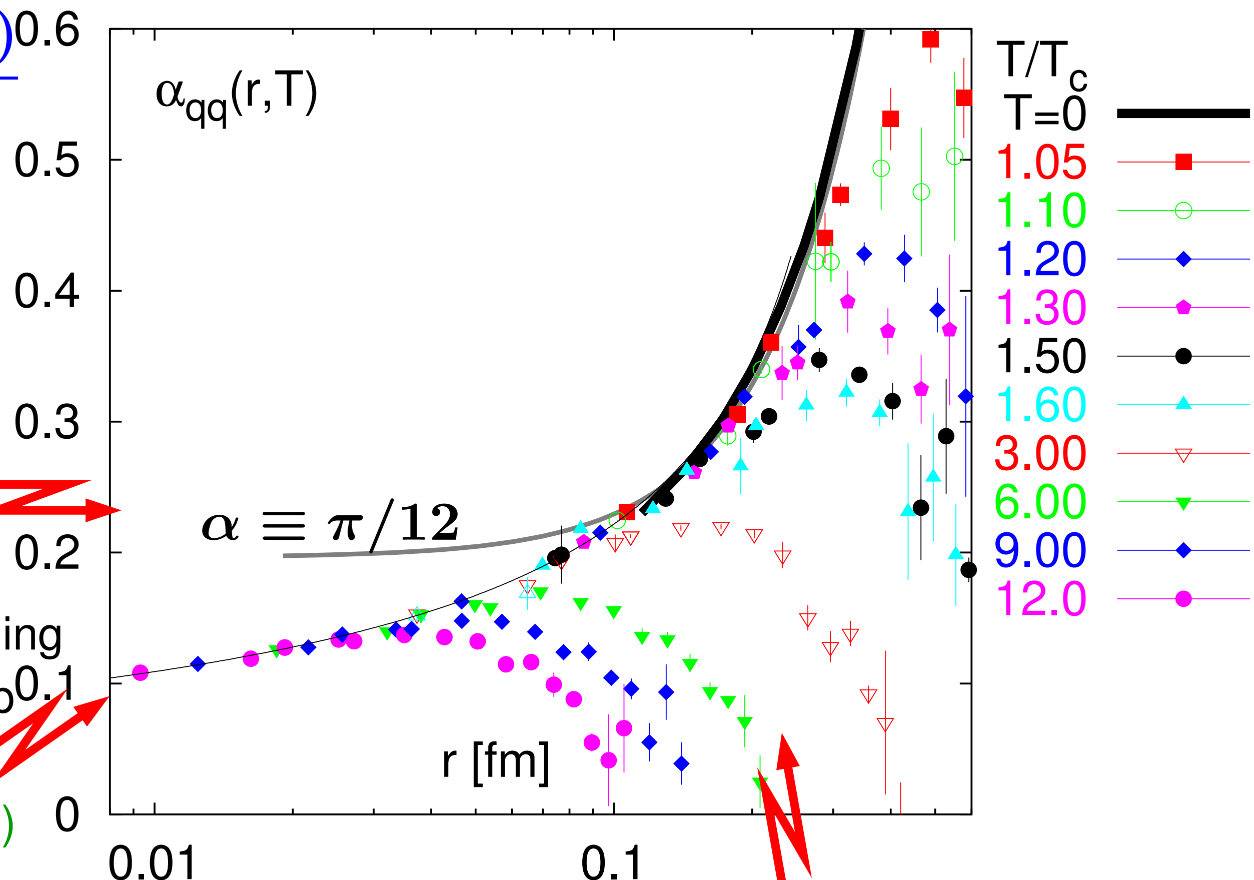
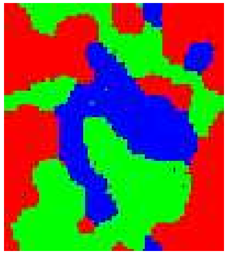


large distance: constant Coulomb term (string model)

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 $T \lesssim 3\ T_c$

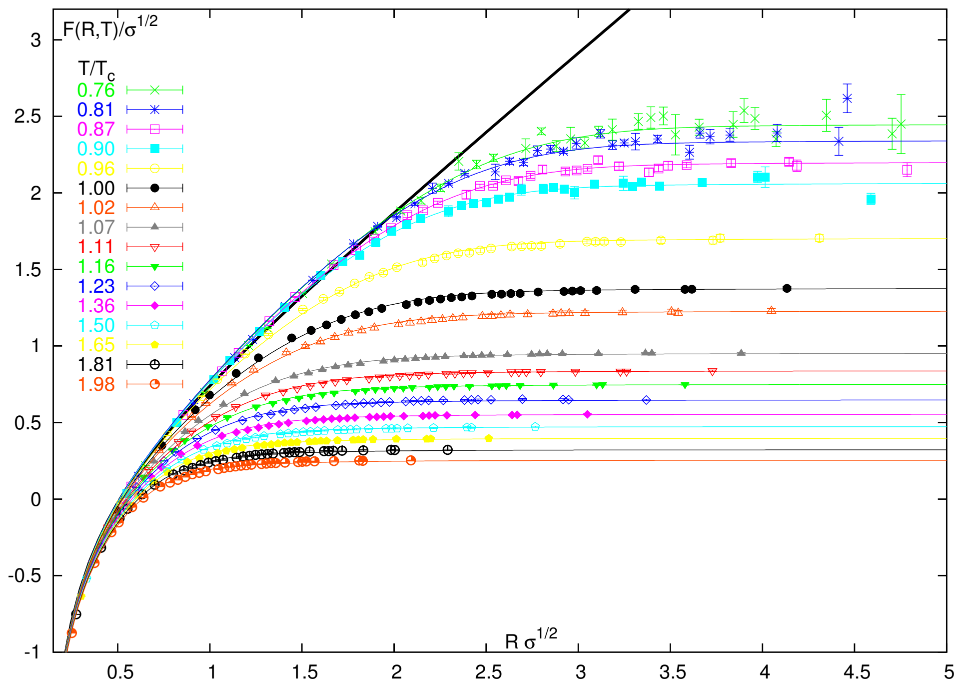
- short distance physics ⇔ vacuum physics



Heavy quark free energy: screening and string breaking

string breaking ⇔ screening with $q\bar{q}$ pairs from the vacuum

2-flavour QCD simulation on a $16^3 \times 4$ lattice



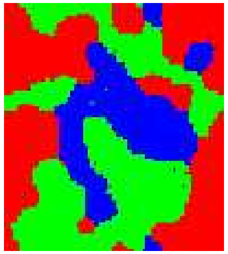
temperature dependence of heavy quark free energy

$(m_q/T = 0.4)$

rapid drop of $F(\infty, T)$ across T_c reflects rapid rise of (parton) density

fit: $$F(r,T) = \frac{\sigma\, r}{x}\left[\frac{\Gamma(1/4)}{2^{3/2}\Gamma(3/4)} - \frac{\sqrt{x}}{2^{3/4}\Gamma(3/4)} K_{1/4}(x^2)\right] - \frac{4}{3}\frac{\alpha}{r}\left[\mathrm{e}^{-x} + x\right] \;,\; x = \mu(T) r$$

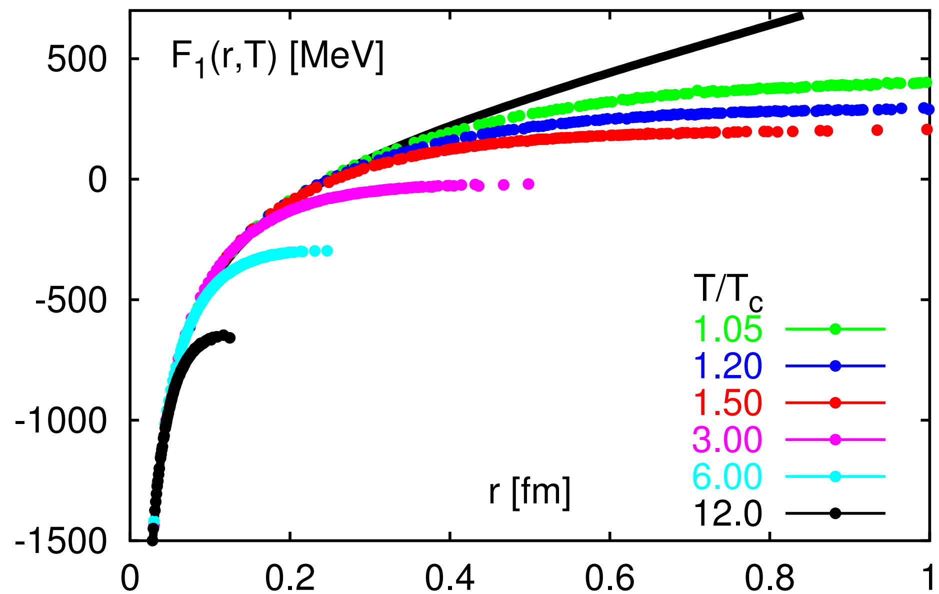
see talks by S. Digal and O. Kaczmarek



From heavy quark free energies to heavy quark potentials

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

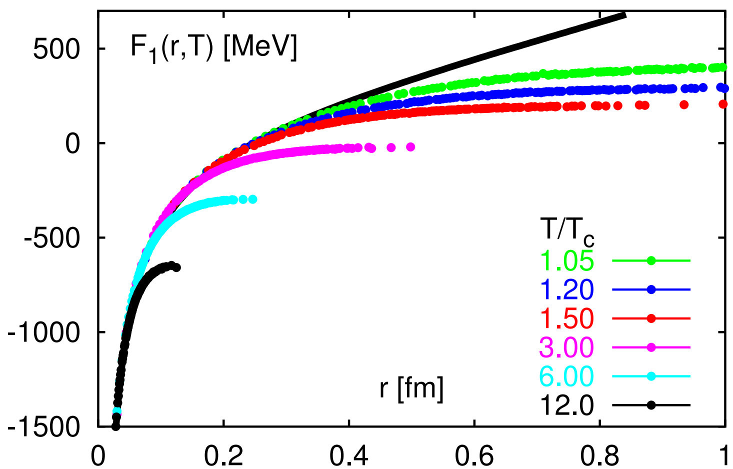
$$F = E - T \cdot S$$



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

- 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!)

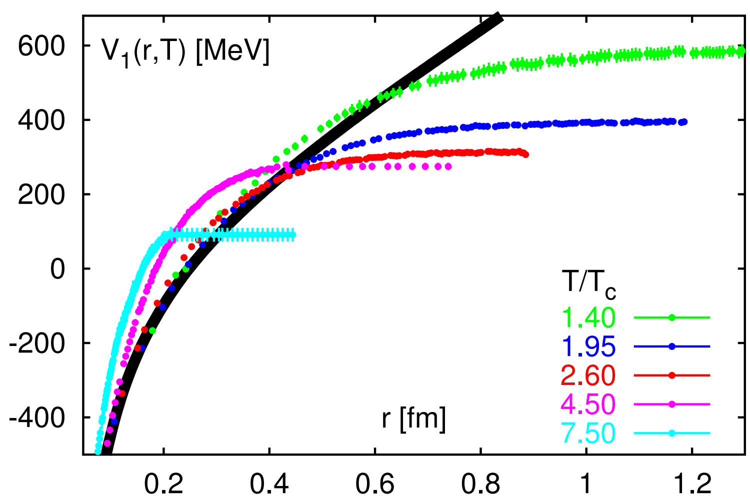
From heavy quark free energies to heavy quark potentials



i) singlet free energy

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

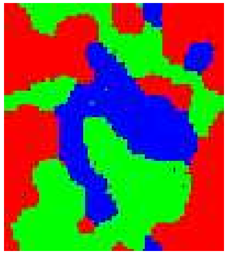
(Coulomb gauge)



ii) singlet energy ⇔ "potential" energy

$$V_1(r,T) \equiv -T^2 \frac{\partial F_1(r,T)/T}{\partial T}$$

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



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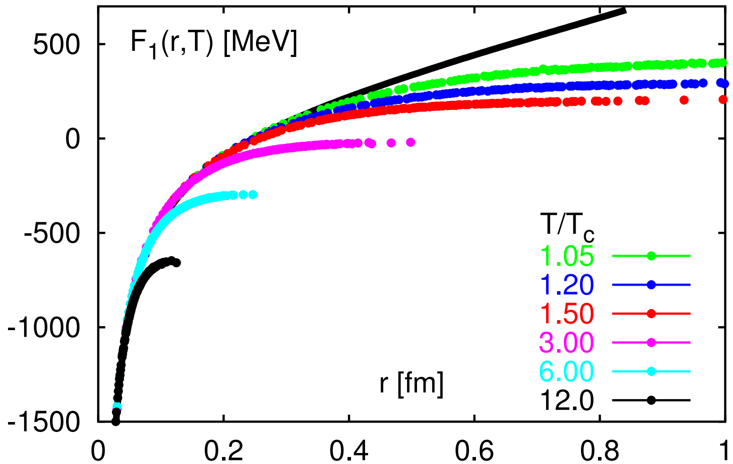
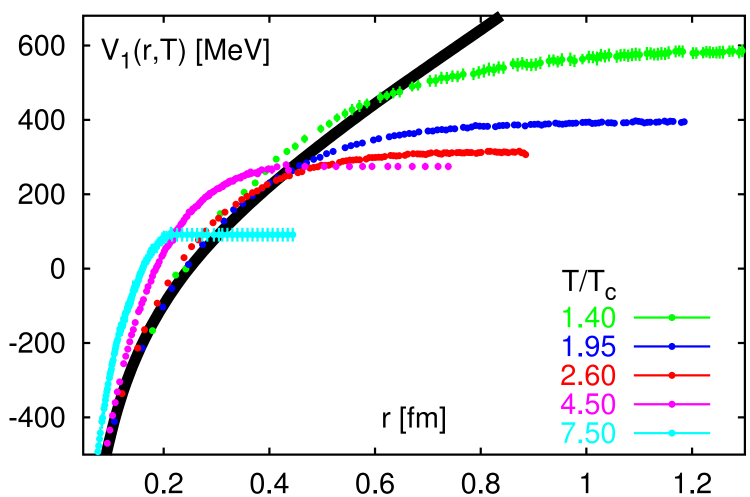


i) singlet free energy

NOTE:

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

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



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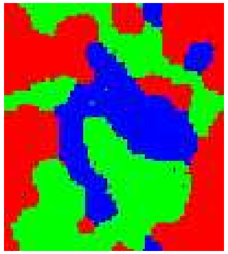

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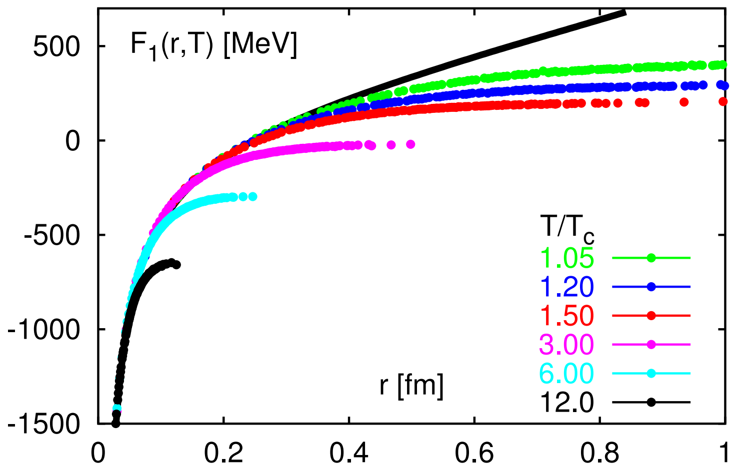

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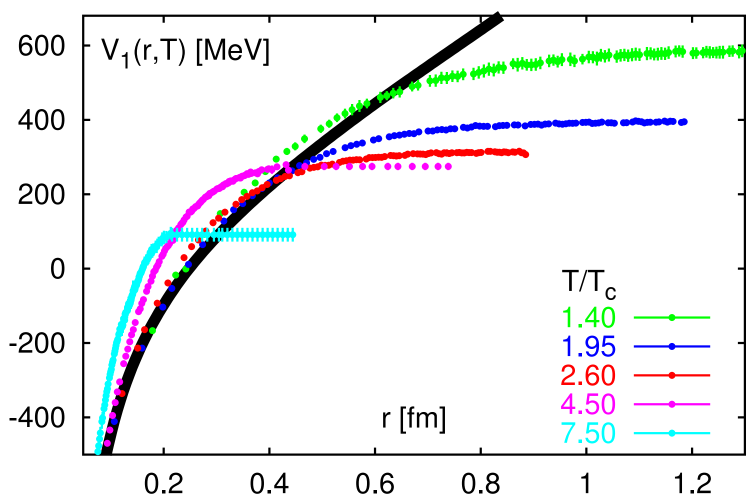
$\Rightarrow$ $V(r,T) \; > \; F(r,T)$



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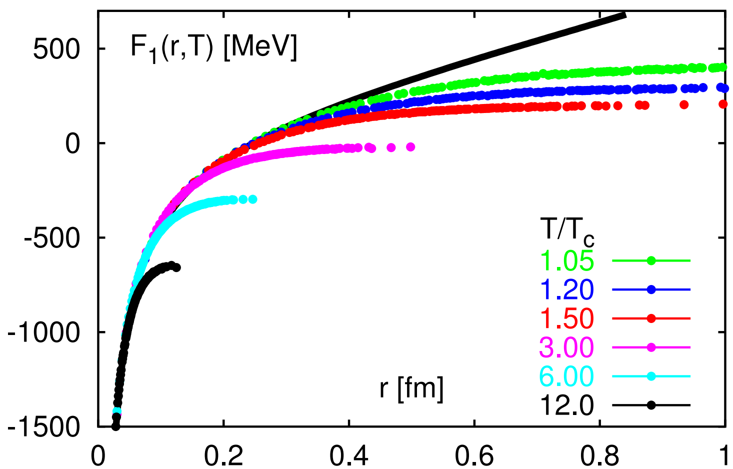

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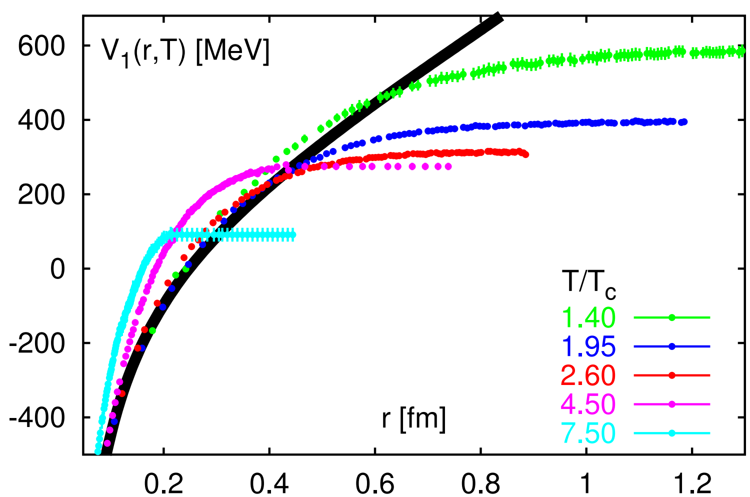
$$F_1(\infty, 1.4T_c) \simeq 200 \text{ MeV}$$

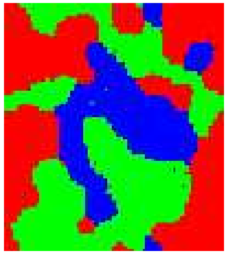
$$V_1(\infty, 1.4T_c) \simeq 600 \text{ MeV}$$



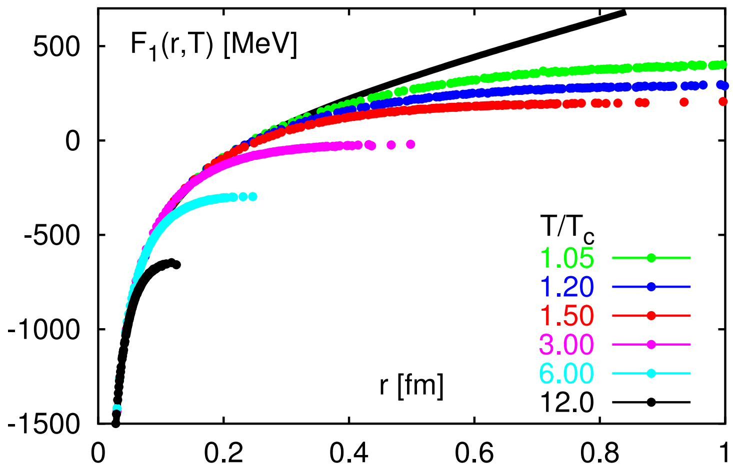
ii) singlet energy $\Leftrightarrow$ "potential" energy

$$V_1(r,T) \equiv -T^2 \frac{\partial F_1(r,T)/T}{\partial T}$$

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



From heavy quark free energies to heavy quark potentials



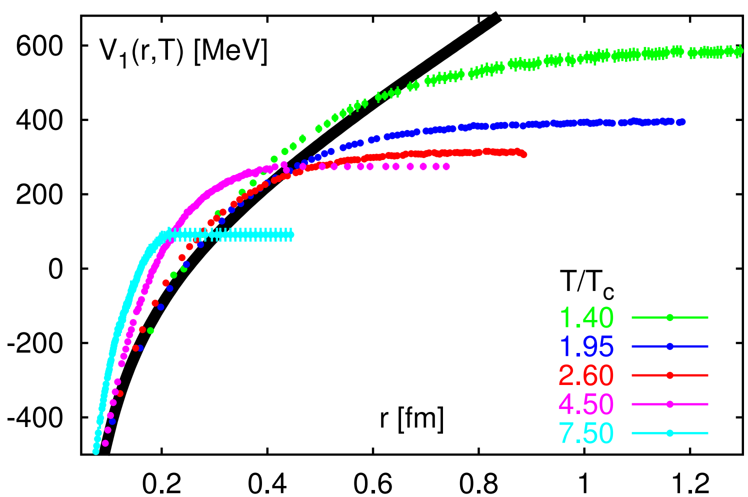
i) singlet free energy

NOTE:

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

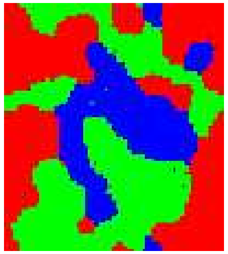
$$F_1(\infty, 1.4T_c) \simeq 200 \text{ MeV}$$

$$V_1(\infty, 1.4T_c) \simeq 600 \text{ MeV}$$



ii) singlet energy ⇔ ”potential” energy

When do heavy quark bound states really disappear?



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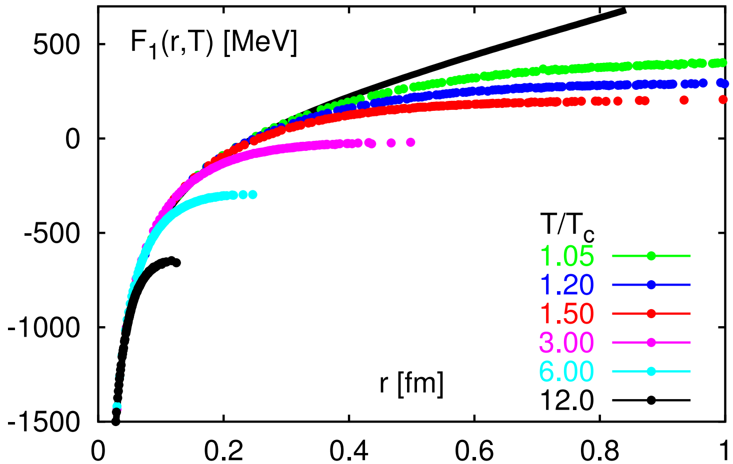

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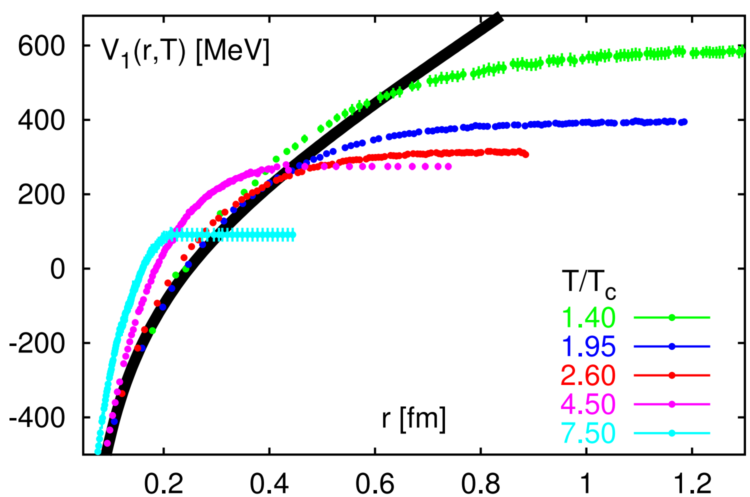

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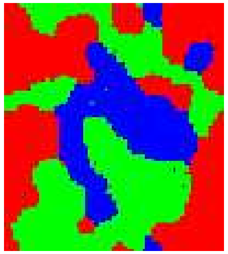
When do heavy quark bound states really disappear?

i) neither V_1 nor F_1 are "potentials"



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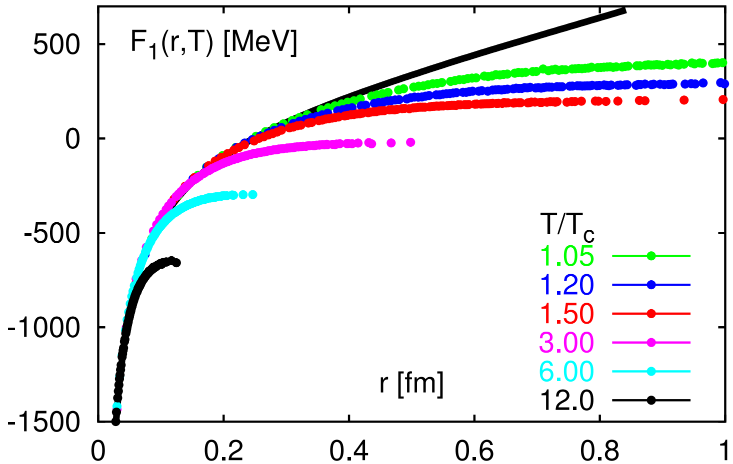

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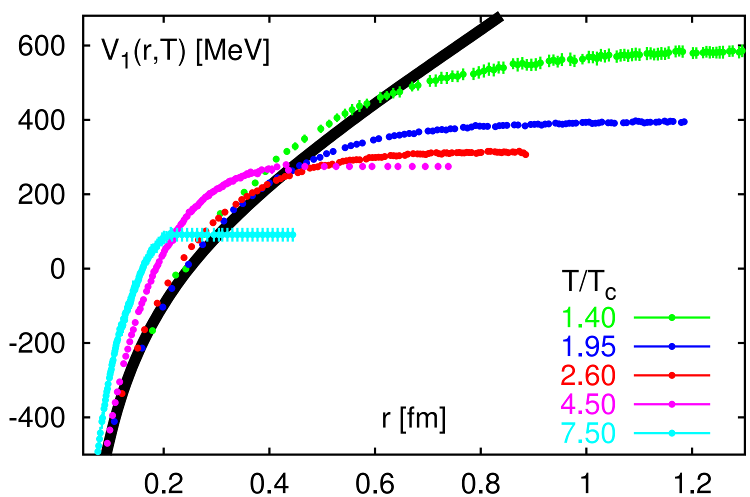

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When do heavy quark bound states really disappear?

i) neither V_1 nor F_1 are "potentials"

ii) potential models are MODELS!

Heavy quark bound states from Schrödinger-Equation

- Schrödinger equation for heavy quarks:

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

  - 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;

  using V_1: C.-Y. Wong, hep-ph/0408020;

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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	–	–

V_1 leads to dissociation temperatures consistent with spectral function analysis

Heavy quark bound states from Schrödinger-Equation

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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 dissolution: $\mathrm{d}n_{J/\psi}/\mathrm{d}t = -n_g\, \langle \sigma_{dis} \rangle$

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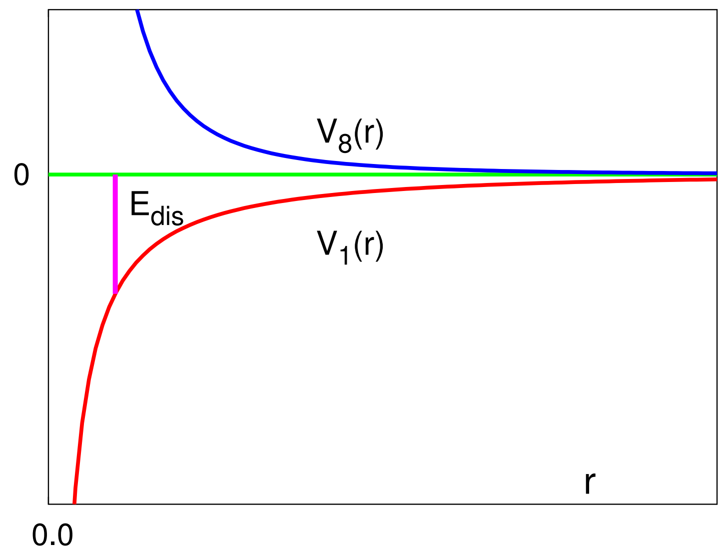

collisional dissociation

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

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

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

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

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

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Time dependence of J/ψ dissolution

- Kinetic Formation
  - dissolution and recombination may occur during cooling of the deconfined medium R.L. Thews et al, PRC63 (2001) 054905
- Statistical Hadronization

  quarkonium formation follows same statistical pattern as light quark bound states P. Braun-Munzinger, J. Stachel, PLB490 (2000) 196

  - produced $c\bar{c}$-pairs "separate" in QGP phase
  - quarkonium and open charm bound states form at freeze out according to thermal hadronization rules
- possibility for J/ψ enhancement (RHIC/LHC)

$$N_{J/\psi} \sim N_{c\bar{c}}^2$$

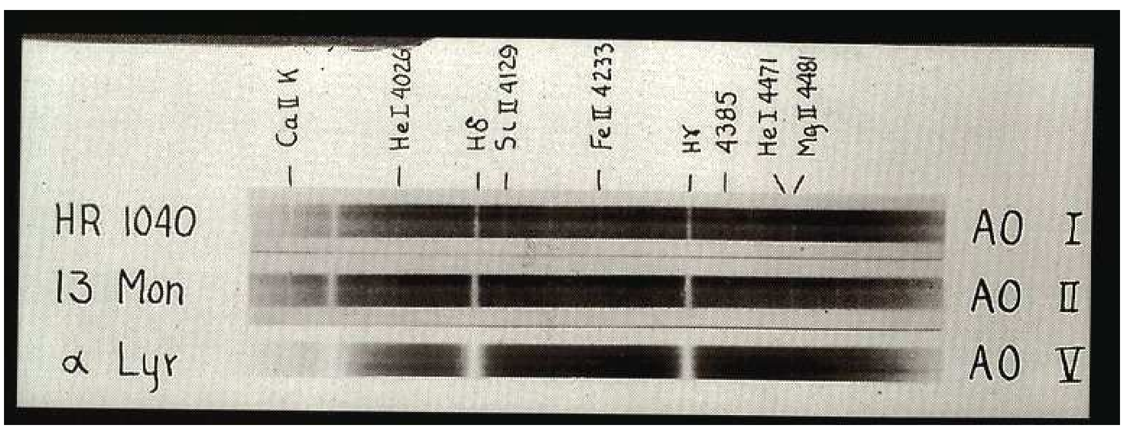
⇒ no sequential suppression pattern

⇒ thermal excitation, collision broadening (in spectral functions)

Spectral lines emitted by stars: pressure broadening

screening, collision/pressure broadening: $\Delta\lambda = \frac{\lambda^2 n\sigma}{\pi c}\left(\frac{2kT}{m}\right)^{1/2}$

- spectral functions incorporate excitation, dissolution and recombination of states
- stellar atmosphere modifies electric field of an emitting atom



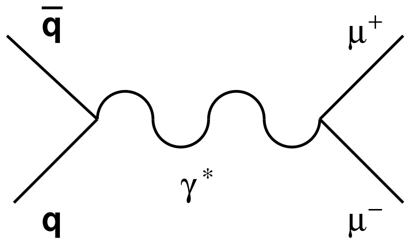
supergiant

giant

dwarf

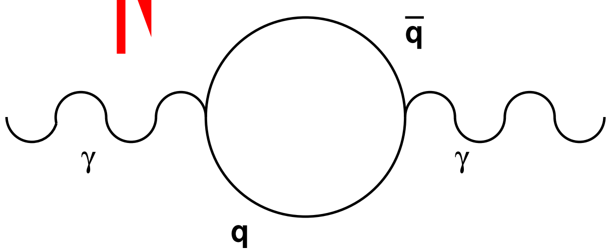
Spectral functions and Dilepton rates

Thermal dilepton rate and vector spectral function



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

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



photon self-energy

⇕

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

spectral representation of dilepton rate

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

Euclidean two-point functions: T > 0

thermal averages over states

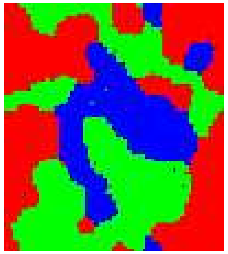
- Hamiltonian $\hat{H}$; temperature $T \equiv \beta^{-1}$;

  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

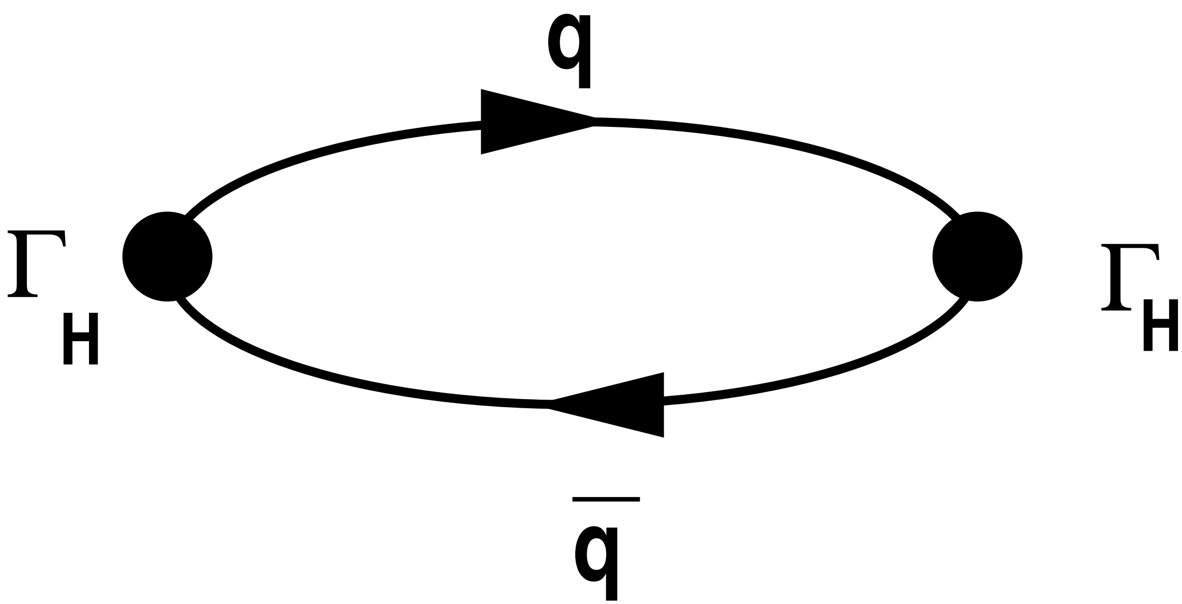
$$
\sigma_\phi(\omega, T) = \frac{2\pi}{Z(\beta)} \sum_{k,l} |\langle k|\hat{\phi}|l\rangle|^2\ \mathrm{e}^{-\beta E_k}\ \left(1 - \mathrm{e}^{-\beta\omega}\right) \delta\left(\omega - (E_k - E_l)\right)
$$



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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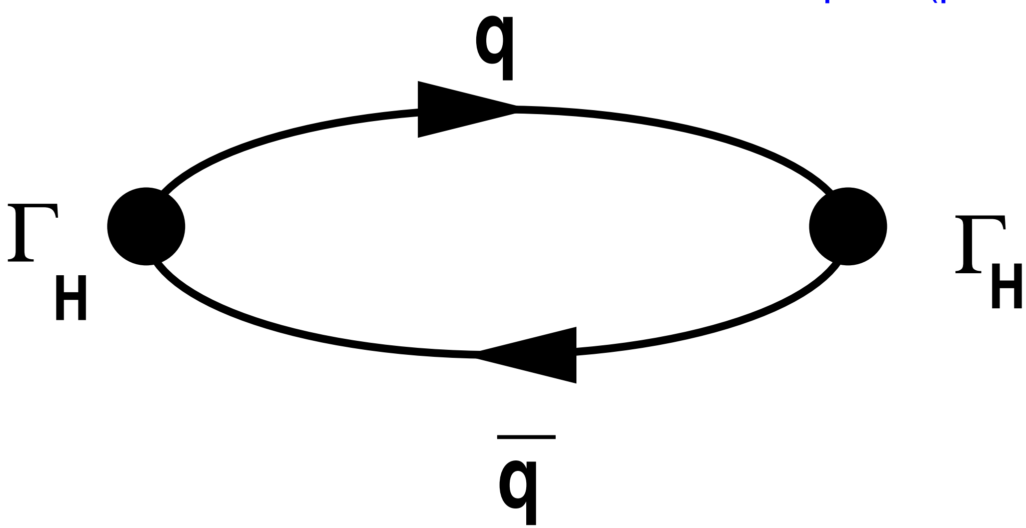

spectral representation of

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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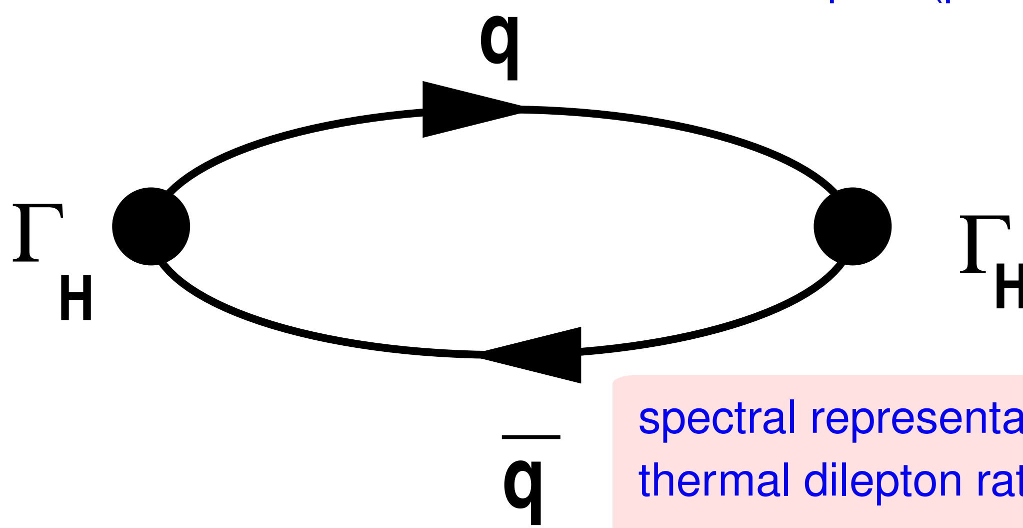

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Thermal correlation functions for hadronic excitations in QCD

thermal modifications of the hadron spectrum is encoded in finite temperature

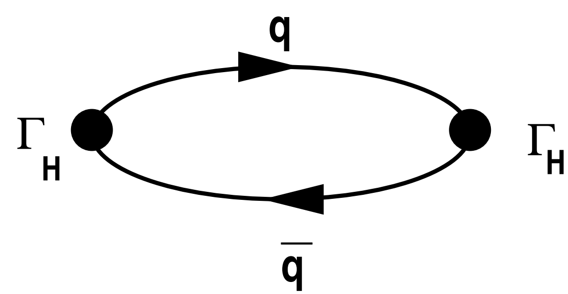
Euclidean correlation functions

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

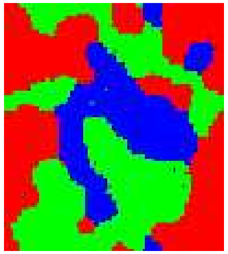
  $J_H = \bar{\psi}(\tau,\vec{r})\ \Gamma_H\ \psi(\tau,\vec{r})$

- $G_H^\beta(\tau,\vec{r}) \ \equiv\ \langle J_H(\tau,\vec{r}) J_H^\dagger(0,\vec{0})\rangle_\beta$

- quantum numbers (H) fixed through Γ_H:



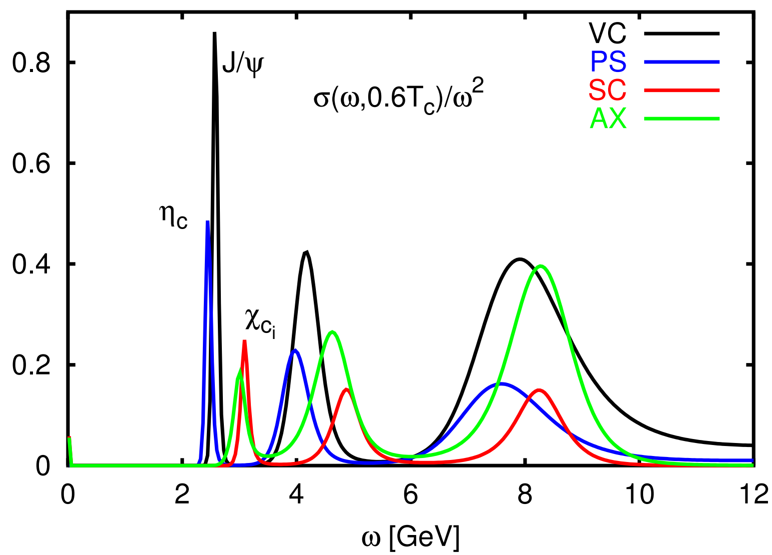
state		J^{PC}	Γ_H	(u,d)-states	$c\bar{c}$-states
scalar	$^3P_0$	0^{++}	1	σ	χ_{c0}
pseudo-scalar	$^1S_0$	0^{-+}	γ_5	π	η_c
vector	$^3S_1$	1^{--}	γ_μ	ρ	J/ψ
axial-vector	$^3P_1$	1^{++}	$\gamma_\mu\gamma_5$	δ	χ_{c1}

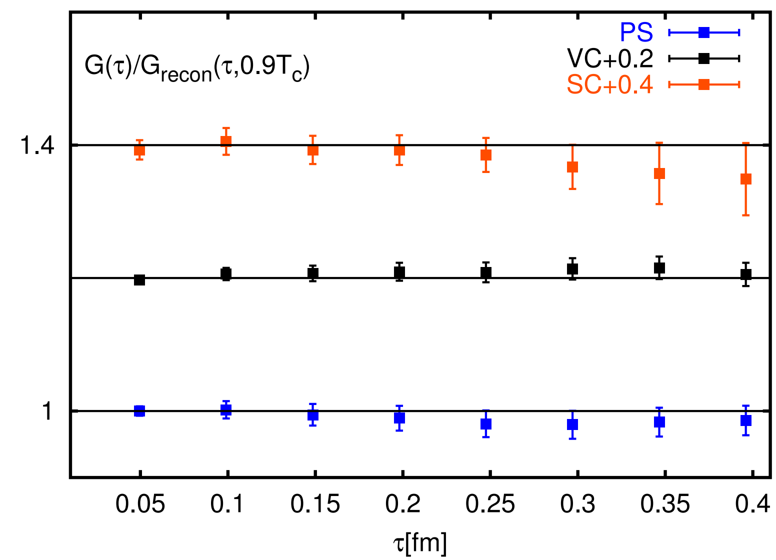


Heavy quark spectral functions and correlation functions

- left: charmonium spectral functions below T_c, *i.e.* at $T \simeq 0.6\ T_c$, lattice size $48^3 \times 24$
- right: correlation function at $T = 0.9T_c$ over reconstructed correlation function at $T \simeq 0.9\ T_c$ using the spectral function generated at $T \simeq 0.6\ T_c$, *i.e.*

$$G_{recon}(\tau, 0.9T_c) = \int \mathrm{d}\omega\ \sigma(\omega, 0.6T_c) \frac{\cosh(\omega(\tau - 1/2T))}{\sinh(\omega/2T)}$$





⇒ no significant temperature dependence below T_c

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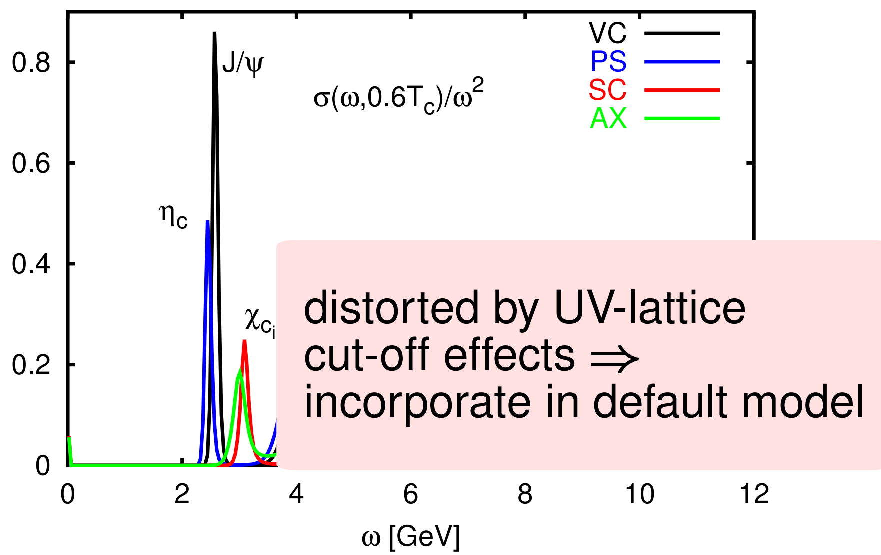
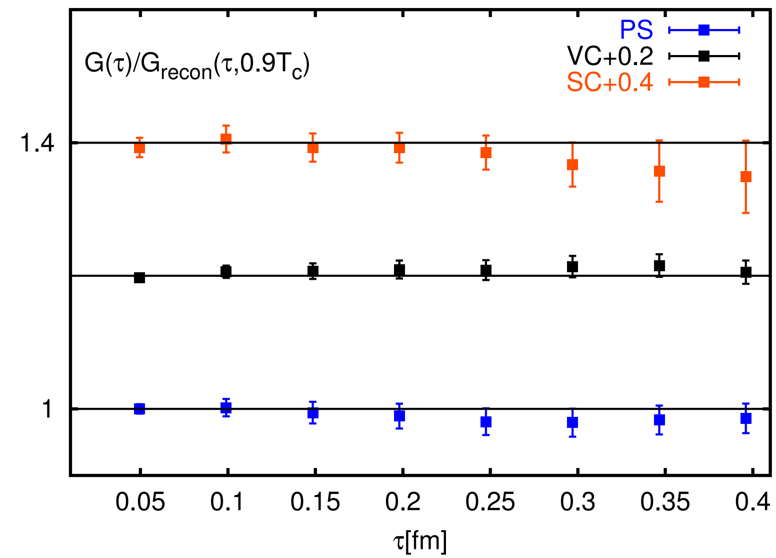


distorted by UV-lattice cut-off effects ⇒ incorporate in default model



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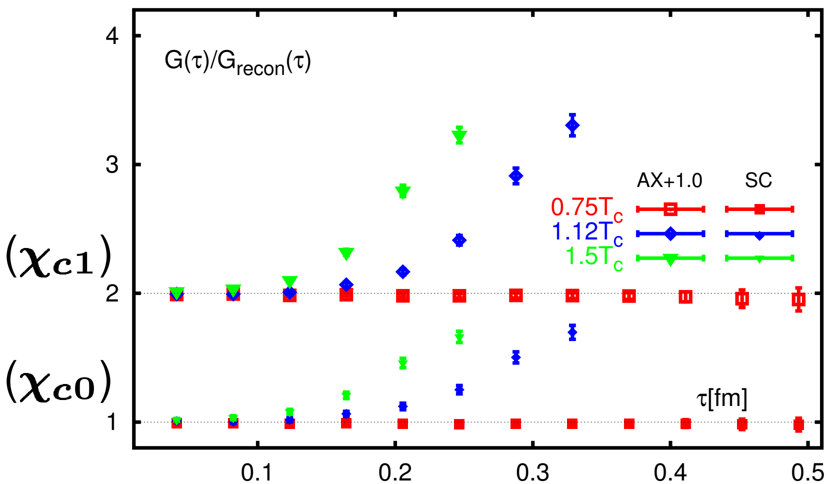
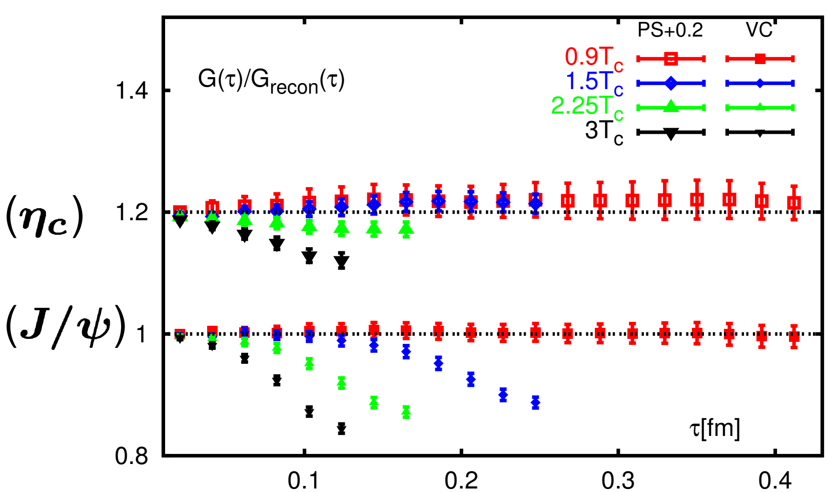
Heavy quark spectral functions and correlation functions

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



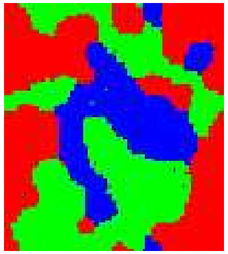
scalar and axial-vector correlation functions:

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)

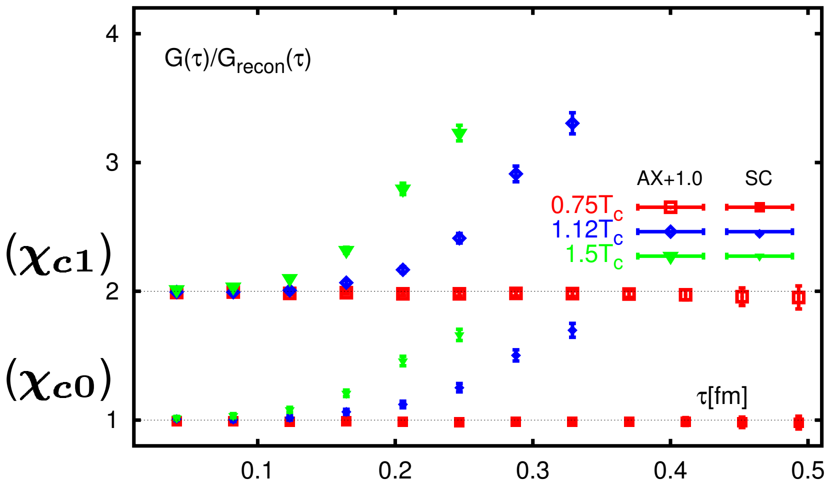


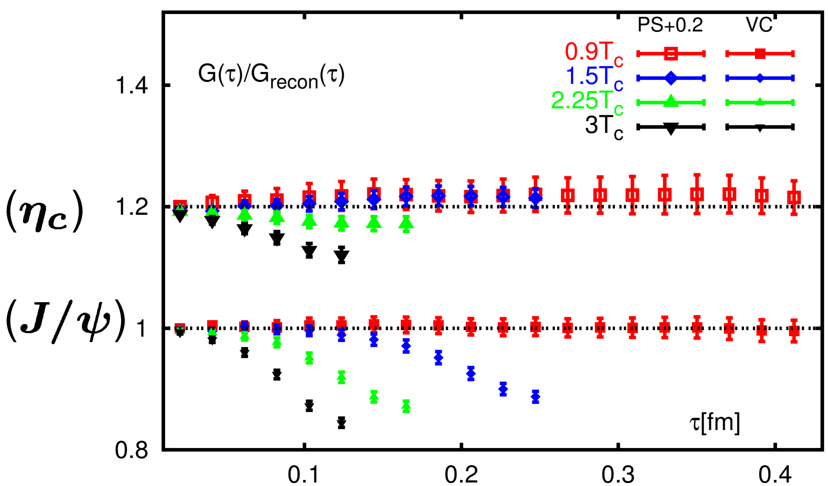
vector and pseudoscalar correlation functions:

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)



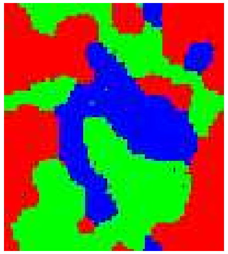
Heavy quark spectral functions and correlation functions

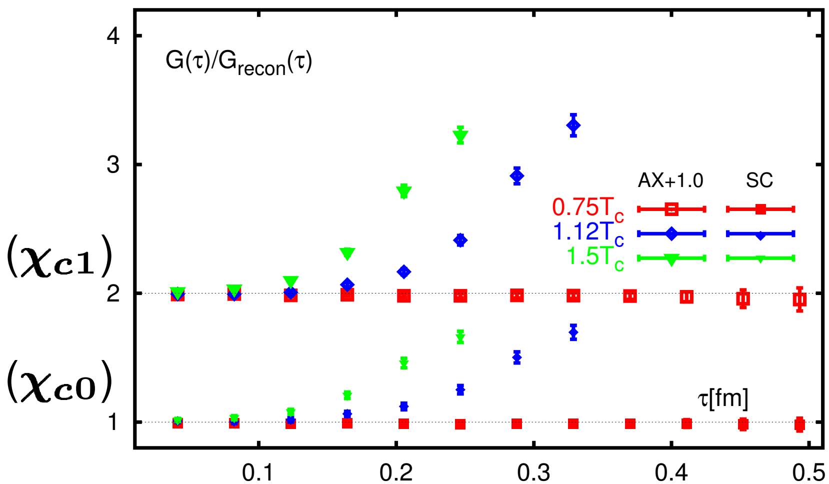


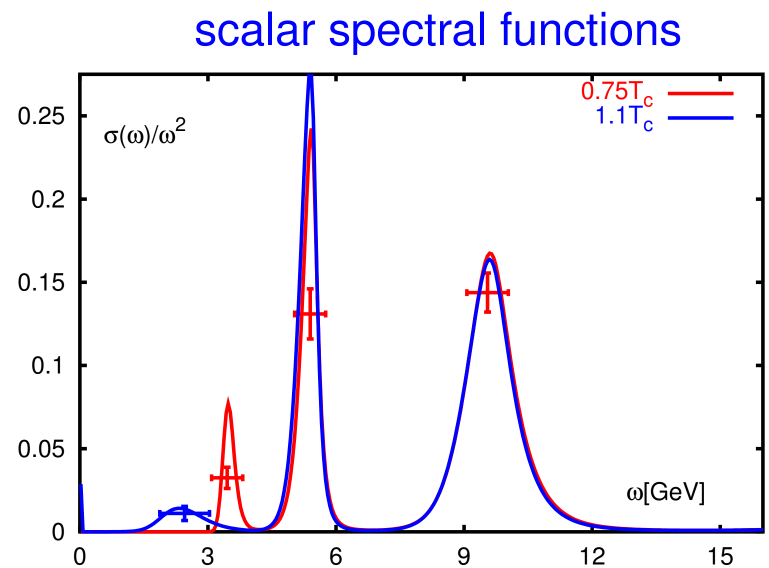


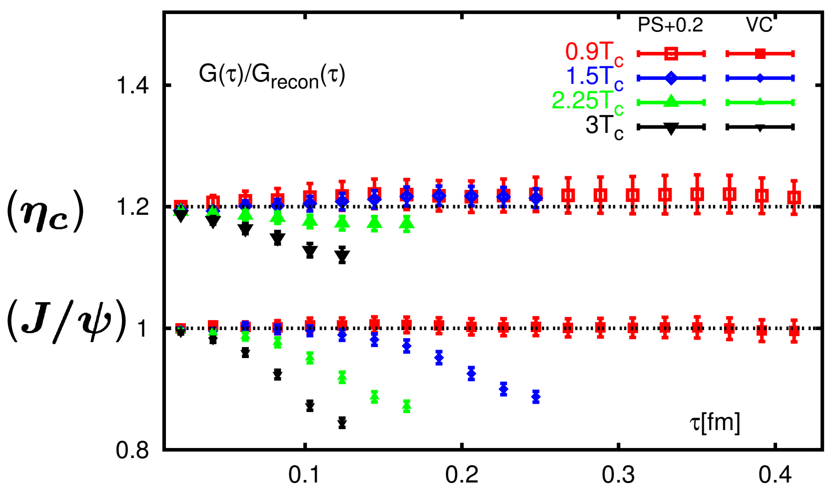
pattern seen in correlation functions also visible in spectral functions

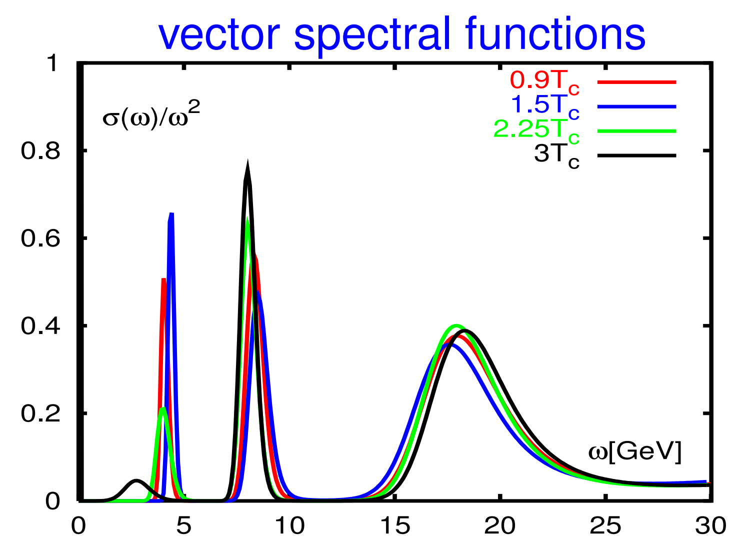
Heavy quark spectral functions and correlation functions











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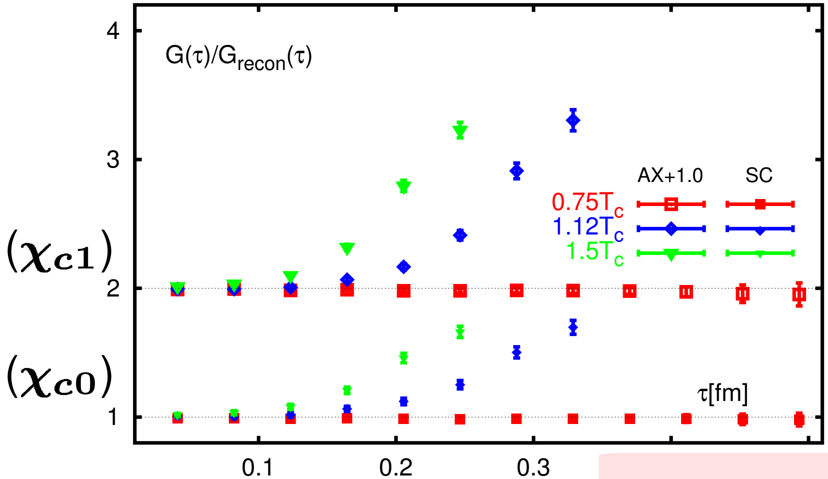
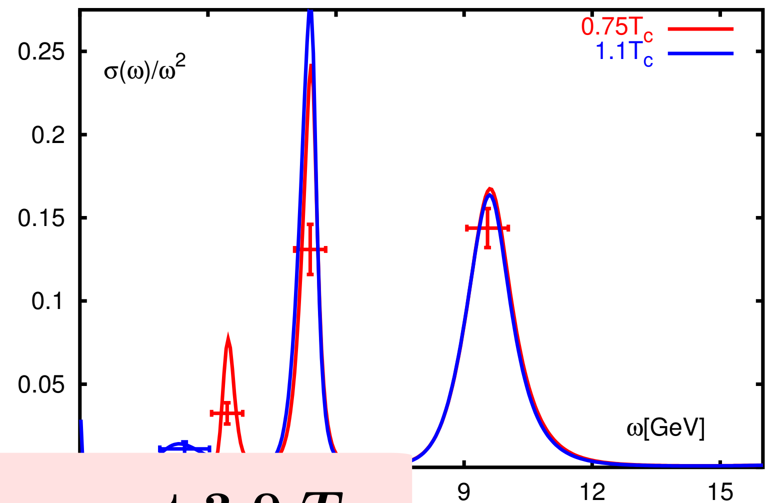
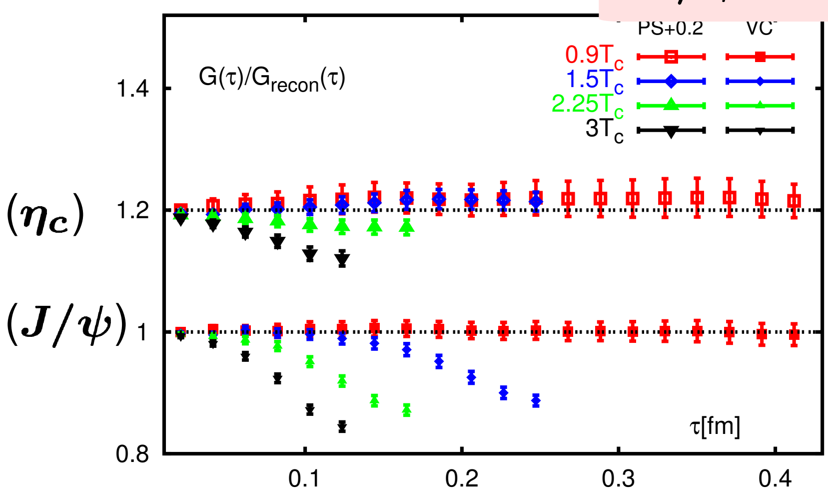


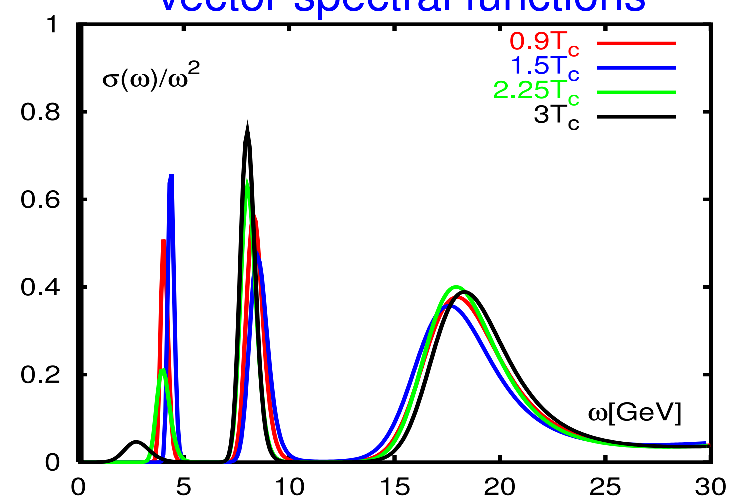
scalar spectral functions



J/ψ and η_c gone at 3.0 T_c



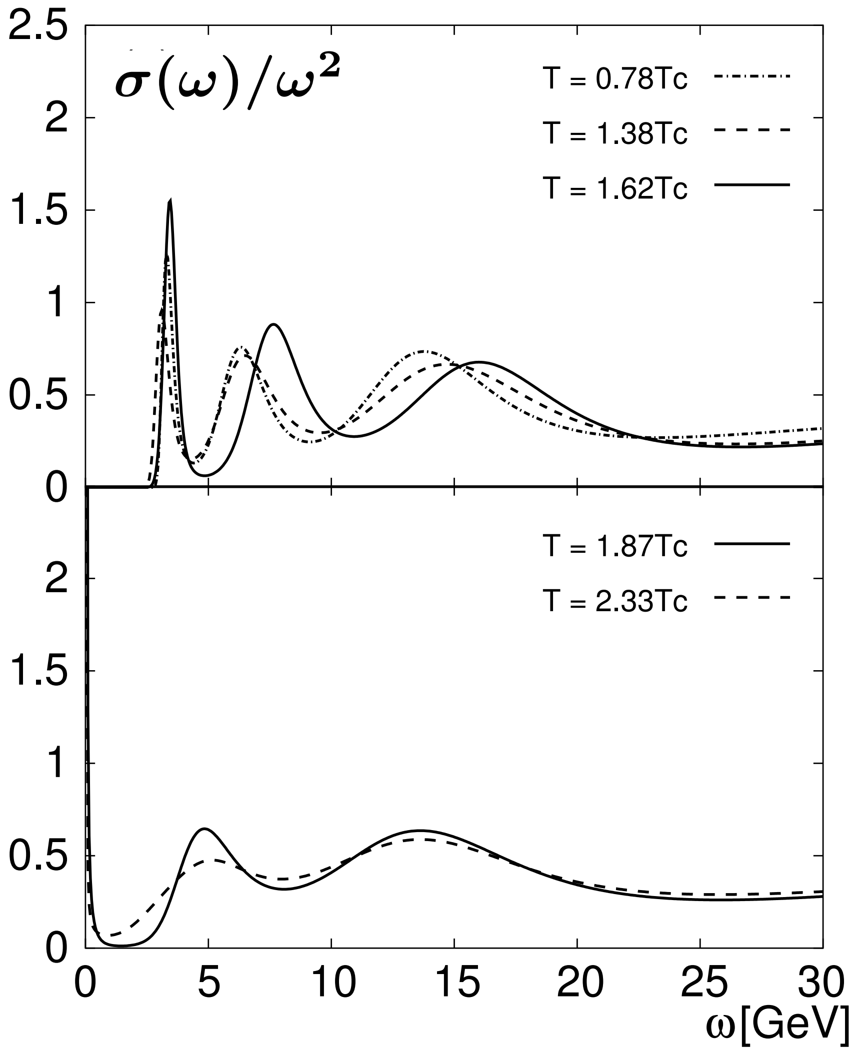
vector spectral functions



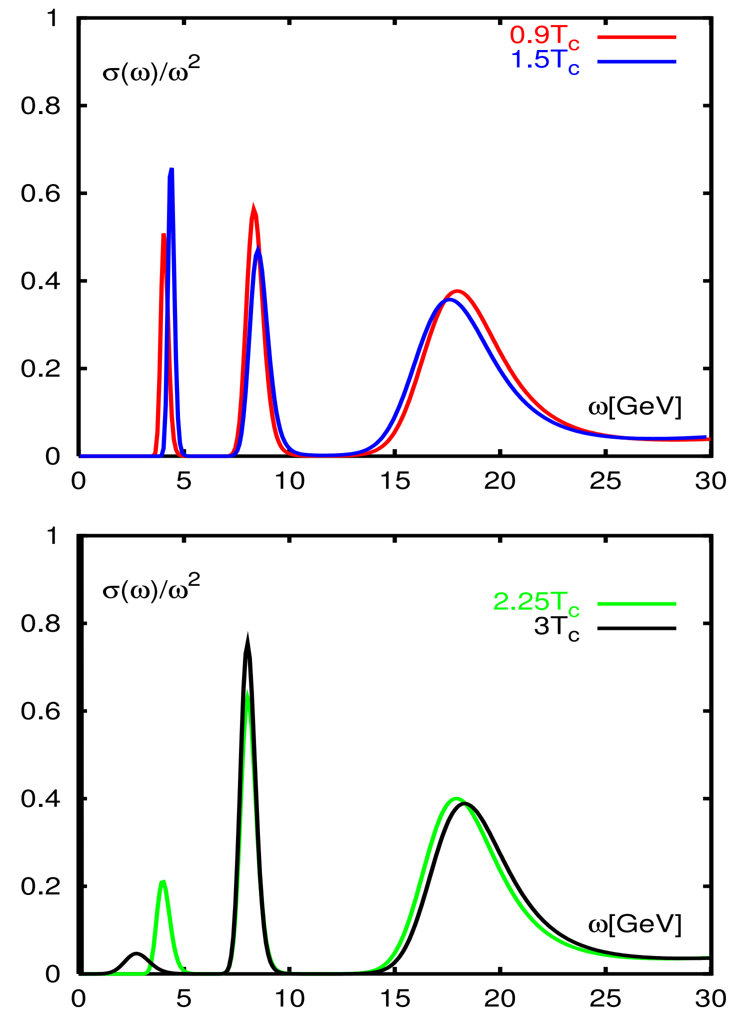
Heavy quark spectral functions
comparison of different approaches

J/ψ spectral function

M. Asakawa, T. Hatsuda, hep-lat/0308034



S. Datta et al., hep-lat/0312037



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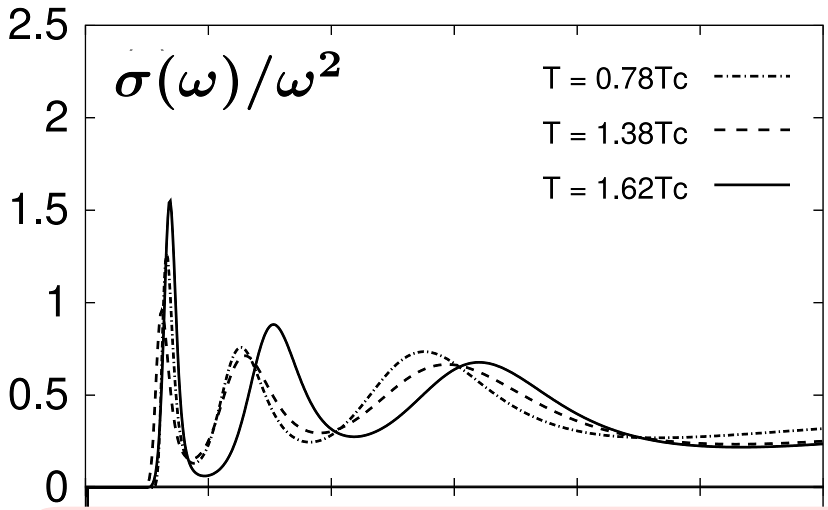
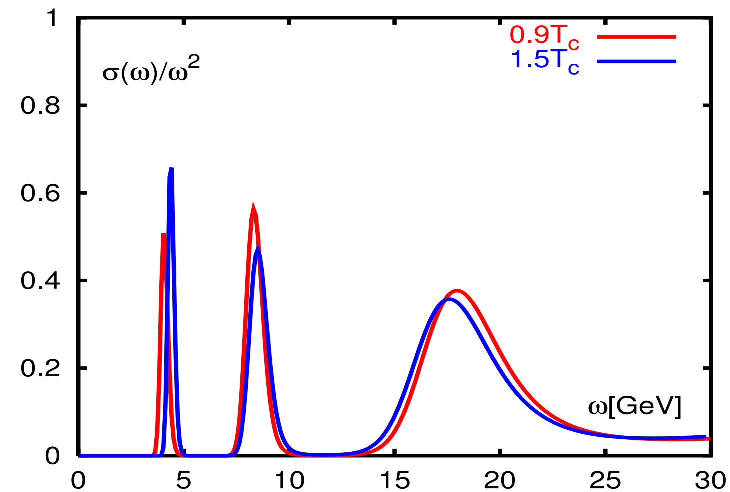
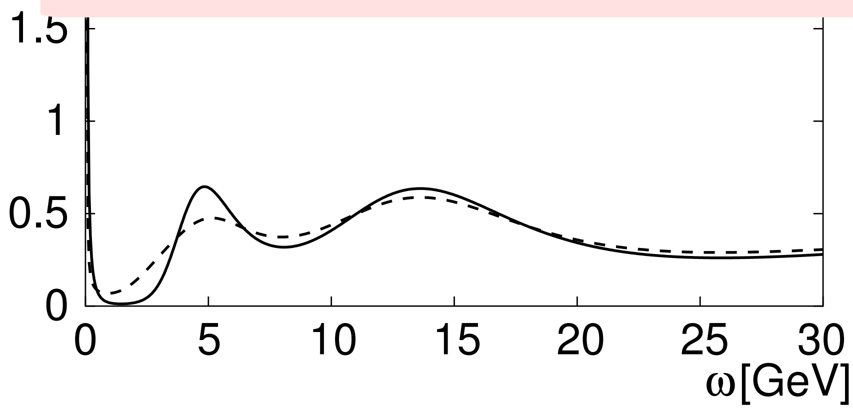
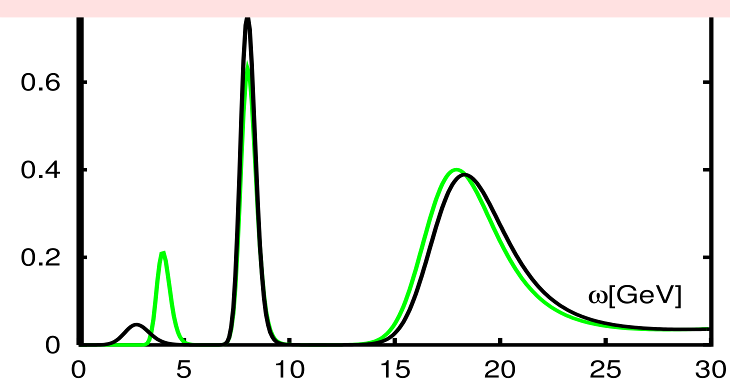


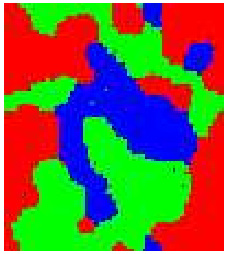


J/ψ dissociates for $1.6T_c \lesssim T \lesssim 1.9T_c$
rather abrupt disappearance of J/ψ

J/ψ gradually disappears for $T \gtrsim 1.5T_c$
J/ψ strength reduced by 25% at $T = 2.25T_c$

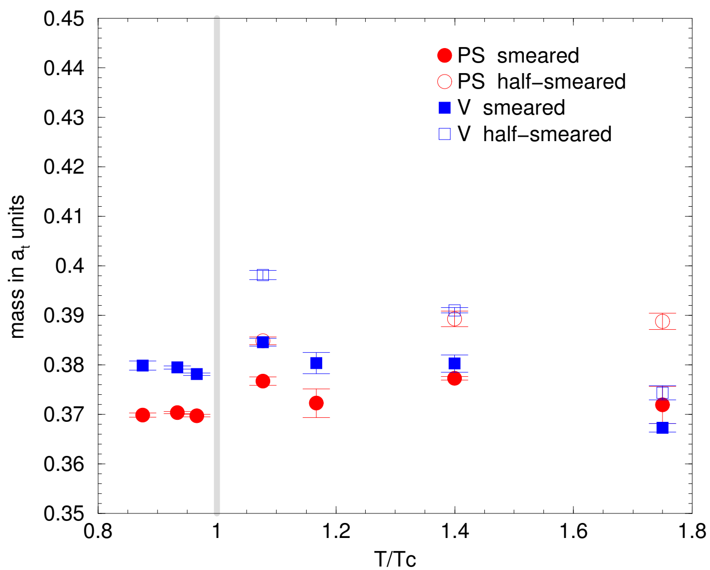


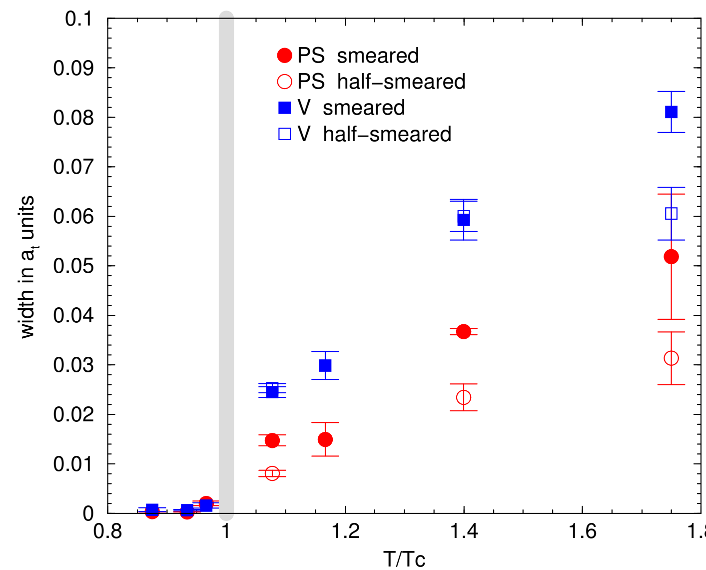




Heavy quark spectral functions
pressure broadening

- thermal broadening of charmonium spectral functions?
- no "first principle" evidence, BUT some evidence using resonance ansatz that incorporates a thermal width



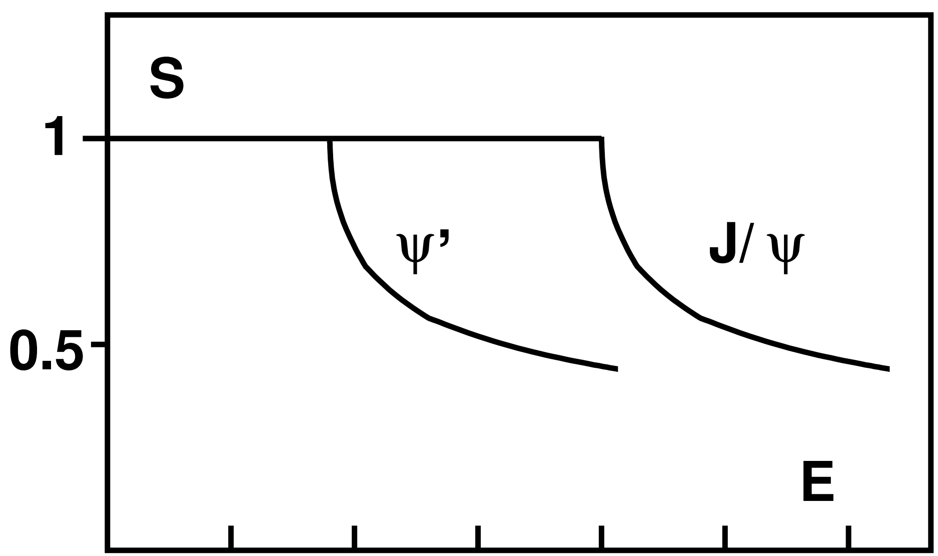


T. Umeda, Proceedings of the RIKEN-BNL workshop on Lattice QCD at finite temperature and density, BNL-72083-2004

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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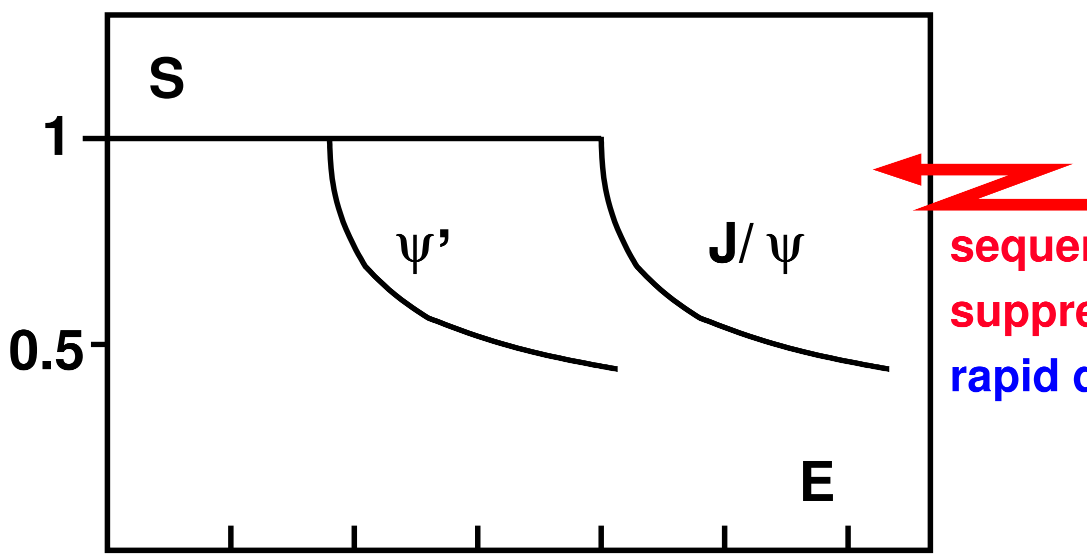

sequential suppression;
rapid drop (χ's first)

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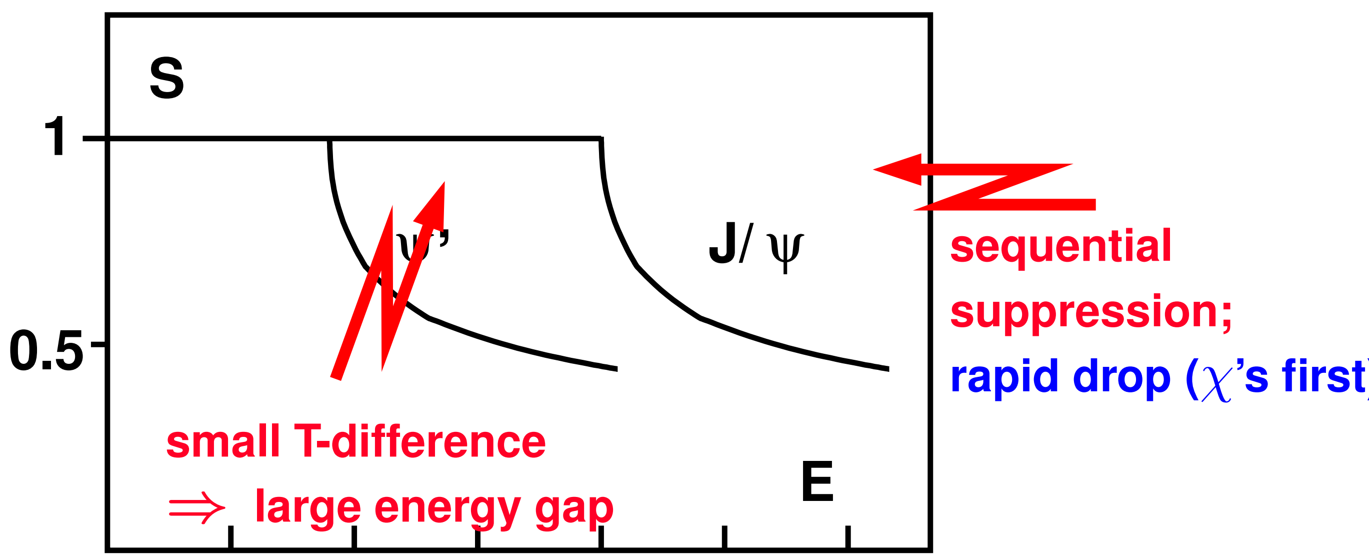


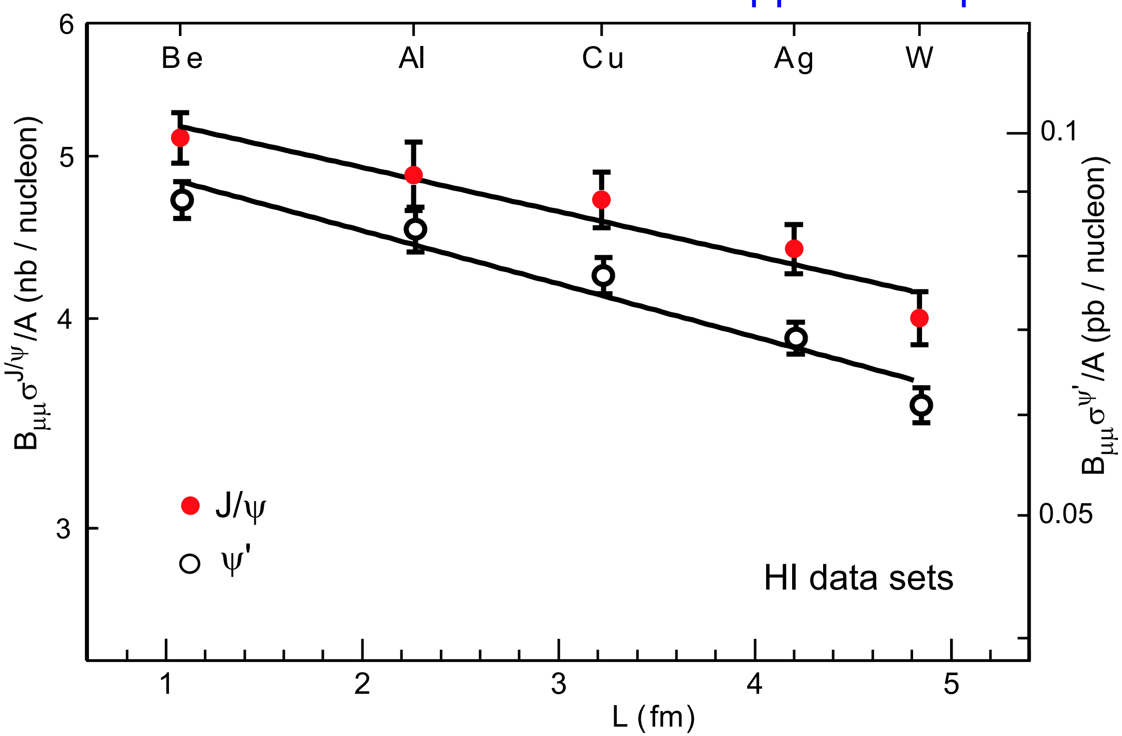
Lattice QCD and Quarkonium Suppression in HI Collisions

- ”conventional complications”: nuclear absorption
  - absorption in p-A collisions well analyzed

NA50, EPJC33 (2004) 31

$$\sigma_{pA} = \sigma_0 \cdot A \ \exp\left(-\sigma_{abs} L\right)$$

$\Rightarrow$ ”normal” suppression pattern



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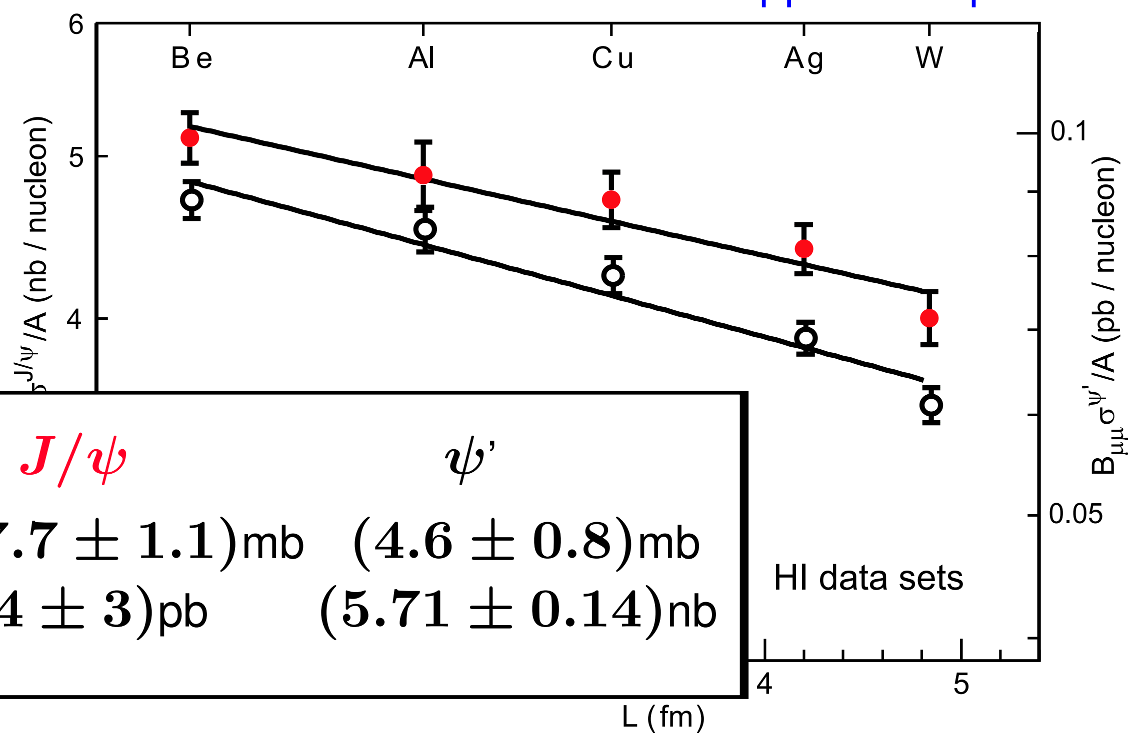


	J/ψ	ψ'
σ_{abs} =	(7.7 ± 1.1)mb	(4.6 ± 0.8)mb
σ_0 =	(104 ± 3)pb	(5.71 ± 0.14)nb

Lattice QCD and Quarkonium Suppression in HI Collisions

- Matsui-Satz: dissolved $c\bar{c}$ never recombine again;

  potential model approach suggests sequential suppression pattern

  - details depend on "potential" used in Schrödinger equation
  - generic features consistent with spectral function studies
    - J/ψ survives the deconfinement transition and melts only at

      $$T_{J/\psi}/T_c \sim (1.5 - 2.5)$$

    - ψ' and χ_c dissolve at (or close to) T_c

      $$T_{\psi'} \; < \; T_\chi \text{ and } T_\chi \gtrsim T_c \text{ ???}$$

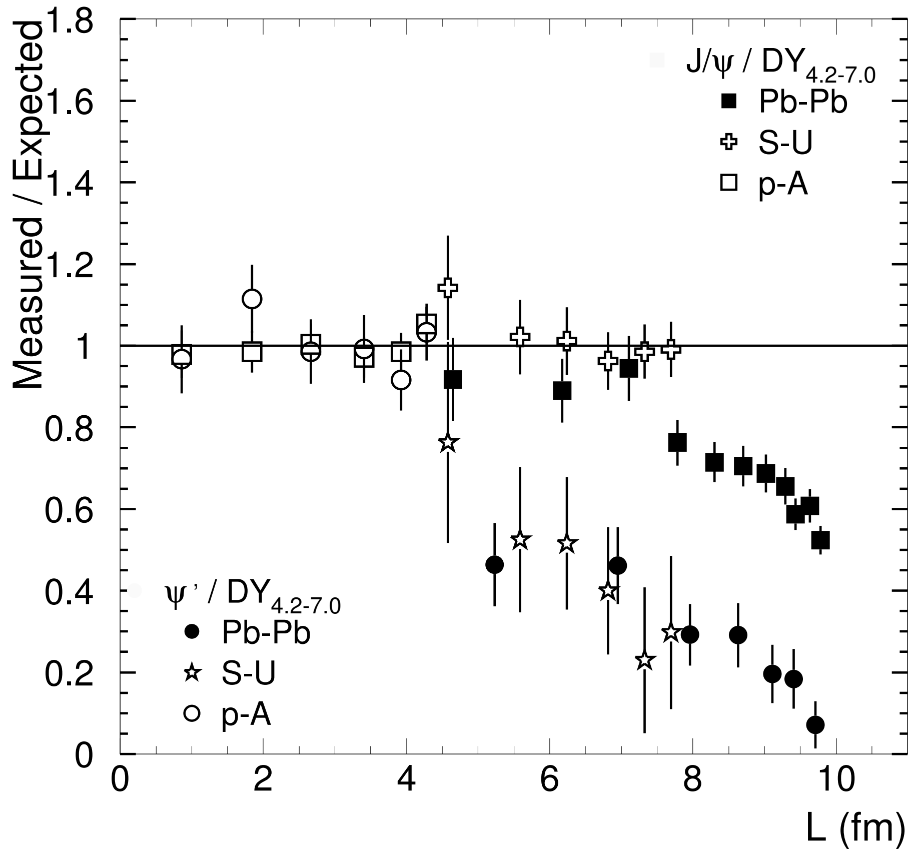
If so: small variations in dissociation temperature close to T_c will have significant effect on suppression pattern (large changes in density)

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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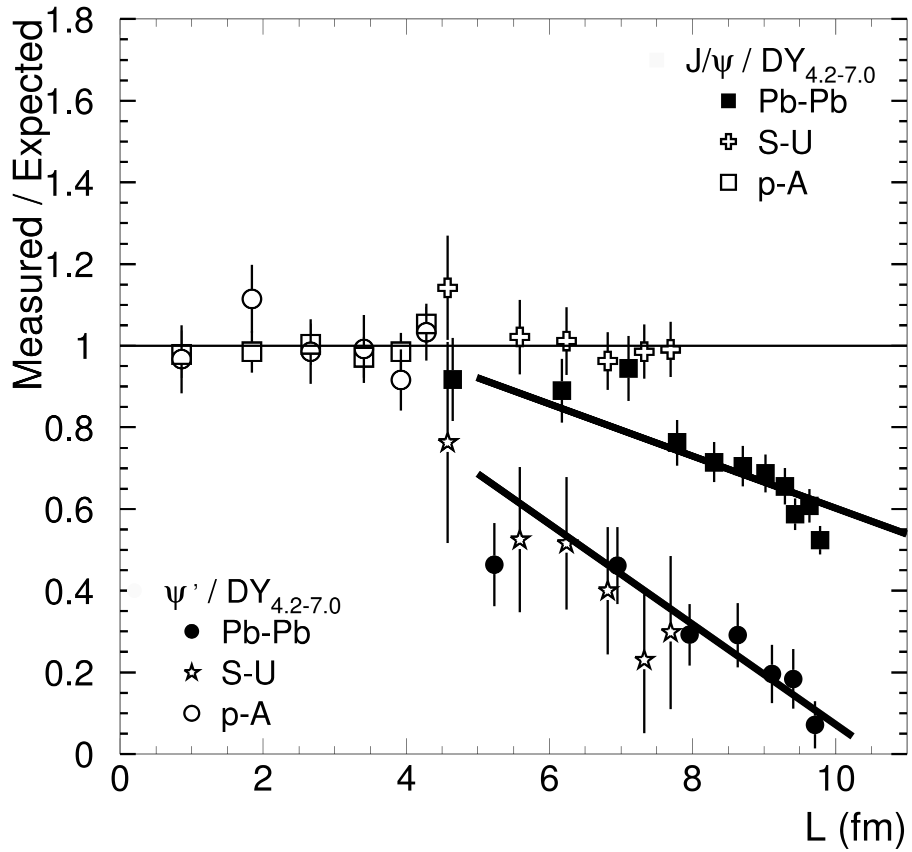

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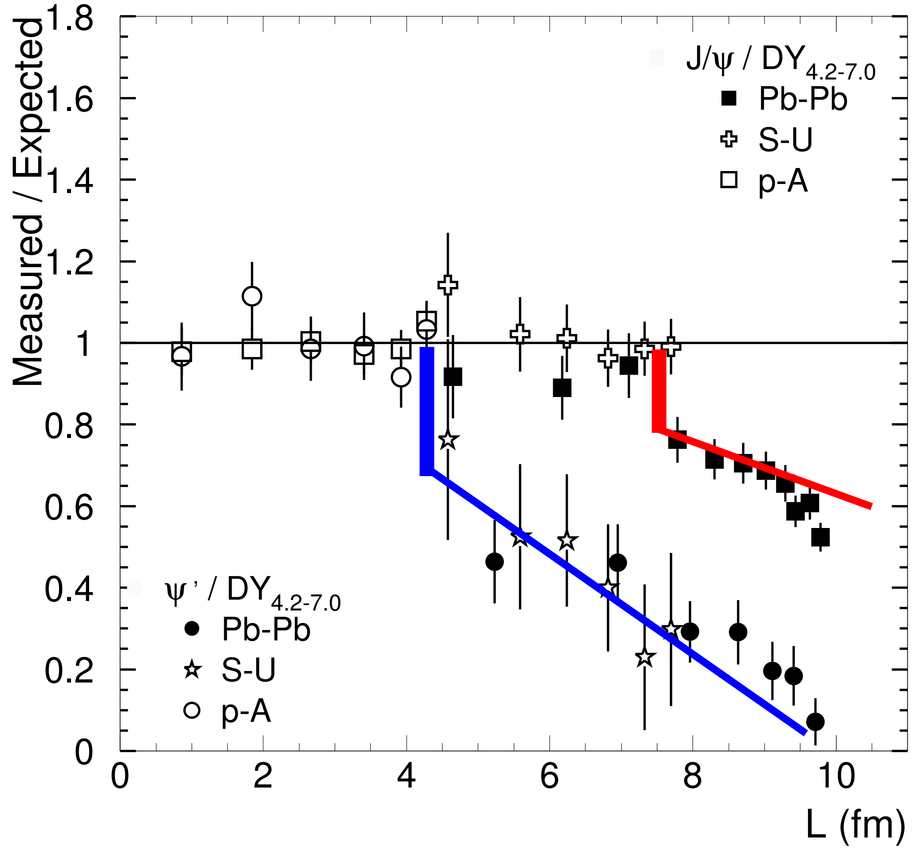

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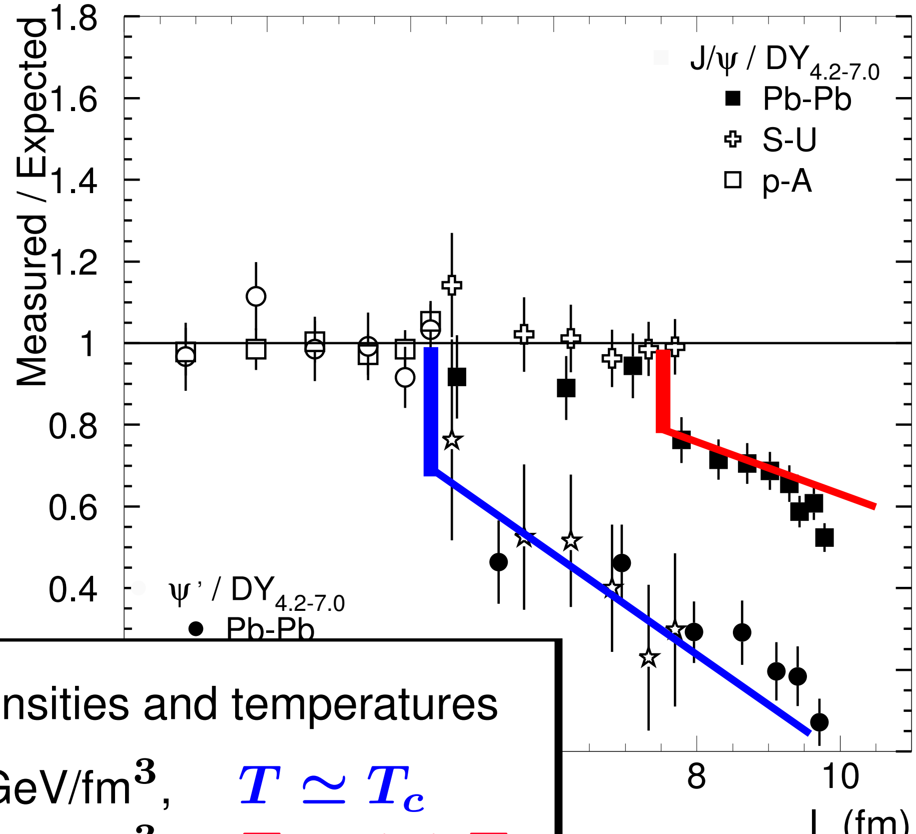

"critical" energy densities and temperatures

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

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

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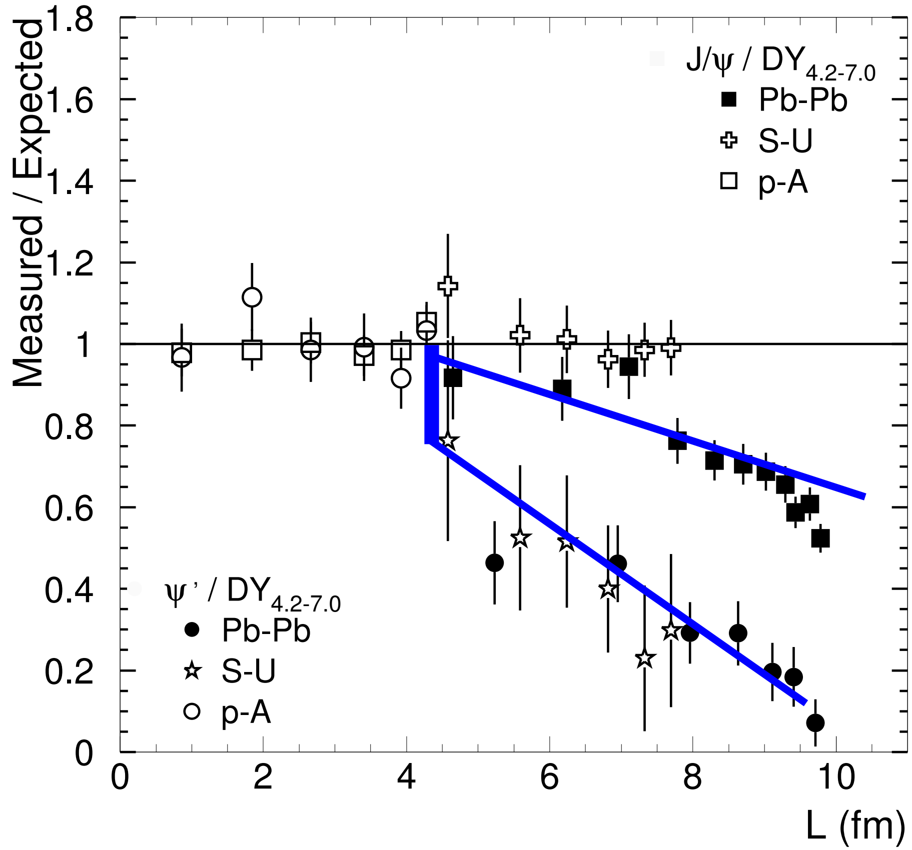

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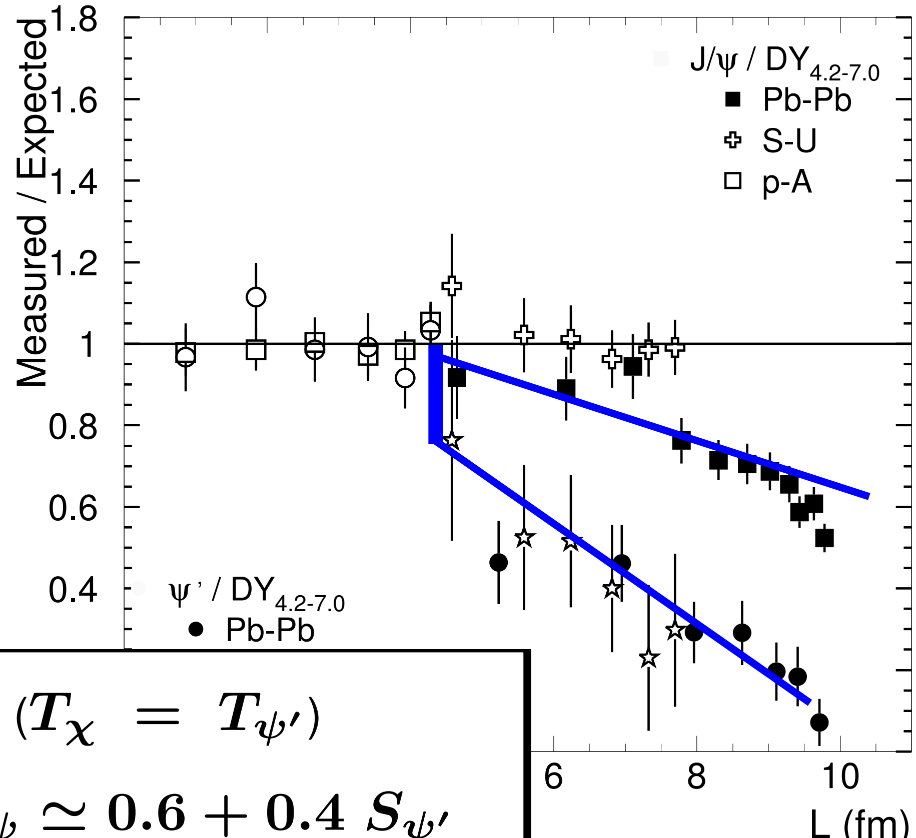
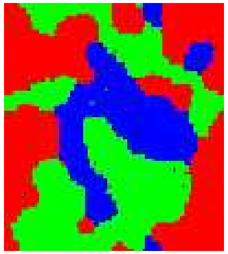


survival probability ($T_\chi = T_{\psi'}$)

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



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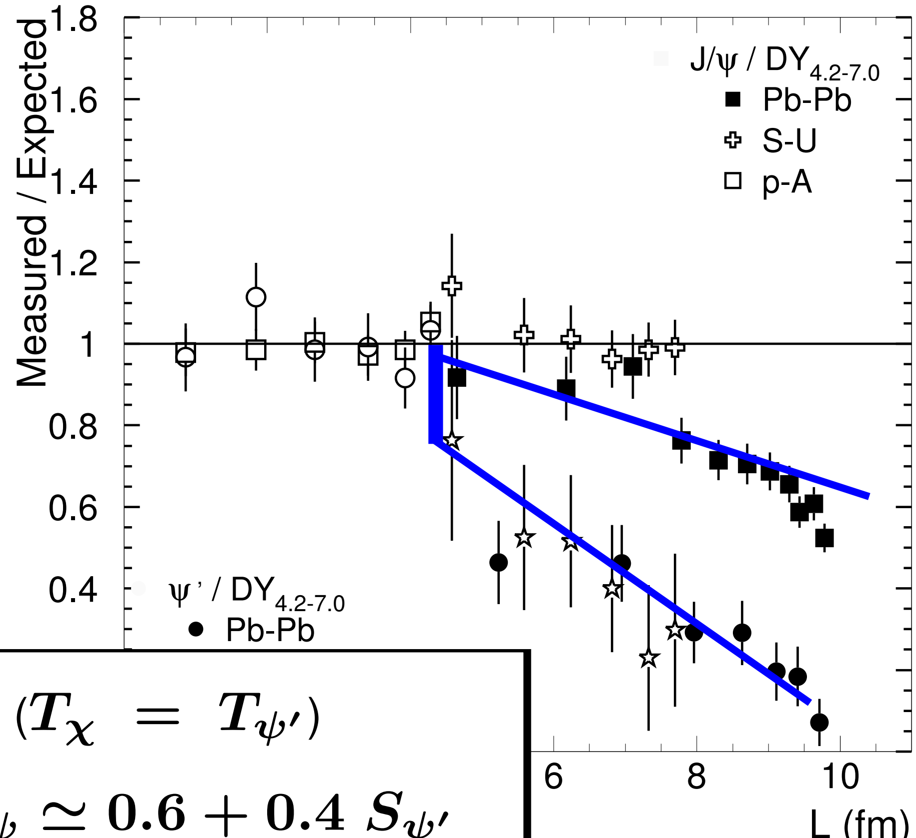

in conflict with S-U data

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

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

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

Deconfinement and Quarkonium Suppression

- Deconfinement, screening and asymptotic freedom
  - deconfinement is density driven
- Heavy quark free energies
  - screening sets in at short distances; 1/r still dominant scale
- Potential models for quarkonium
  - dissociation may spoil 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