Lecture 3:

Heavy quarks & Quarkonia

Where Do We Stand Now

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International School on

Quark Gluon Plasma and Heavy Ion Collisions

December 8-14, 2008, Torino, Italy

The menu

- Refresher from lecture 2
- Understanding lattice data
- Upgrading potential model analysis
- Lessons and the next upgrade

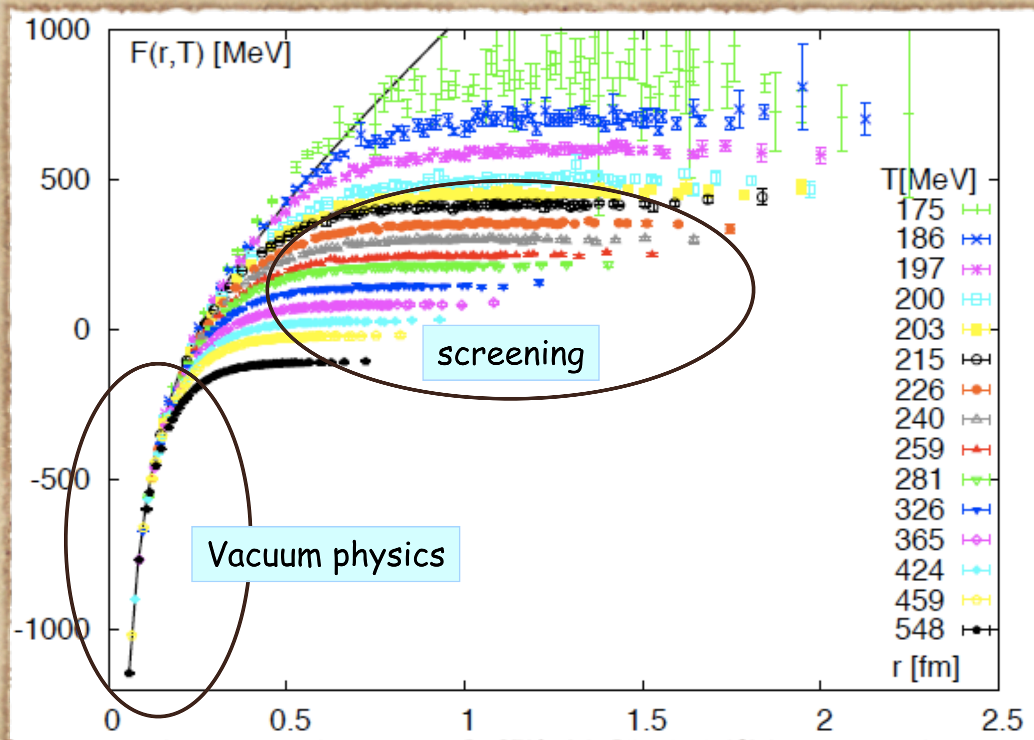
Free energy

$r > r_{scr}(T)$

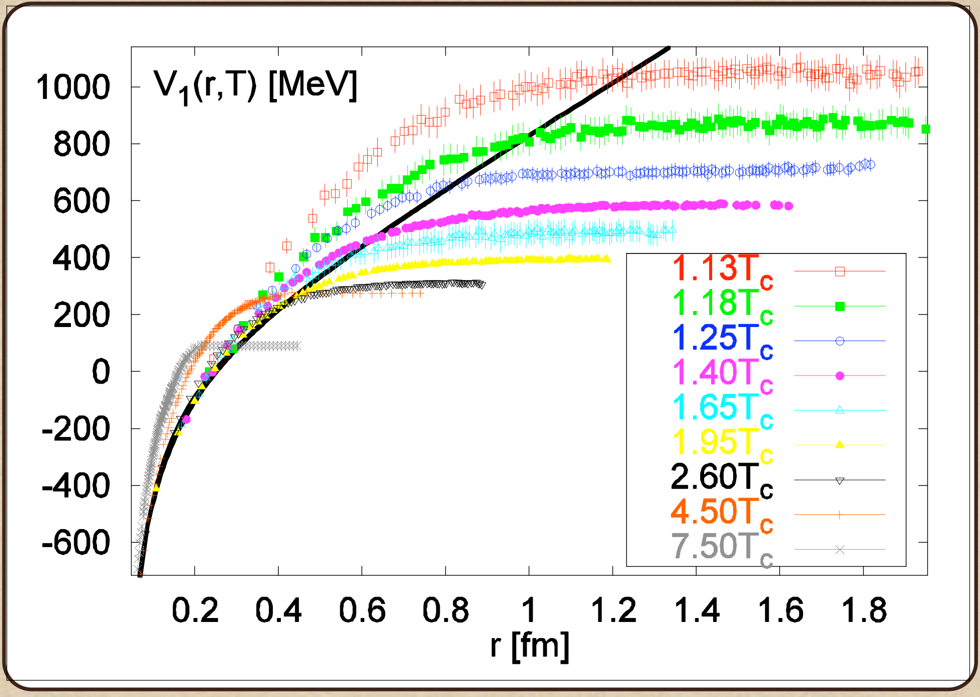
$F(r,T) \approx F(T)$

$r < r_{med}(T)$

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



Internal energy



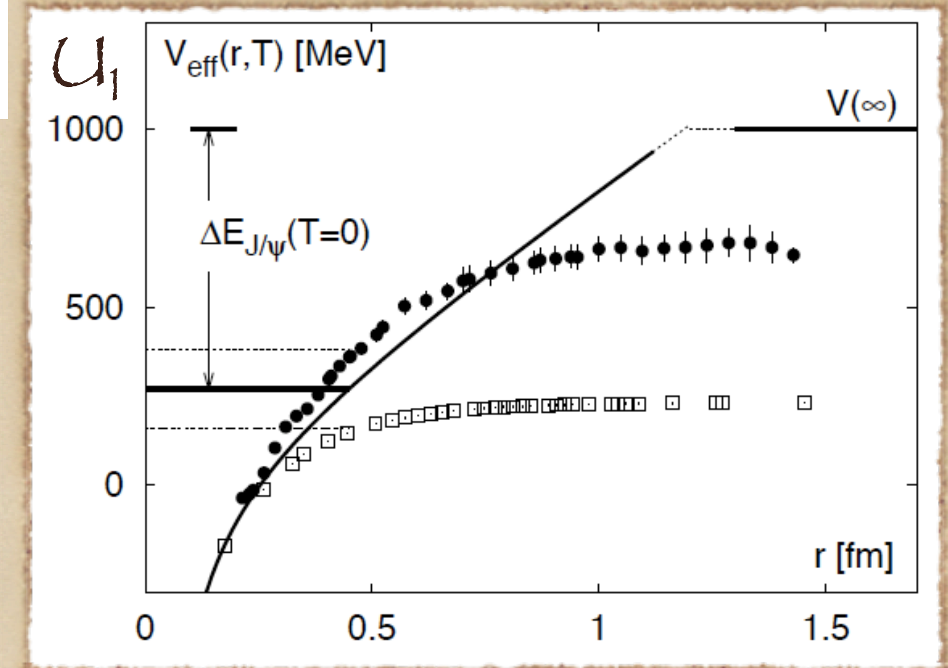
$$U_i(r,T) = T^2 \frac{\partial}{\partial T} \ln\left(\frac{Z^i_{Q\bar{Q}}(r,T)}{Z(T)}\right) = F_i(r,T) + TS_i(r,T), \quad i = 1, 8, av.$$

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

Internal energy as potential

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

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



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 $V_{eff}(r,T) = F_1(r,T)$

F_1 and U_1 is not V

So what potential should be used in the models?

Lattice spectral function

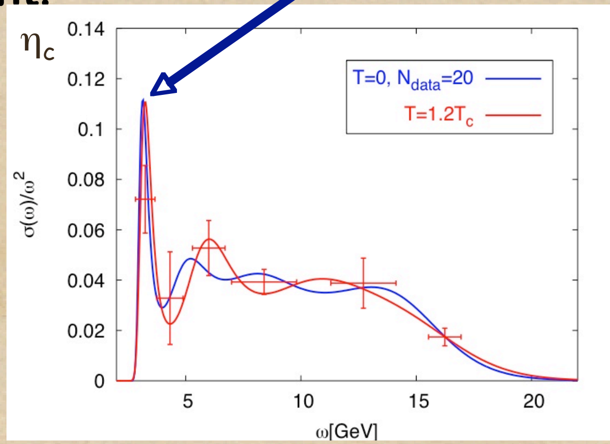
$G(\tau, \vec{p}, T)$ ➡ MEM ➡ $\sigma(\omega, \vec{p}, T)$

$$G(\tau,T) = \int_0^\infty d\omega \sigma(\omega,T) \frac{\cosh(\omega(\tau - 1/(2T))}{\sinh(\omega/(2T))}$$

- **Shows no large T-dependence**
- **Peak has been commonly interpreted as ground state**
- **Uncertainties are significant!**

limited # data points
limited extent in tau
systematic effects
prior-dependence

Details cannot be resolved.



Jakovac et al, PRD (2007)

"..it is difficult to make any conclusive statement based on the shape of the spectral functions ... "

Jakovác et al PRD (2007)

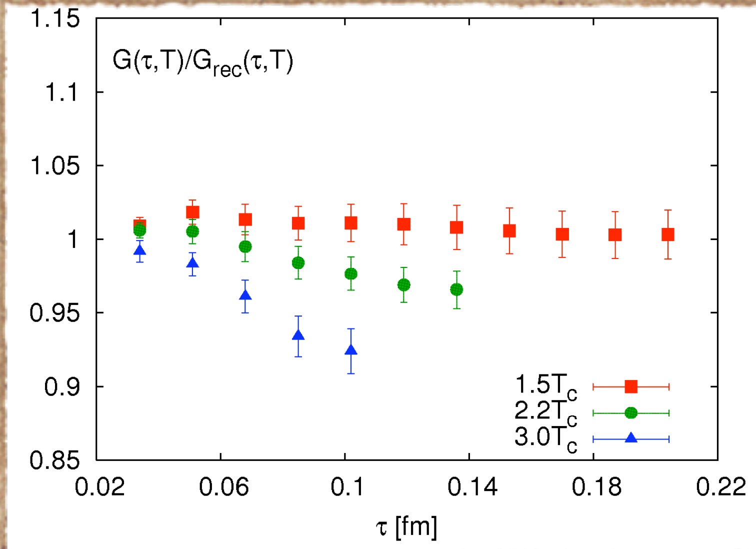
Analyze correlator ratio

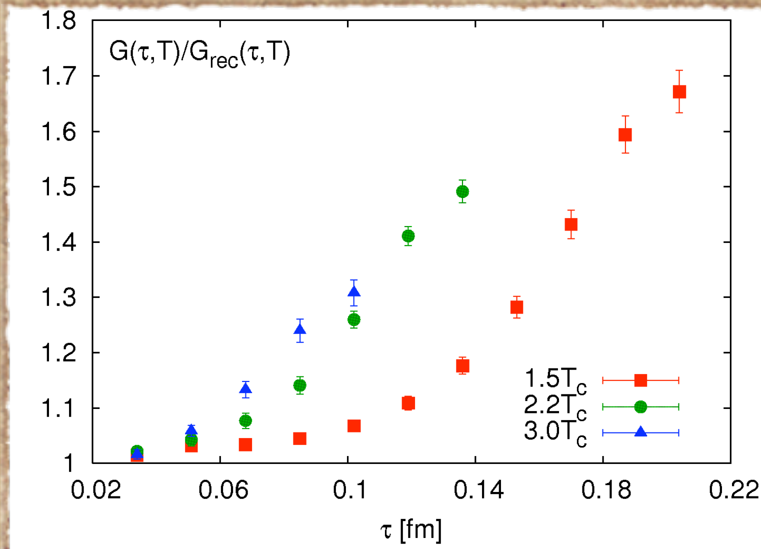
$$\frac{G(\tau,T) = \int \sigma(\omega,T)K(\tau,\omega,T)d\omega}{G_{rec}(\tau,T) = \int \sigma(\omega,T=0)K(\tau,\omega,T)d\omega}$$

Initial interpretation

- $G/G_{rec} \approx 1$ means spectral function unchanged, state survives
- $G/G_{rec} \neq 1$ means spectral function modified, state dissociated

Charmonium correlators





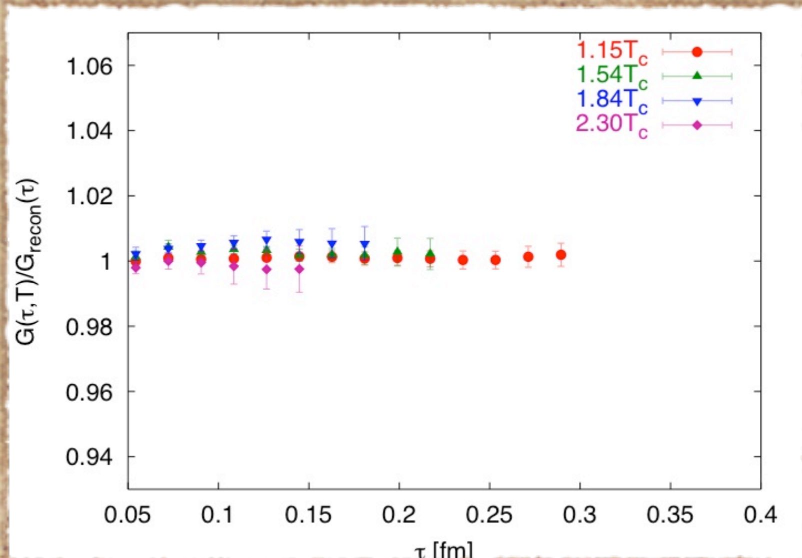
Jakovac et al, PRD 75 (2007)

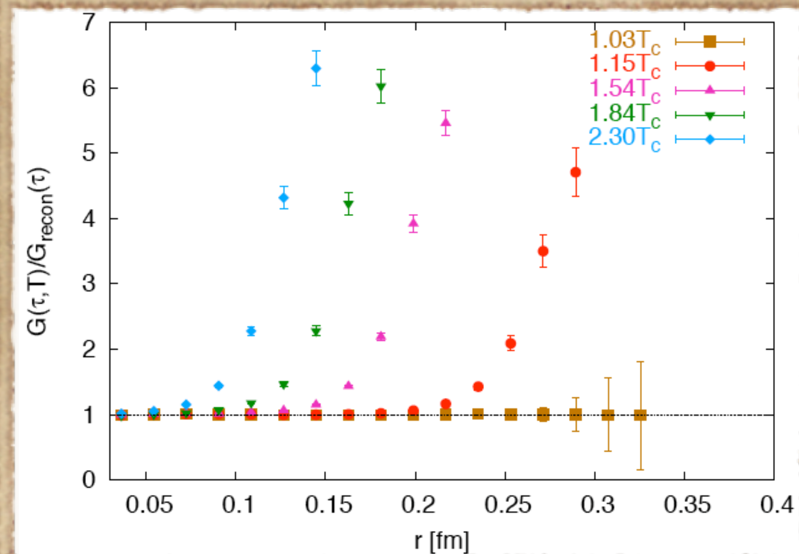
Initial interpretation **$J/\psi(\eta_c)$ survives up to 1.5-2T_c AND χ_c melts by 1.1 T_c**

Seemingly in agreement with spectral function interpretation.

2004: "J/ψ melting" replaced by "J/ψ survival"

Bottomonium correlators





Jakovac et al, PRD 75 (2007)

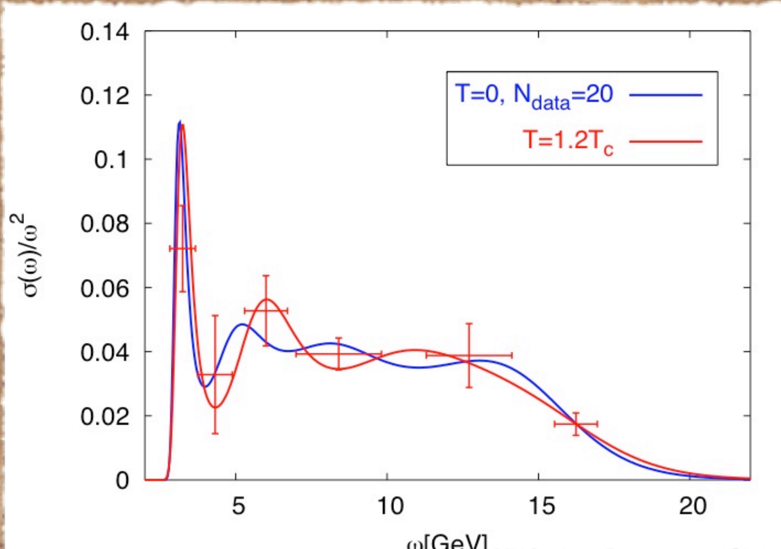
Initial interpretation

Υ and η_b survive well above $2T_c$

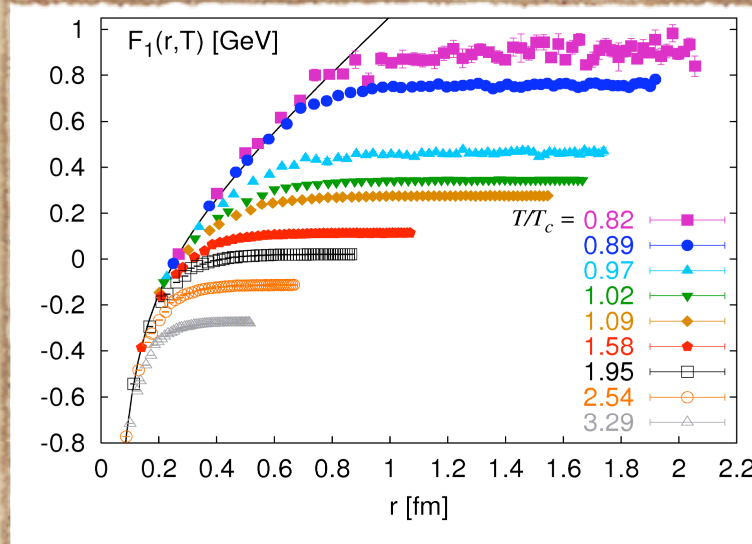
χ_b melts by 1.1 T_c

Why is the chib so different than the Jpsi, when their sizes are about the same?

Could the J/Ψ survive unaffected in the QGP until well above T_c even if there is strong screening in the plasma?



Jakovac et al, PRD 75 (2007)



Kaczmarek et al, PRD 70 (2004)

So what can we make of all this? Can we learn anything? Can we reconcile all the info?

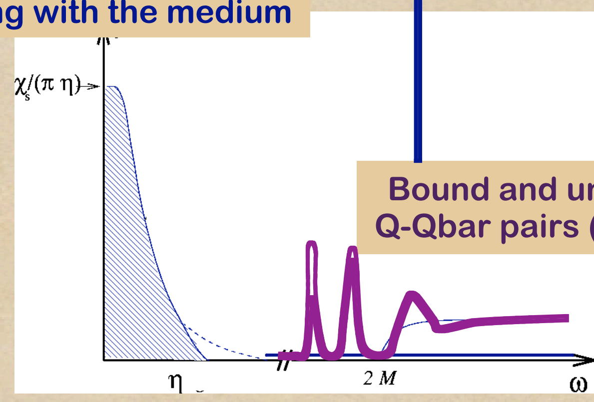
Recently: zero-modes

Low frequency contribution to spectral function at finite T,
scattering states of single heavy quarks (commonly overlooked)

$$\sigma(\omega,T) = T\chi_s(T)\omega\delta(\omega) + \sigma^{high}(\omega,T)$$

Quasi-free heavy quarks interacting with the medium

Bound and unbound Q-Qbar pairs ($\omega > 2m_Q$)

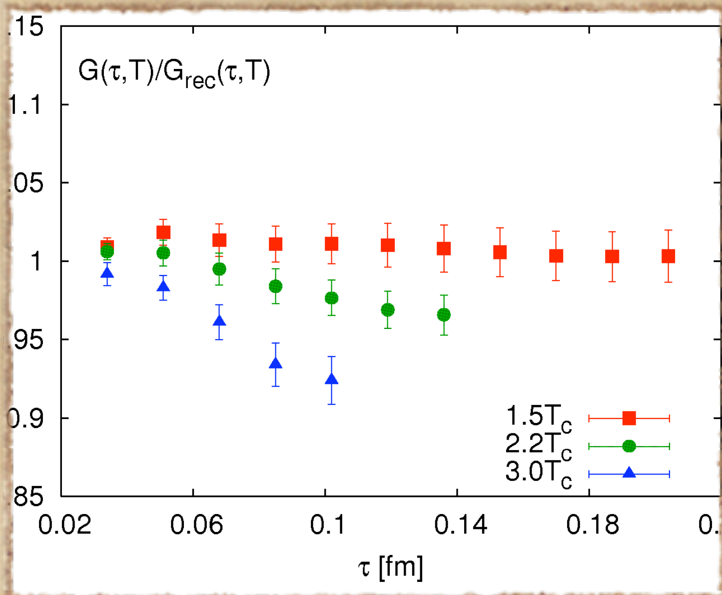


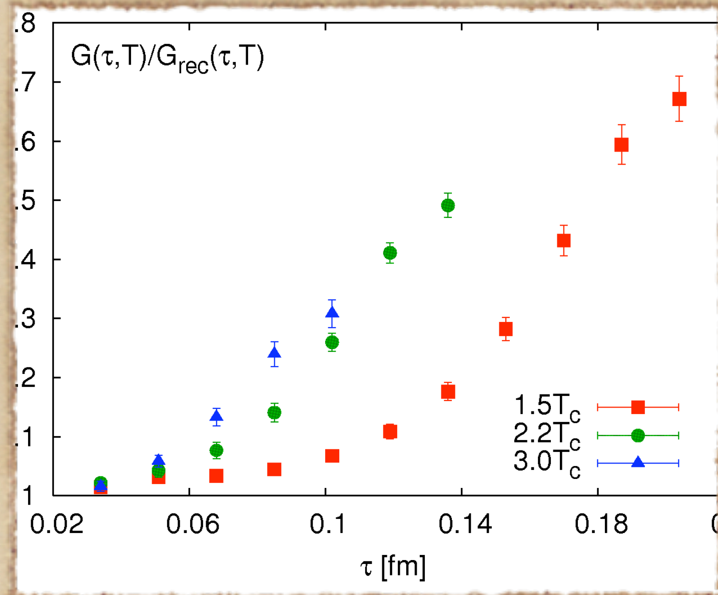
Gives constant contribution to correlator =>> Look at derivatives

Umeda, PRD 75 (2007)

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

Correlators

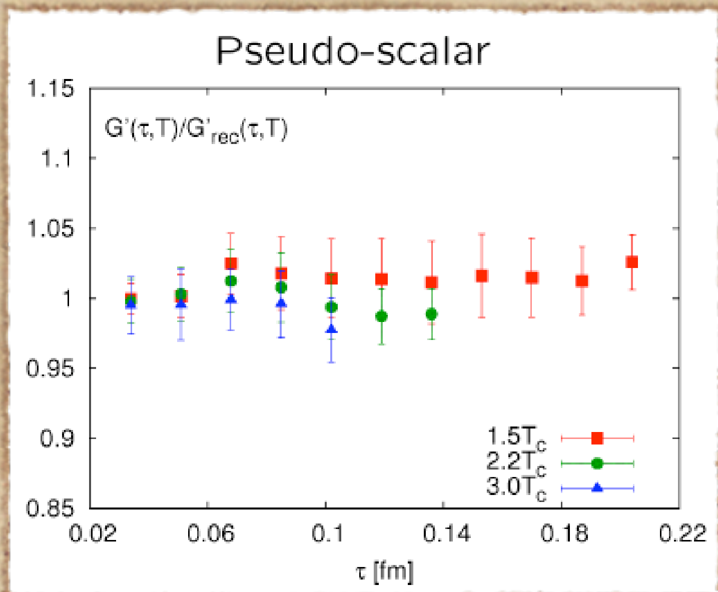


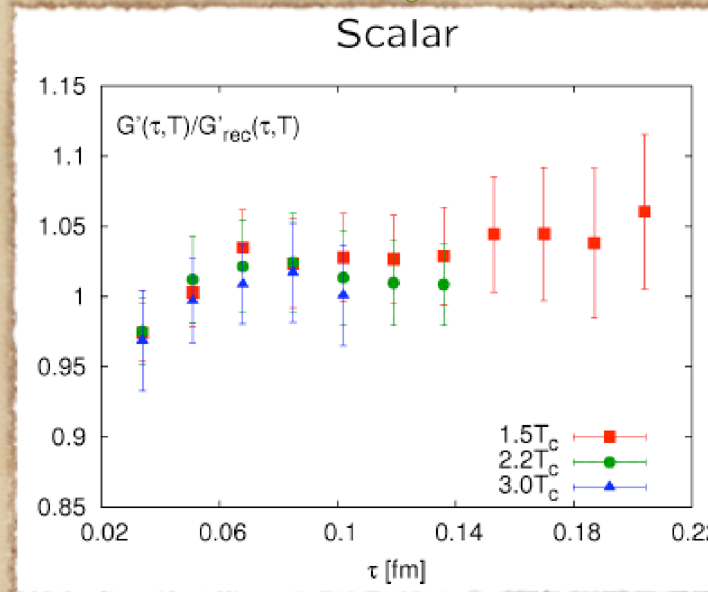


Datta et al, PRD 69 (2004)

Correlator derivatives

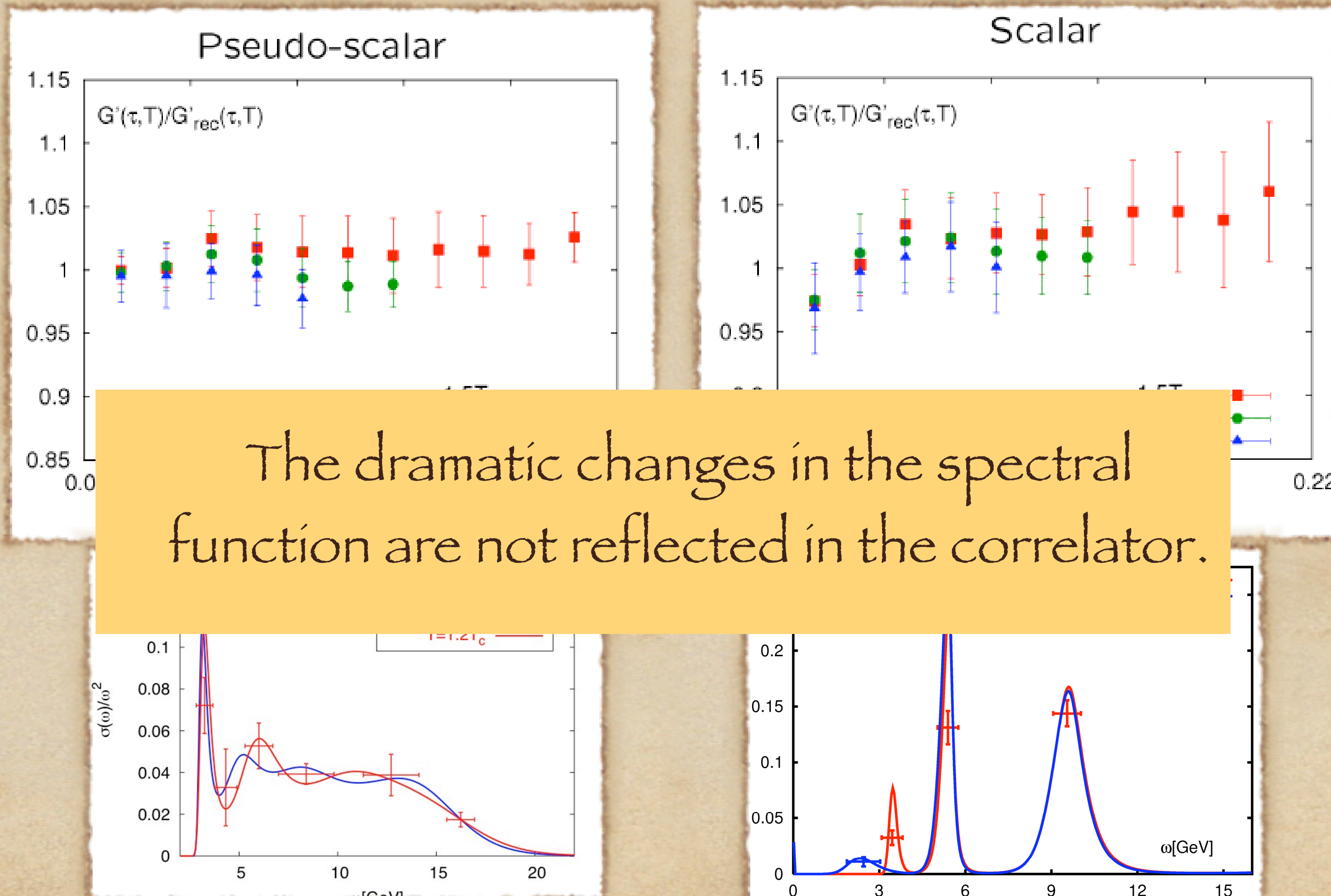
Datta, Petreczky, (2008)





Correlators in all the channels are flat! Flatness is not related to survival: no change in the derivative scalar up to $3T_c$! $_c$ survives until $3T_c$??? Almost the entire T-dependence comes from zero-modes. Understood in terms of quasi-free quarks with some effective mass - indication of free heavy quarks in the deconfined phase

What we have from the lattice

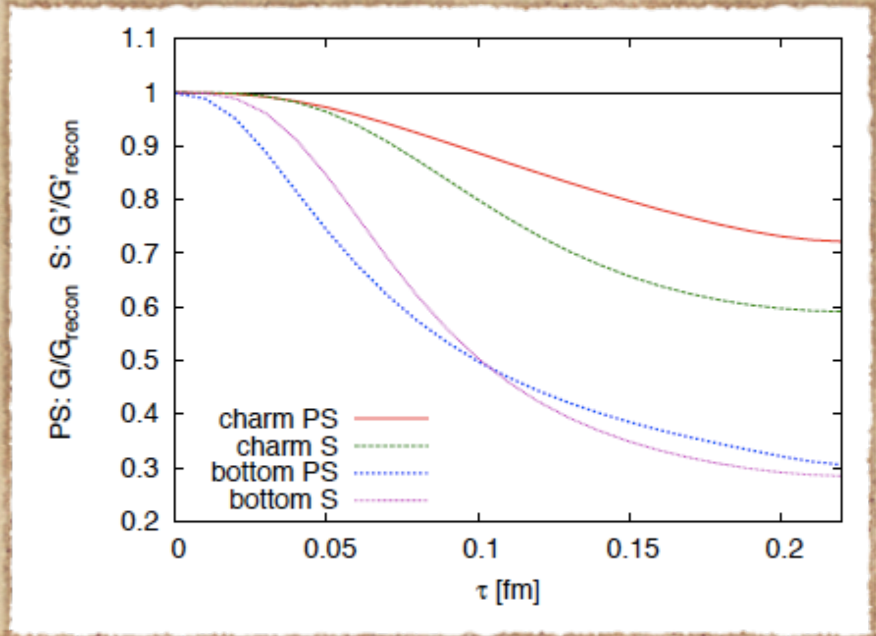


The dramatic changes in the spectral function are not reflected in the correlator.

With free spectral functions

We cannot tell about dissociation or survival from the lattice correlator ratio, BUT we can tell is that the spectral function is <u>not</u> the free spectral function: huge decrease is not seen on the lattice

$$\sigma_{free}(\omega,T) = \frac{N_c}{8\pi^2}\omega^2\left(a + b\frac{s_0^2}{\omega^2}\right)\tanh\frac{\omega}{4T}\sqrt{1-\frac{s_0^2}{\omega^2}}$$



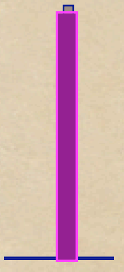
Mocsy, Petreczky, PRD 77 (2008)

Revisit potential models

1. Calculate spectral functions instead of individual states
2. Dissociation condition E_{diss}=0 is obsolete. Replace it!
3. We have accurate correlators from lattice. Compare models to these

1. Calculate spectral functions

narrow resonances - spectroscopy ok



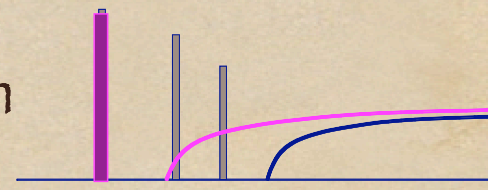
broad resonances - need total cross section

Spectral function contains all the info about a channel: provides unified treatment of bound states, continuum and threshold.

Disappearance of a peak means dissociated bound state

1. Calculate spectral functions

Simplified: bound states + continuum



$$\sigma_H(\omega,T) = \frac{1}{\pi}\mathrm{Im}G_H(\omega)$$
$$= \sum_n |\langle 0|j_H|n\rangle|^2\,\delta(\omega - E_n)$$
$$= \sum_n F^2_{H,n}\delta(\omega - M_n) + \theta(\omega - s_0)F^2_{H,\omega-s_0}$$

Alberico et al , PRD 75 (2007)

$$\sigma_H(\omega,T) = \sum_n F^2_{H,n}\delta(\omega - M_n) + \frac{3}{8\pi^2}\omega^2\theta(\omega - s_0)f_H(\omega,s_0),$$

Mocsy, Petreczky, PRD 73 (2005);
Alberico et al, PRD 75 (2007)

Full calculation

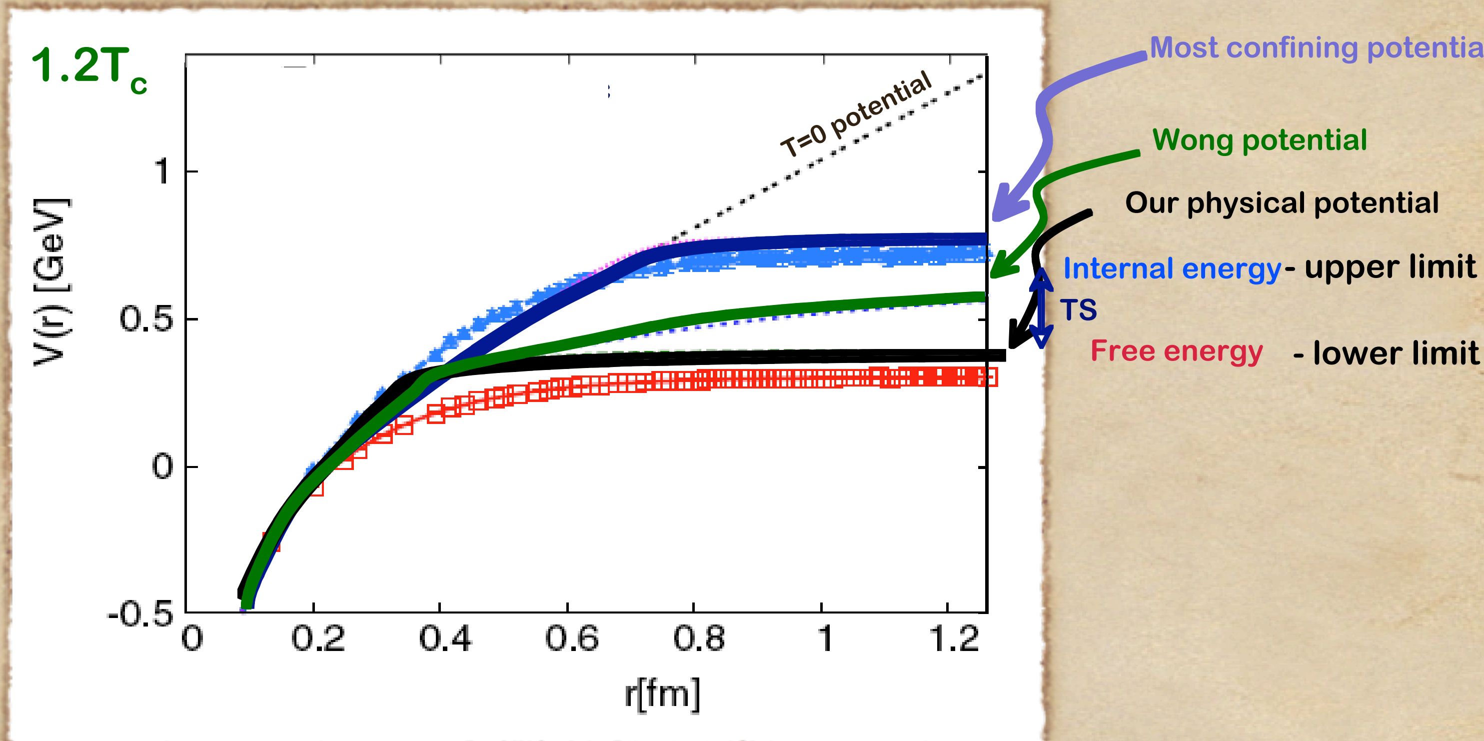
$$\left[-\frac{1}{m}\nabla^2 + V(\vec{r}) + E\right]G^{NR}(\vec{r},\vec{r}\,',E) = \delta^3(\vec{r}-\vec{r}\,')$$

$$\sigma(E) = \frac{2N_c}{\pi}\mathrm{Im}G^{NR}(\vec{r},\vec{r}\,',E)_{\vec{r}=\vec{r}\,'=0}$$

Solve Schrödinger equation
for non-relativistic Green's function

Cabrera, Rapp, PRD 74 (2007);
Mocsy, Petreczky, PRD 77 (2008)

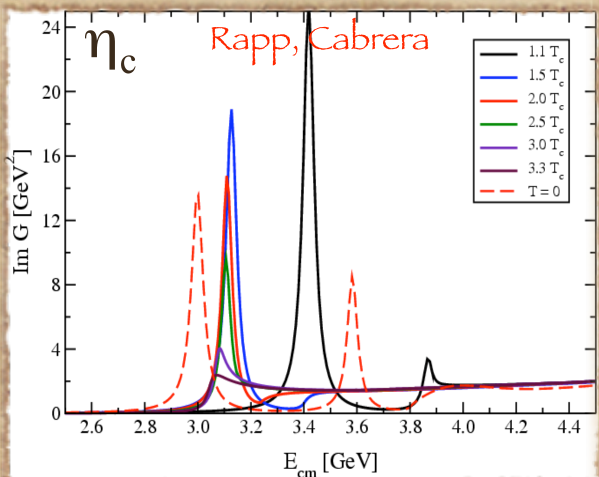
Lattice-based potentials

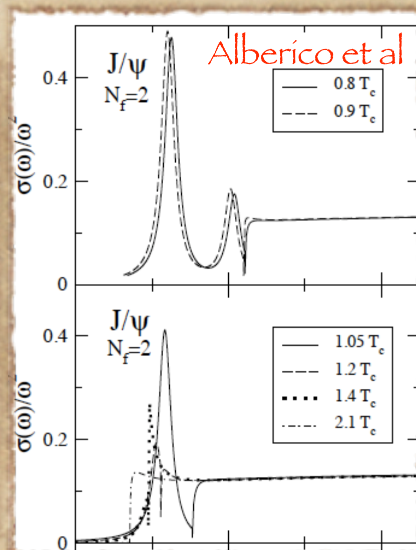


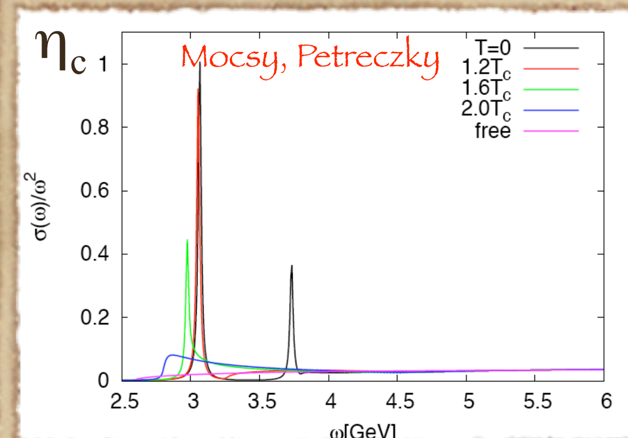
Mocsy, Petreczky, PRD 77 (2008)

Spectral functions

Results from different potential models with different ways to determine spectral functions







You can see peak centered around ground state mass for $T>T_c$

State dissociates when peak structure cannot be seen

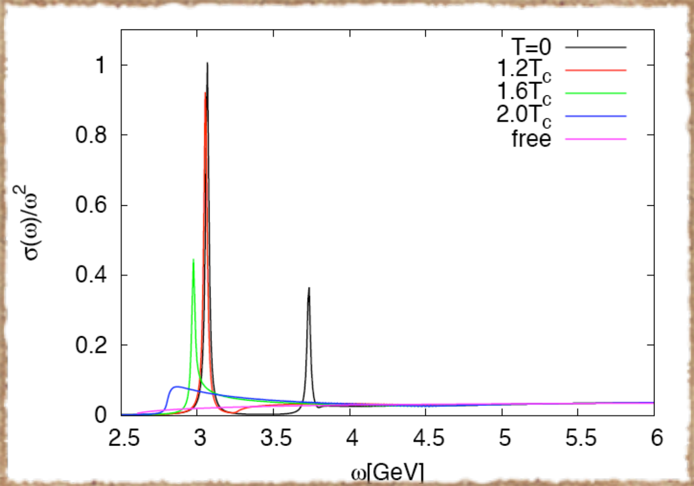
When is that? At E_{bin}=0?!

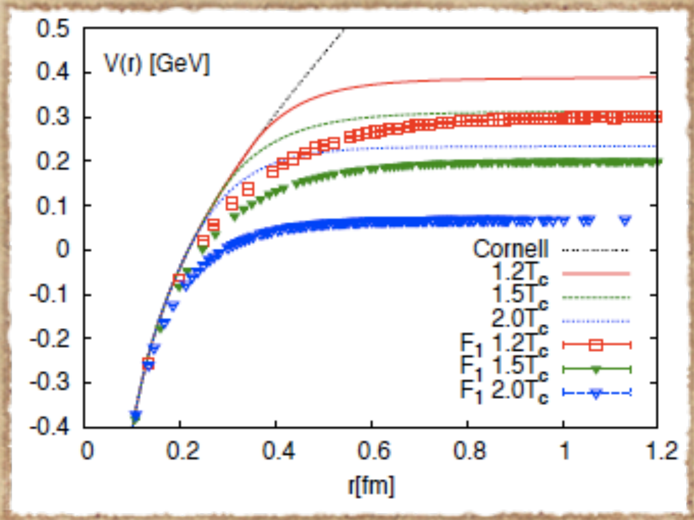
2. Dissociation condition

- Common for all the model spectral functions that peak may be there BUT the distance between peak and continuum threshold decreases with increasing T

$E_{bin} = 2m_q + V_\infty(T) - M$

- easy to understand: threshold (determined by V_∞) is decreasing with increasing T

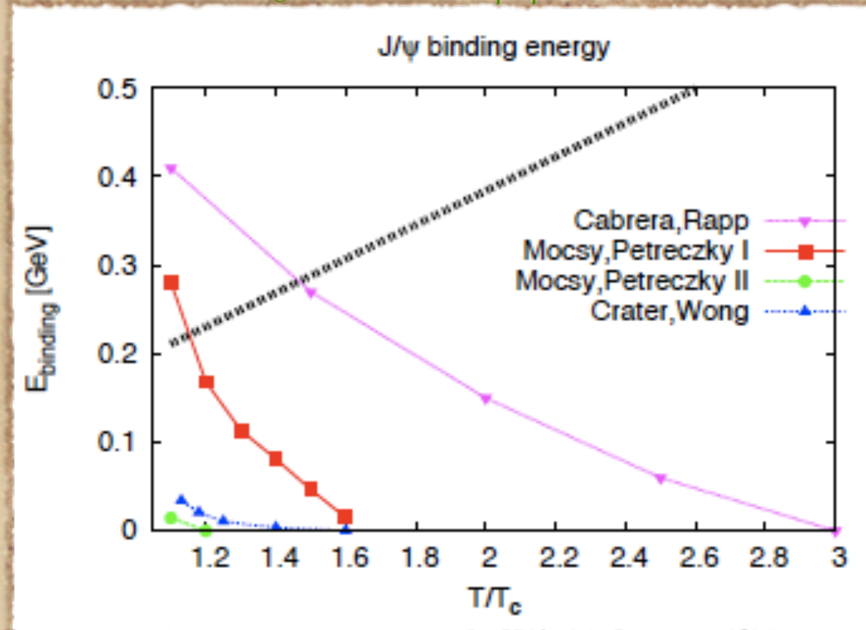




Binding energies

- Smooth decrease with increasing temperature
- What is the meaning of a 3GeV mass J/Ψ that has a 40 MeV binding energy at 1.5Tc?
    - remember, this is the dissociation energy, i.e. the energy to be provided to the state to dissociate it.

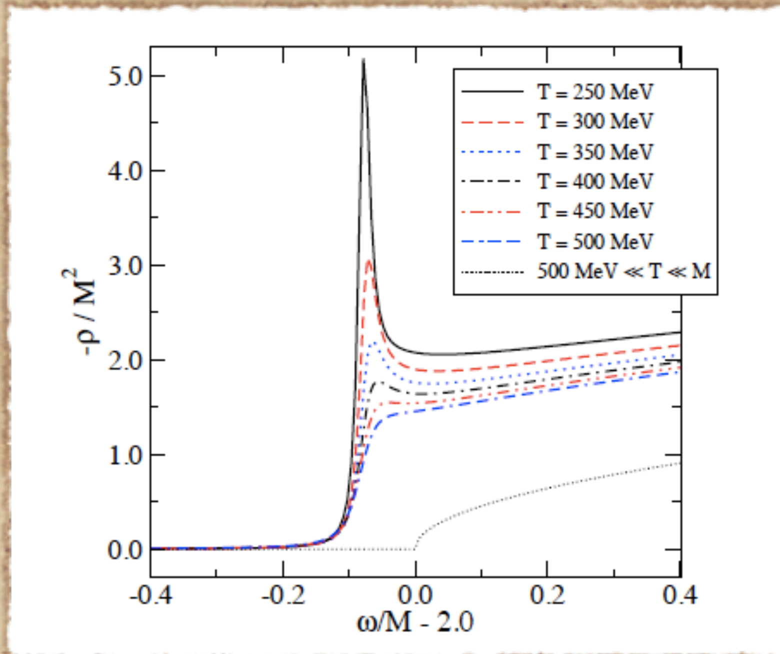
Mocsy, 0811.0337[hep-ph] (2008)



- when E_{bin} ~ T thermal broadening

Broadening of states

- When E_{bin} ~ T thermal broadening - we can estimate
- No need to reach E_{bin} =0 condition
- this lowers the dissociation T

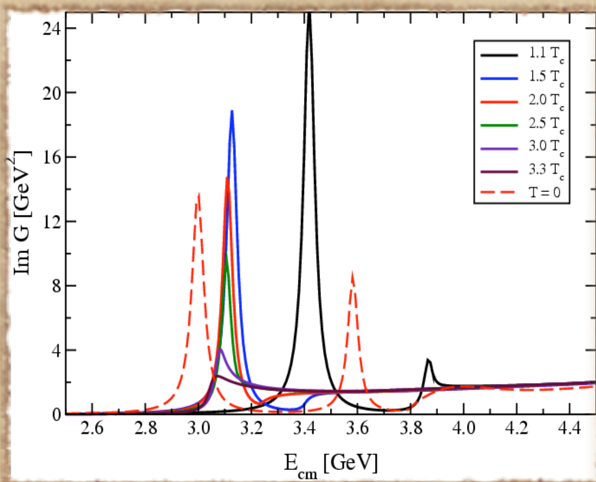


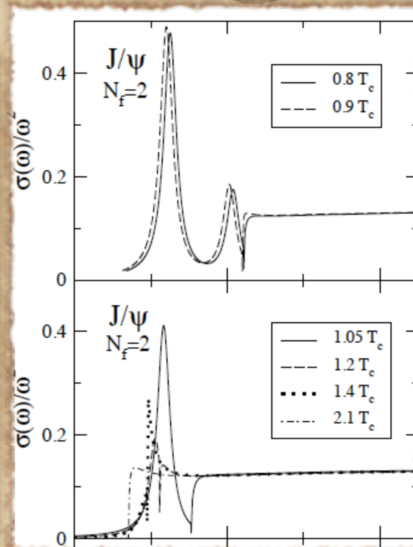
Laine, JHEP (2007)

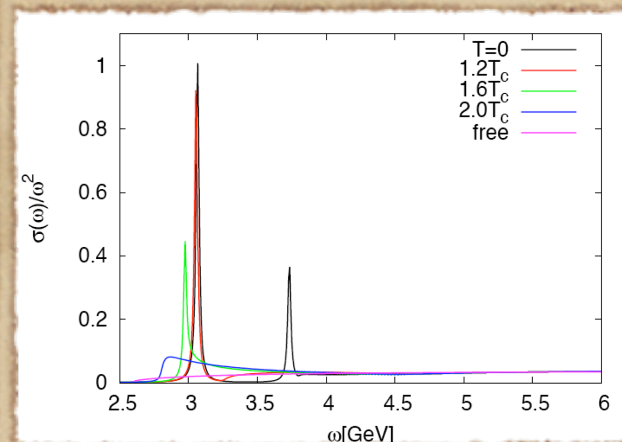
Broadening in agreement with:

- ✓**pQCD calculation** Park et al
- ✓**QCD sum rule** Lee, Morita
- ✓**Imaginary part in resummed pQCD** Laine,Philipsen

Broadening of states







WARNING! None of the spectral functions show physical widths - sofar these are meaningless peaks

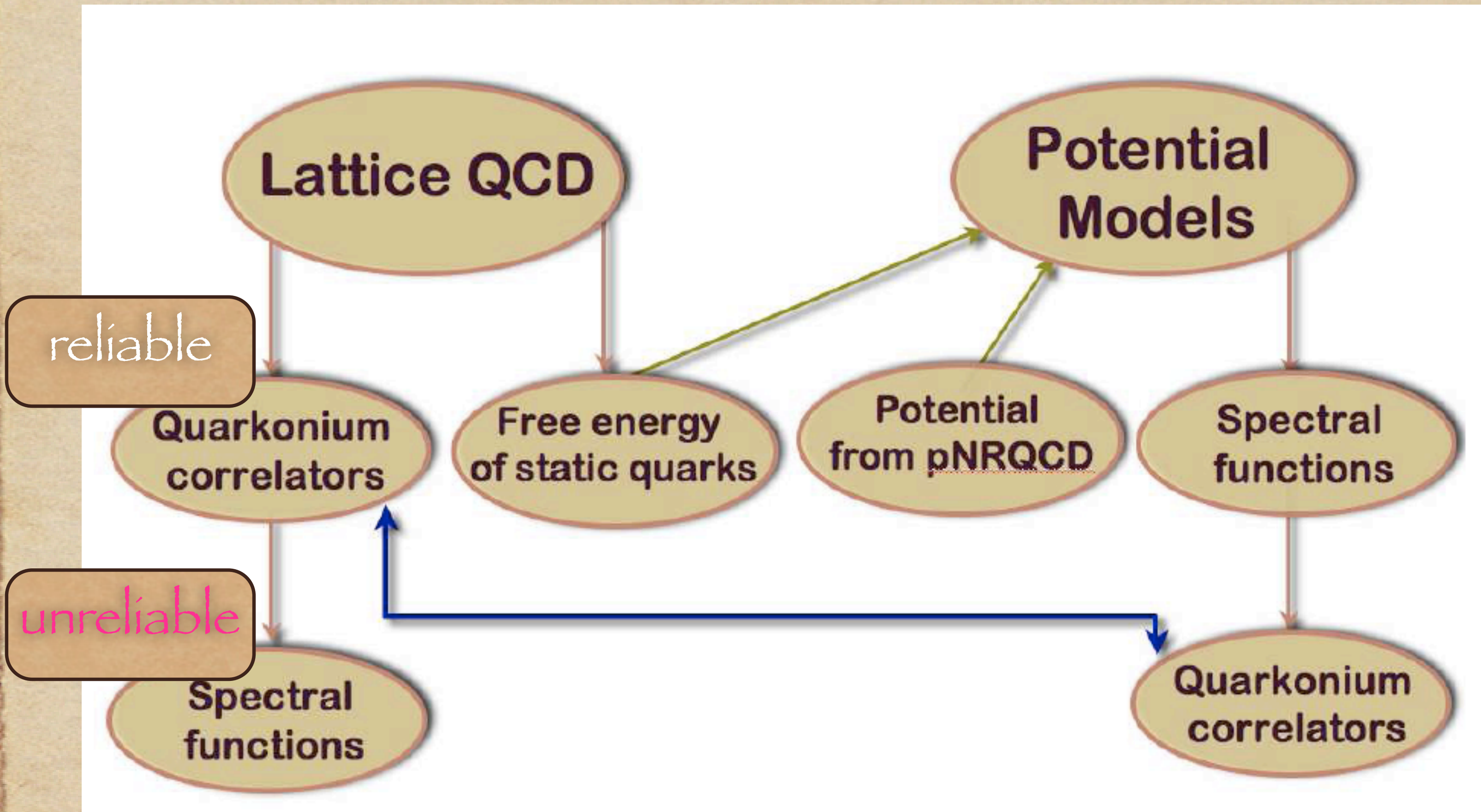
Do not need to reach E_{bin}=0 to dissociate a state.

$$\Gamma(T) \geq 2E_{bin}(T)$$

J/ψ melts before it bounds.

Mocsy, Petreczky, PRL (2008)

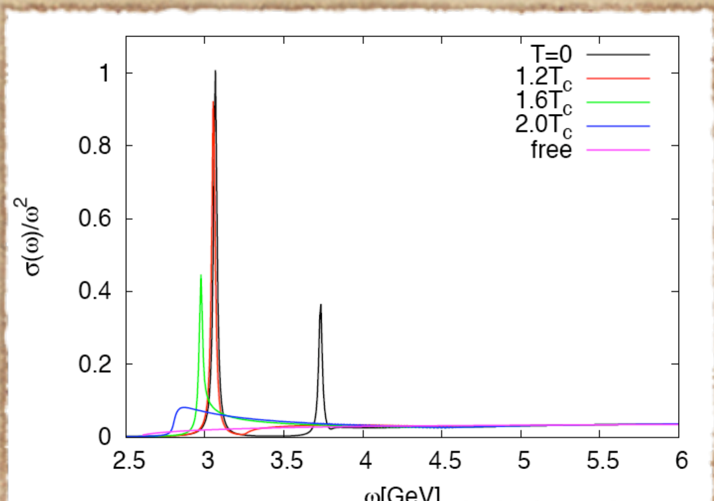
3. Compare to lattice data

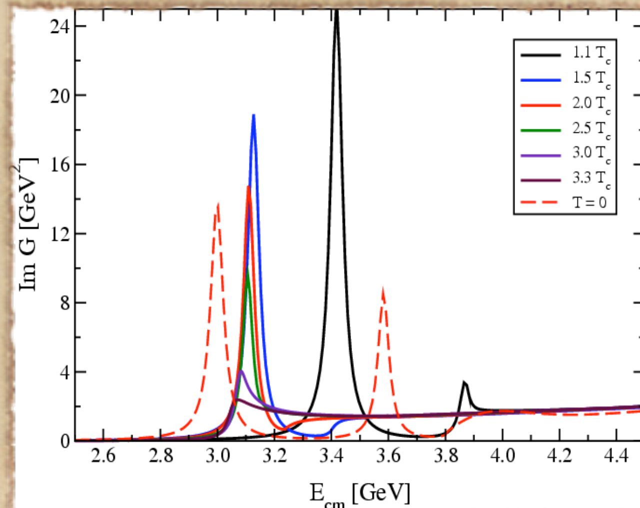


Mocsy, 0811.0337[hep-ph] (2008)

Threshold enhancement

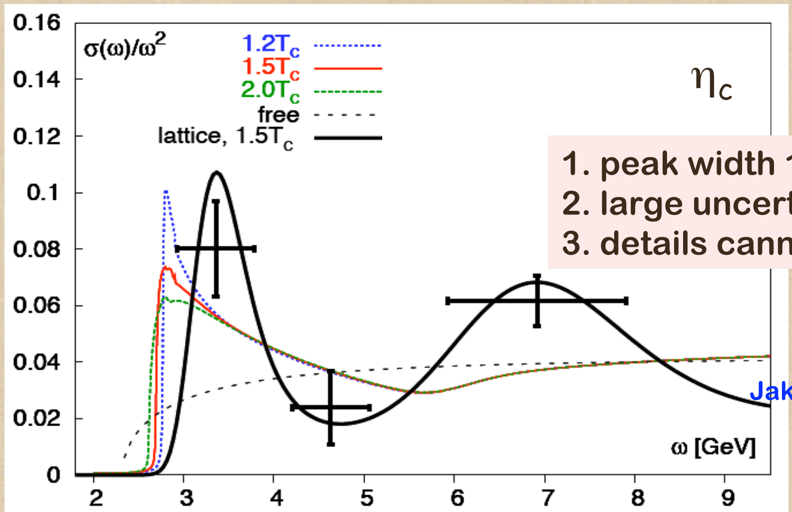
- Large re-scattering enhancement common feature to all of these models
- indication of correlation remaining between c and cbar





Compare spectral functions

Mócsy, Petreczky PRD (2007)



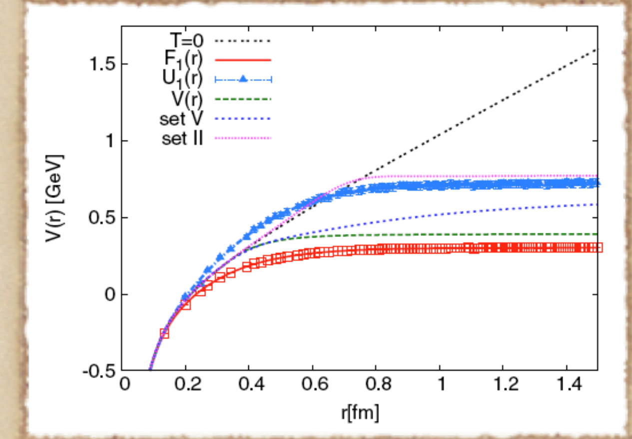
1. peak width 1 GeV
2. large uncertainties
3. details cannot be resolved

Jakovac et al PRD (07)

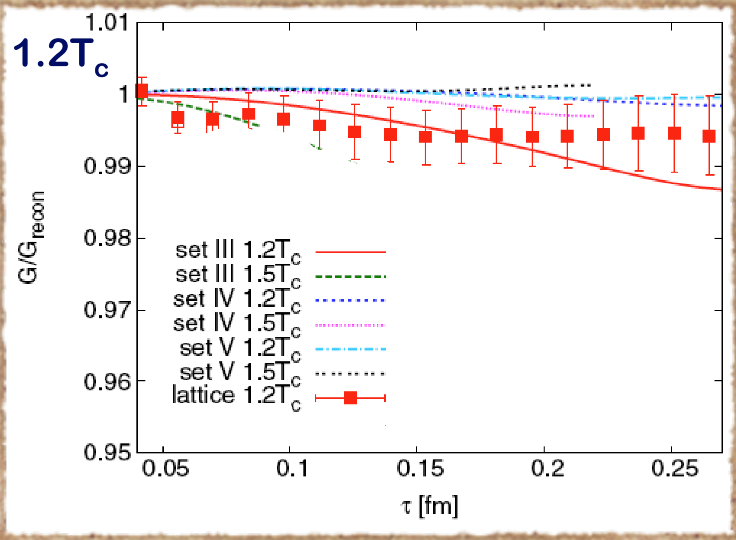
Spectral function integrated from 2.7-4.5 GeV unchanged from T=0 and 1.5T_c

Lattice data is consistent with J/psi melting just above T_c

- The idea was to identify the correct potential by comparing correlators from potential models to correlators from lattice

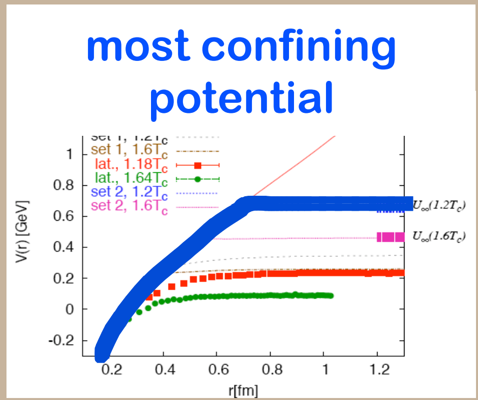


- Set of potentials yield indistinguishable results
- threshold enhancement compensates for the melting of the states, keeping the correlator ratio flat
- Cannot determine quarkonium properties from such comparisons.



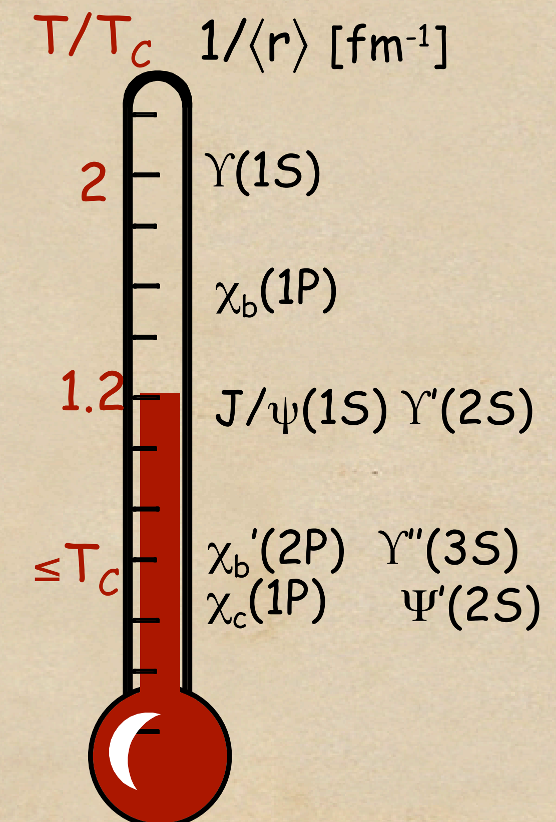
Upper limit for dissociation

- Use the most confining potential that is still in agreement with lattice
- Determine the T-dependence of the binding energy
- Estimate the thermal width



$$\Gamma(T) \geq 2E_{bin}(T)$$

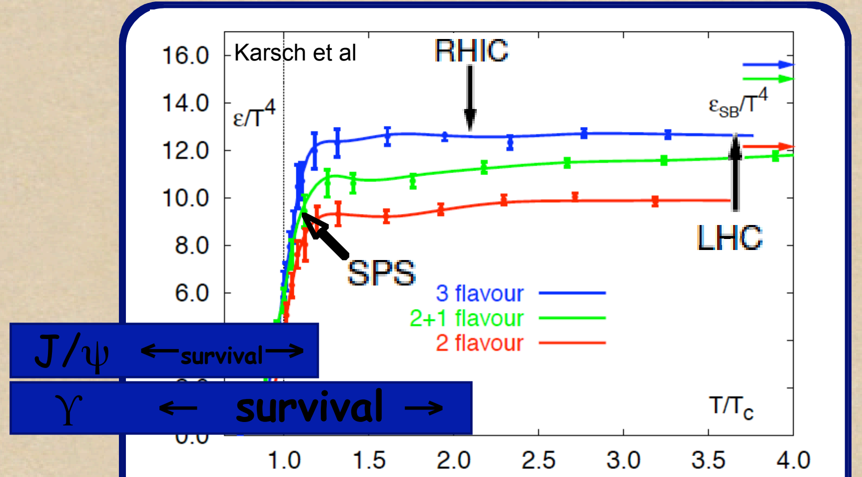
Upper limit for dissociation



Mocsy, Petreczky, PRD (2008)

Mocsy, 0811.0337[hep-ph] (2008)

Implications for experiment



state	χ_c	ψ'	J/ψ	Υ'	χ_b	Υ
T_{dis}	$\leq T_c$	$\leq T_c$	$1.2T_c$	$1.2T_c$	$1.3T_c$	$2T_c$

Consequences:

J/ R_{AA}: J/ should melt at SPS and RHIC

suppressed at RHIC (centrality dependent?); definitely at LHC

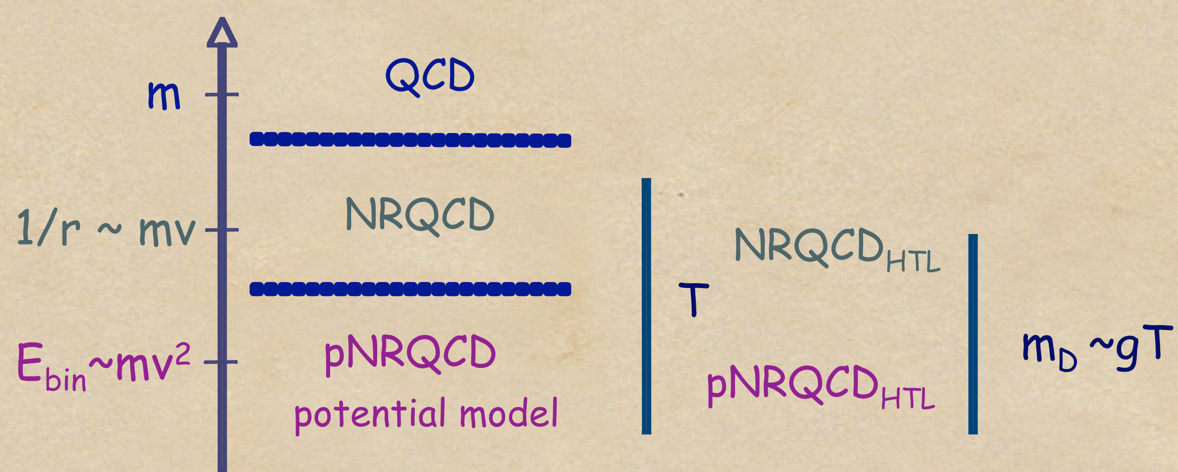
expect correlations of heavy-quark pairs, i.e. non-statistical recombination

Young, Shuryak: 50% will not diffuse away

The future of potential models

Effective field theories from QCD at finite T

Real and Imaginary part of potential derived



Brambilla et al (2008)

Laine et al, Blaizot et al (2008)

Lessons to take home

- Golden signal of J/Ψ suppression is more like an amalgam of different suppression, enhancement effects
- Potential models, in accordance with lattice data tell that J/Ψ will broaden above Tc and c-cbar will not be bound, but correlation could persist
  - Dissociation at E_{bin}=0 is obsolete
- Lattice does not tell about quarkonium properties. Must find the potential from QCD
- Don't forget: All this is static. Need dynamic medium

see: Young , Shuryak (2008)

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lattice QCD

Umeda et al Eur. Phys. J C 39S1 (2005) 9
Asakawa, Hatsuda, PRL 92 (2004) 012001
Datta et al PRD 69 (2004) 094507
Jakovac et al PRD 75 (2007) 014506
Aarts et al Nucl Phys A785 (2007) 198
Iida et al PRD 74 (2006) 074502
Umeda PRD 75 (2007) 094502

potential models

Matsui, Satz, PLB 178 (1986) 416
Digal, Petreczky, Satz, PRD 64 (2001) 094015
Wong PRC 72 (2005) 034906;
PRC 76 (2007) 014902
Wong, Crater, PRD 75 (2007) 034505
Mannarelli, Rapp, PRC 72 (2005) 064905
Cabrera, Rapp, Eur Phys J A 31 (2007) 858;
PRD 76 (2007) 114506
Alberico et al,PRD 72 (2005) 114011;
PRD 75 (2007) 074009
PRD 77 (2008) 017502
Mócsy, Petreczky, Eur Phys J C 43 (2005) 77;
PRD 73 (2006) 074007
PRD 77(2008) 014501;
PRL 99 (2007) 211602

the end