# Quarkonium Theory
## Overview

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Pratt Institute, Brooklyn

**Hard Probes**
Cape Town, South Africa, 2013 November 4-8

# Quarkonium in Hot Bath

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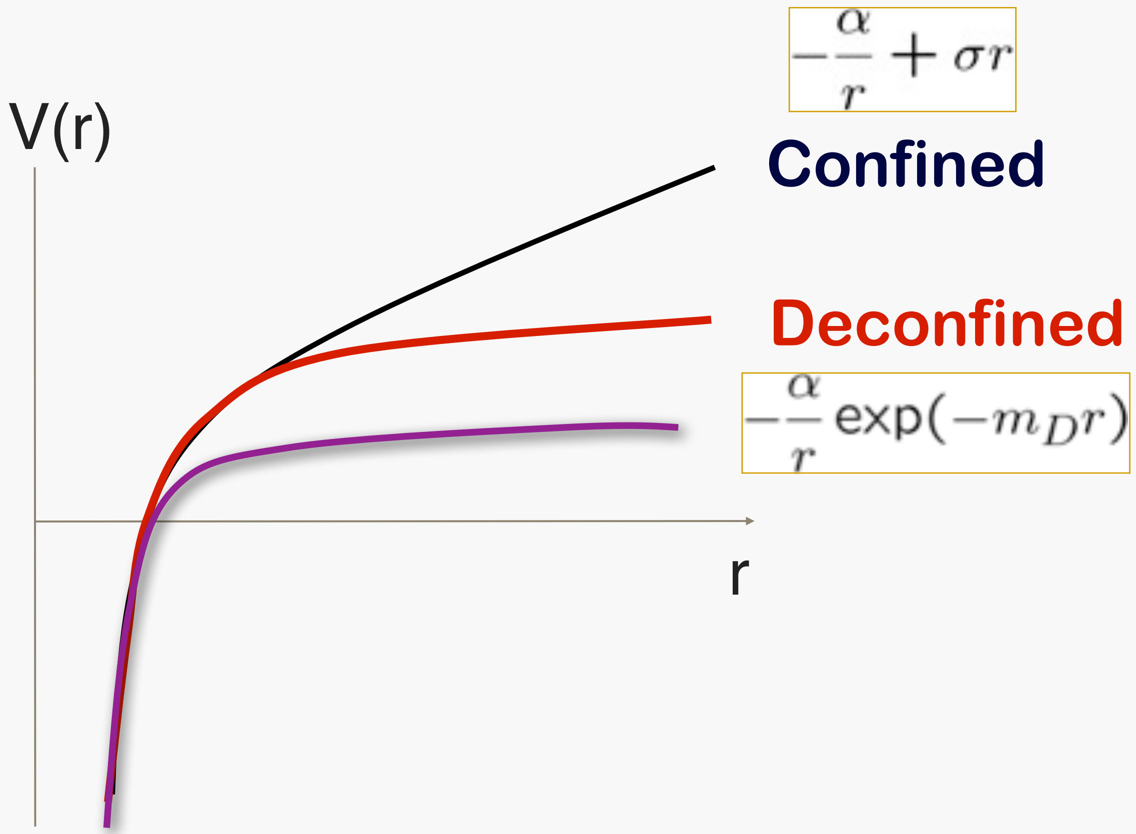
Deconfinement and Quarkonium Melting

Quarkonium Correlation Functions from Lattice

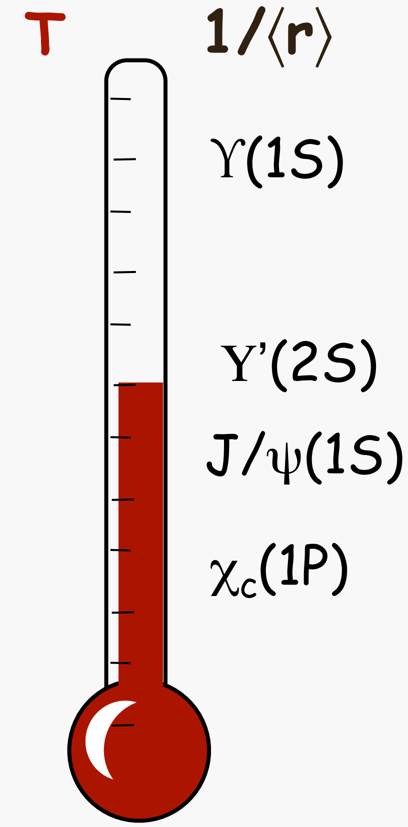
Heavy Quark Potential and Spectral Functions

Implications for Quarkonium in Heavy-Ion Collisions

# The Quarkonium Story

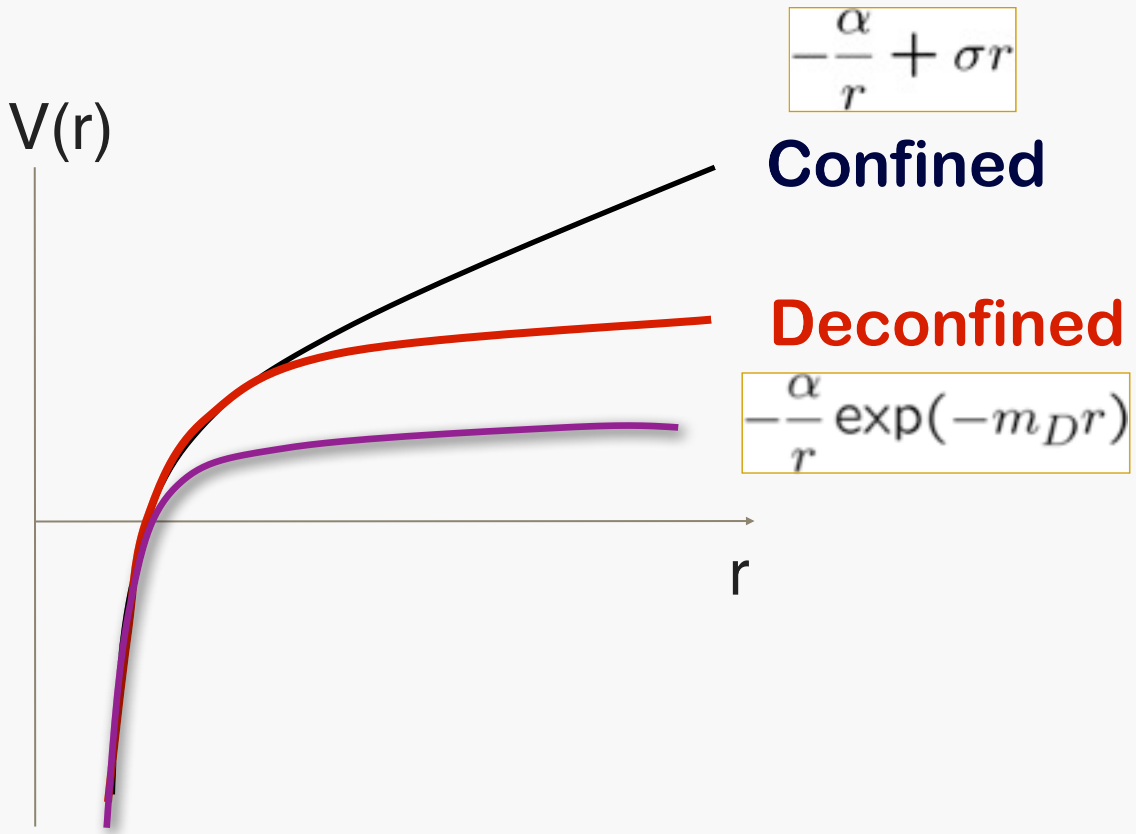



Matsui, Satz, PLB 178 (1986) 416




Mócsy, EPJC 61 (2009) 705

# The Quarkonium Story

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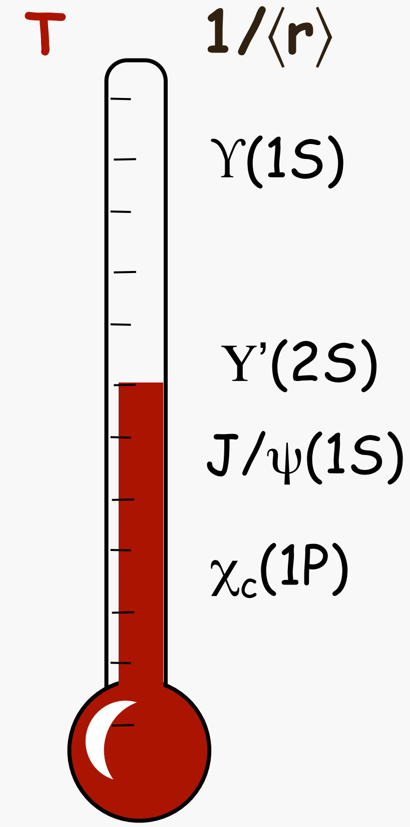



Móscy, EPJC 61 (2009) 705

What do we mean by bound states at finite T ?

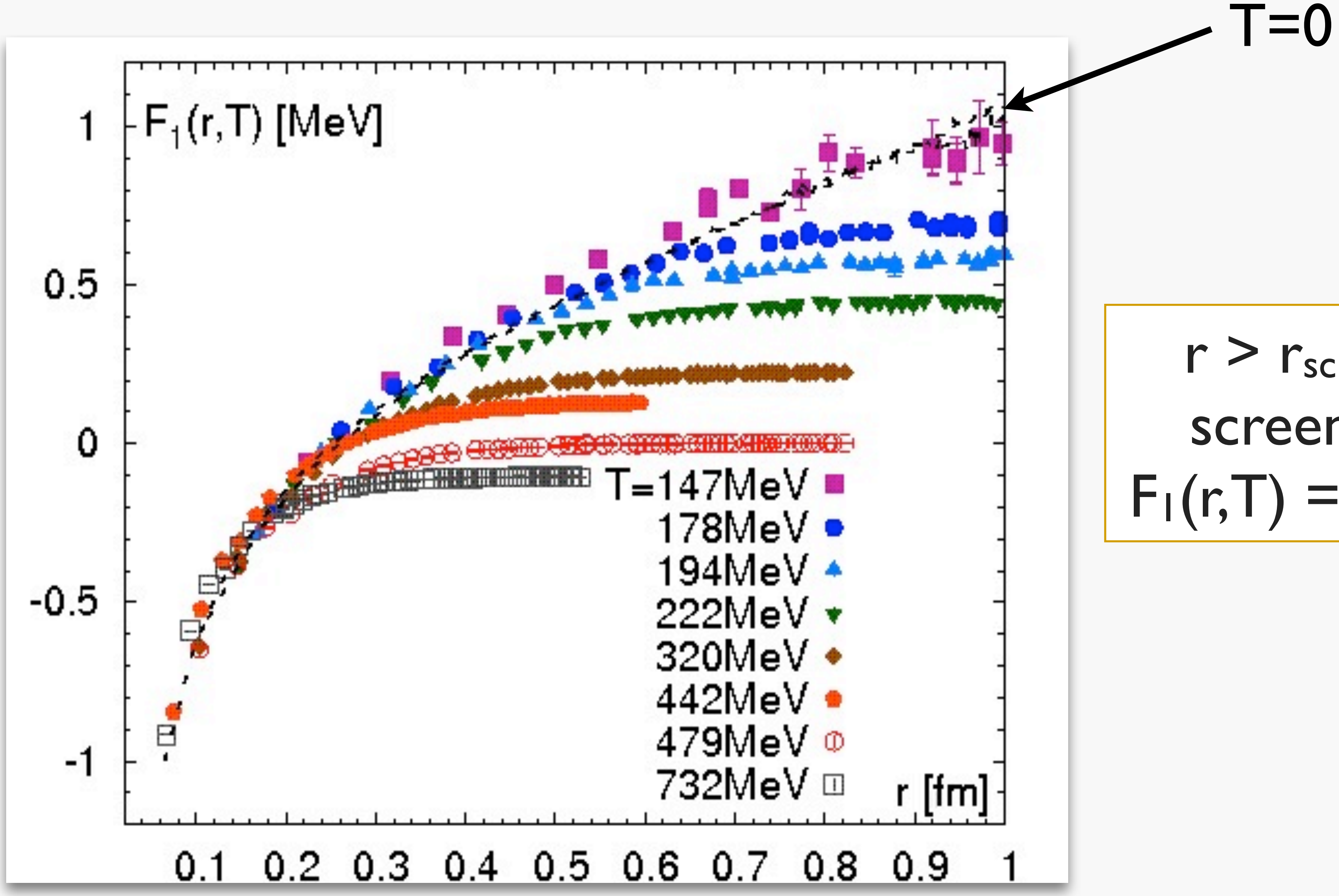
Can we describe medium effects with a T-dependent potential ?

and if so, what is the potential?

# Color Screening

Singlet free energy of a static Q-$\bar{Q}$ in a heat bath in 2+1 flavor lattice QCD

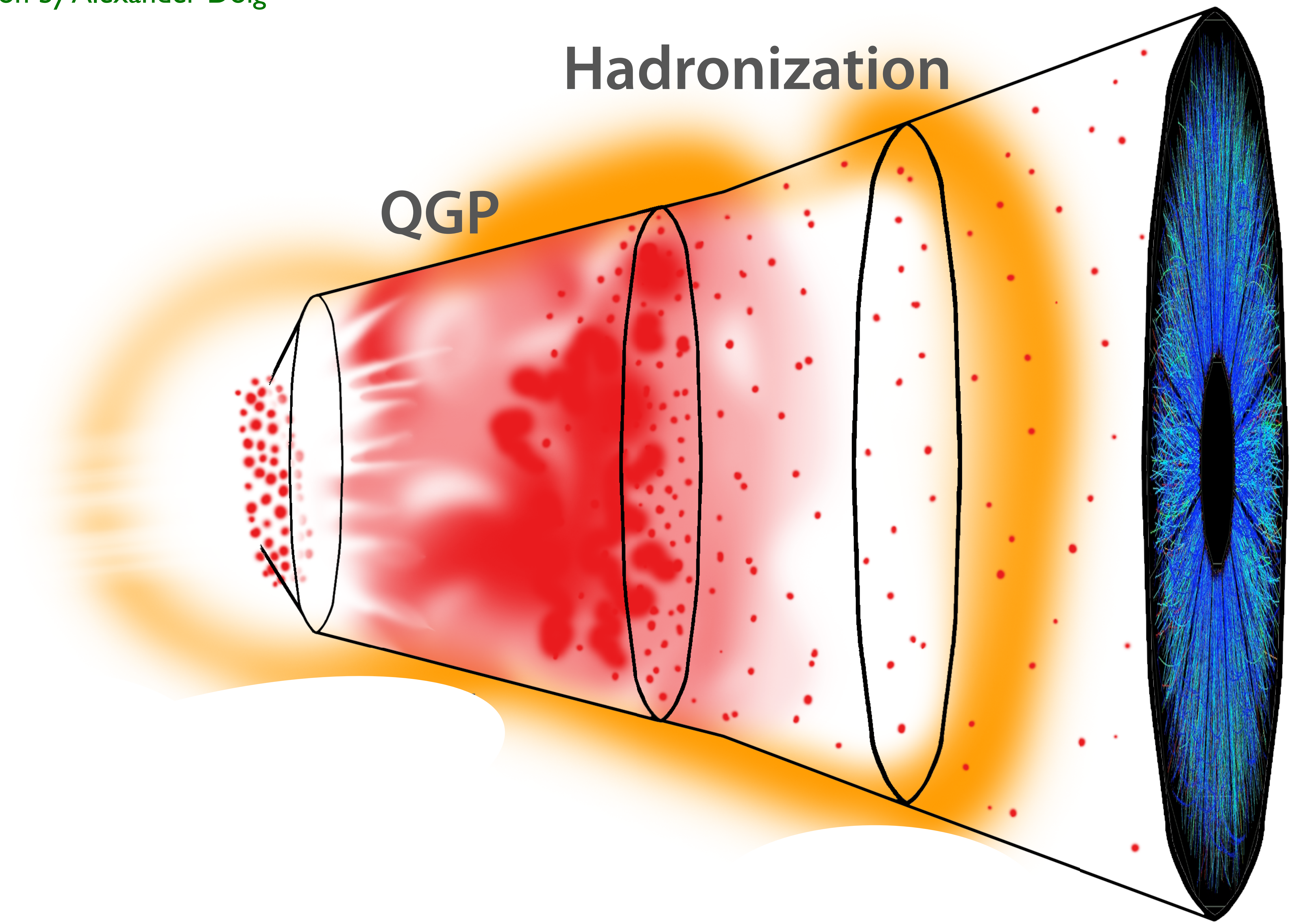
$r < r_{med}(T)$
vacuum physics
$F_1(r,T) = V(r)$




$r > r_{scr}(T)$
screening
$F_1(r,T) = F_1(T)$

Bazavov, Petreczky, arXiv:1211.5638

illustration by Alexander Doig



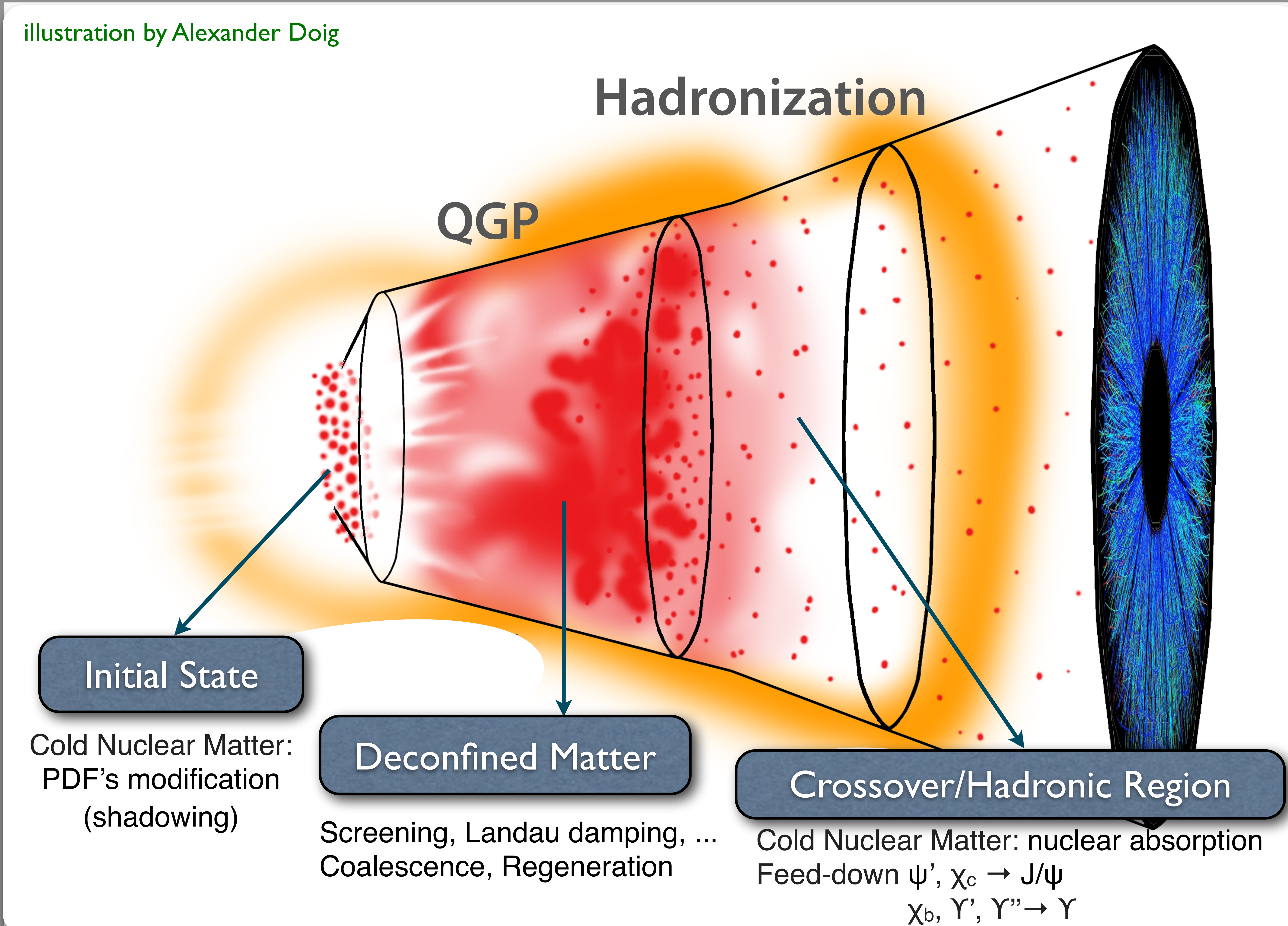


illustration by Alexander Doig
Hadronization
QGP
Initial State
Cold Nuclear Matter:
PDF's modification
(shadowing)
Deconfined Matter
Screening, Landau damping, ...
Coalescence, Regeneration
Crossover/Hadronic Region
Cold Nuclear Matter: nuclear absorption
Feed-down ψ', χc → J/ψ
χb, ϒ', ϒ"→ ϒ

Since Matsui and Satz, we have:

- two decades of data,
- lots of ad-hoc phenomenological modeling,
- and lots of controversy,

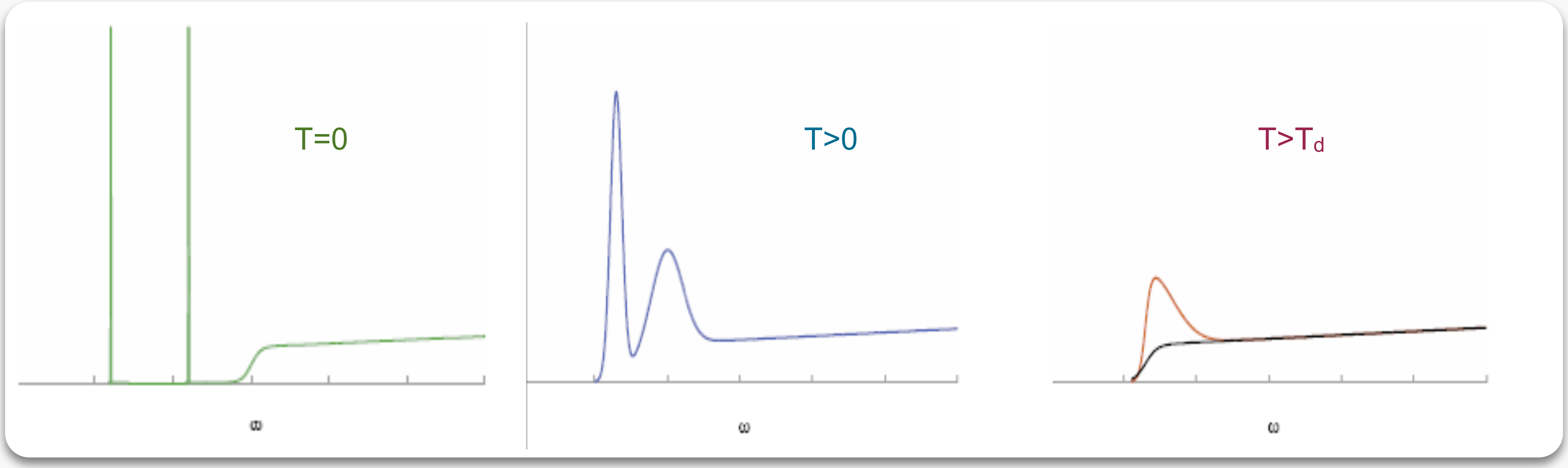
but in recent years

Considerable progress has been achieved and a coherent QCD-based picture is emerging

# Spectral Function

In-medium properties are encoded in spectral functions:

$$\sigma(\omega, p, T) = \frac{1}{2\pi} \text{Im} \int_{-\infty}^{\infty} dt e^{i\omega t} \int d^3x e^{ipx} \langle [J(x,t), J(x,0)] \rangle_T$$




Melting seen as progressive broadening and disappearance of bound-state peaks

So how do we determine the spectral function?

# Euclidean Correlators

Ding talk at Hard Probes 2013

Correlation function of mesonic currents in Euclidean time

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

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

→ MEM → $\sigma(\omega,T)$

Uncertainties are significant, details cannot be resolved

**But it is difficult to draw solid conclusions about finite temperature quarkonium from the shape of lattice spectral functions**

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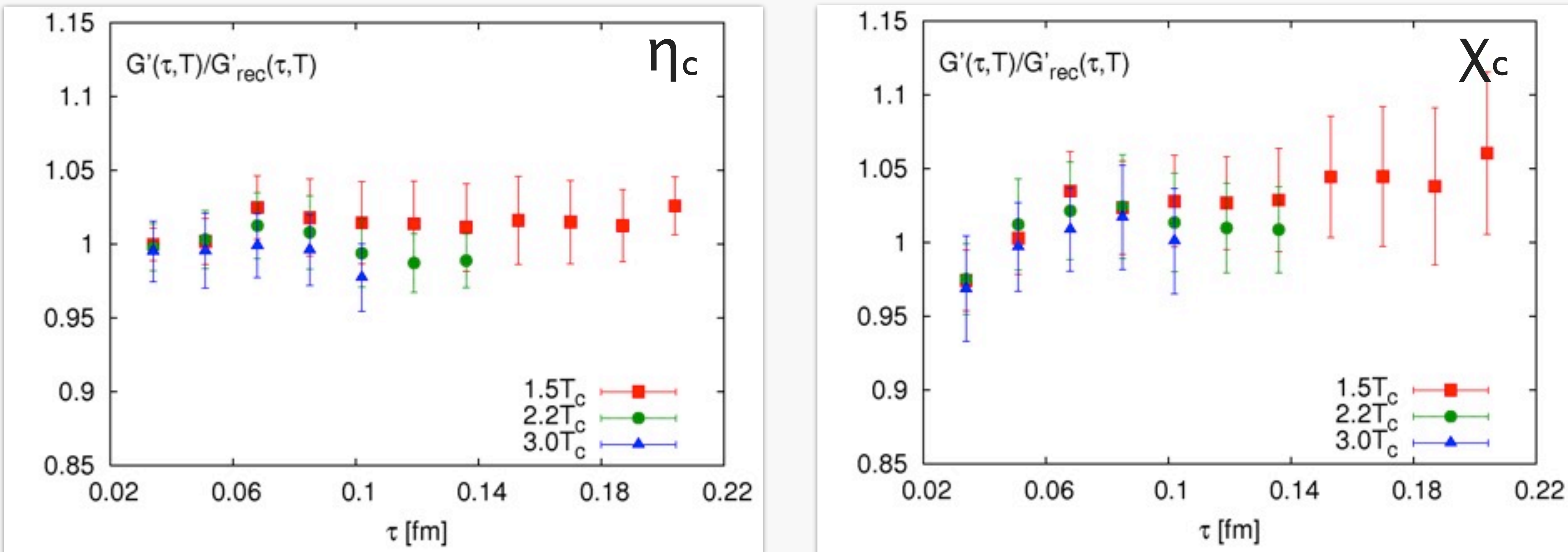
# Euclidean Correlators

Zero mode contribution is not present in the time derivative of the correlator

Umeda, PRD 75 (2007) 094502

Ratios of correlator derivatives do not change until very high T




Petreczky, EPJC 62 (2009) 85

*Temporal* quarkonium correlators are not very sensitive to changes in the spectral functions due to the limited $\tau_{max}=1/(2T)$

# Spatial Correlators

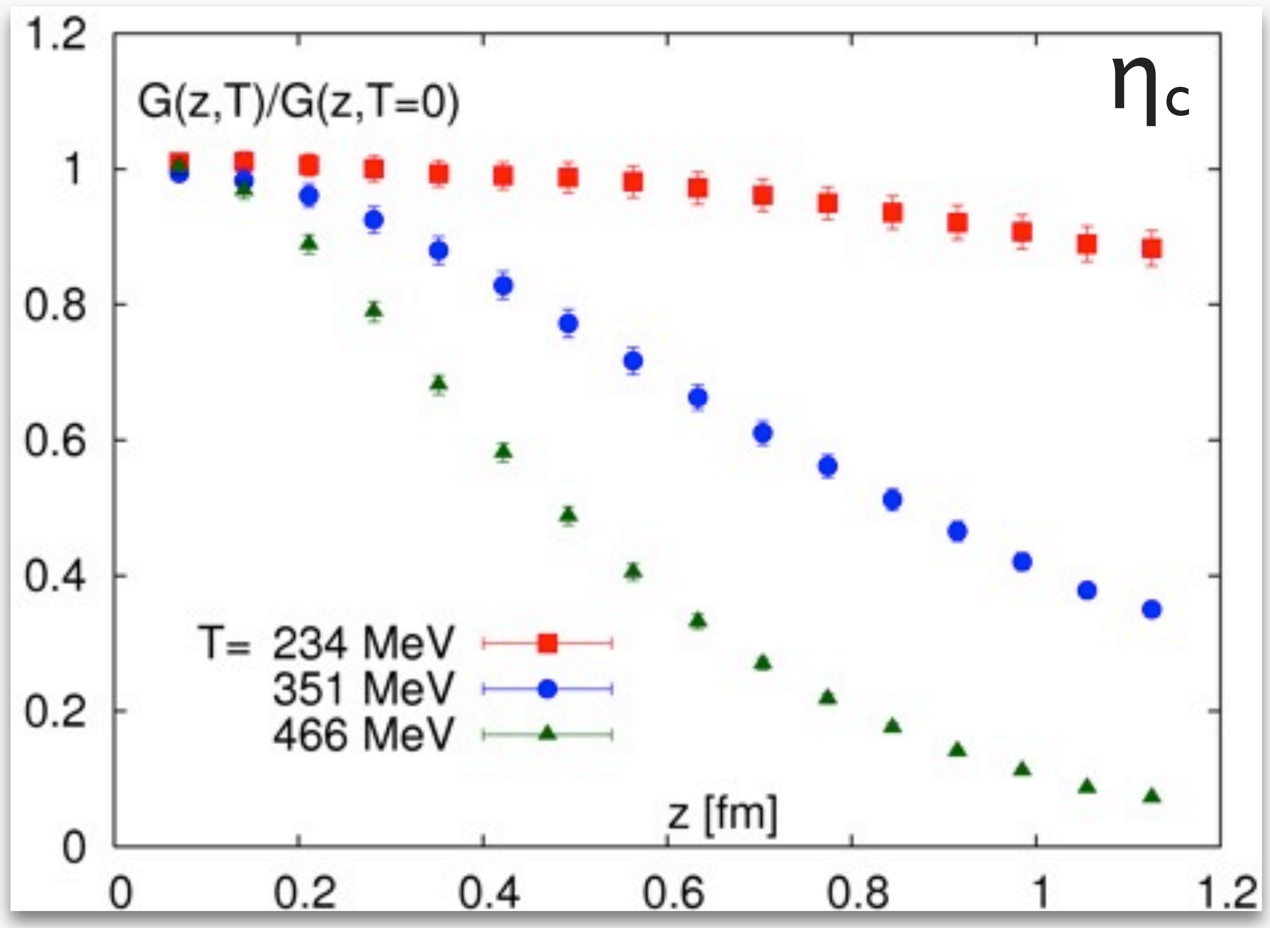
can be calculated for arbitrarily large distances

$$G(z,T) = \int_0^{1/T} d\tau \int dx dy \langle J(\mathbf{x}, -i\tau), J(0,0)\rangle_T$$

related the spectral functions :

$$G(z,T) = \int_{-\infty}^{\infty} e^{ipz} \int_0^{\infty} d\omega \frac{\sigma(\omega, p, T)}{\omega}$$

Significant T-dependence in the deconfined phase



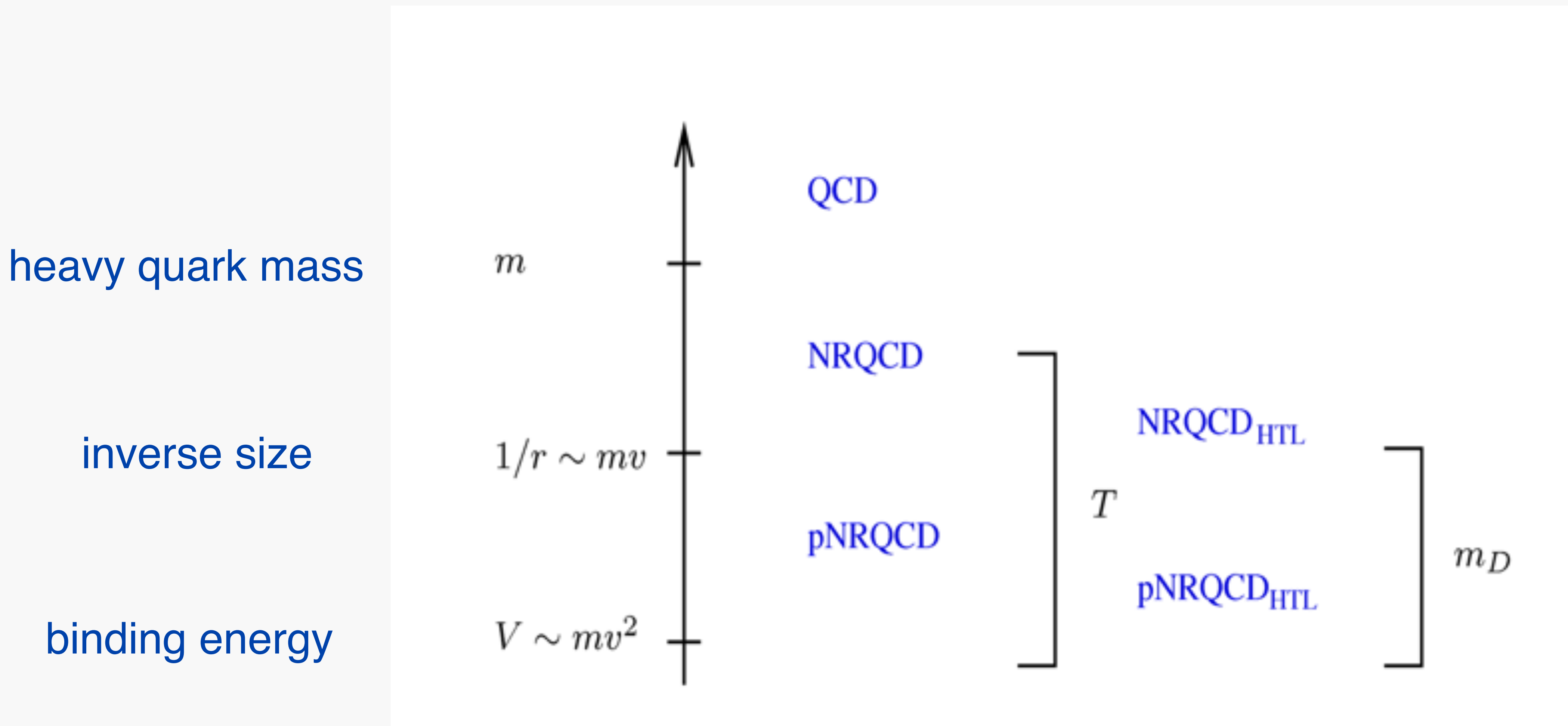

Karsch, Laermann, Mukherjee, Petreczky, PRD 85 (12) 114501

Detailed analysis suggest :

First direct evidence from lattice QCD for melting of the *1S* charmonium

# Effective Field Theory Approach

Scale separation allows us to construct a sequence of effective theories; can be used to rigorously define the potential




Laine et al, Brambilla et al, Blaizot et al, Escobado, Soto, ...

Potential model is derived from QCD, appears as the tree level approximation of pNRQCD and can be systematically improved

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# Thermal pNRQCD

Ultrasoft quark and gluons

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu} + \sum_{i=1}^{n_f} \bar{q}_i\, i\not{D} q_i$$

Singlet $Q\bar{Q}$ field — Octet $Q\bar{Q}$ field

$$+\int d^3r\ \mathrm{Tr}\left\{\mathrm{S}^\dagger\left[i\partial_0 - \frac{-\nabla^2}{m} - V_s(r,T)\right]\mathrm{S} + \mathrm{O}^\dagger\left[iD_0 - \frac{-\nabla^2}{m} - V_o(r,T)\right]\mathrm{O}\right\}$$

$$+V_A\,\mathrm{Tr}\left\{\mathrm{O}^\dagger\vec{r}\cdot g\vec{E}\,\mathrm{S} + \mathrm{S}^\dagger\vec{r}\cdot g\vec{E}\,\mathrm{O}\right\} + \frac{V_B}{2}\mathrm{Tr}\left\{\mathrm{O}^\dagger\vec{r}\cdot g\vec{E}\,\mathrm{O} + \mathrm{O}^\dagger\mathrm{O}\vec{r}\cdot g\vec{E}\right\} + \dots$$

Brambilla, Ghiglieri, Petreczky, Vairo, PRD 78 (08) 014017

Tree level: free field equation for S is the Schrödinger equation

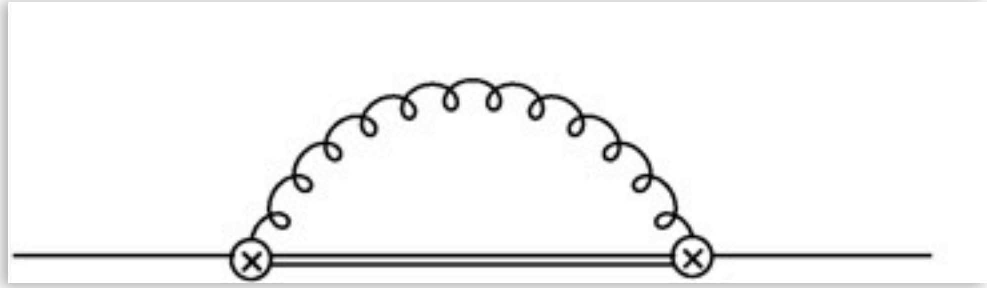
$$\left[i\partial_0 - \frac{-\nabla^2}{m} - V_s(r,T)\right]S(r,t) = 0 \quad \Rightarrow \quad \sigma(\omega,T)$$

$V_s$ temperature-dependent complex potential *only* for $E_{bin} < T$

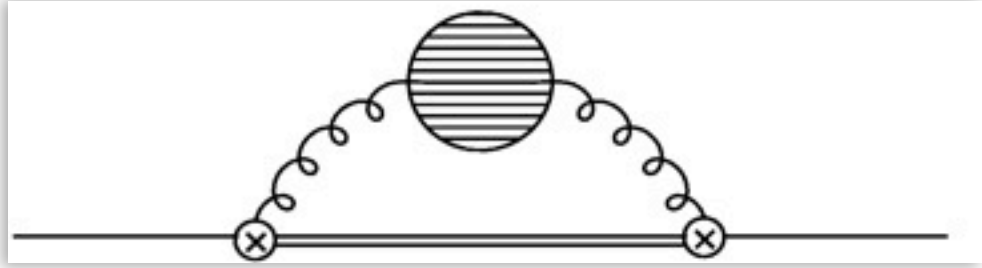
# How to Calculate the Potential

Weak coupling :

Singlet-octet transition



Landau damping



Brambilla et al (2008), Laine (2007)

Strong coupling :

Above deconfinement the binding energy is reduced and eventually is the smallest scale

$$T, m_D, \Lambda_{QCD} >> E_{bind} = mv^2$$

all scales can be integrated out

medium effects are described by a temperature-dependent potential = static energy -- calculable on the lattice

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# Potential from Lattice

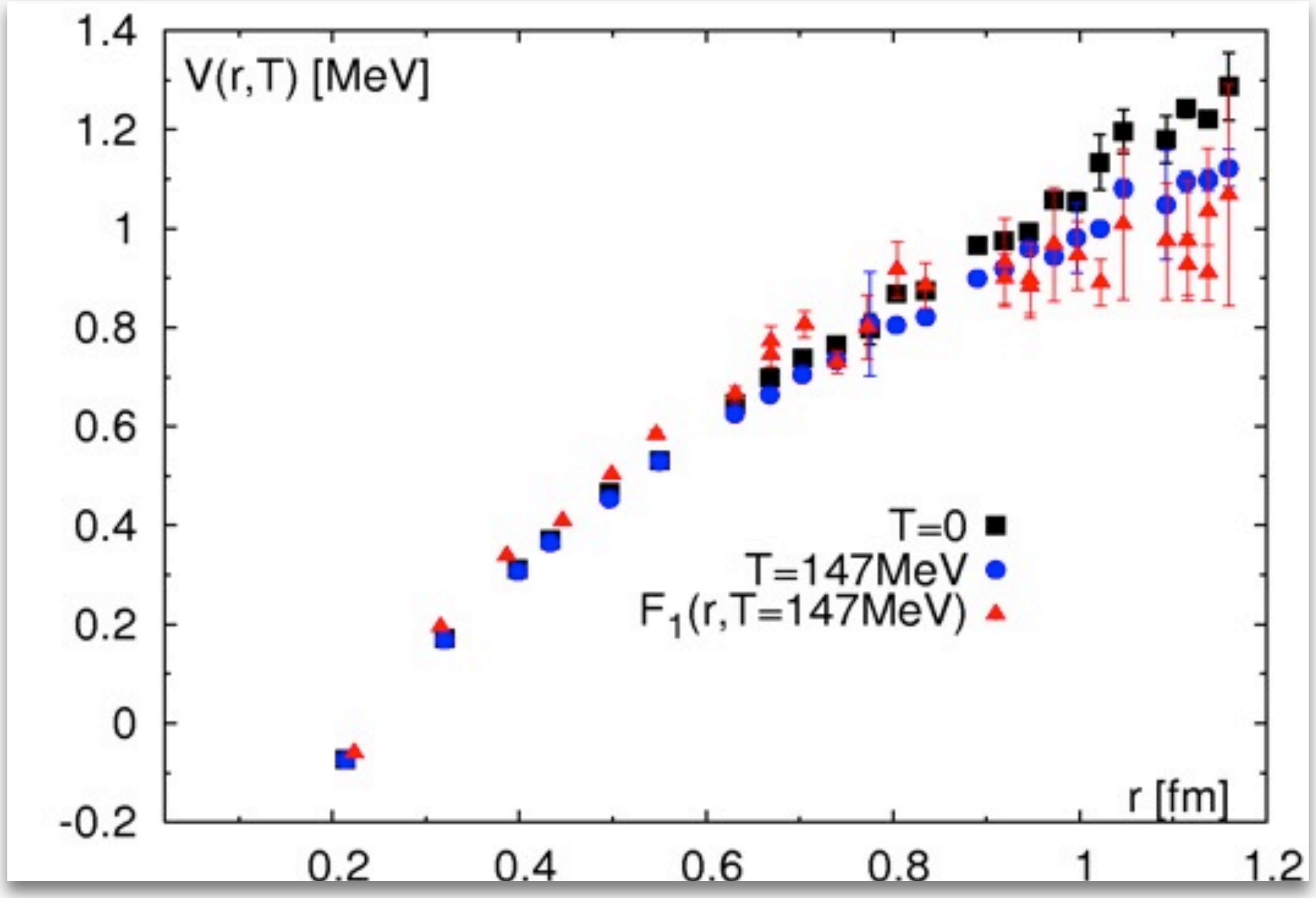
Extract the static Q-Qbar energy from lattice using the spectral decomposition of the Wilson loops

$$W(r,\tau) = \int_{-\infty}^{\infty} d\omega \sigma_r(\omega, T) e^{-\omega\tau}, \tau < 1/T$$

Not related to $F_l$

Rothkopf, PoS LAT2009 (2009) 162
Hatsuda, Rothkopf, PRL 108 (2012) 162001

$\sigma_r$ has a peak at $\omega = \mathrm{ReV}_r$ and a width $\Gamma = \mathrm{ImV}_r$




Bazavov, Petreczky NPA 904 (2013)

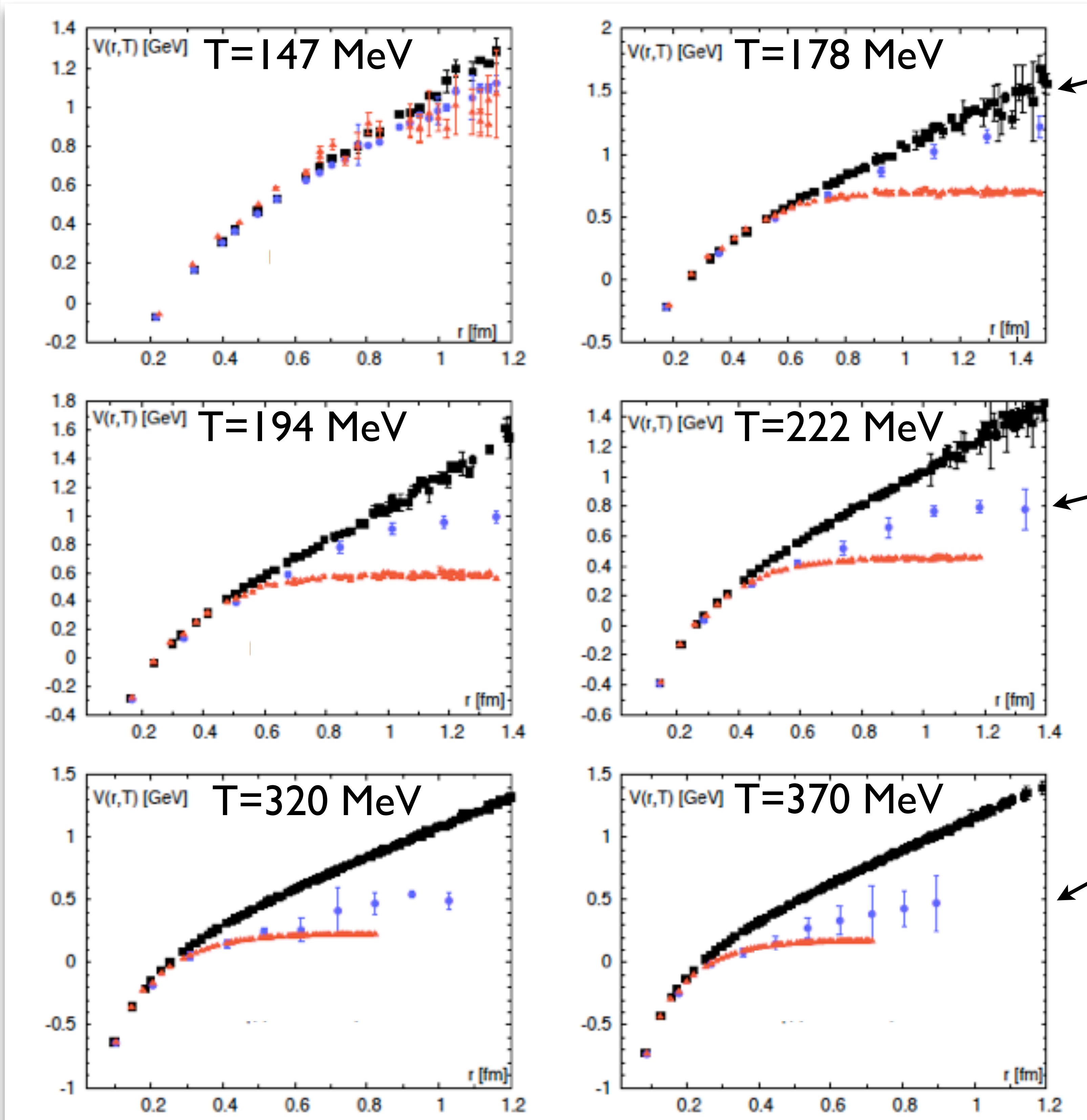
Extract σ with MeM or a fit

Burnier, Rothkopf, 1208.1899 (2012)

Bazavov, Petreczky NPA 904 (2013)

For T=147 MeV, the potential V is the same as the zero temp. potential and agrees with the singlet free energy $F_l$

# ReV from Lattice




V differs slightly from V(T=0) but much larger than $F_l$: no screening

V significantly modified: screening apparent

V approaches $F_l$ from above, never larger than V(T=0)

high T similar behavior in quenched QCD
Burnier, Rothkopf, arXiv:1208.1899

<< Bazavov, Petreczky NPA 904 (2013)

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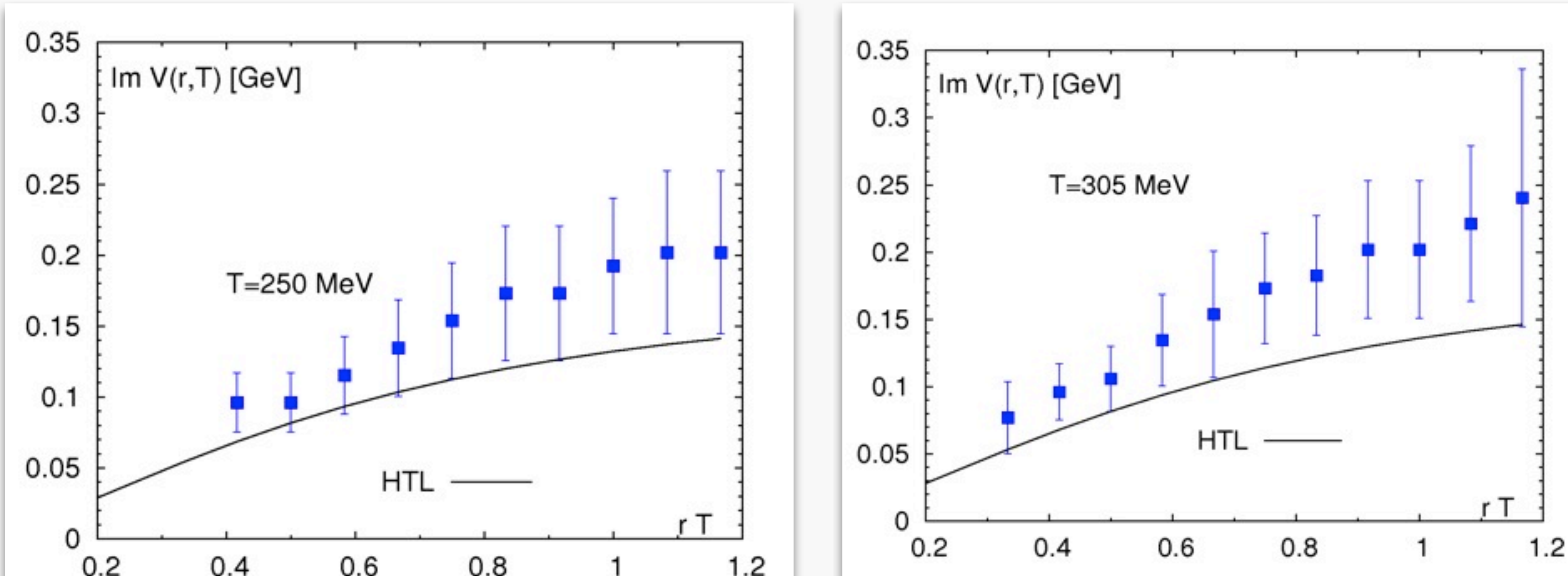
# ImV from Lattice

Petreczky talk at Hard Probes 2013




Large errors on Im V: spectral function width is difficult to extract from the lattice correlators

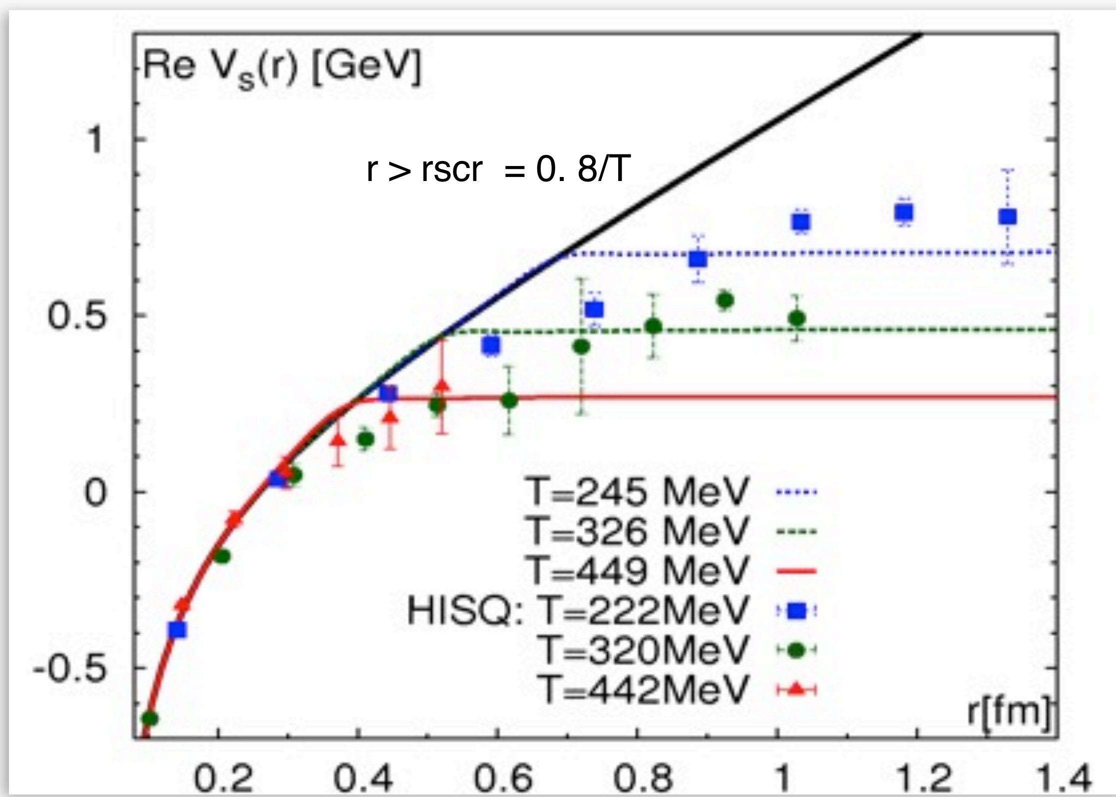
Tends to be larger than in HTL perturbation theory

# Potential for Spectral Functions

## Re $V_S$ (r,T)

Lattice potential matches "maximally binding" parametrization from:

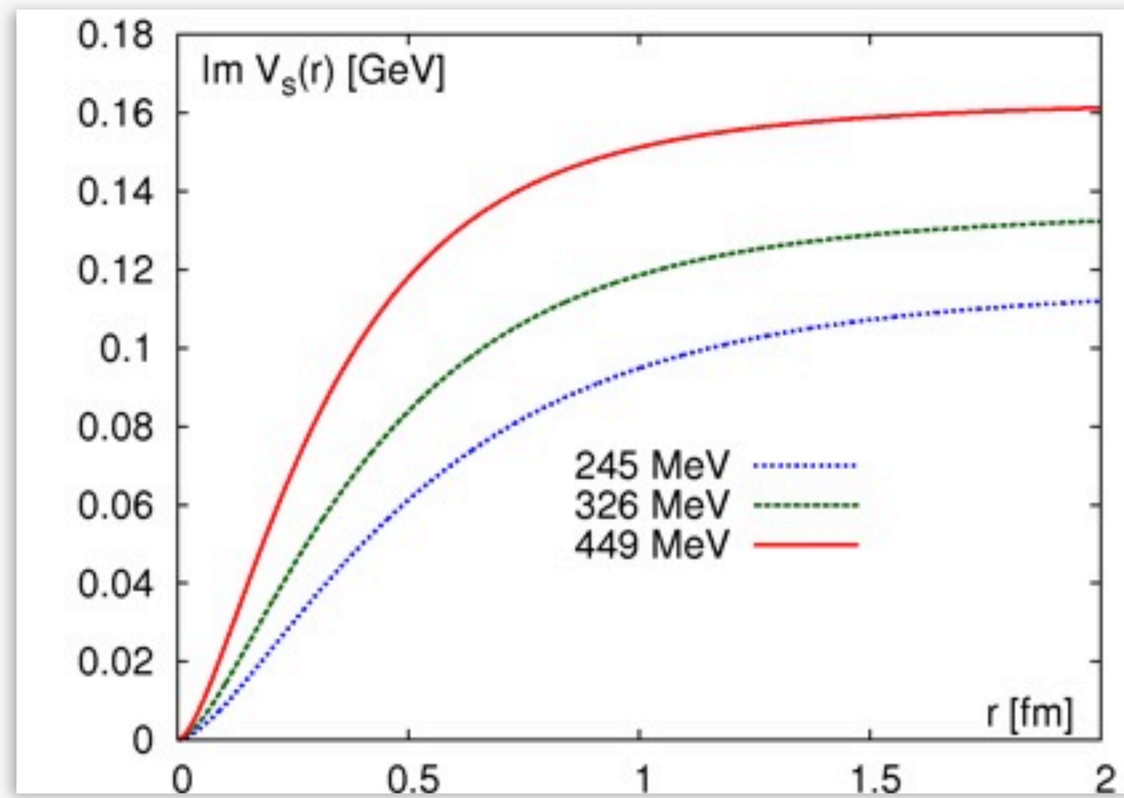
Mócsy, Petreczky, PRL 99 (07) 211602




## Im $V_S$ (r,T)

From pQCD "minimal" value

Burnier, Laine, Vepsalainen JHEP 0801 (08) 043
Beraudo, arXiv:0812.1130




Miao, Mócsy, Petreczky, NPA (2011)

Encodes effects of screening
Determines quarkonium binding energy

Encodes dissipative effects
Determines bound state widths

# Potential for Spectral Functions

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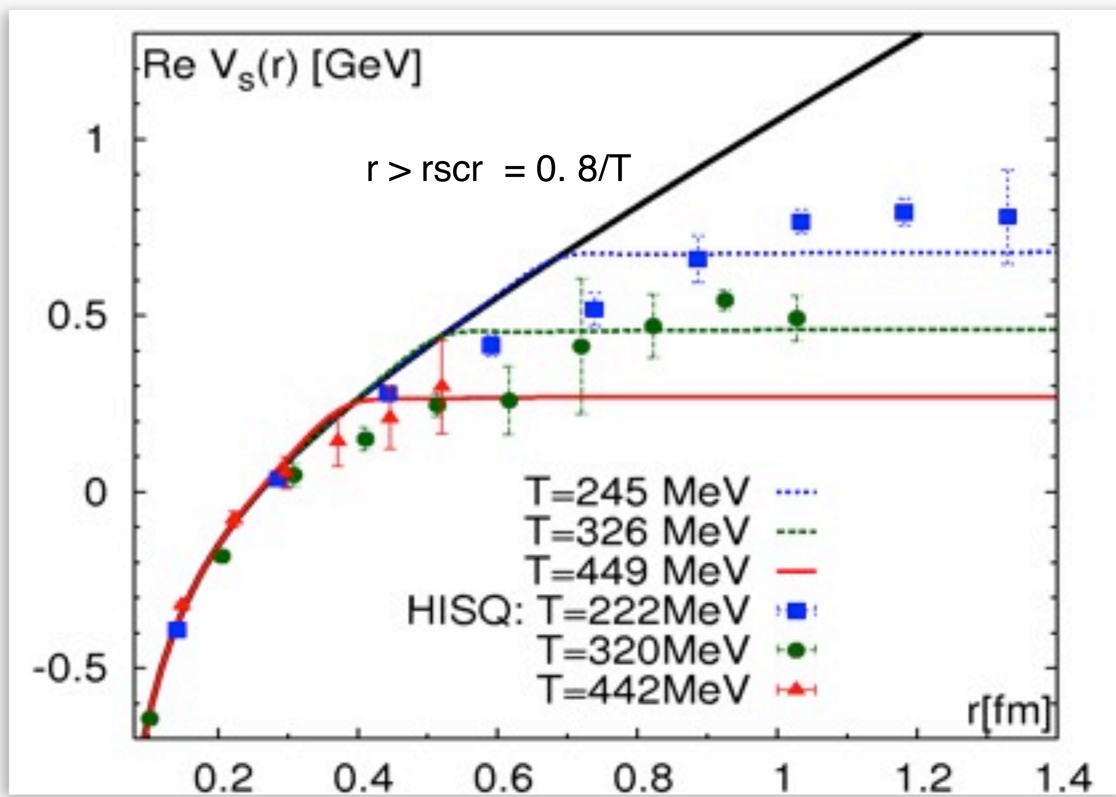


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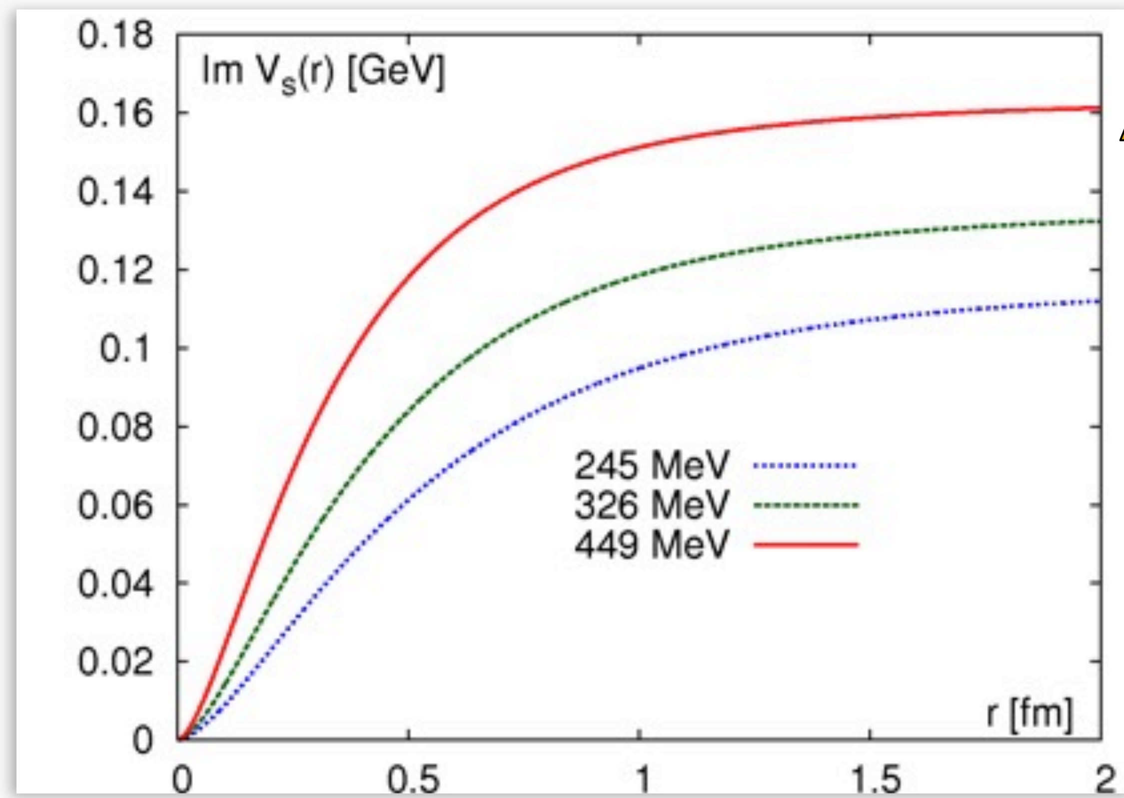


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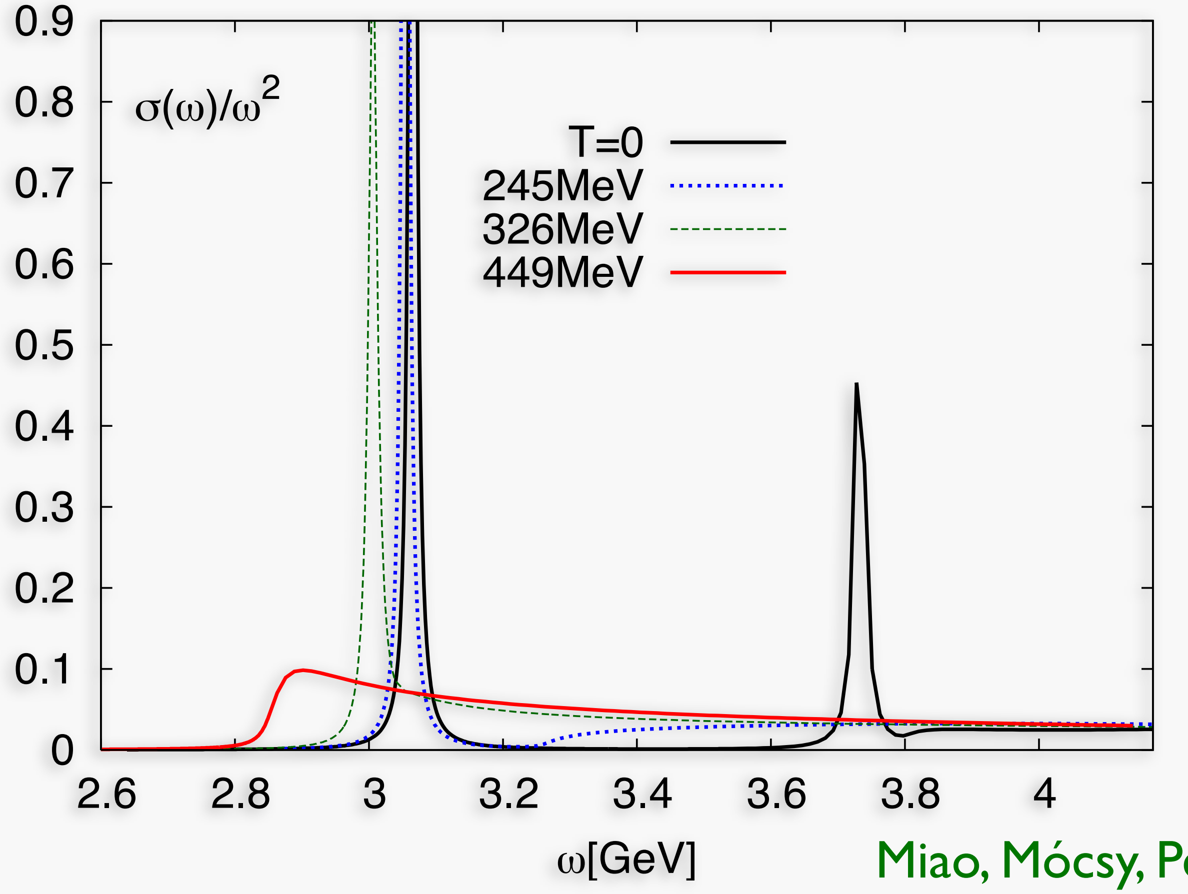
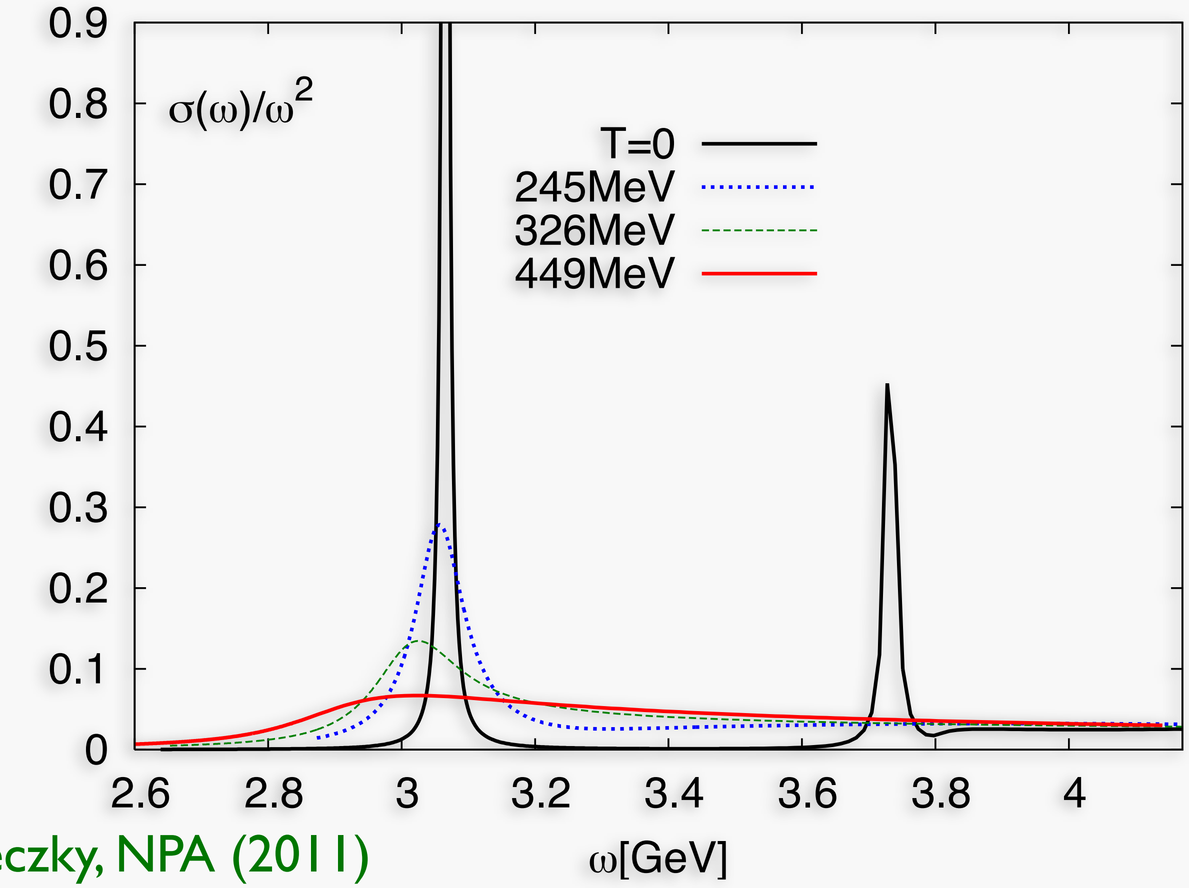
# Role of ImV for Charmonium

Im $V_s(r) = 0$

Im $V_s(r) \neq 0$




Miao, Mócsy, Petreczky, NPA (2011)

1S survives for $T$ = *330* MeV
reduced binding energy, threshold
enhancement → c-cbar correlations

dramatic broadening
all states dissolves for $T$ > *240* MeV,
threshold enhancement → c-cbar correl.

No charmonium state could survive above T= 240 MeV

Consistent with earlier analysis: Mócsy, Petreczky, PRL 99 (07) 211602 *($T_{dec}$ ~ 204MeV)*
and Riek, Rapp, New J. Phys. 13 (2011) 045007

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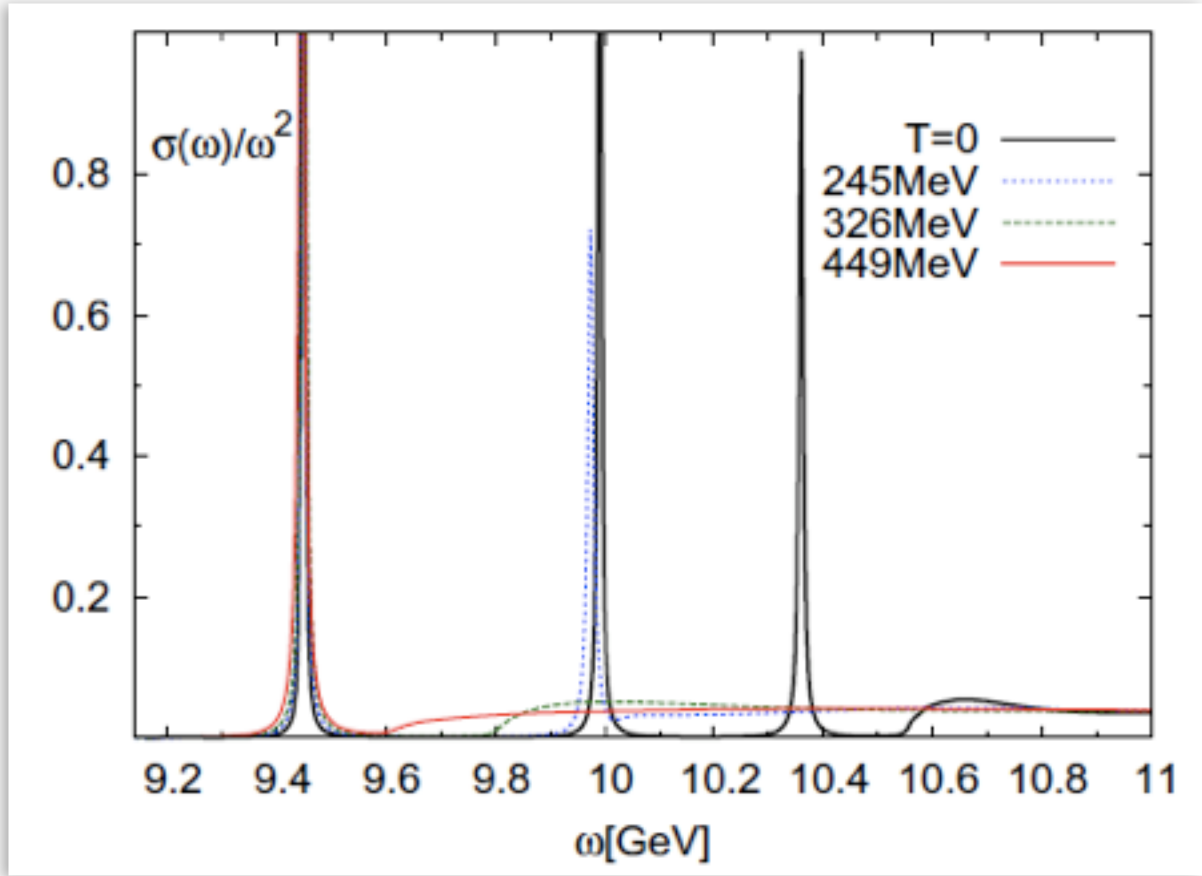
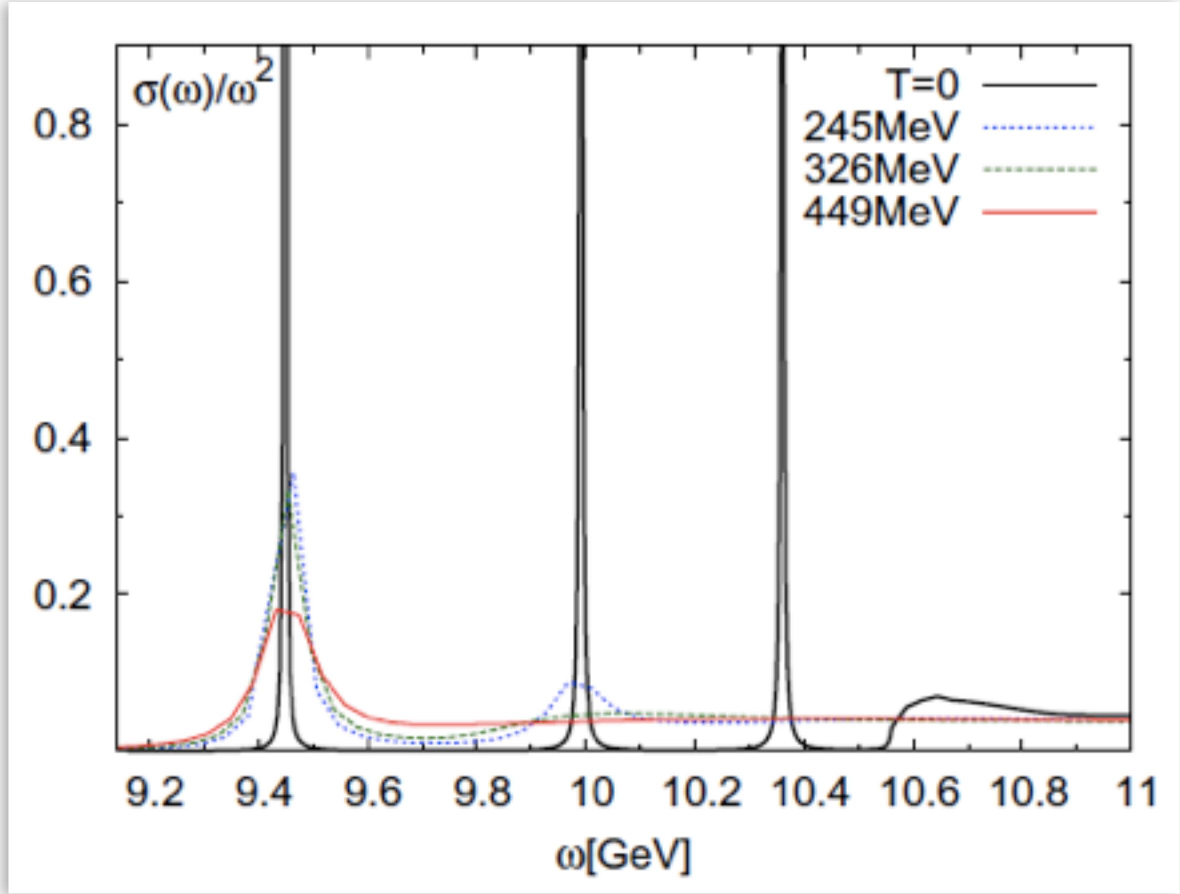
# Role of ImV for Bottomonium

$\mathrm{Im}\, V_s(r) = 0$

$\mathrm{Im}\, V_s(r) \neq 0$




Miao, Mócsy, Petreczky, NPA (2011)

1S and 2S there at high T
reduced binding energies

Dramatic broadening
Re part had little effect

ϒ(2S) and ϒ (3S) melts by *T ~ 250* MeV and ϒ(1S) melts by ~*350* MeV

Microscopic mechanism behind J/Ψ and ϒ melting might be different

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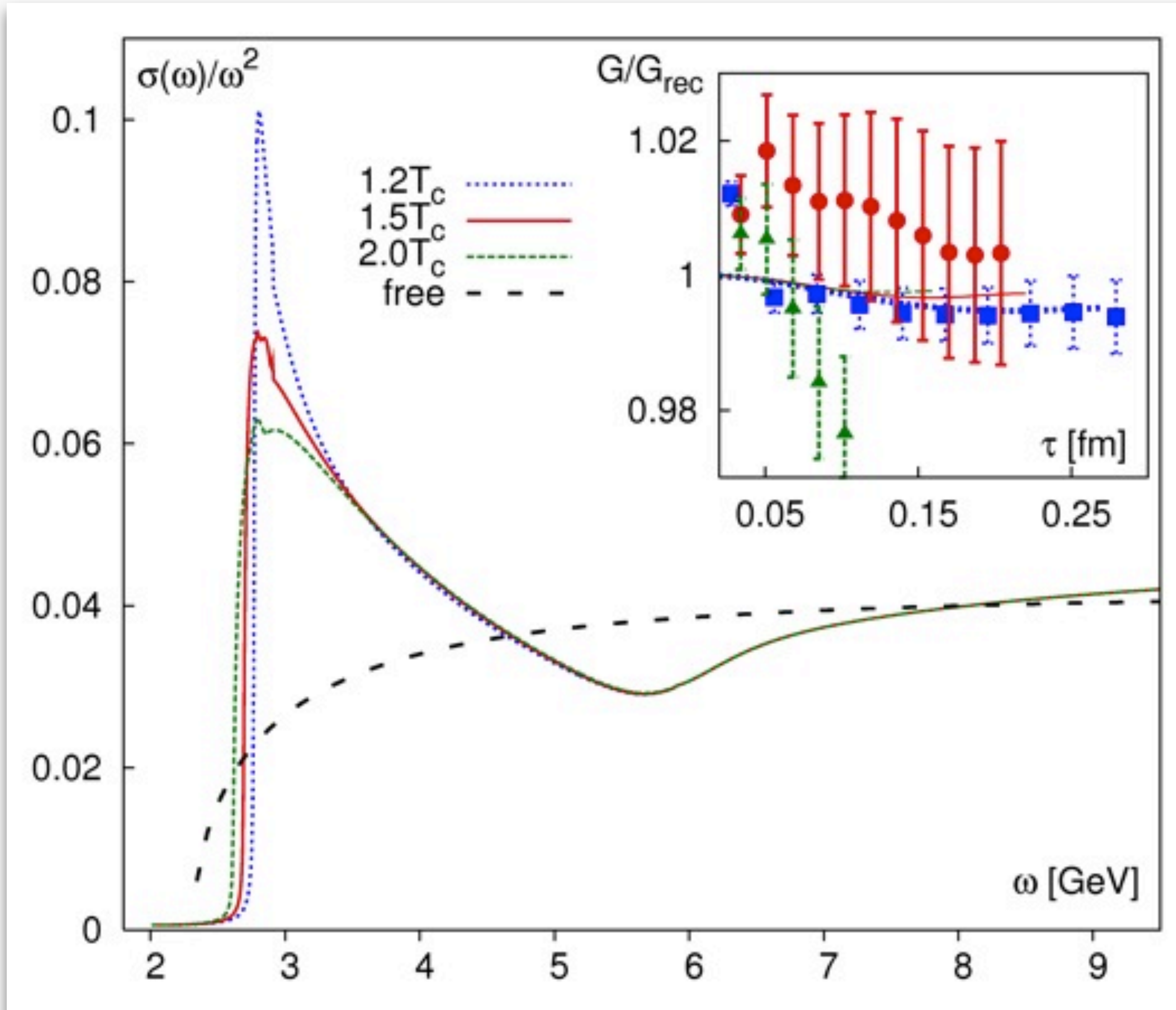
# Back to Correlators

Test the approach vs. LQCD :




Mócsy, Petreczky, PRL 99 (07), PRD77 (08), EPJC (08)

Correlators don't change despite the melting of the bound states

Strong threshold enhancement above free case → indication of correlations

It's difficult to distinguish bound state from threshold enhancement in lattice

This resolved the apparent puzzle between strong modification of potential and small T-dependence of correlators

# Bridge to Experiments

Quarkonium spectral functions cannot be measured in experiment, instead they are input for phenomenological models

- Spectral function → no bound states only correlated c-cbar pairs
- forming J/Ψ depends on
  - lifetime of medium
  - dissipative effects   Svetitsky PRD37 (88) 2484

Microscopic dissipative mechanisms encoded in ImV → gives rise to stochastic force

$$\Psi_{Q\bar{Q}}(X,t) = \mathsf{T}\ \exp(-i\int_0^t dt'(H+\Theta(X,t')))\Psi_{Q\bar{Q}}(X,0)$$

$$H = \frac{-\nabla^2}{2m} + \mathrm{Re}V(x) \quad \langle\Theta(X,t)\Theta(X,t')\rangle \sim \mathrm{Im}V(X)\delta(t-t')$$

Akamatsu, Rothkopf, arXiv:1110.1203, Akamatsu, arXiv:1209.5068

Previously postulated Langevin description showed that:

Young, Shuryak (2009, 2010)
Young et al (2012)

Correlations can explain why $R_{AA}$ *(J/Ψ)* is non-zero even with no bound states

# Summary

From Lattice QCD and from EFT+lattice-based potential model :
J/Ψ is melted, but c-cbar correlations persist,
yet Euclidean meson correlators don't change

Although J/Ψ is gone there is still non-zero suppression at RHIC:
because of finite QGP lifetime there's no time to decorrelate

Bottomonium is more complicated, but we know what to calculate, how to calculate, so we need to calculate it

# The End

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# Summary

EFT approach allows to define the heavy quark potential from QCD, the potential at T>0 has both real and imaginary parts and is different from the free energy and internal energy

QCD matter shows color screening at temperatures $T > 200$ MeV, the static potential can be calculated in lattice QCD from the Wilson loops

The imaginary part of the potential plays a prominent role as a quarkonium dissolution mechanism => dissolution of the 1S charmonium and excited bottomonium states for $T \approx 250$ MeV and dissolution of the 1S bottomonium states for $T \approx 450$ MeV. Microscopic mechanism for Jpsi and Y melting can be different

The study of the spatial meson correlation functions provides the 1st direct lattice QCD evidence for melting of the *1S* charmonium in agreement with potential model studies

# Spatial Charmonium Correlators

Spatial correlation functions can be calculated for arbitrarily large distances

$$G(z,T) = \int_0^{1/T} d\tau \int dx dy \langle J(\mathbf{x}, -i\tau), J(\mathbf{x}, 0)\rangle_T$$

and are related to the same spectral functions

$$G(z,T) = \int_{-\infty}^{\infty} e^{ipz} \int_0^{\infty} d\omega \frac{\sigma(\omega, p, T)}{\omega}$$

Medium effects expected at $z > 1/T$

$$G(z \to \infty, T) \simeq A e^{-m_{scr}(T) z}$$

# Spatial Charmonium Correlators

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Medium effects expected at $z > 1/T$ $\quad G(z \to \infty, T) \simeq A e^{-m_{scr}(T)z}$

Low $T$ limit :

lowest lying meson state $M_{mes}$ governs the large z behavior

$$\sigma(\omega,p,T) \simeq A_{mes}\delta(\omega^2 - p^2 - M_{mes}^2)$$

$$A_{mes} \sim |\psi(0)|^2 \to m_{scr}(T) = M_{mes}$$

$$G(z,T) \simeq |\psi(0)|^2 e^{-M_{mes}(T)z}$$

High $T$ limit :

c and cbar are unbound

$$m_{scr}(T) \simeq 2\sqrt{m_c^2 + (\pi T)^2}$$

Transition between these limits can indicate charmonium melting

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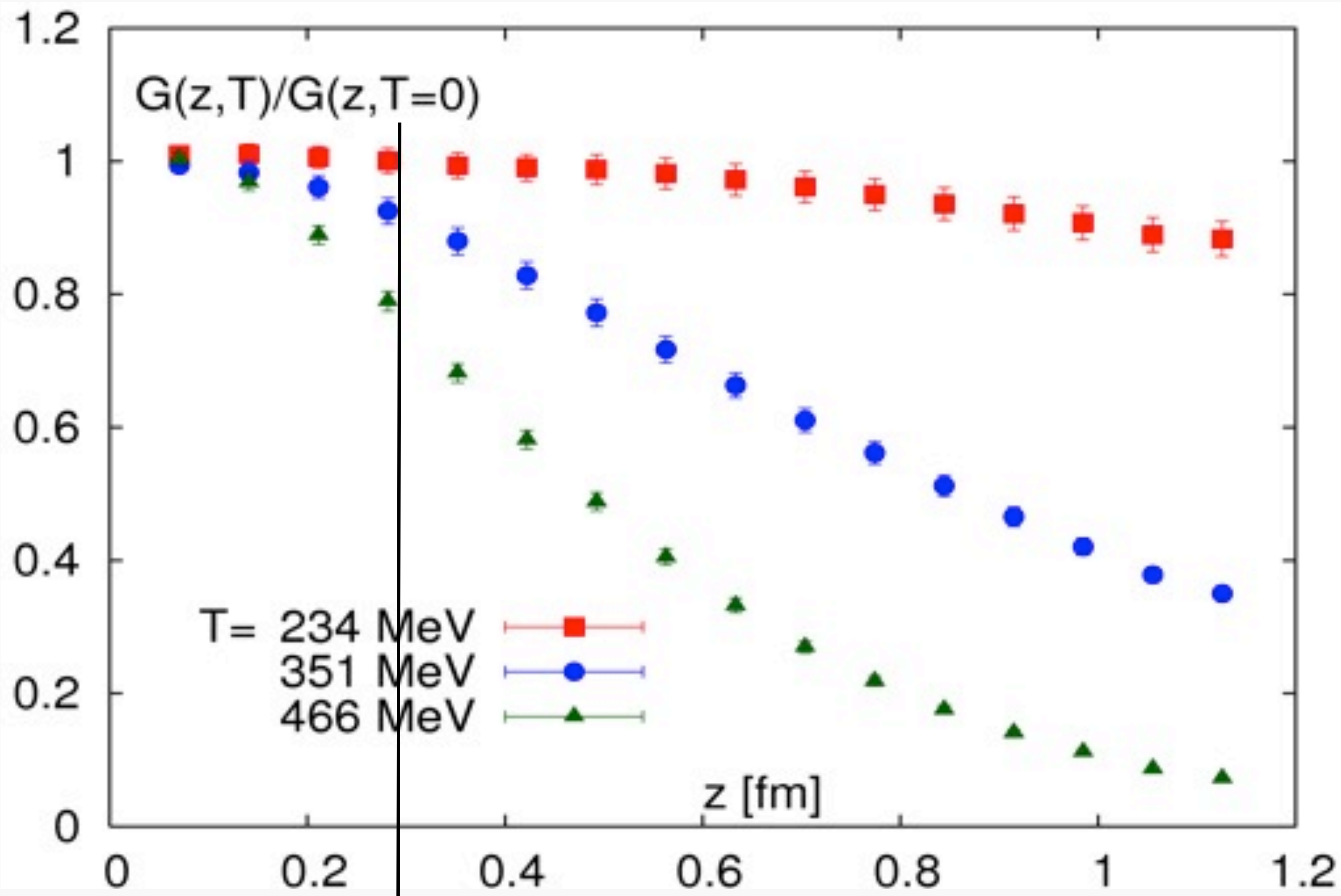
# Spatial Charmonium Correlators

pseudo-scalar channel => 1S state

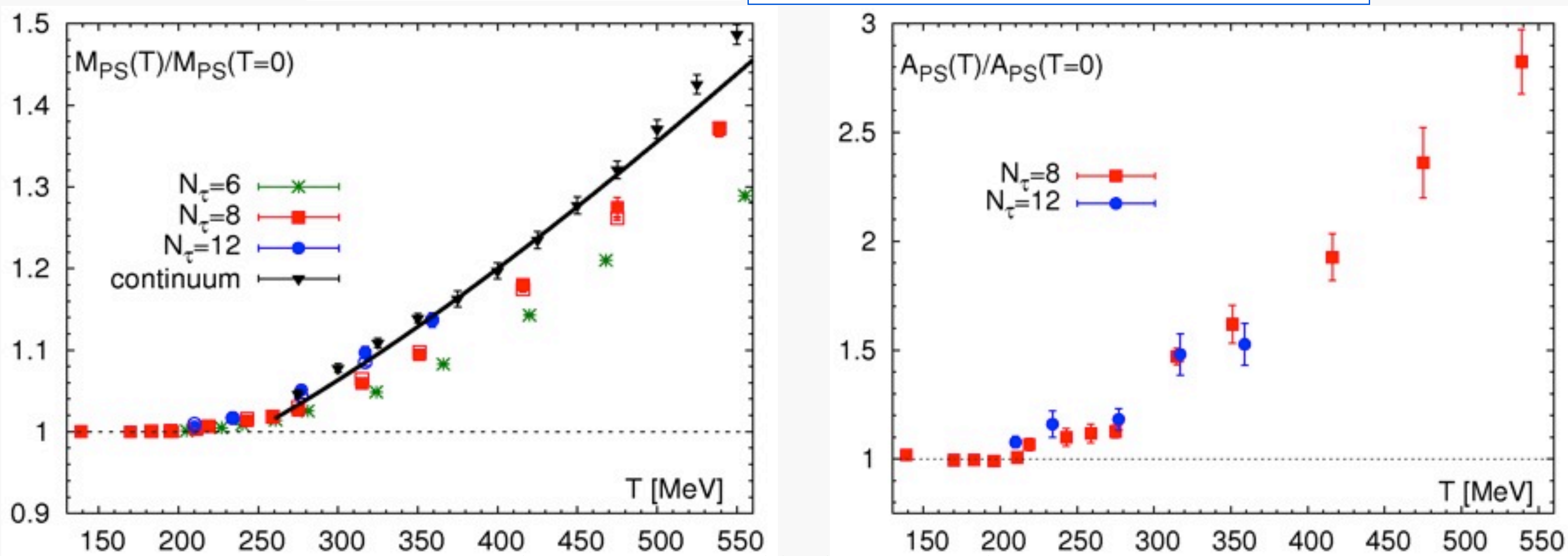



Karsch, Laermann, Mukherjee, PP, PRD 85 (12) 114501

- Changes are smaller for quarkonium than for light mesons
- Significant temperature dependence already for $T > 200$ MeV at $zT > 1/2$
- Larger T more prominent *T*-dependence in the deconfined phase

# Spatial Charmonium Correlators

at large distances $G(z \to \infty, T) \simeq A e^{-m_{scr}(T) z}$




Karsch, Laermann, Mukherjee, Petreczky, PRD 85 (12) 114501

***T* < 200 MeV** no *T*-dependence in the screening masses and amplitudes (wave functions)

**200 < *T* < 275 MeV** moderate, but statistically significant *T*-dependence => medium modification of the ground state

***T* > 275 MeV** Strong *T*-dependence of the screening masses and amplitudes, compatible with free unbound quark behavior => dissolution of 1S charmonium !

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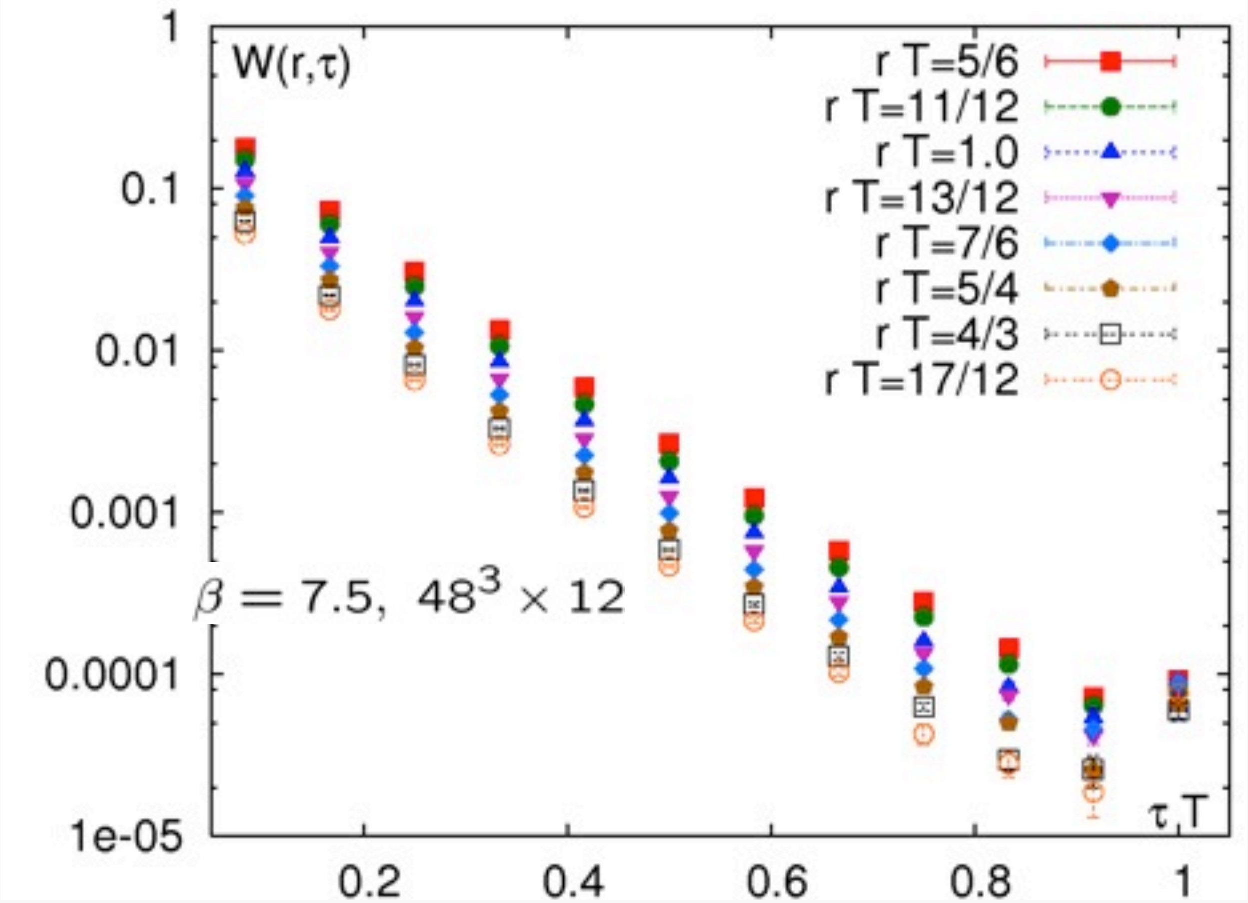
# Static Energy in Lattice QCD

In the limit of small binding energy all the thermal scales can be integrated out, and the heavy quark potential can be approximated by the static energy.
Extract the static Q-Qbar energy from lattice using the spectral decomposition of the Wilson loops

$$W(r,\tau) = \int_{-\infty}^{\infty} d\omega \sigma(\omega, T) e^{-\omega\tau}, \tau < 1/T$$

or the correlation function of two temporal Wilson lines separated by r




assume single state dominance:

$$\sigma(\omega, T) \sim \delta(\omega - V(r,T))$$

at large tau W(r, tau) ~ exp(-V(r) tau)

Rothkopf, PoS LAT2009 (2009) 162
Hatsuda, Rothkopf, PRL 108 (2012) 162001

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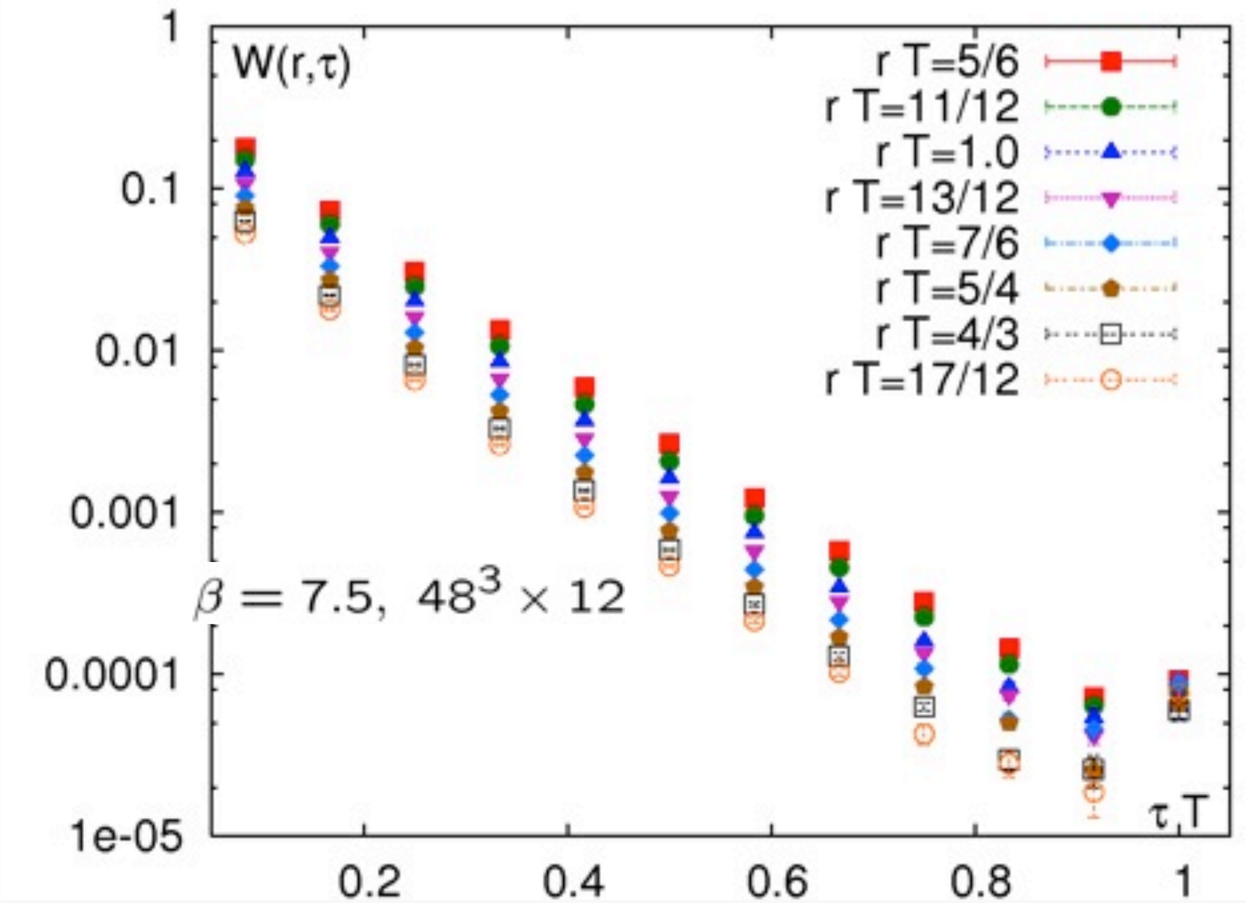


Bazavov, Petreczky (2013)

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Rothkopf, PoS LAT2009 (2009) 162
Hatsuda, Rothkopf, PRL 108 (2012) 162001
Allton et al, JHEP 1111 (2011) 103

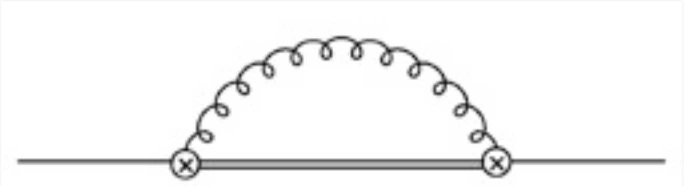
# pNRQCD: $T > E_{bin}$

ReVs (r,T)

ImVs (r,T)

$T < E_{bin}$

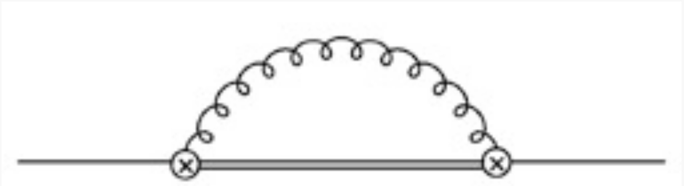
- no T corrections to ReV
- non-potential T contributions (interactions with ultrasoft gluons reduce the binding energy)



Octet transition

$T > E_{bin}$

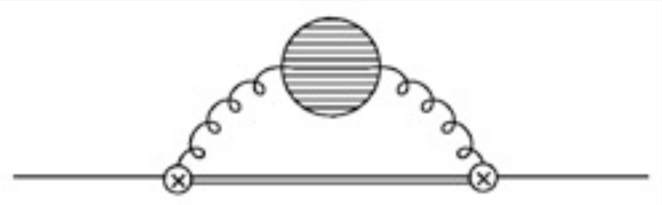
- there are T corrections to ReV



Brambilla et al 2009

thermal breakup of a Q-$\bar{Q}$ color singlet into a color octet state and gluons

Landau damping



Laine 2007

gluon self-energy, scattering of gluons off thermal excitations in the medium

# pNRQCD: T > $E_{bin}$

## ReVs (r,T)

**T < $E_{bin}$**

- no T corrections to ReV
- non-potential T contributions (interactions with ultrasoft gluons reduce the binding energy)

**T > $E_{bin}$**

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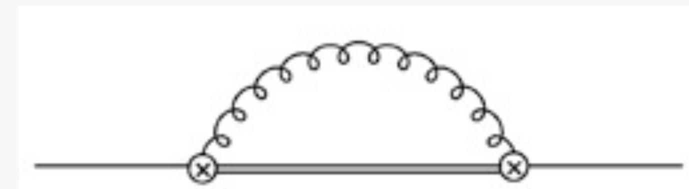
- only for r > 1/$m_D$ exponential screening

$$V_s(r) = -\frac{4}{3}\frac{\alpha_s}{r}e^{-m_D r} + i\frac{4}{3}\alpha_s T\frac{2}{r m_D}\int_0^\infty dx\,\frac{\sin(m_D r\,x)}{(x^2+1)^2} - \frac{4}{3}\alpha_s(m_D + iT)$$

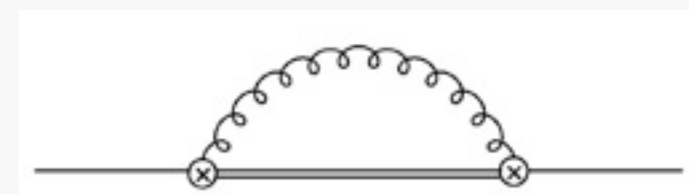
$$\text{Re}V_s(r,T) = F_1(r,T)$$

Laine et al 2007
Blaizot et al 2008

## ImVs (r,T)



Octet transition



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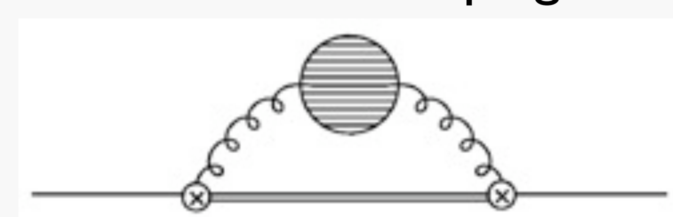

Laine 2007

gluon self-energy, scattering of gluons off thermal excitations in the medium

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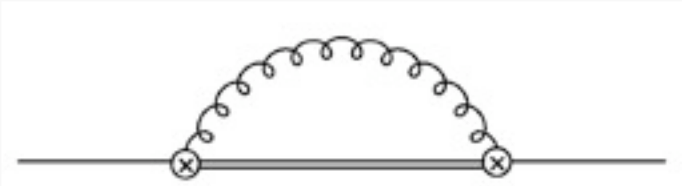
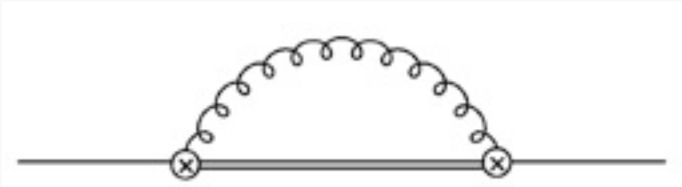


Octet transition



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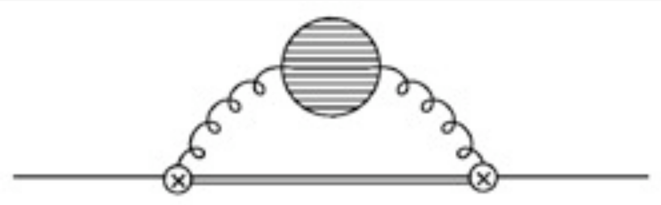

Laine 2007

gluon self-energy, scattering of gluons off thermal excitations in the medium

**EFT's importance: provides a framework in which quarkonium at finite temperature can be studied systematically**

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# New Potential Models

Above deconfinement the binding energy is reduced and eventually is the smallest scale (zero binding) $T, m_D, \Lambda_{QCD} >> E_{bind} = mv^2$ => most of medium effects can be described by a *T*-dependent potential

Potential model is ***not*** a model but derived from QCD, pNRQCD

If the octet-singlet interactions due to ultra-soft gluons are neglected, the dynamics of singlet fields is determined by the Schrödinger equation :

$$\left[i\partial_0 - \frac{-\nabla^2}{m} - V_s(r,T)\right] S(r,t) = 0 \quad \Rightarrow \quad \sigma(\omega, T)$$

The potential Vs(r,T) is complex - its form depends on the relation of scales

In the transition region scale separation does not hold, and effect of non-perturbative scales $gT^2$ and $\Lambda_{QCD}$ => rely on lattice to constrain the potential

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# Bridge to Experiments

Quarkonium spectral functions cannot be measured in experiment, instead they are input for phenomenological models

- Most quarkonia formed inside QGP : $\tau_{onia} \approx \tau_{QGP} \approx 0.5$ fm
- Spectral function → no bound states only correlated c-cbar pairs
- forming J/Ψ depends on
  - lifetime of medium
  - dissipative effects — Svetitsky PRD37 (88) 2484

Microscopic dissipative mechanisms encoded in ImV → gives rise to stochastic force

$$\Psi_{Q\bar{Q}}(X,t) = \mathrm{T}\ \exp(-i\int_0^t dt'(H+\Theta(X,t')))\Psi_{Q\bar{Q}}(X,0)$$

$$H = \frac{-\nabla^2}{2m} + \mathrm{Re}V(x) \quad \langle\Theta(X,t)\Theta(X,t')\rangle \sim \mathrm{Im}V(X)\delta(t-t')$$

Akamatsu, Rothkopf, arXiv:1110.1203, Akamatsu, arXiv:1209.5068

At $r \to \infty$ $\mathrm{Im}V=2\Gamma_Q$ damping rate of quarks and $\Gamma_Q$~D — Blaizot et al (2008), Pisarski (1993)

Results in the previously postulated Langevin description — Young, Shuryak (2009, 2010)
Young et al (2012)

**Correlations explained $R_{AA}$ (J/Ψ) is non-zero even if there are no bound states**

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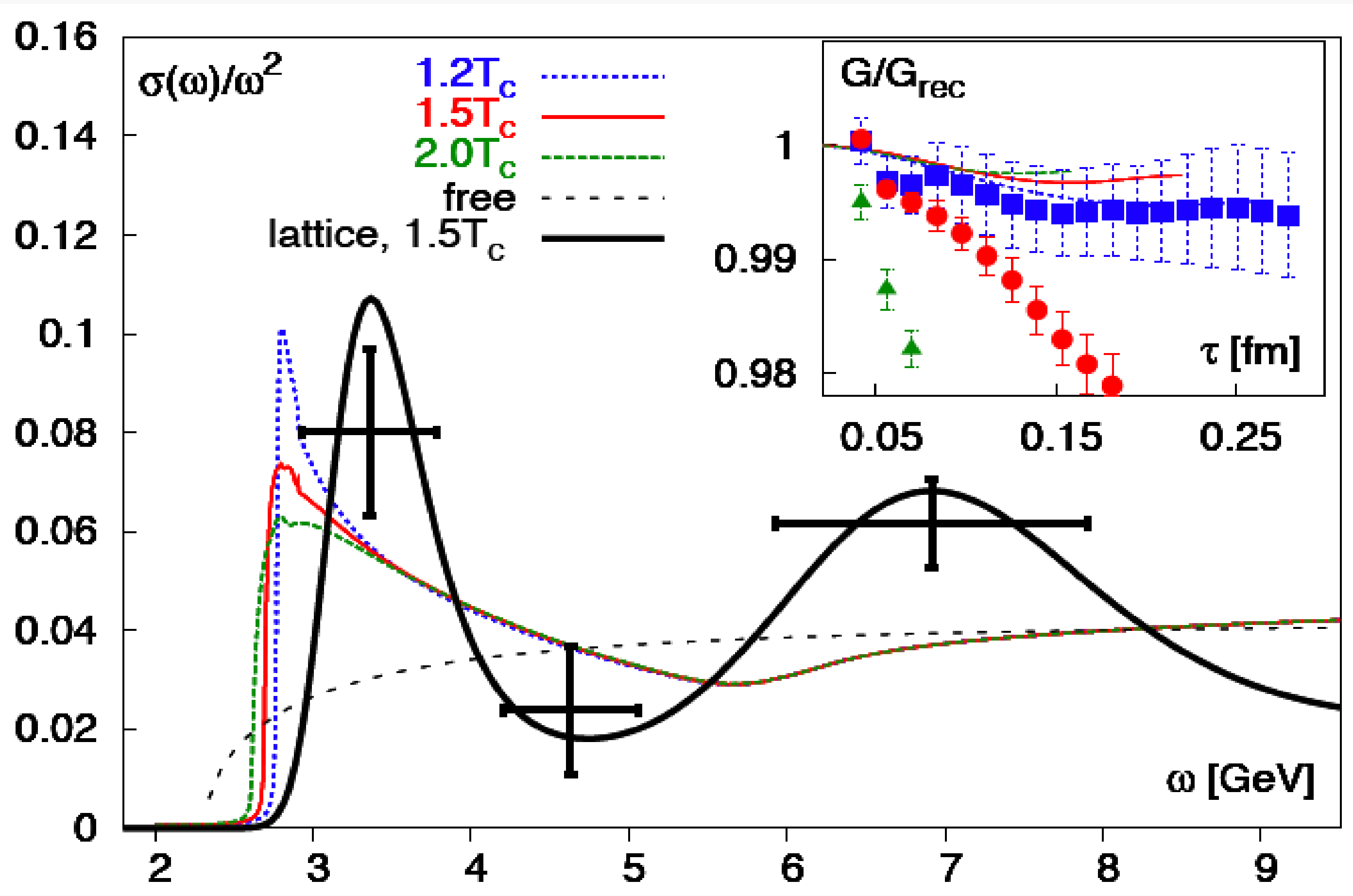
# Potential Model

Test the approach vs. LQCD :

quenched approximation $F_l(r,T) < ReV_s(r,T) < U_l(r,T)$ and $ImV(r,T) \approx 0$

Mócsy, P.P., PRL 99 (07) 211602, PRD77 (08) 014501, EPJC ST 155 (08) 101




- Resonance-like structures disappear already by *1.2T$_c$*
- Strong threshold enhancement above free case => indication of correlations
- Height of bump in lattice and model are similar
- Correlators do not change despite the melting of the bound states => it's difficult to distinguish bound state from threshold enhancement in lattice
- Precise choice of potential doesn't matter

This resolved the apparent puzzle between strong modification of potential and small T-dependence of correlators

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# From spectral functions to experiment ?

Quarkonium spectral functions cannot be measured in experiment unlike light meson spectral functions, instead should be used as input into phenomenological models

Most onia are formed (generated) inside QGP : $\tau_{onia} \approx \tau_{QGP} \approx 0.5$ fm

Imaginary potential => open quantum system, the evolution of the QQbar pair is governed by Hamiltonian with noise

$$\Psi_{Q\bar{Q}}(X,t) = \mathrm{T}\ \exp(-i\int_0^t dt'(H+\Theta(X,t')))\Psi_{Q\bar{Q}}(X,0)$$

$$H = \frac{-\nabla^2}{2m} + \mathrm{Re}V(x) \quad \langle\Theta(X,t)\Theta(X,t')\rangle \sim \mathrm{Im}V(X)\delta(t-t')$$

Akamatsu, Rothkopf, arXiv:1110.1203, Akamatsu, arXiv:1209.5068

=> Langevin Dynamics

Narrow peak in the spectral functions : rate equations for onia dissociation (formation)

Thews and Rafelski, Rapp et al, Strickland and Bazow …

$$\frac{dN_\Psi}{dt} = -\Gamma_D N_\Psi + \Gamma_F N_c N_{\bar{c}}$$

Very broad peak in the spectral functions: Langevin dynamics of correlated quark anti-quark pair, Young and Shuryak

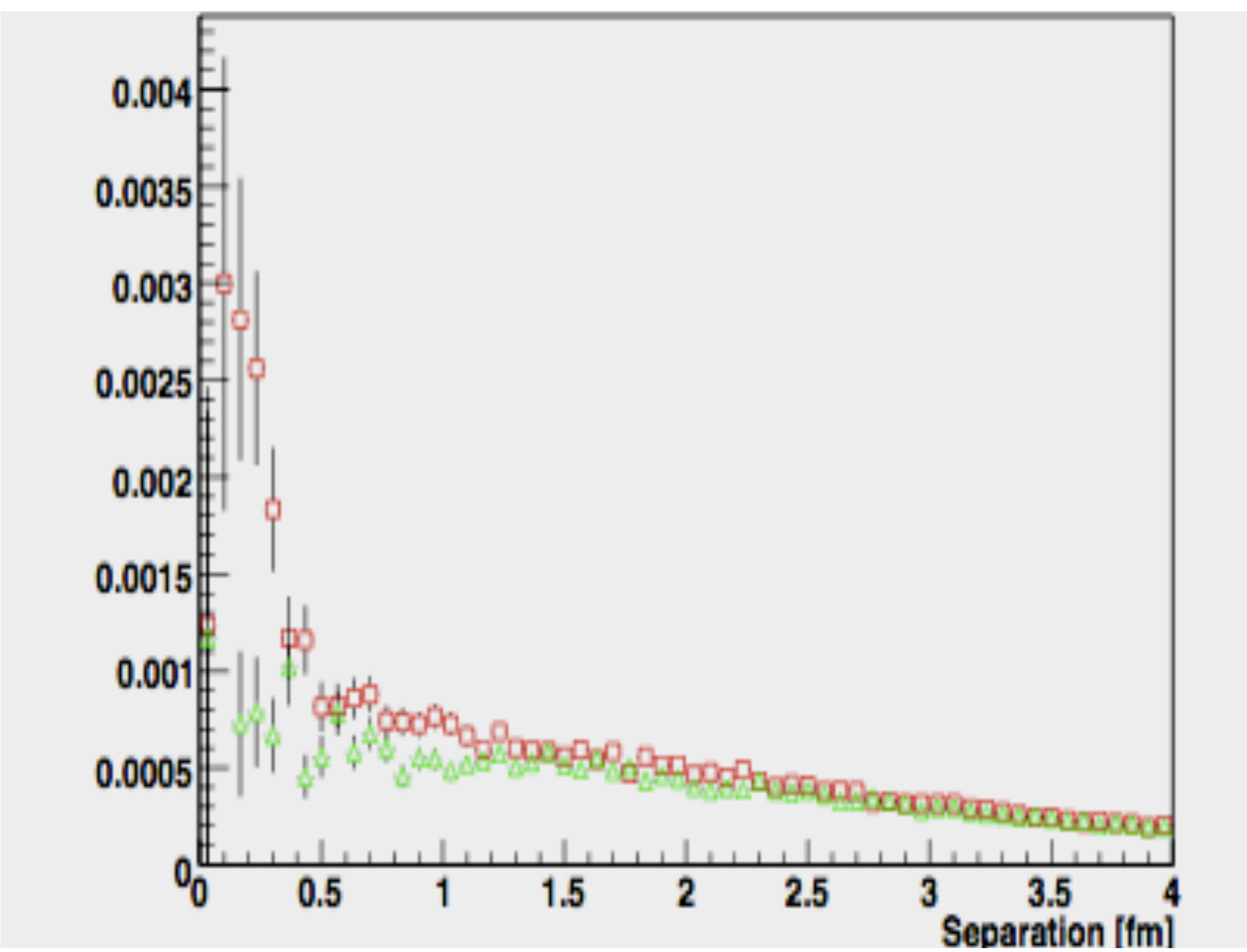
# Langevin dynamics and charmonium suppression

The quarkonium yield at HI is determined not only by the in-medium interaction of quark and anti-quark but also by the in-medium charm difussion (drag)

Svetitsky PRD37 (88) 2484

$$\frac{d\mathbf{p}}{dt} = -\eta\mathbf{p} + \xi - \nabla U$$ ⟵ attractive force between QQbar

$$\frac{d\mathbf{r}}{dt} = \frac{\mathbf{p}}{m_c}$$




1) diffusion constant from analysis of open charm yield
Moore, Teaney, PRC71 (05) 064904

2) the bulk matter is simulated by hydro

3) $U$ is taken from lattice QCD

4) initial charm distribution from PYTHIA

Young, Shuryak, PRC79 ('09) 034907
$R_{AA}$ $(J/\Psi)$ is non-zero even if there are no bound states because because there is not Enough time in HI collisions to decorrelate the Qqbar pair. Recombinant production can also be calculated, Young, Shuryak, arXiv:0911:3080