# Theory aspects of quarkonia production in heavy ion collisions

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## Where do we stand ?

In this talk:

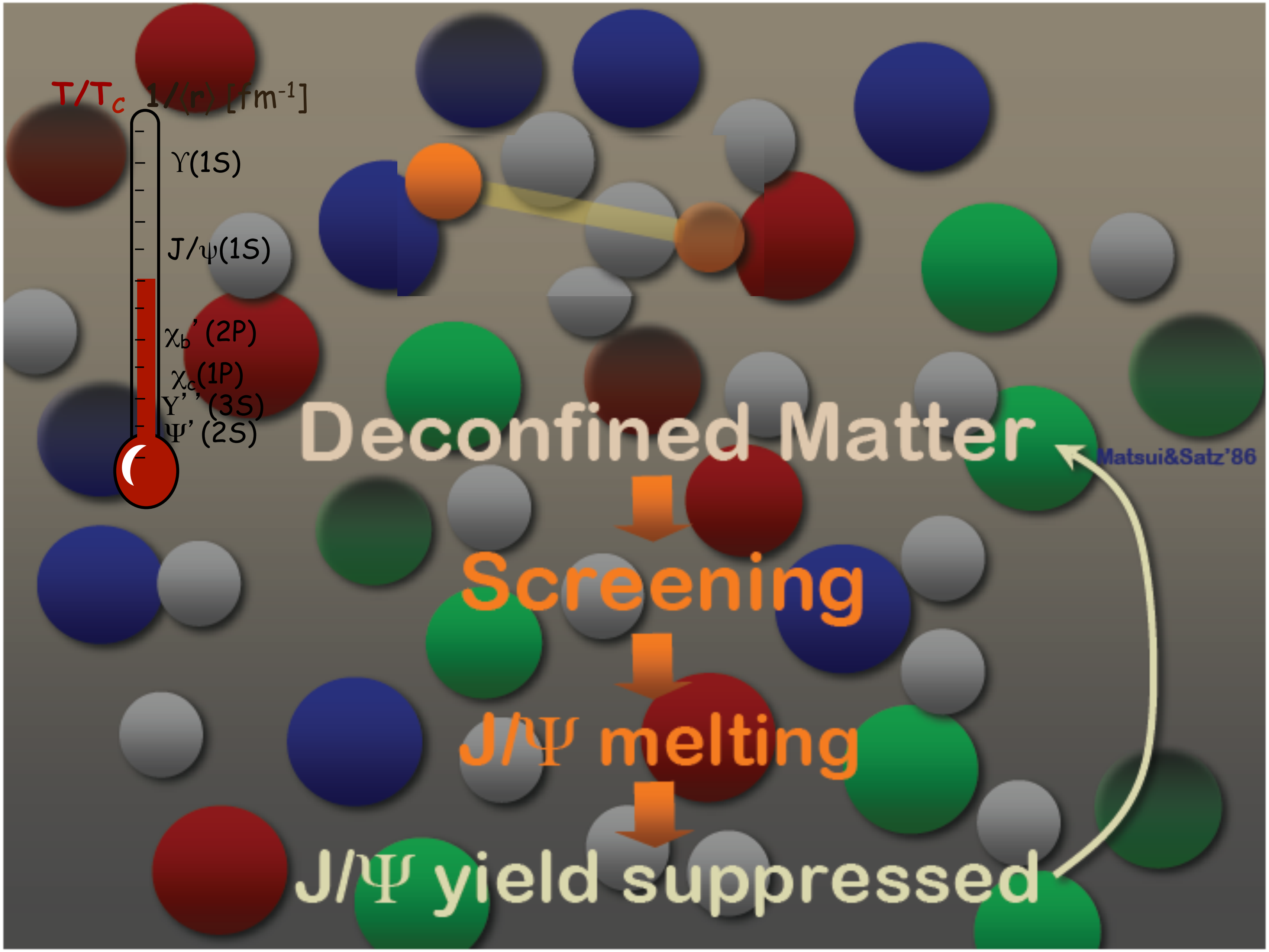
Times scales of quarkonium production and of the medium

Some phenomenological models of quarkonium production

Sequential melting and lattice QCD: color screening and meson correlation functions

Role of heavy quark diffusion in quarkonium production

ECT* Workshop: New Observables in Quarkonium Production



Deconfined Matter

Screening

J/Ψ melting

J/Ψ yield suppressed

From Mocsy '08

# What do we know from RHIC and LHC experiments and what are the implications for quarkonium ?

Rapid thermalization $t_{therm} < 1$ fm in heavy ion collisions the formed medium
Behaves hydrodynamically with $\eta/s = 0.08\text{-}0.2$, i.e. strongly coupled
Heavy quarks interact strongly with the medium

Quarkonium are formed in the deconfined medium not in the vacuum
$t_{form} \sim 1/(mv^2) \sim t_{therm}$ :

⇒ Onium Production in AA is very different from onium production in pp
( color singlet vs. color octet mechanism is irrelevant to some extent )

⇒ One should deal with in-medium formation of onium rather than with suppression of already formed onium states

Heavy quark diffusion is relevant for quarkonium production

# A model for in-medium quarkonium production

Transport model by Zhao & Rapp PRC82 (2010) 064905

- Quarkonium states can be formed for $T < T_D$ and their number is estimated using statistical recombination:

$$N_\Psi^{\rm stat}(T) = \gamma_c^2(N_{c\bar{c}};T)\, V_{\rm FB}\, d_\Psi \int \frac{d^3p}{(2\pi)^3} f^\Psi(p;T)$$

$$N_\Psi^{\rm eq} = \mathcal{R}(\tau)\, N_\Psi^{\rm stat}\ ,\ \mathcal{R}(\tau) = 1 - \exp(-\tau/\tau_c^{\rm eq})$$

- Quarkonium states are dissociated by the medium at rate determined by the in-medium width $\Gamma_\psi$

$$\frac{{\rm d}N_\Psi}{{\rm d}\tau} = -\Gamma_\Psi(T)\,[N_\Psi - N_\Psi^{\rm eq}(T)]$$

Need to determine $T_D$, $M_\psi(T)$, $\Gamma_\psi(T)$ from QCD calculations (need the spectral functions from EFT/LQCD)

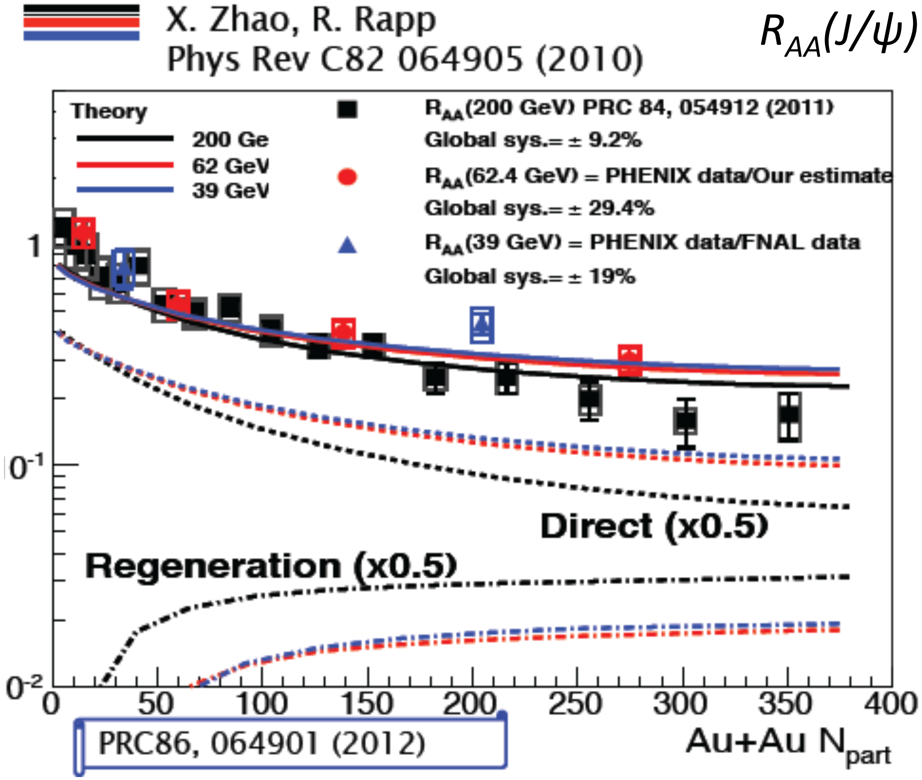
Need fireball/correlation volume $V_{FB}$ from microscopic calculations, e.g. Langevin dynamics

# Highlights of the model :

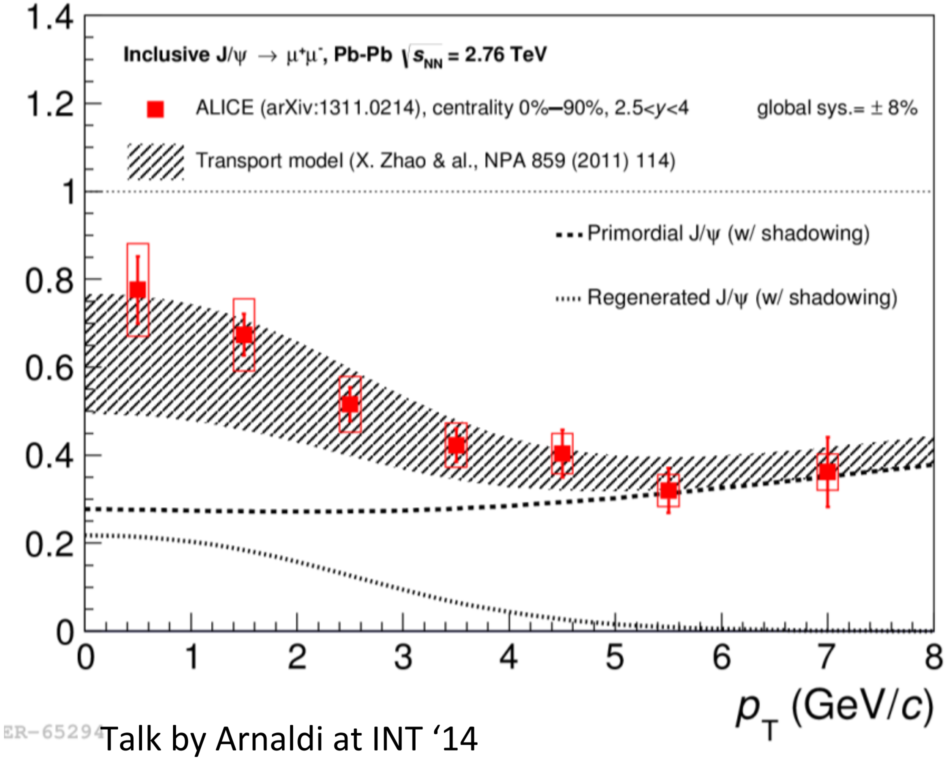
Can explains the energy energy independence of $R_{AA}(J/\psi)$

Can explain the centrality independence of and the size of $R_{AA}(J/\psi)$ observed at LHC

Can explain the $p_T$ dependence of J/ yield



$R_{AA}(J/\psi)$



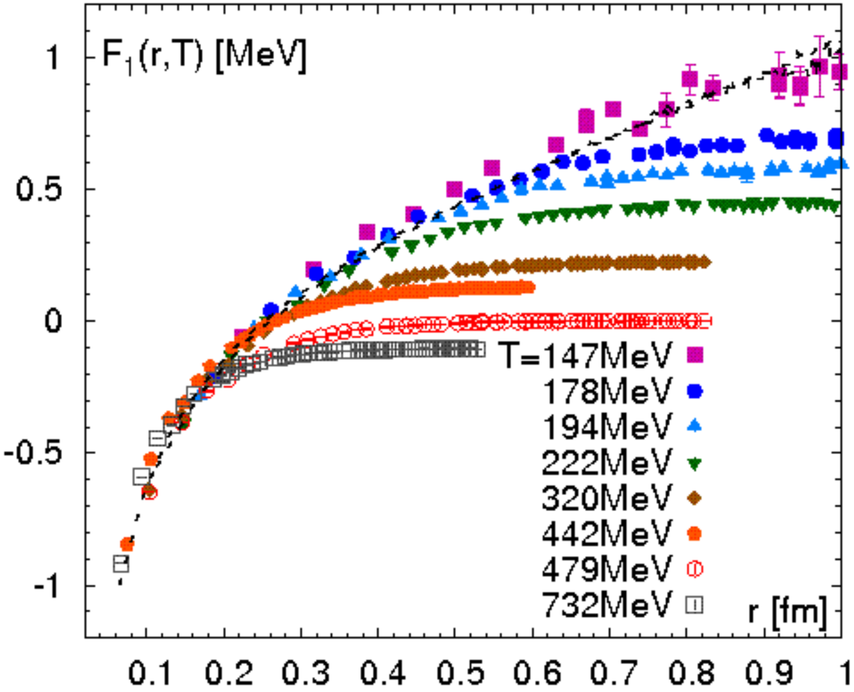
Talk by Rosati at INT '14

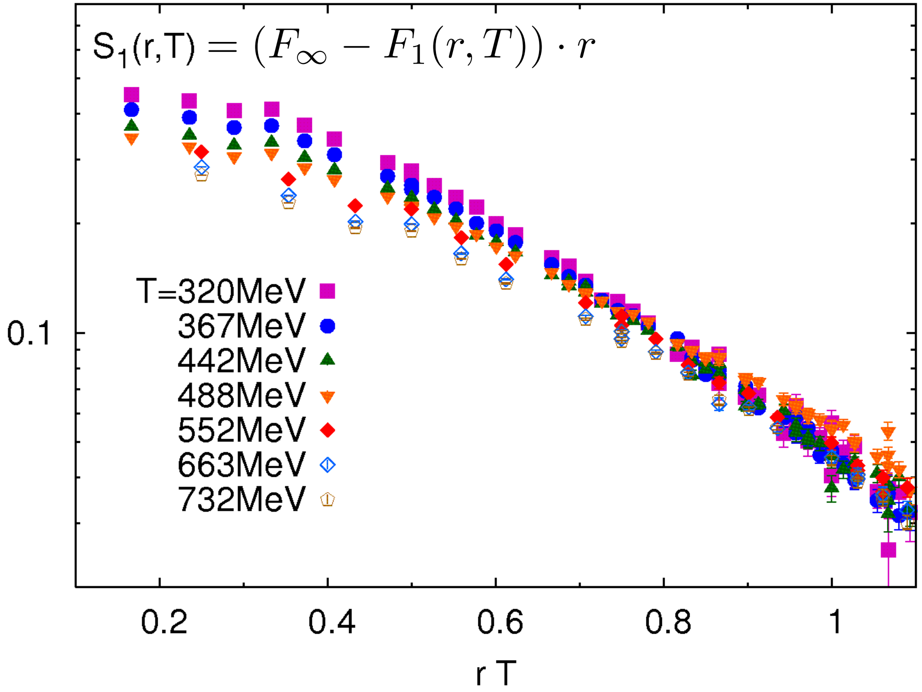
Talk by Arnaldi at INT '14

Works also for bottomonium, Emerick, Zhao and Rapp, Eur.Phys.J. A48 (2012) 72

# Color screening in lattice QCD: singlet free energy

HISQ action, $24^3 \times 6$, $16^3 \times 4$ (high T) lattices, $m_\pi \simeq 160$ MeV





$F_1(r,T)$ $T$-independent at short distances

$F_1(r,T)$ scales with $T$ and is exponentially screened for $r > 0.8/T$

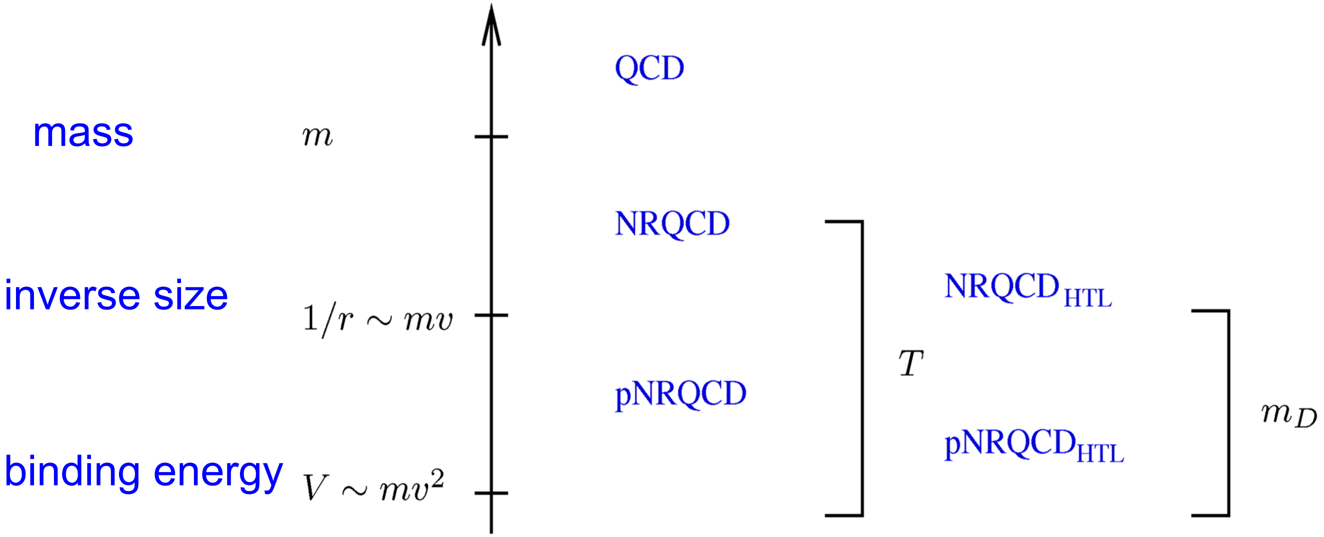
$$F = F_\infty - A\exp(-m_D r)/r$$

$r_{screen} < 0.8/T$ → Rough idea about the melting temperatures $T_D$

How to go from completely static picture to quarkonium ?

# Effective field theory approach for heavy quark bound states and potential models

The heavy quark mass provides a hierarchy of different energy scales



QCD

mass $m$

NRQCD

inverse size $1/r \sim mv$

$T$

$\mathrm{NRQCD}_{\mathrm{HTL}}$

pNRQCD

$\mathrm{pNRQCD}_{\mathrm{HTL}}$

$m_D$

binding energy $V \sim mv^2$

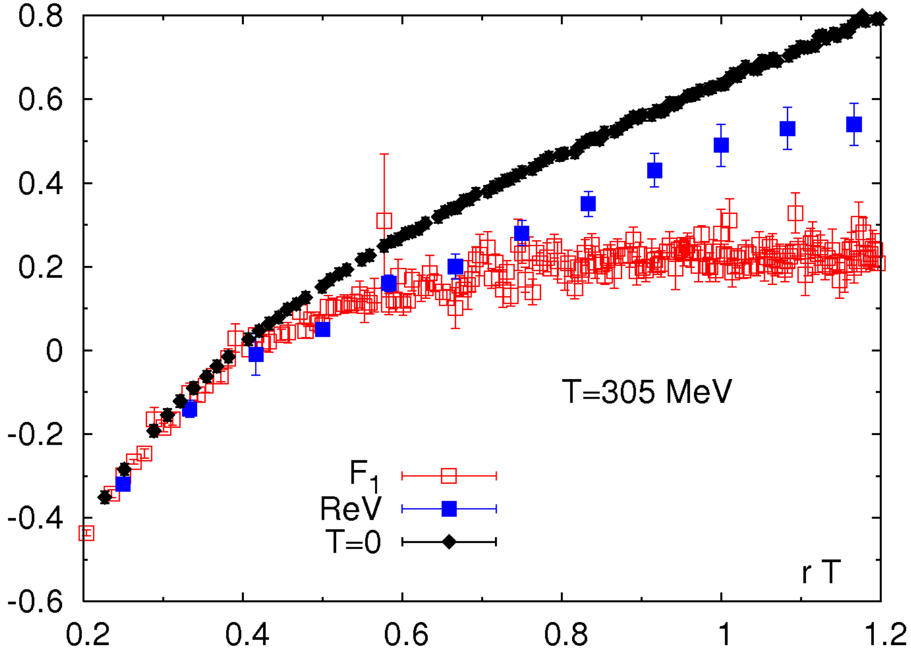
The scale separation allows to construct sequence of effective field theories: NRQCD, pNRQCD

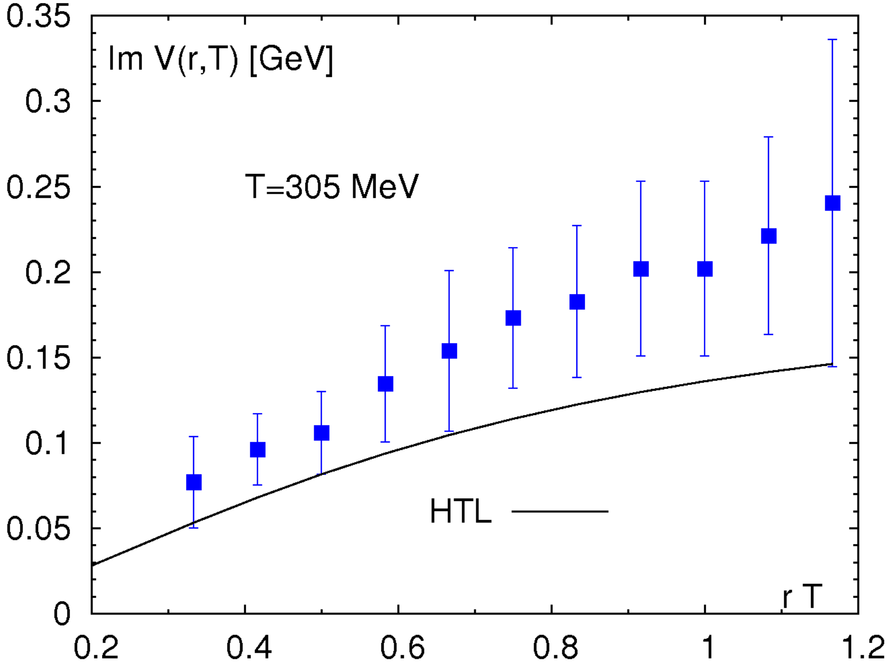
$\Rightarrow$ Complex potential, imaginary part is related to gluo-dissociation and Landau damping

Potential model appears as the tree level approximation of the EFT and can be systematically improved

# Static energy from LQCD

Bazavov, Burnier, PP, arXiv:1404.4267





- For $r\,T < 0.7$ the real part of the potential is roughly equal to the singlet free energy
- At larger distances it is between the singlet free energy and the $T=0$ potential
- The imaginary part increases with $r$ and saturates at $r\,T \sim 1$

# pNRQCD beyond weak coupling and potential models

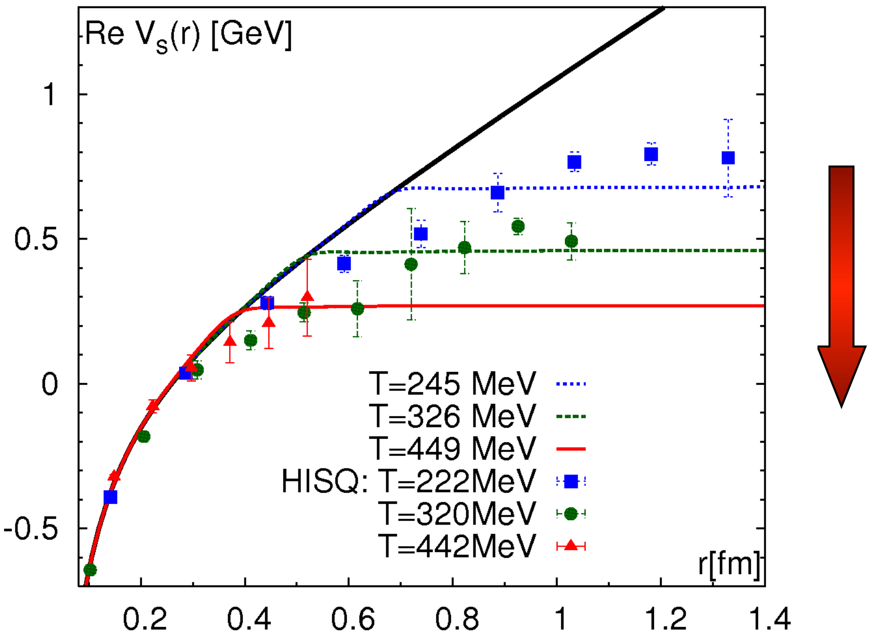
Above deconfinement the binding energy is reduced and eventually $E_{bind}$~$mv^2$ is the smallest scale in the problem (zero binding) $2\pi T, m_D, \Lambda_{QCD} >> mv^2$ => most of medium effects can be described by a $T$-dependent potential :

*static energy = potential*

Determine the potential by non-perturbative matching to static quark anti-quark potential calculated on the lattice

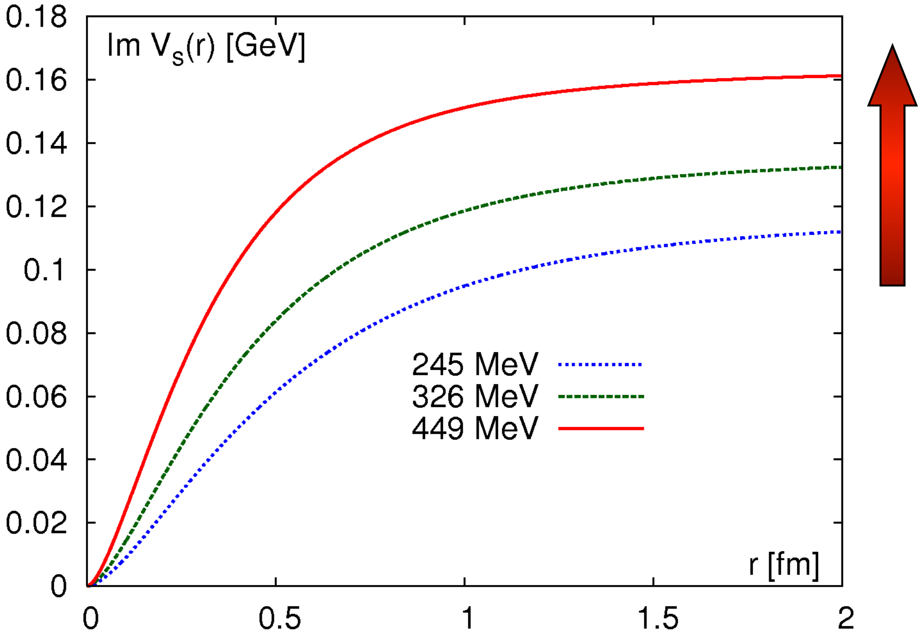
Take Im$V_s(r)$ from pQCD calculations

"Maximal" value for the real part



Mócsy, P.P., PRL 99 (07) 211602

Minimal (perturbative) value for imaginary part



Laine et al, JHEP0703 (07) 054,
Beraudo, arXiv:0812.1130

# Charmonium spectral functions

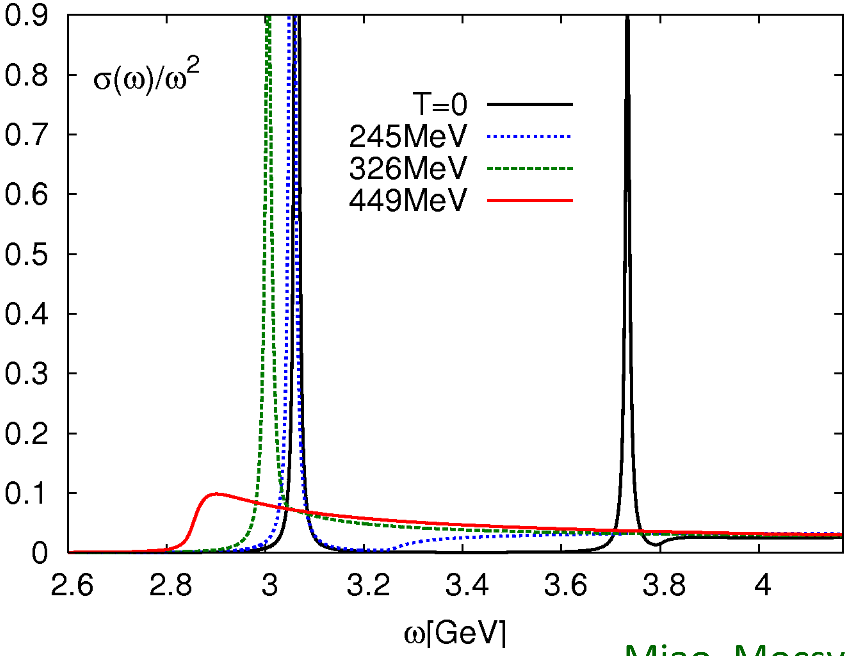
Take the upper limit for the real part of the potential allowed by lattice calculations

Mócsy, P.P., PRL 99 (07) 211602

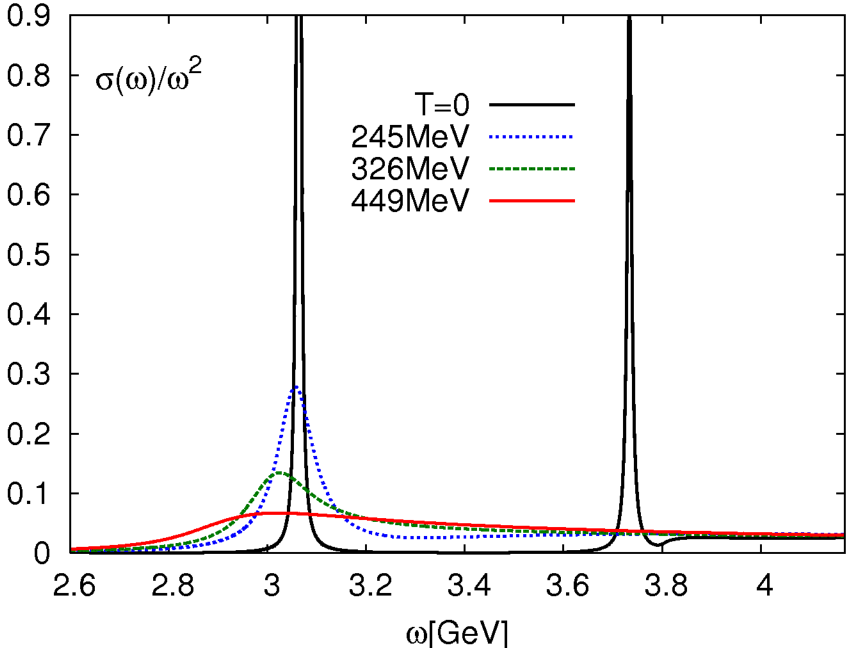
Take the perturbative imaginary part

Burnier, Laine, Vepsalainen JHEP 0801 (08) 043

*Im $V_s(r)$ =0 :*
1S state survives for *T = 330* MeV



imaginary part of $V_s(r)$ is included :
all states dissolves for *T>245* MeV



Miao, Mocsy, P.P., NPA855 (2011) 125

no charmonium state could survive for *T> 245* MeV

# Bottomonium spectral functions

Take the upper limit for the real part of the potential allowed by lattice calculations

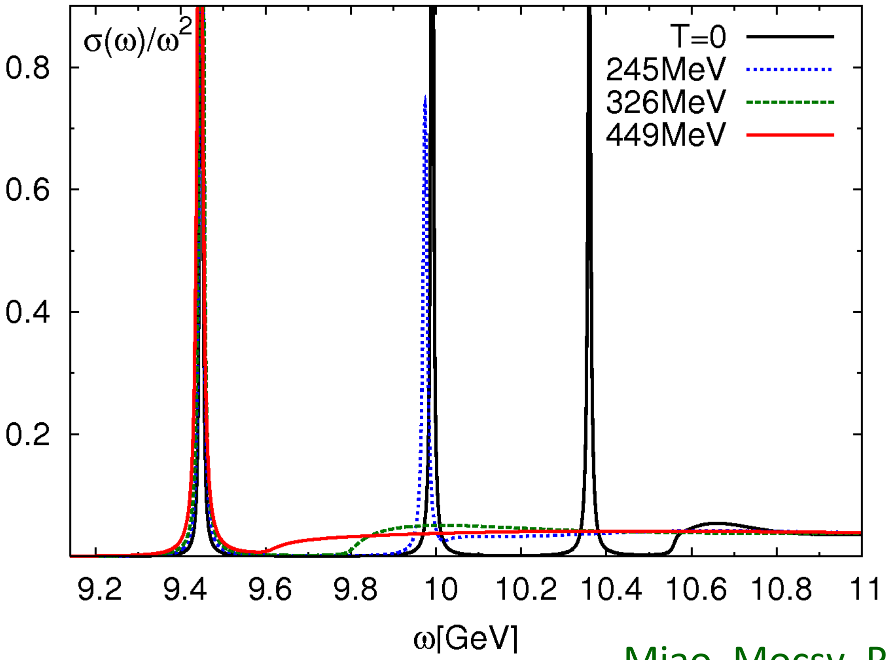
Mócsy, P.P., PRL 99 (07) 211602,

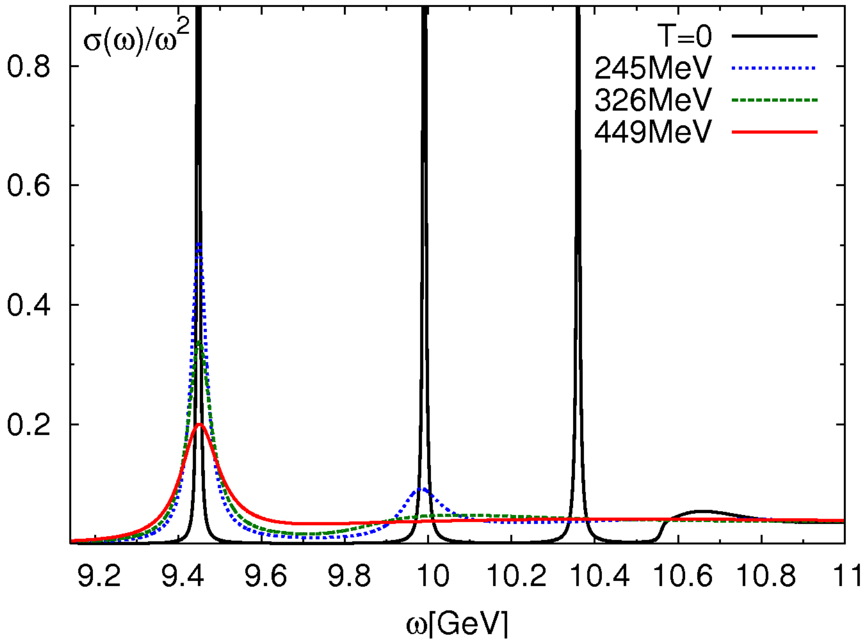
Take the perturbative imaginary part

Burnier, Laine, Vepsalainen JHEP 0801 (08) 043

*Im* $V_s(r)$ *=0:*
2S state survives for *T > 245* MeV
1S state could survive for *T>450* MeV

with imaginary part:
*2S* state dissolves for *T>245* MeV
*1S* states dissolves for *T>450* MeV





Miao, Mocsy, P.P., NPA855 (2011) 125

Excited bottomonium states melt for *T ≈ 250* MeV ; 1S state melts for *T ≈ 450* MeV

# Sequential quarkonium melting

Pattern of melting temperatures or more generally the extent of in-medium Modifications follows the size of different quarkonium states:

$$T_D(\chi_c) \simeq T_D(\chi_b') \simeq T_D(\Upsilon'') \simeq T_c$$

$$T_D(\chi_b) \simeq T_D(\Upsilon') \simeq T_D(J/\psi) \simeq 245\ \mathrm{MeV}$$

$$T_D(\Upsilon) \simeq 450\ \mathrm{MeV}$$

Need to verify this pattern using LQCD :

Meson correlators in Euclidean time are related to spectral functions

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

Problem:

Limited extent in $\tau < 1/(2\ T)$ limitted sensitivity to the $T$-dependence of the spectral function

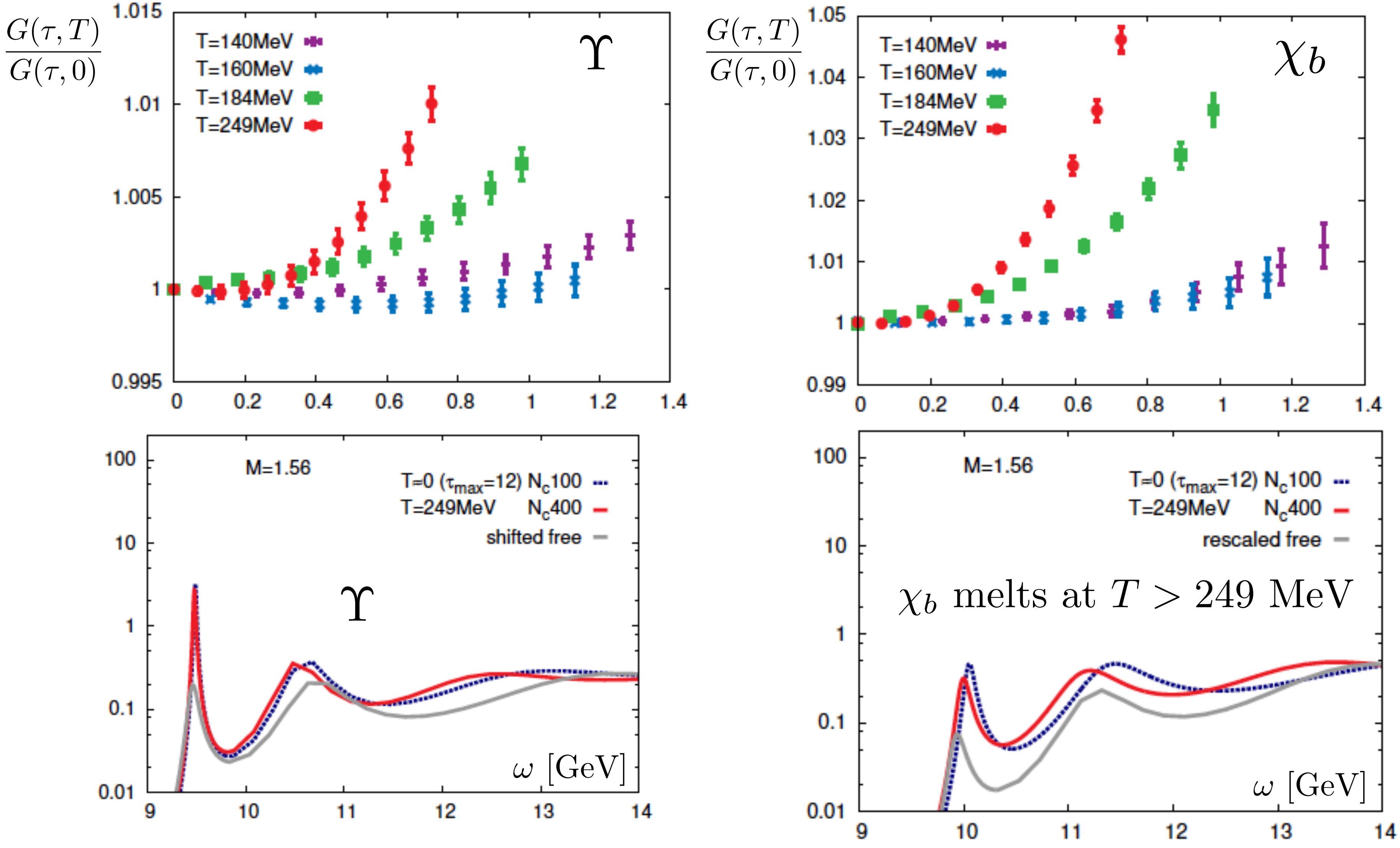
Lattice NRQCD

Spatial correlation functions

# Lattice NRQCD: charmonium correlators

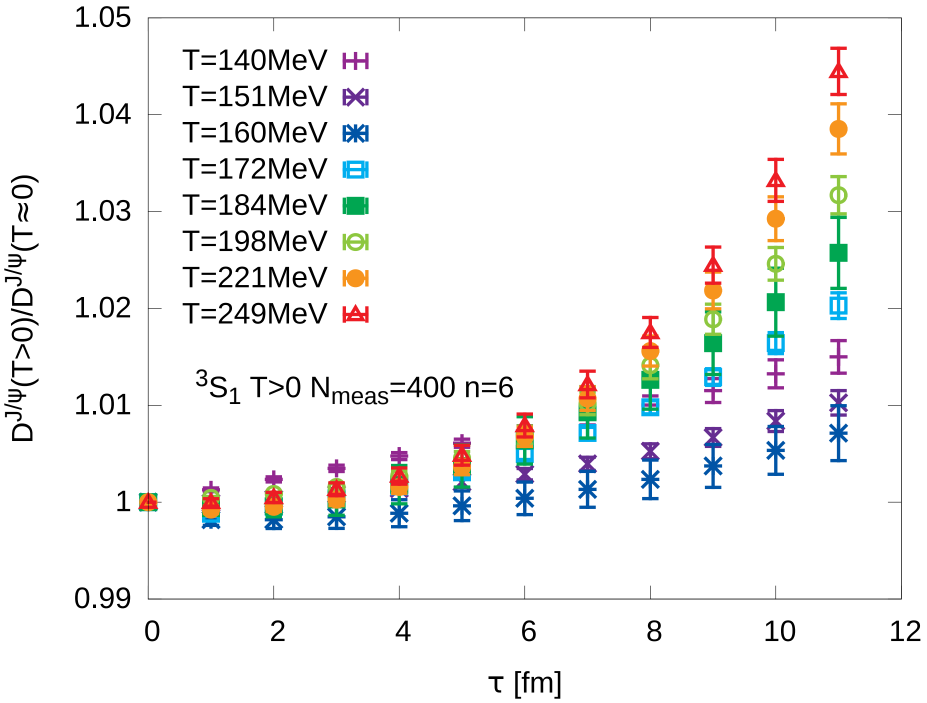
Discretize NRQCD instead of QCD, Kim, PP, Rothkopf, PRD91 (2015) 054511

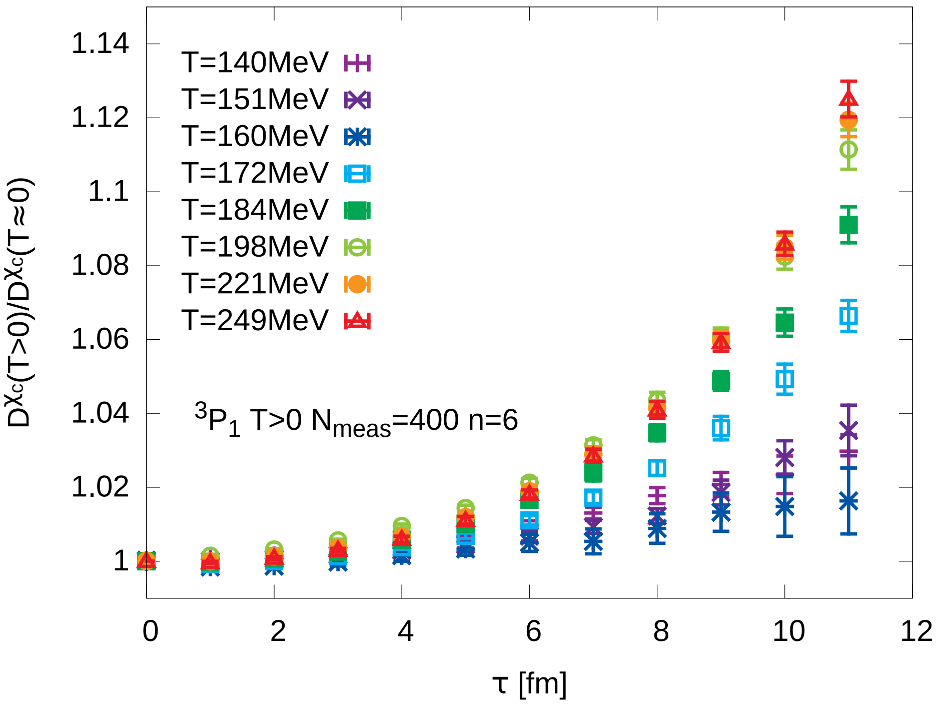
⇒ Simpler quarknium spectral functions, twice larger temporal extent $\tau < 1/T$



$\chi_b$ melts at $T > 249$ MeV

# Lattice NRQCD: charmonium correlators





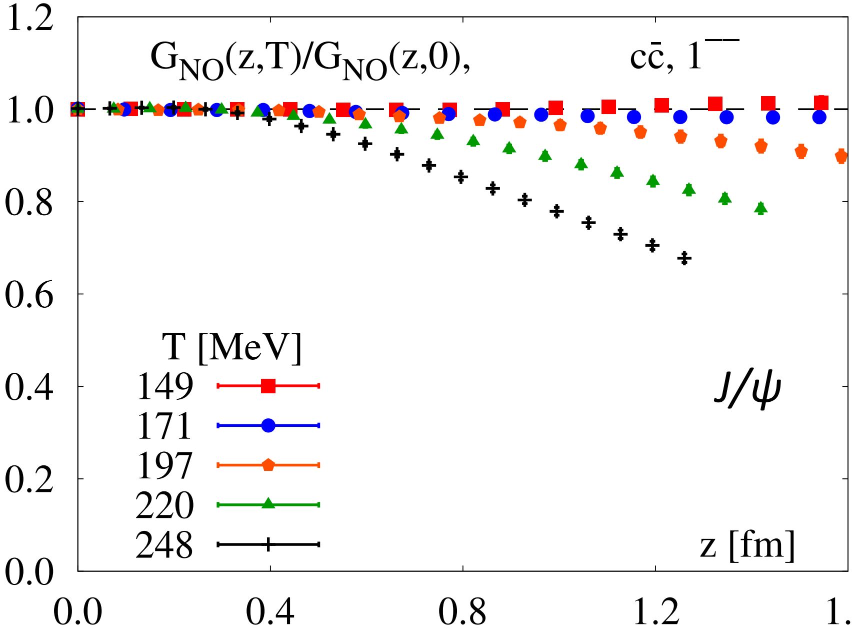
change in $J/\psi$ correlator $< 5\%$

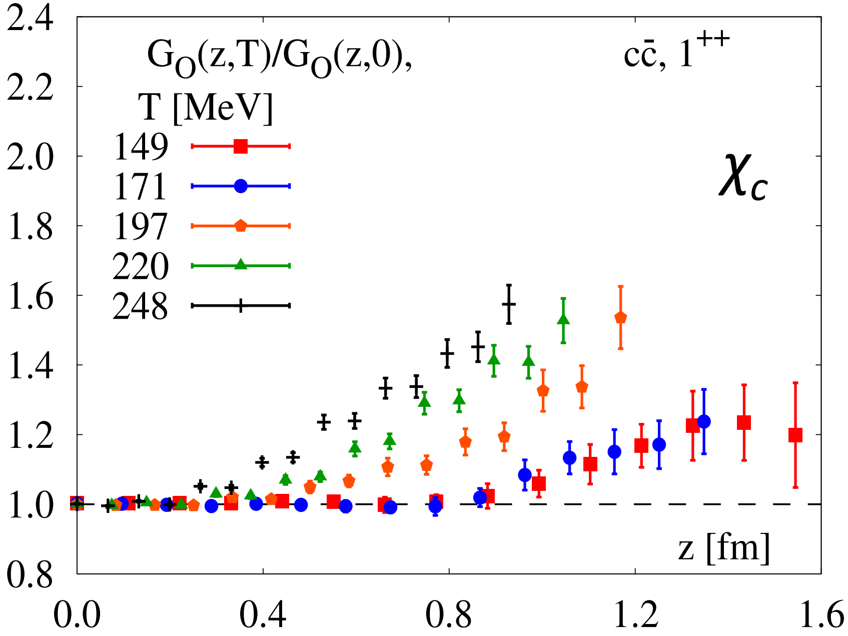
change in $\chi_{c1}$ correlator $< 12\%$

$\Rightarrow$ hints for sequential melting pattern:
changes in the $J/\psi$ correlator are about the same as in the $\chi_b$ correlator (same size); changes in the $\chi_c$ correlators are factor of two larger

Kim, PP, Rothkopf, arXiv:1511.04151

# Temperature dependence of spatial charmonium correlators





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

Bazavov et al, PRD91 (2015) 054503

Almost no medium modification of S-wave charmonium correlators across $T_c \approx 154$ MeV,
Medium modification of the correlators start to be visible for $T > 197$ MeV

Significant medium modification of P-wave charmonium correlators already at $T_c$
and larger T-dependence than for 1S correlator for

Fits into the picture of sequential charmonium melting:
$\chi_c$ melts at smaller temperature than the more tightly bound $J/\psi$

# Langevin dynamics for charmonium

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

$$\frac{d\mathbf{p}}{dt} = -\eta\mathbf{p} + \xi - \nabla U \longleftarrow$$

attractive force between QQbar

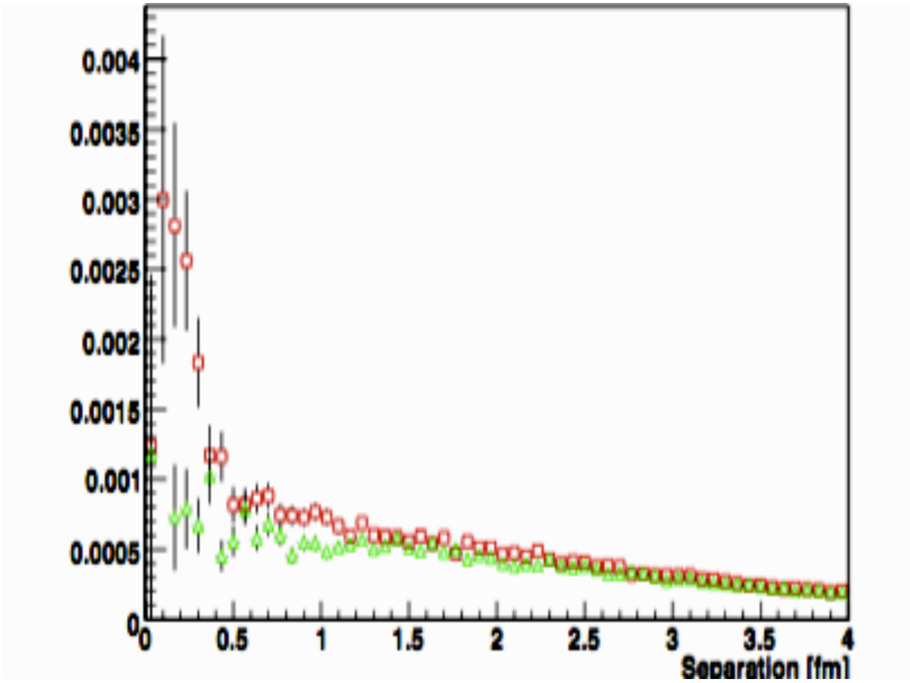
$$\frac{d\mathbf{r}}{dt} = \frac{\mathbf{p}}{m_c}$$

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

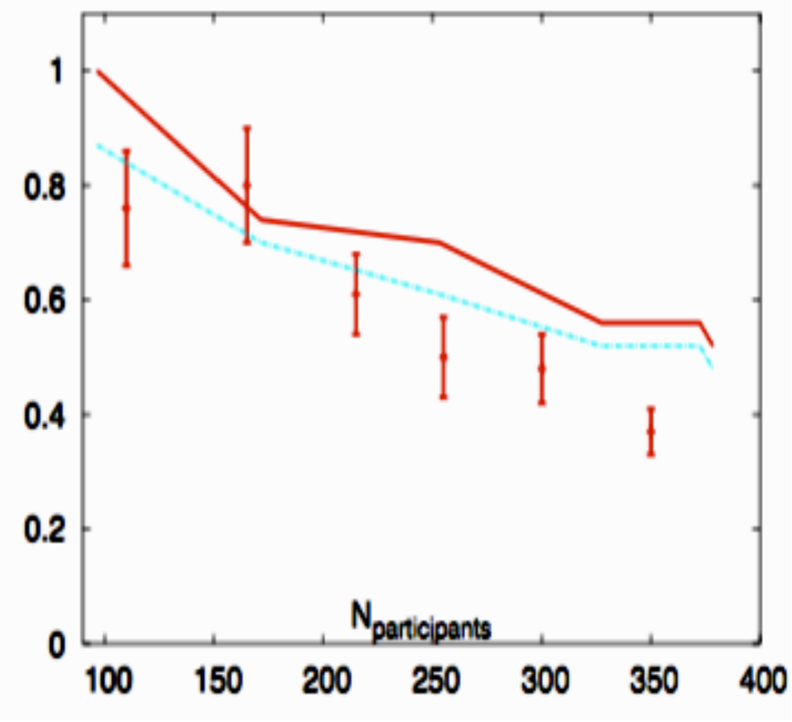


Young, Shuryak, PRC79 ('09) 034907

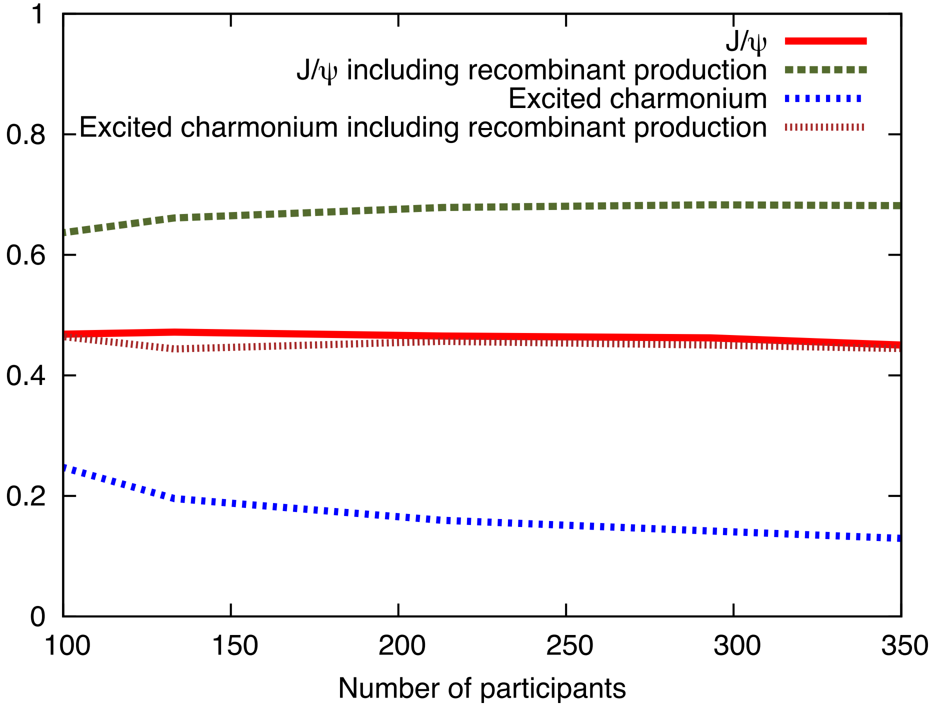
$R_{AA}$ $(J/\Psi)$ is non-zero even if there are no bound states because because there is not Enough time in HI collisions to decorrelate the QQbar pair. Off-diagonal production can also be calculated, Young, Shuryak, arXiv:0911:3080

# Charmonium $R_{AA}$ in Langevin dynamics

Young, Shuryak, PRC79 ('09) 034907
Langevin dynamics + ideal hydro



Young, Schenke, Jeon, Gale, arXiv:1111.0647
Langevin dynamics for heavy quarks+MARTINI



Moderate suppression at RHIC
with centrality; recombinant production
Works for a single QQbar pair

Centrality independent $R_{AA}$ for LHC

# Summary

Dynamical models that assumed in-medium formation of charmonium states can described the basic features of the $J/\psi$ nuclear modification factor: Energy, centrality and $p_T$ dependence

$\Rightarrow$ Charmonium formation in deconfined medium

the production excited bottomonium should be similar

Quarkonium properties can be studied in LQCD/EFT inspired approach

$\Rightarrow$ Sequential melting patern:

$$T_D(\chi_b) \simeq T_D(\Upsilon') \simeq T_D(J/\psi) \simeq 245 \text{ MeV}$$

$$T_D(\Upsilon) \simeq 450 \text{ MeV}$$

This sequntial melting patern is confirmed now by LQCD studies of spatial correlators and temporal correlators in NRQCD

The experimental data obtained so far can be understood in terms of sequential Quarkonium (re)generation rather than in terms of sequential melting

To learn about QGP propertis form experimental results on quarkonium a Comprehensive theory + modeling effort is needed