Charmonium Dissociation and Heavy Quark Transport in Hot Quenched Lattice QCD

Anthony Francis

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JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

E-mail: francis@kph.uni-mainz.de

Outline

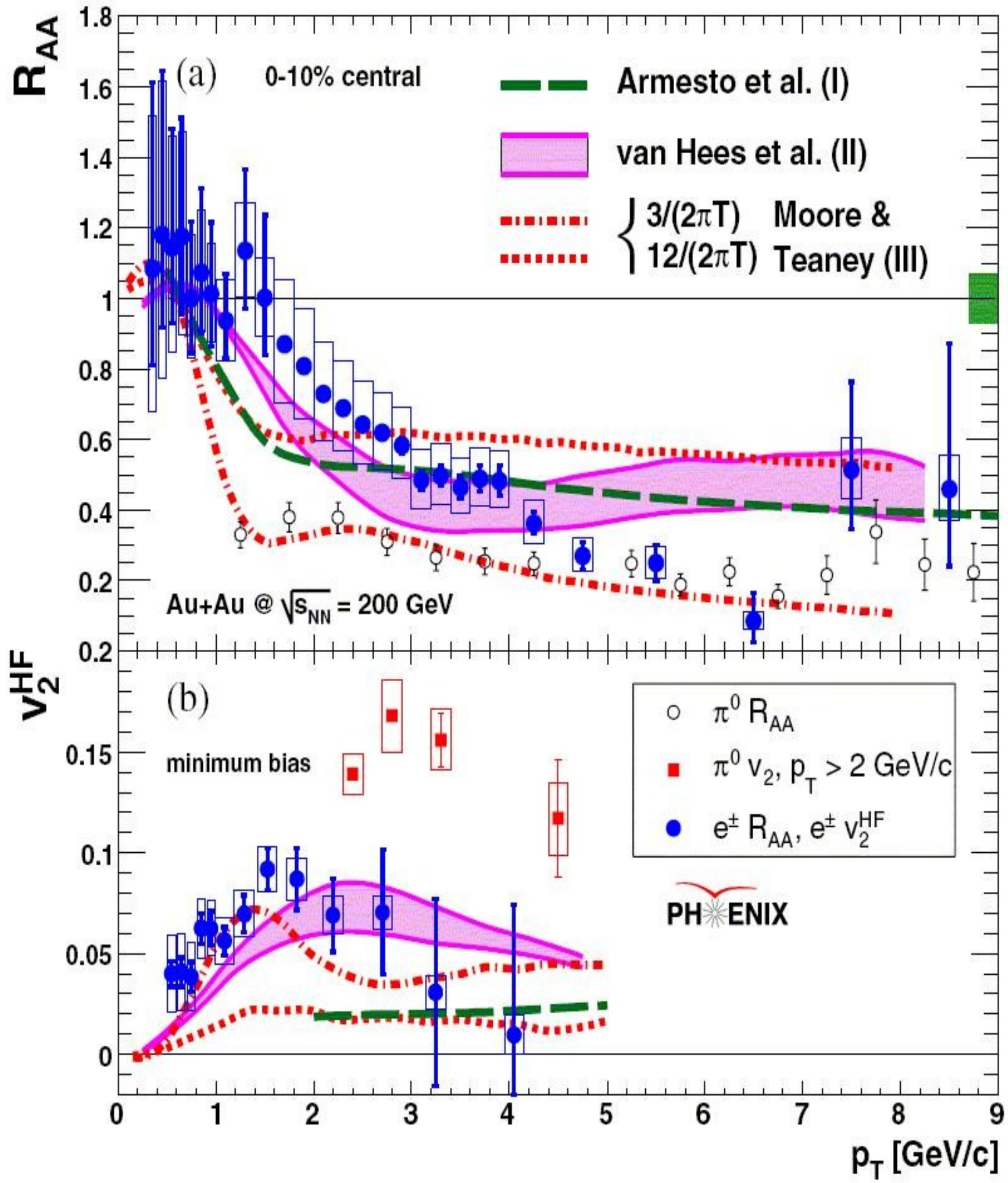
Heavy quarks at finite temperature and spectral functions	• Motivation from experiments • Quarkonium dissociation and the diffusion of heavy quarks from the p.o.v. of spectral functions • Expectations for quarkonium spectral functions at finite temperature
Lattice correlators and spectral functions	• Connection of spectral functions and correlators
Results on spectral functions from lattice QCD	• Results on the behavior of spectral function directly from lattice correlators • Maximum entropy method and the default model • Charmonium spectral functions from lattice QCD
Conclusions	• Results on the dissociation of charmonium and charm quark diffusion in the quark-gluon-plasma

Introduction and motivation

- In HIC-experiments, e.g. @RHIC or @LHC one can study heavy quarkonium dynamics through:
  - Elliptic flow v_2^{HF}
  - Modification factor R_{AA}

- Two interesting questions:
  - Quarkonium dissociation
  - Heavy quark diffusion

Two questions where lattice QCD can provide some hints and answers

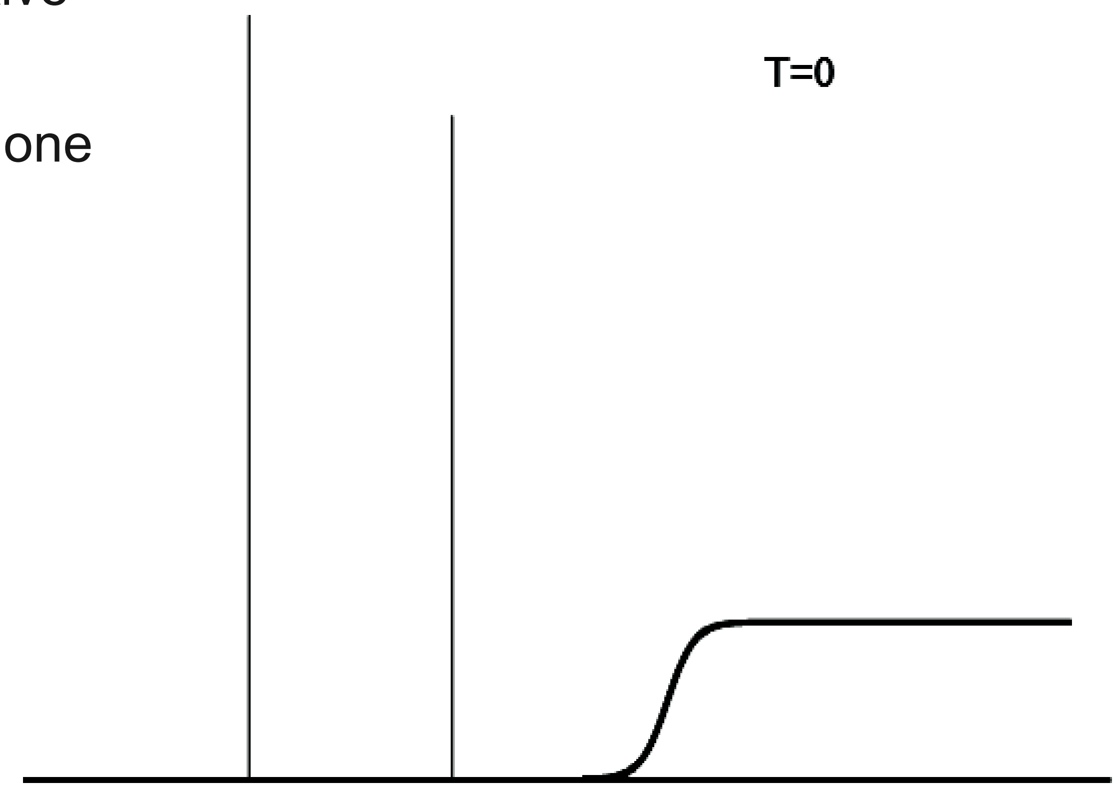


Adare et al.; Phys.Rev. C84 (2011) 044905

Charmonium spectral functions

All the desired information on charmonium physics is embedded in the spectral function (SPF):

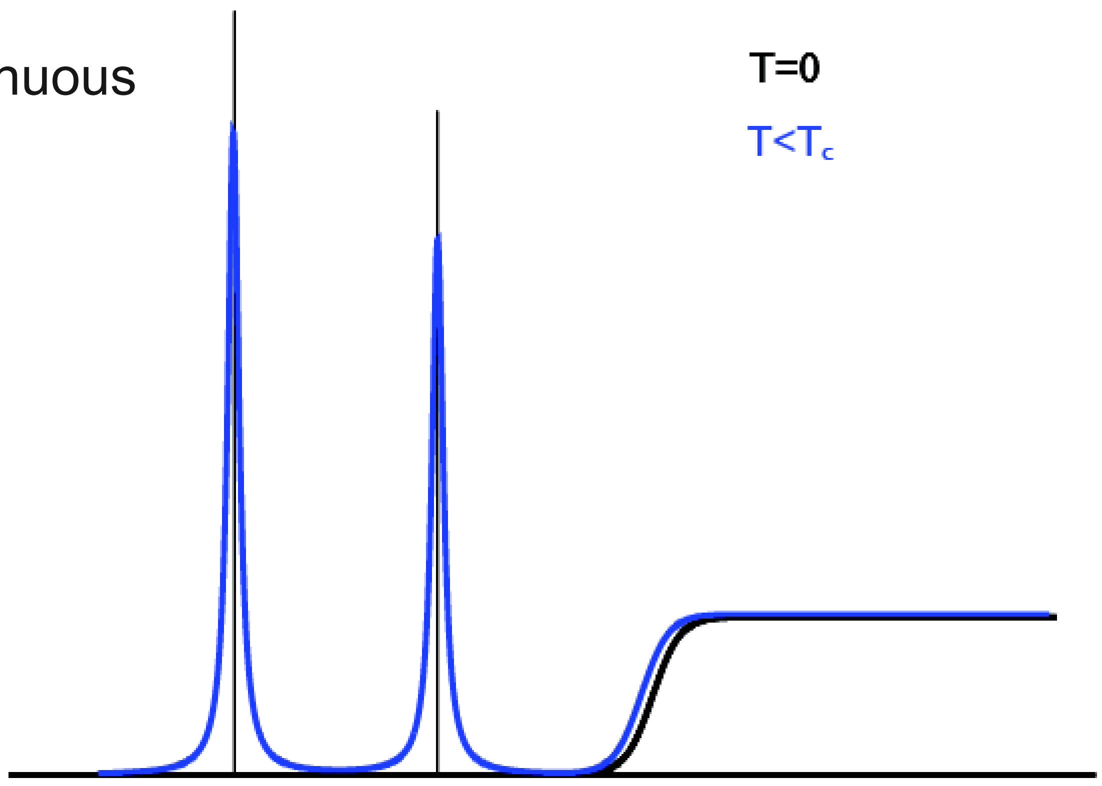
- At vanishing temperature T the bound states of charmonium are peaks at their respective mass thresholds
- At very large frequencies one encounters a continuous spectrum



Charmonium spectral functions

All the desired information on charmonium physics is embedded in the spectral function (SPF):

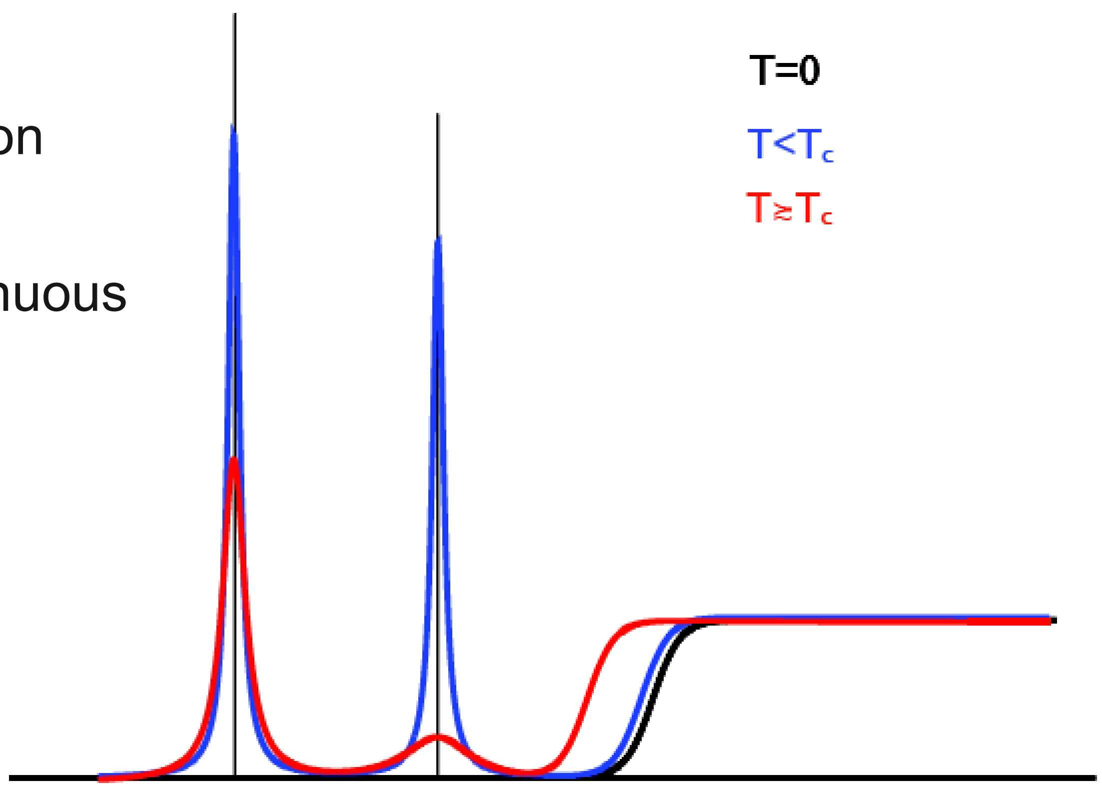
- As the temperature increases the bound state peaks are smeared
- The threshold to the continuous spectrum shifts to smaller frequencies



Charmonium spectral functions

All the desired information on charmonium physics is embedded in the spectral function (SPF):

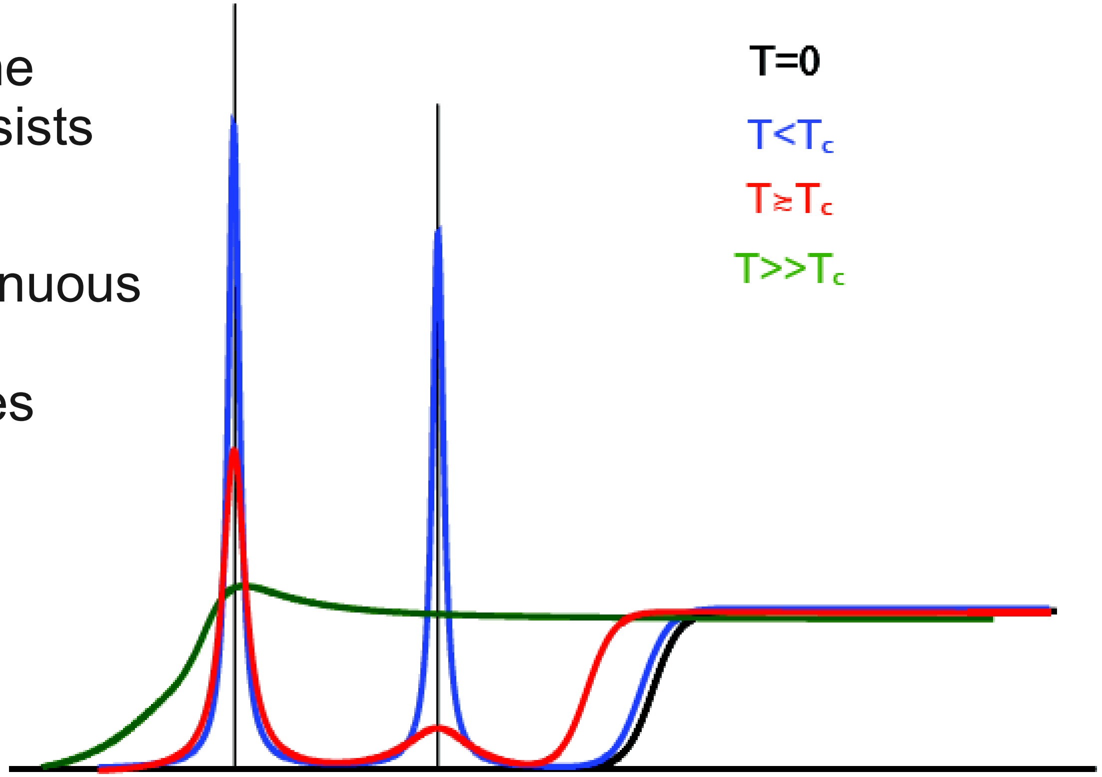
- Around/Above T_c the higher excited states begin to dissociate
- At very low frequencies a visible transport contribution emerges
- The threshold to the continuous spectrum shifts to smaller frequencies



Charmonium spectral functions

All the desired information on charmonium physics is embedded in the spectral function (SPF):

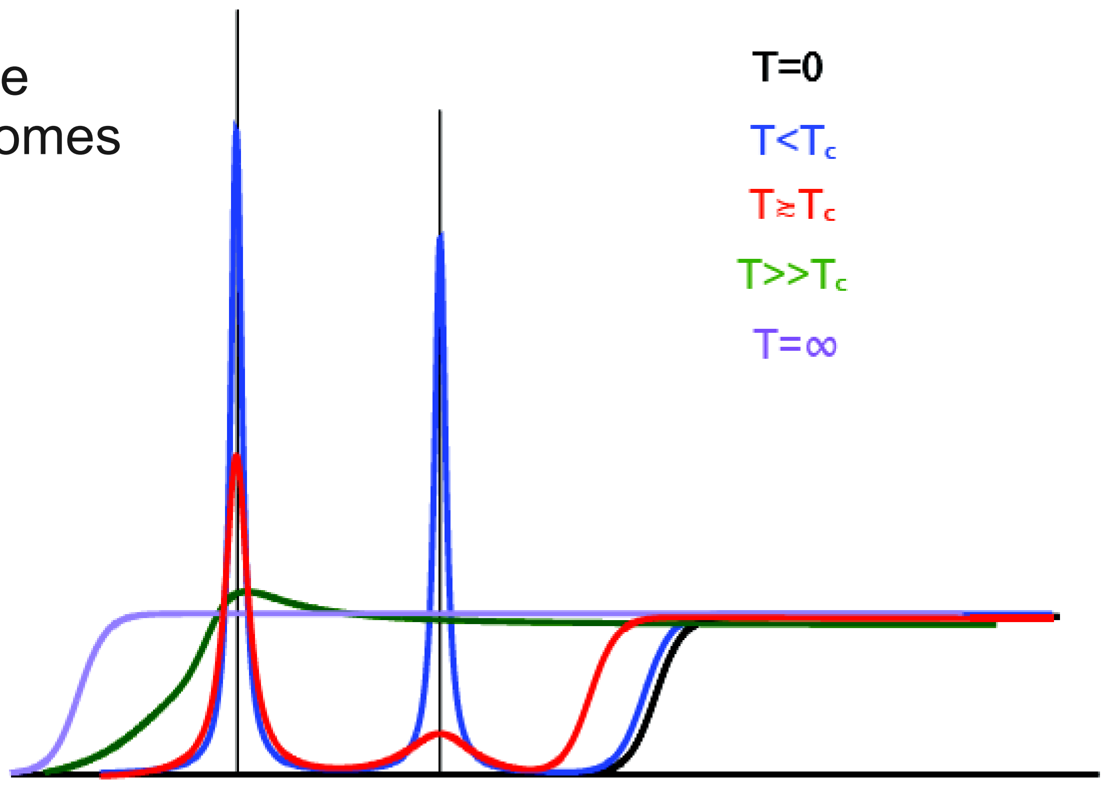
- At temperatures somewhat larger than T_c also the ground state peak begins to dissociate
- At very low frequencies the transport contribution persists and becomes stronger
- The threshold to the continuous spectrum shifts to smaller frequencies and dominates most frequencies



Charmonium spectral functions

All the desired information on charmonium physics is embedded in the spectral function (SPF):

- At asymptotically high temperatures the bound states have dissociated
- At very low frequencies the transport contribution becomes large, but finite
- The continuous spectrum dominates



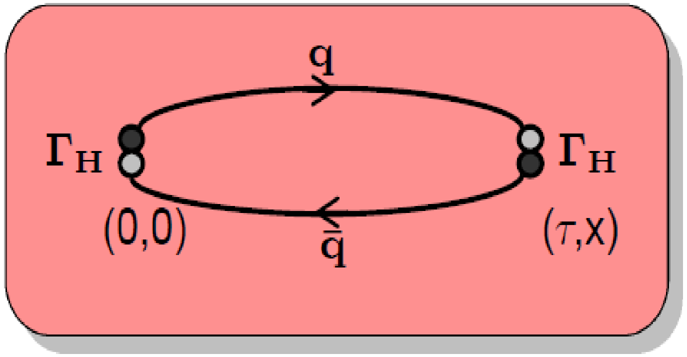
SPF via lattice QCD

- In lattice QCD one has to analyze the correlation function of heavy currents:

$$G_V(\tau,\vec{p}) = \int d^3x \langle J_\mu(\tau,\vec{x}) J_\mu(0,0)\rangle$$

$$J_\mu(\tau,\vec{x}) = \bar{q}(\tau,\vec{x})\Gamma_H q(\tau,\vec{x})$$

Channel	Γ_H	$^{2S+1}L_J$	J^{PC}	I^G	$c\bar{c}$	M($c\bar{c}$)[GeV]
PS	γ_5	$^1S_0$	0^{-+}	0^+	η_c	2.980(1)
VC	γ_μ	$^3S_1$	1^{--}	0^-	J/ψ	3.097(1)
SC	1	$^3P_0$	0^{++}	0^+	χ_{c0}	3.415(1)
AV	$\gamma_5\gamma_\mu$	$^3P_1$	1^{++}	0^+	χ_{c1}	3.510(1)



- The **Euclidean** lattice correlator can be connected to the SPF:

$$G_H(\tau,\vec{p},T) = \int_0^\infty \frac{d\omega}{2\pi} \frac{\cosh(\omega(\tau - 1/2T))}{\sinh(\omega/2T)} \rho_H(\omega,\vec{p},T)$$

using: $G(\tau,T) = D^+(-i\tau)\ ,\quad \rho(\omega) = 2\mathrm{Im}D^R(\omega) = D^+(\omega) - D^-(\omega)$

Lattice setup

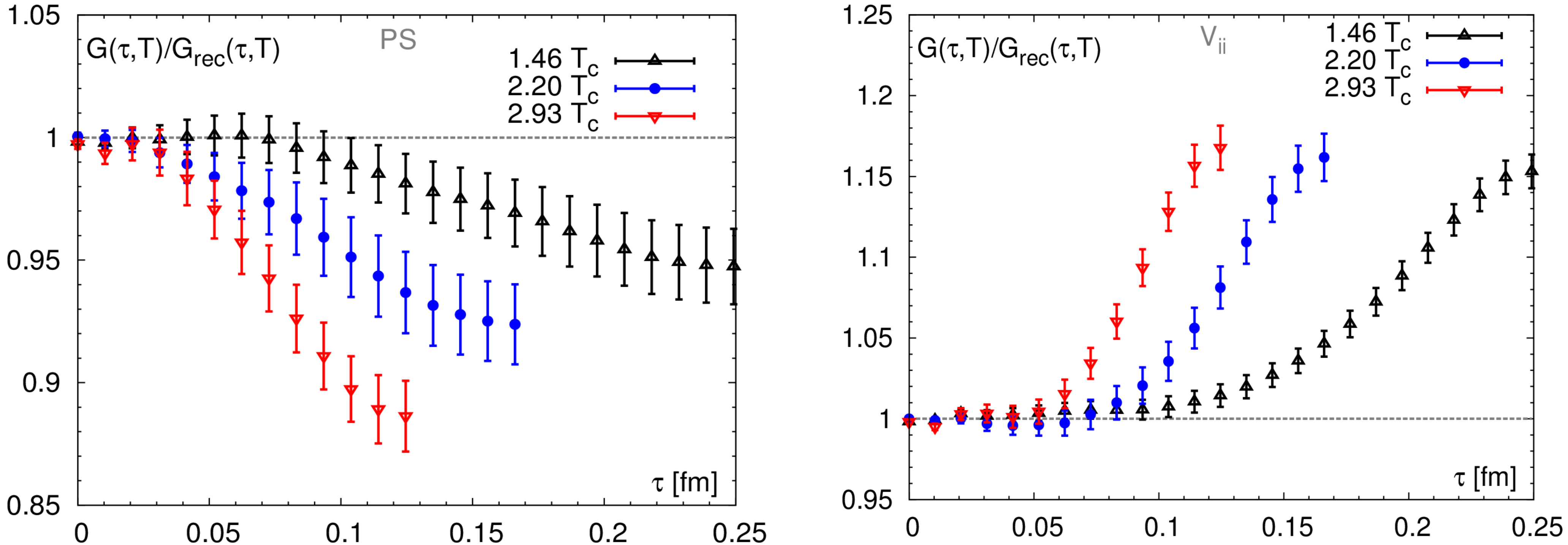
- Non-perturbatively improved Wilson-Clover fermions
- Large, isotropic quenched lattices
- Very fine lattices (close to continuum)
- Parameters tuned close to physical J/Ψ-mass
- Large extent in τ-direction

β	a [fm]	a^{-1}[GeV]	L_σ [fm]	c_{SW}	κ	$N_\sigma^3 \times N_\tau$	T/T$_c$	N_{conf}
6.872	0.031	6.432	3.93	1.412488	0.13035	$128^3 \times 32$	0.74	126
						$128^3 \times 16$	1.49	198
7.457	0.015	12.864	1.96	1.338927	0.13179	$128^3 \times 64$	0.74	179
						$128^3 \times 32$	1.49	250
7.793	0.010	18.974	1.33	1.310381	0.13200	$128^3 \times 96$	0.73	234
						$128^3 \times 48$	1.46	461
						$128^3 \times 32$	2.20	105
						$128^3 \times 24$	2.93	81

Study via lattice correlators

- First let's see what can be learnt from correlators directly

$$G_{rec}(\tau,T) = \int \frac{d\omega}{2\pi}\rho(\omega, 0.75T_c)K(\omega,\tau,T)$$



- No zero-mode contribution in PS

T-effect due to modification of bound states

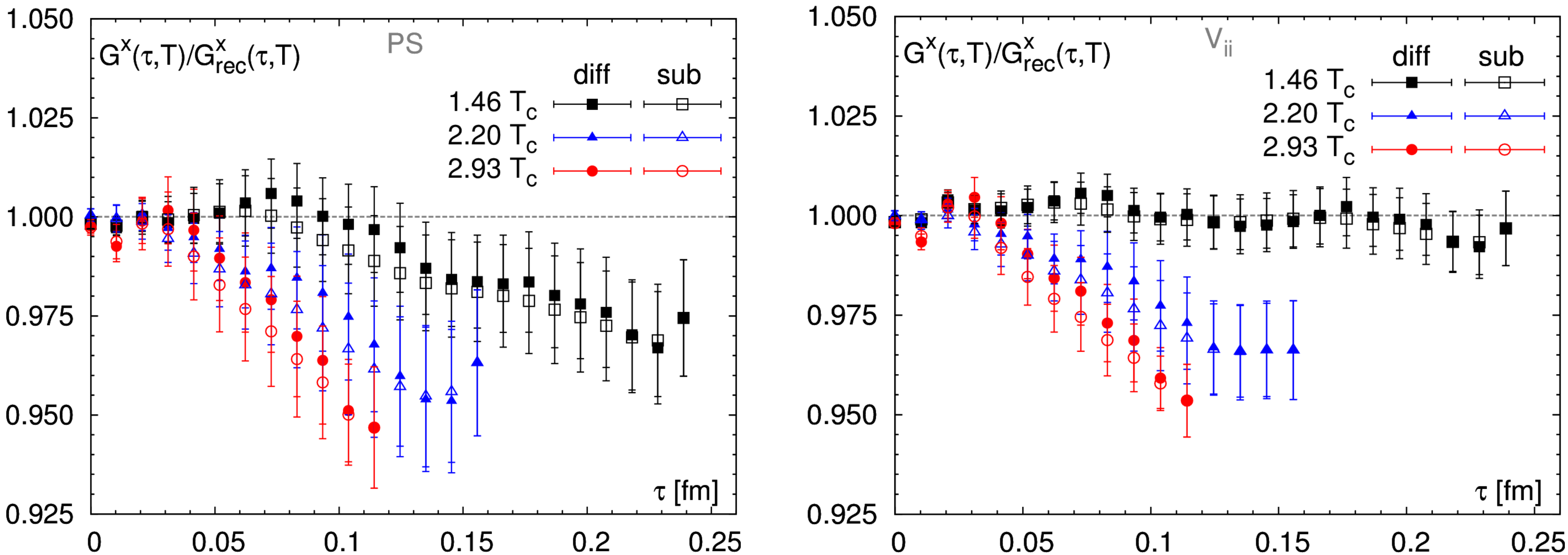
- Large modification

T-effect mainly due to zero-mode contribution

Study via lattice correlators

$$G_{diff}(\tau,T) = G(\tau,T) - G(\tau+1,T)$$

$$G_{sub}(\tau,T) = G(\tau,T) - G(\tau = N_\tau/2,T)$$



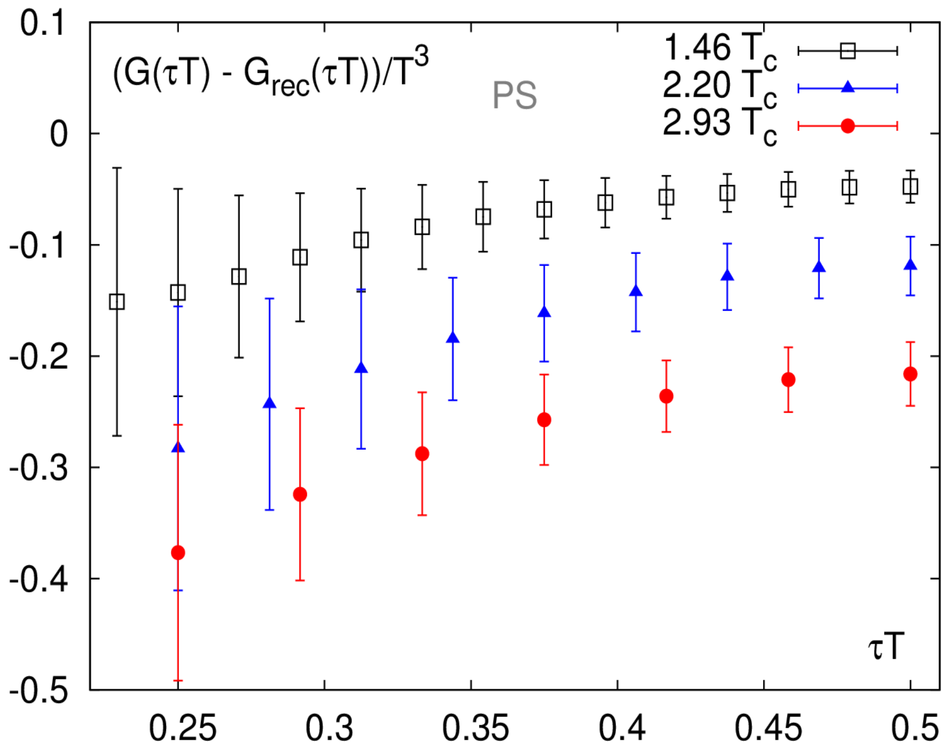
- No zero-mode contribution in PS

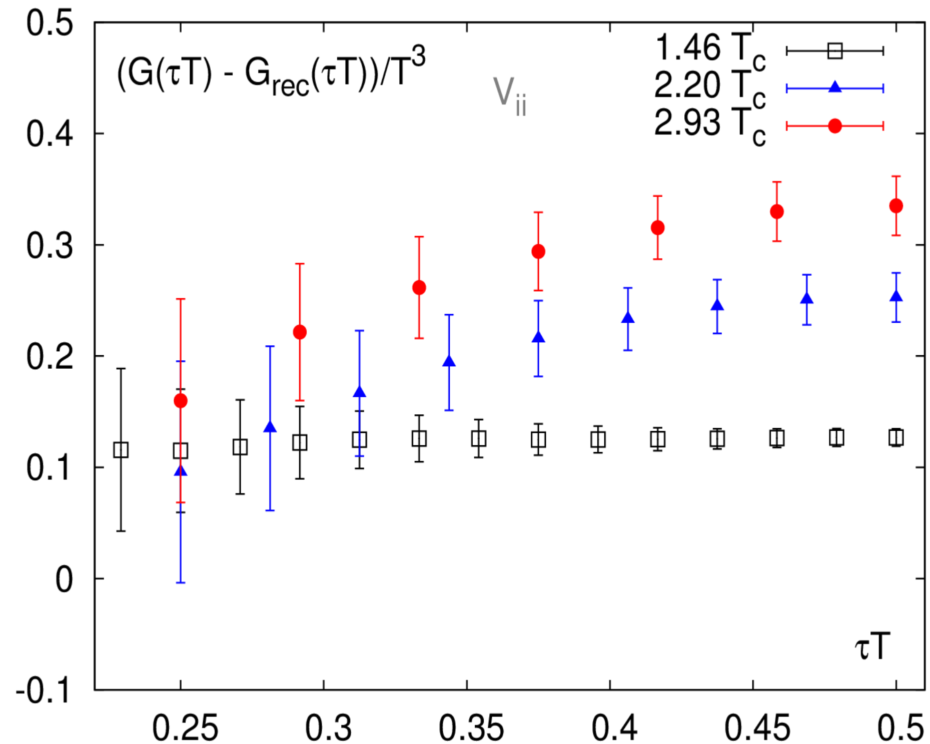
➡ Similar behavior in PS and V channels

- **Diff/Sub corrs. effectively remove the zero-mode contribution**

➡ T-effect mainly due to zero-mode contribution

Study via lattice correlators





- Negative difference for all T
- Positive slope

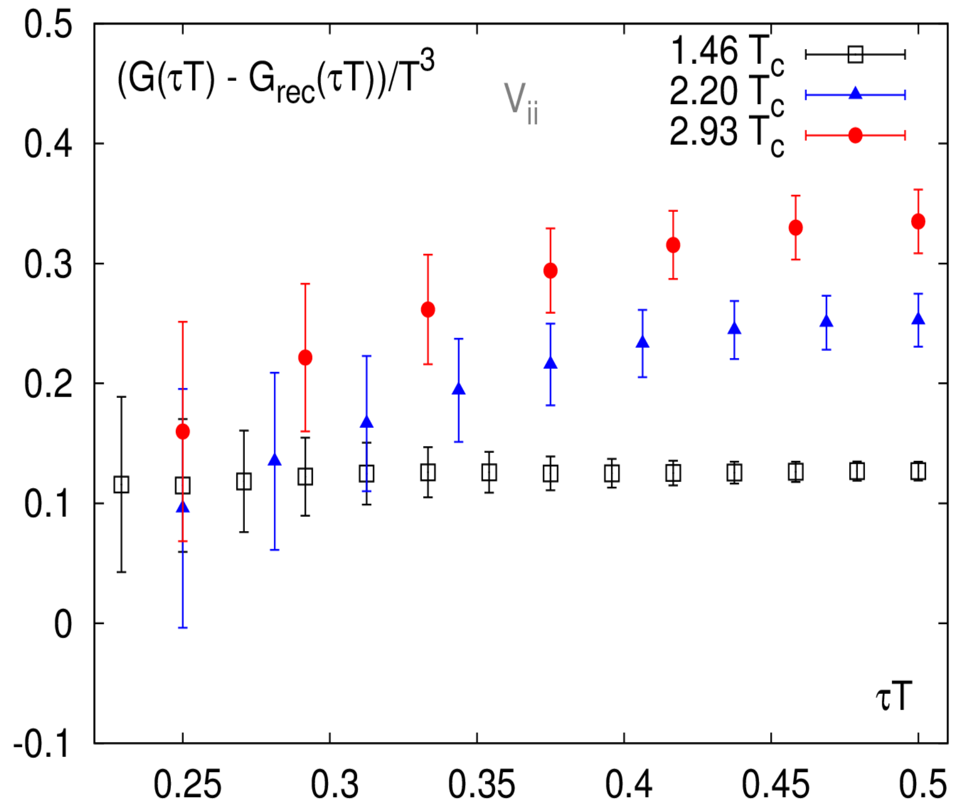
indicative of modification in the bound state region

- Recall: No transport contribution in this channel

- Positive difference due to small frequency contribution
- Positive slope, **as in PS case**
- Small frequency contribution determines transport coefficient

Fit estimate: $2\pi T D \approx 0.6 - 3.4$

Estimate of charm quark diffusion



- Recall the Kubo formula for heavy quark diffusion:

$$D = \lim_{\omega \to 0} \frac{\rho_V(\omega, T)}{6\chi_{00}\omega}$$

$$\rho_V(\omega) = \rho_{ii}(\omega) - \chi_{00}\omega\delta(\omega)$$

- Assume all change in the SPF is due to the change in the zero-mode contribution
- Then fit to (at $1.46T_c$) $G(\tau T = 1/2) - G_{rec}(\tau T = 1/2)$

$$I.)\quad \rho(\omega \ll T) = 2\chi_{00}\frac{T}{M}\frac{\omega\eta}{\omega^2+\eta^2}\ .\ \eta = \frac{T}{MD}$$

$2\pi TD \approx 0.6 - 3.4$

$$II.)\quad \rho(\omega \ll T) = \frac{\pi T}{3\chi_{00}}\ b\ \omega$$

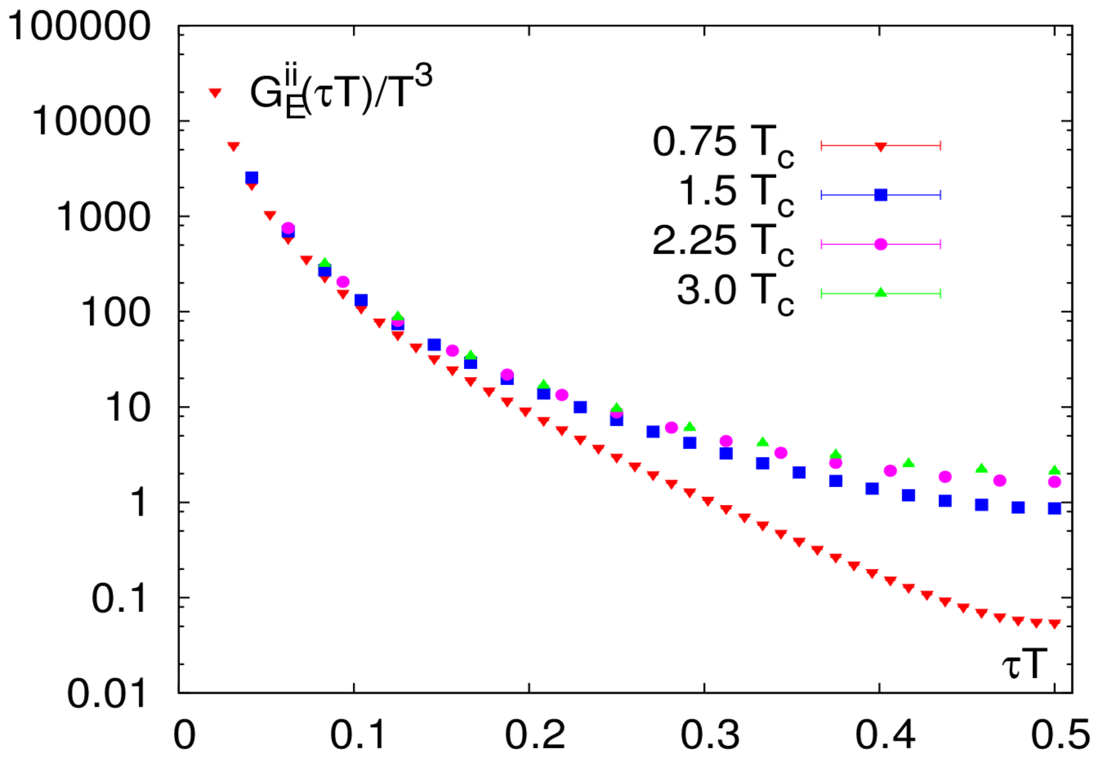
$2\pi TD \approx 2$

SPF via lattice QCD

- To learn more we have to analyze the SPF directly, this is possible via:

$$G_H(\tau,\vec{p},T) = \int_0^\infty \frac{d\omega}{2\pi} \frac{\cosh(\omega(\tau - 1/2T))}{\sinh(\omega/2T)} \rho_H(\omega,\vec{p},T)$$

Discrete number of points from the lattice



Continuous SPF

Ill-posed problem

Analysis via Bayes' theorem

- **Maximum Entropy Method (MEM)** M.Asakawa, T.Hatsuda, Y.Nakahara; Prog.Part.Nucl.Phys. 46 (2001)
  - Find the most probable image given the data with errors and some prior (known) information
  - Ingredients of MEM:

$$P[\rho|GH] \sim P[G|\rho H] \; P[\rho|H]$$

$$P[G|\rho H] \sim \exp[-\chi^2/2] \qquad P[\rho|H] \sim \exp[\alpha S]$$

$$S = \int_0^\infty \frac{d\omega}{2\pi}\left[\rho(\omega) - m(\omega) - \rho(\omega)\ln\left(\frac{\rho(\omega)}{m(\omega)}\right)\right]$$

Information entropy

- $m(\omega)$, the default model (DM), contains the prior information on $\rho(\omega)$
  - The DM is the **only** input parameter provided to the MEM analysis

Dependence of the output $\rho(\omega)$ on $m(\omega)$ must be carefully analyzed!

Prior information and the DM

- At large frequencies the behavior of the SPF should resemble that of the free theory

➡ Input rather the free lattice than the free continuum

- At low frequencies consider:

➡ I: Non-interacting case

$$\rho(\omega) \sim \omega\delta(\omega)$$

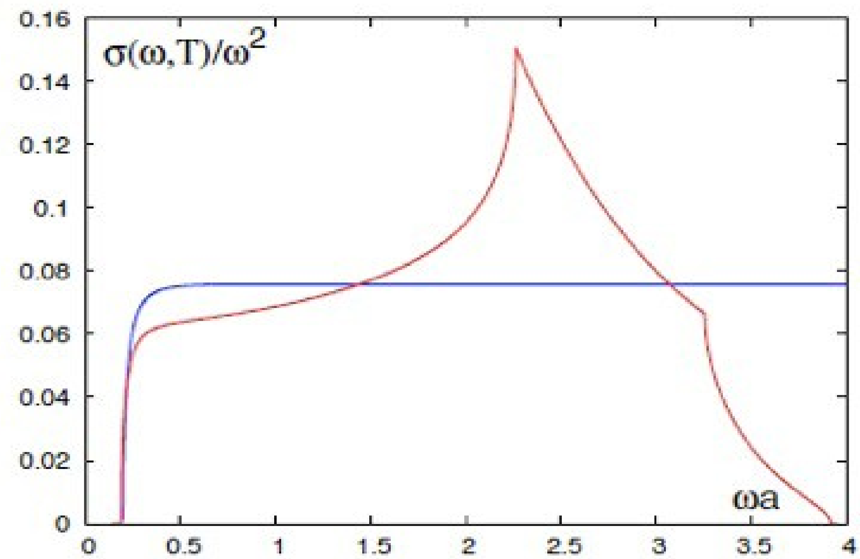
  - In correlator: τ-independent constant
  - This zero mode contribution exists in the vector, axial-vector and scalar channels

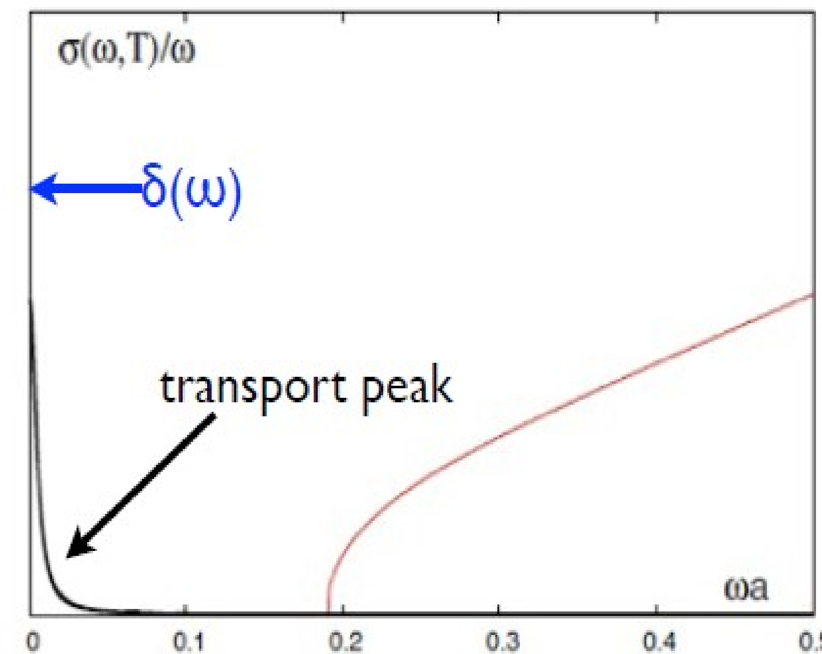
➡ II: Interacting case

G.Aarts, M.Resco; Nucl.Phys. B726 (2005) 93-108

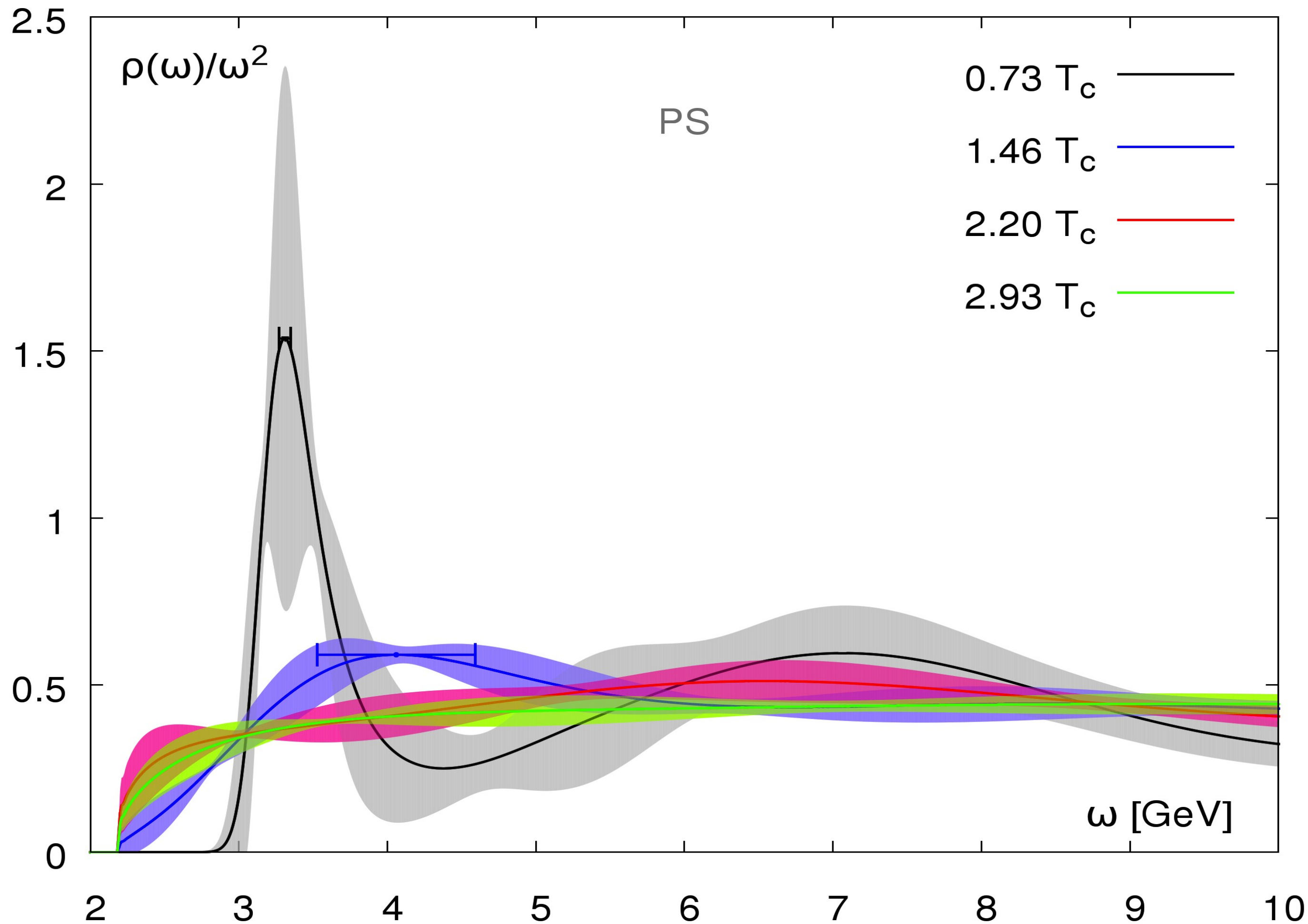
$$\rho(\omega) \sim \frac{\eta}{\omega^2+\eta^2}$$

  - $\delta(\omega)$ is smeared into transport peak





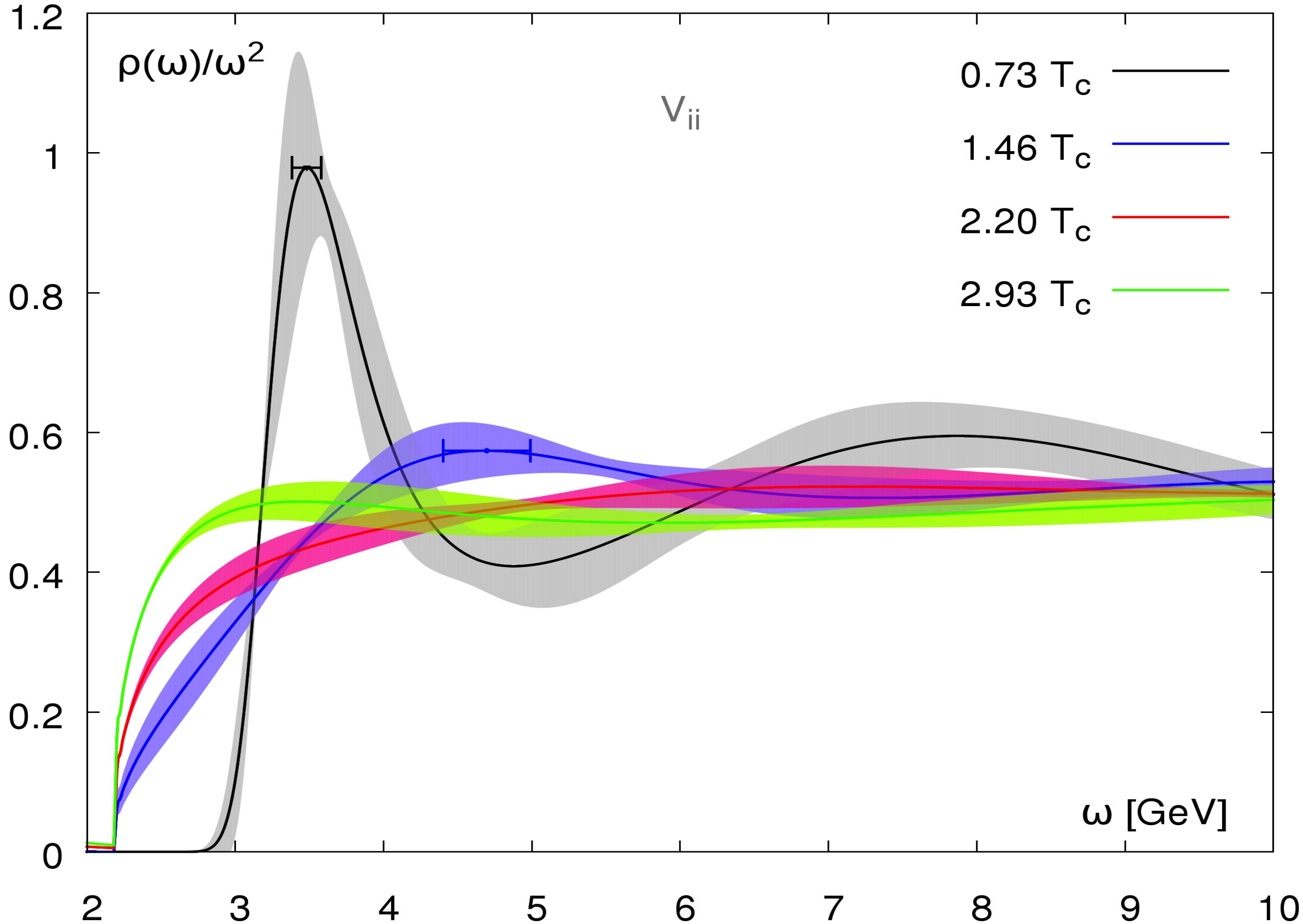
Charmonium spectral functions



- Error bands: Statistical error from Jackknife analysis
- Error bars: Peak location from DM dependence

no clear signal of bound states above $1.46T_c$

Charmonium spectral functions

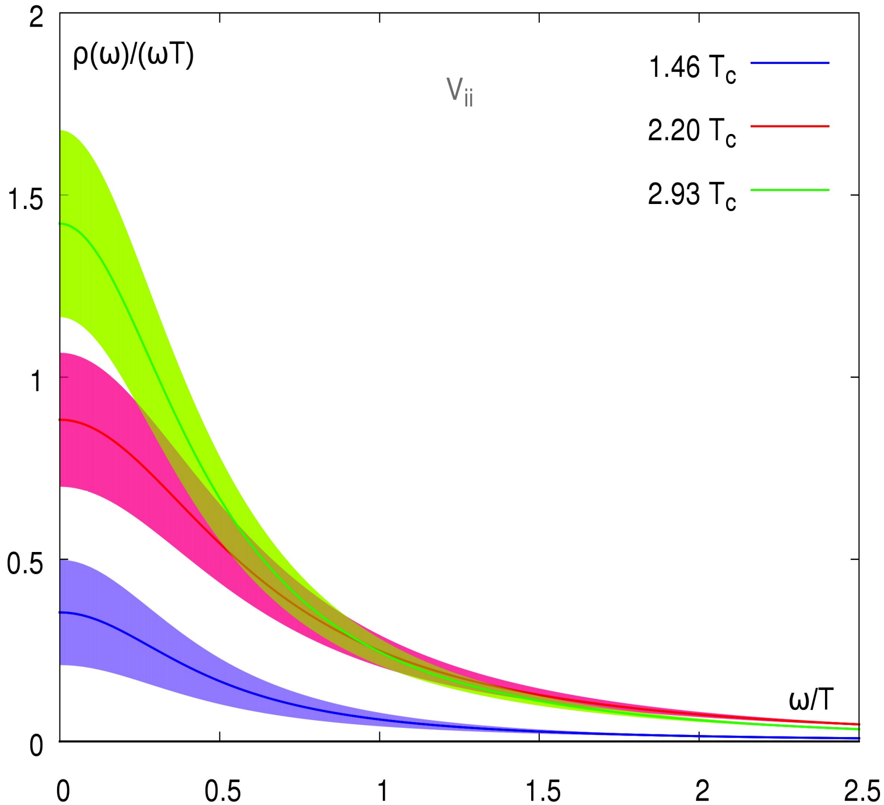


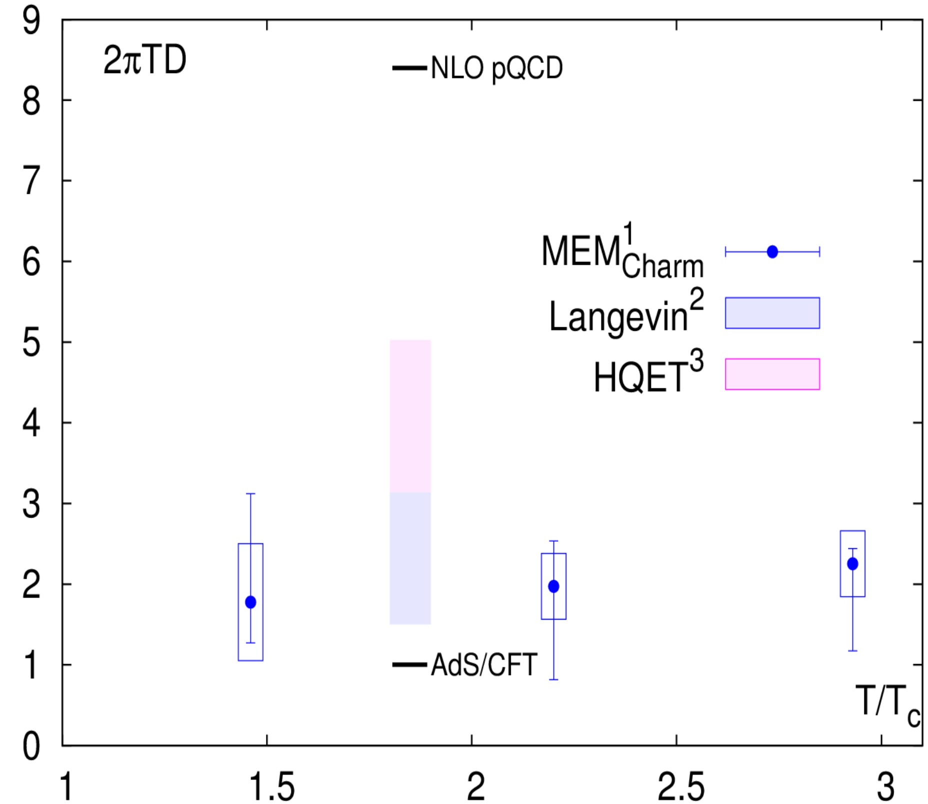
- Error bands: Statistical error from Jackknife analysis
- Error bars: Peak location from DM dependence

no clear signal of bound states above $1.46T_c$

Charm quark diffusion

$$D = \lim_{\omega \to 0} \frac{\rho_V(\omega, T)}{6\chi_{00}\omega}$$





$$2\pi T D \sim 1.8 - 2.3$$

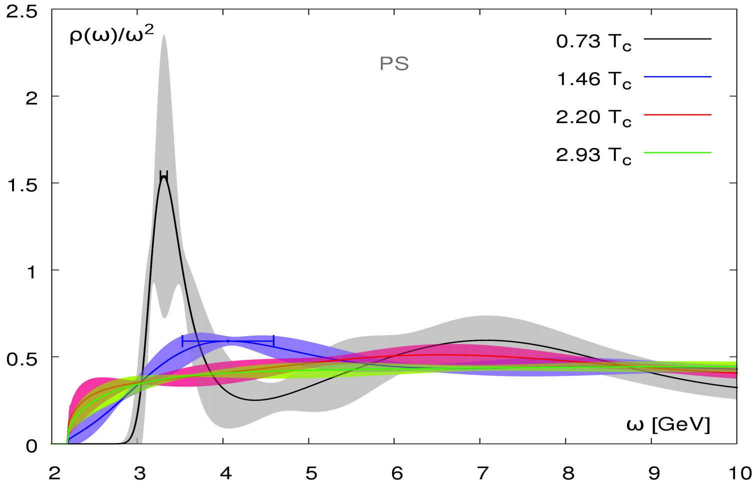
AdS/CFT) P.Kovtun, D.T.Son, A.O.Starinets; JHEP 0310(2003)064

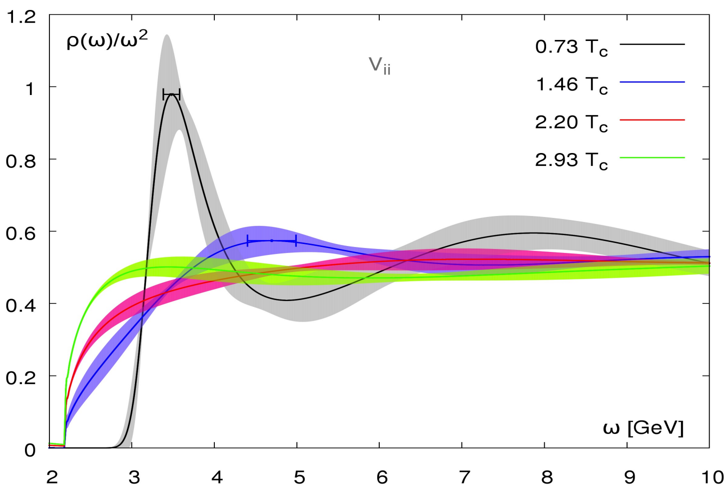
NLO) G.D.Moore, D.Teaney; PRD71 (2005) 064904
S.Caron-Huot, G.D.Moore; PRL 100 (2008) 052301

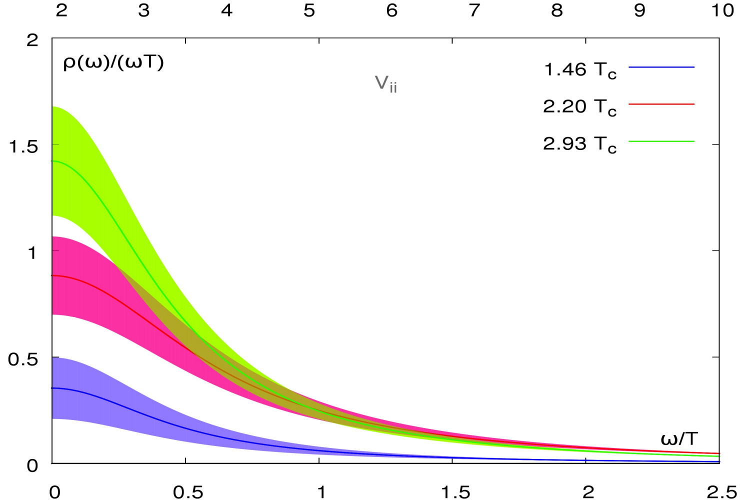
1) H.T.Ding, A.F, O.Kaczmarek, F.Karsch, H.Satz, W.Soeldner; J.Phys.G G38 (2011) 124070

2) G.D.Moore, D.Teaney; Phys.Rev. C71 (2005) 064904

3) A.F., O.Kaczmarek, J.Langelage, M.Laine; PoS LATTICE2011 (2011) 202
D. Banerjee, S. Datta, R. Gavai, P. Majumdar; RD 85 (2012) 014510





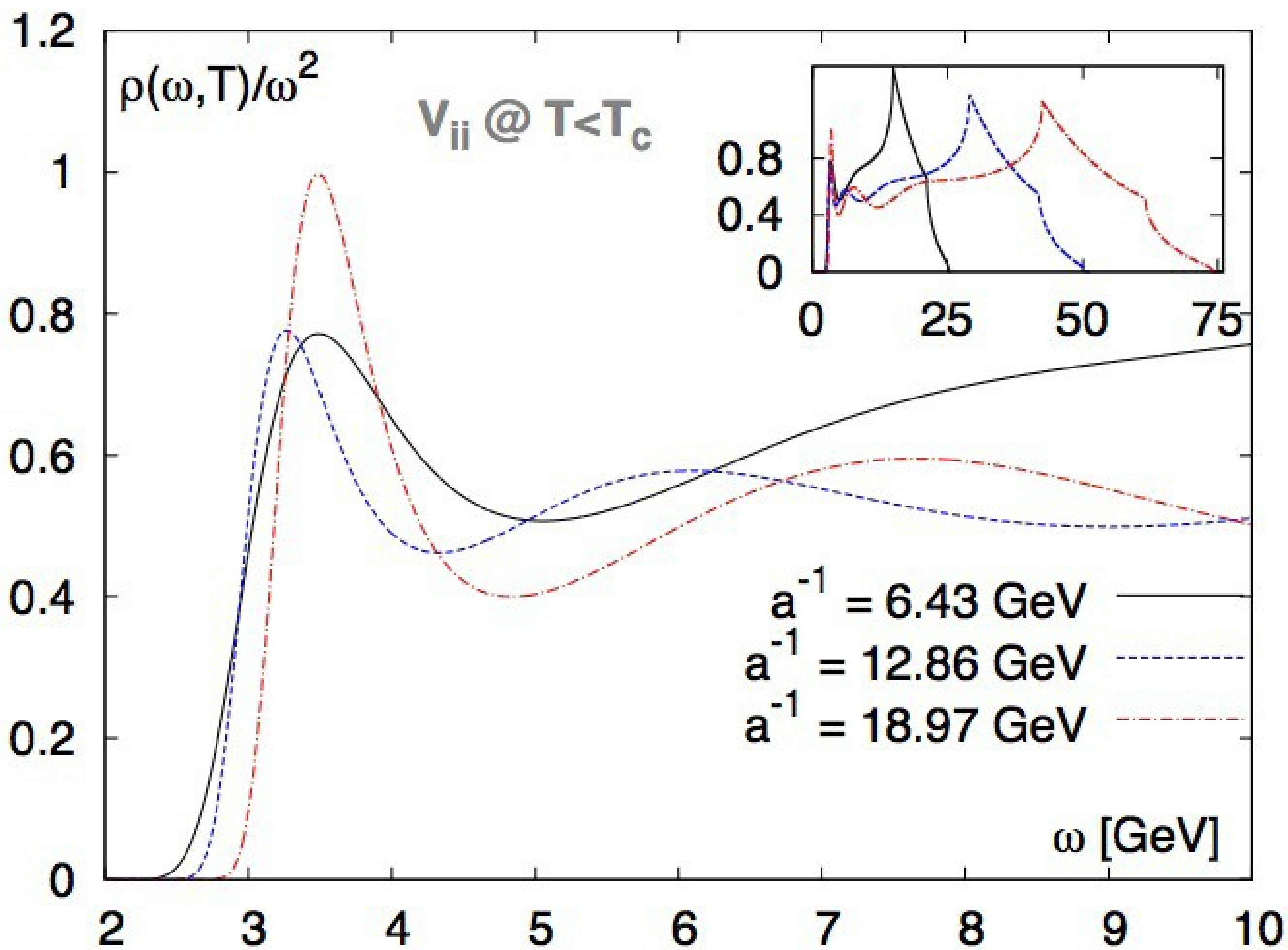


Conclusions

- Using quenched lattice QCD we computed the current-current correlation functions on very fine and large, isotropic lattices at various temperatures to unprecedented precision.
- We found:
  - **The pseudo scalar and vector bound states are dissociated already at temperatures** $T \simeq 1.46 T_c$
  - **In the accessible temperature region we estimated the charm quark diffusion coefficient to be** $2\pi T D \sim 1.8 - 2.3$
- In the near future we will go to lower temperatures to pinpoint the dissociation temperature, in addition of doing a continuum extrapolation.

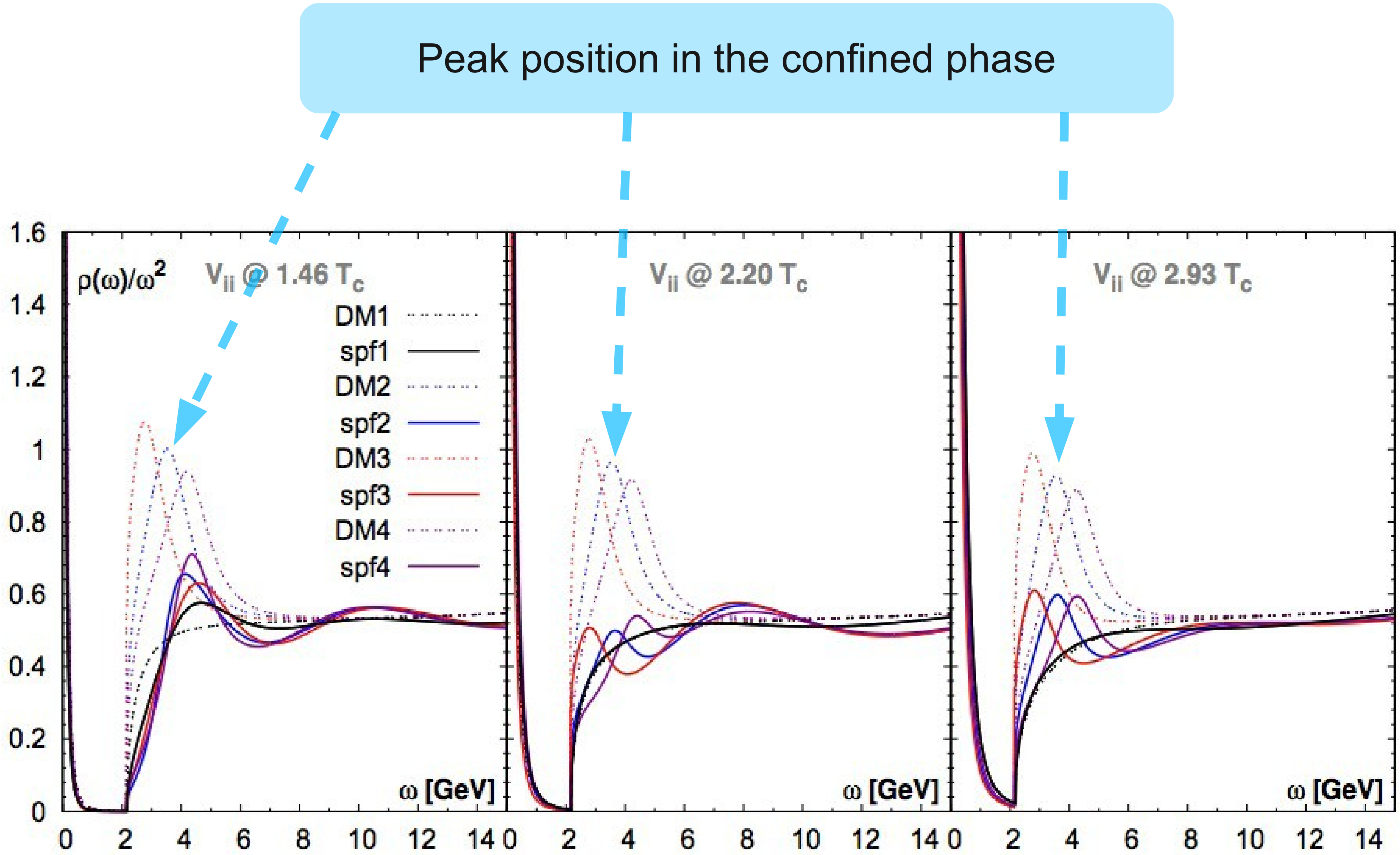
Further Details

Dependence on th lattice spacing

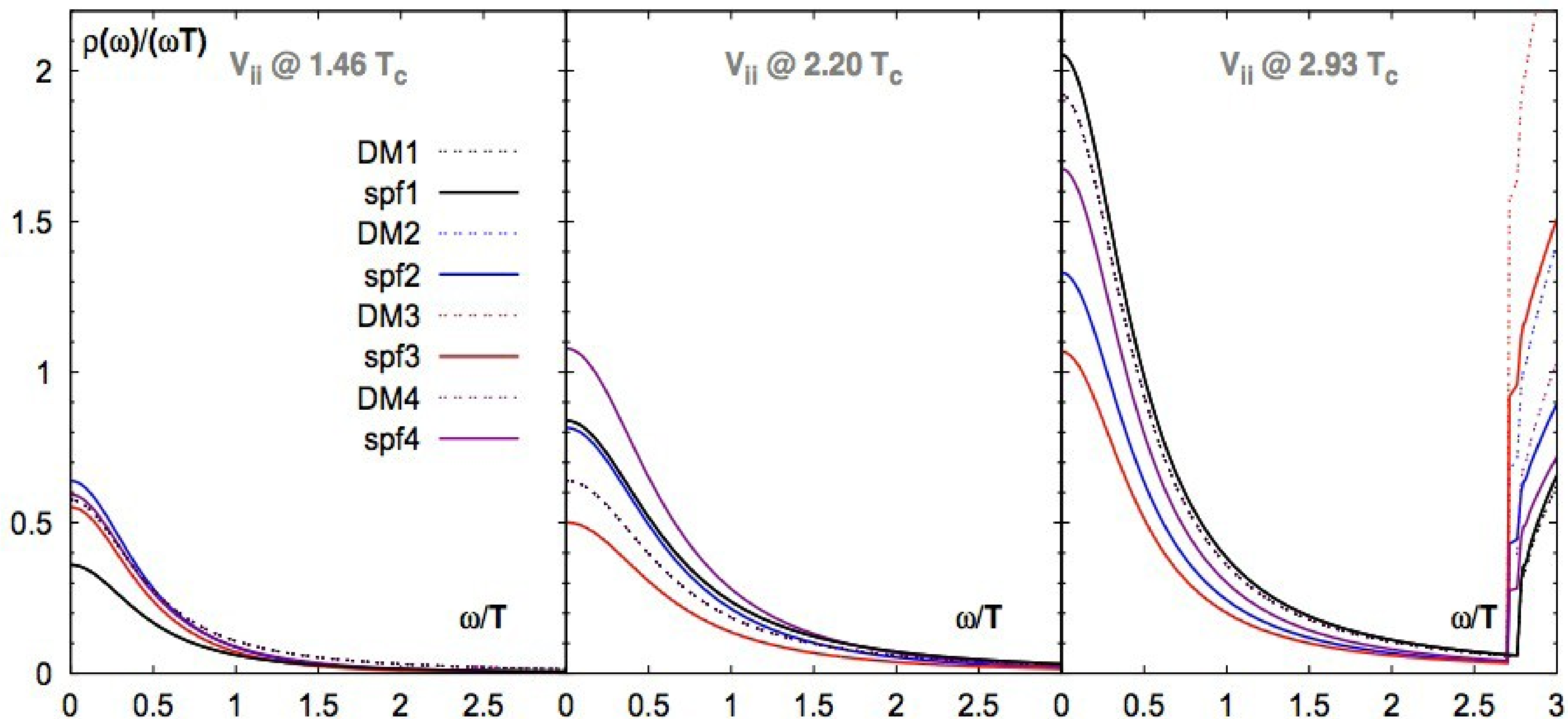


- The gross features are the same through three consecutive lattice spacings
- Here we have shown only the results of the finest lattice (i.e. largest cut-off)

DM-dependence: Particle Peak

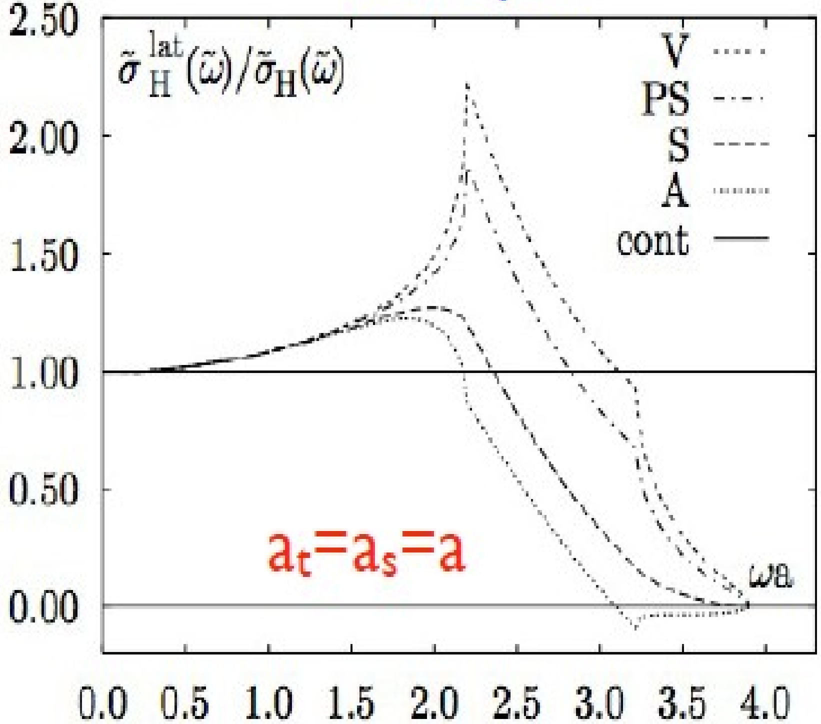


DM-dependence: Transport Peak



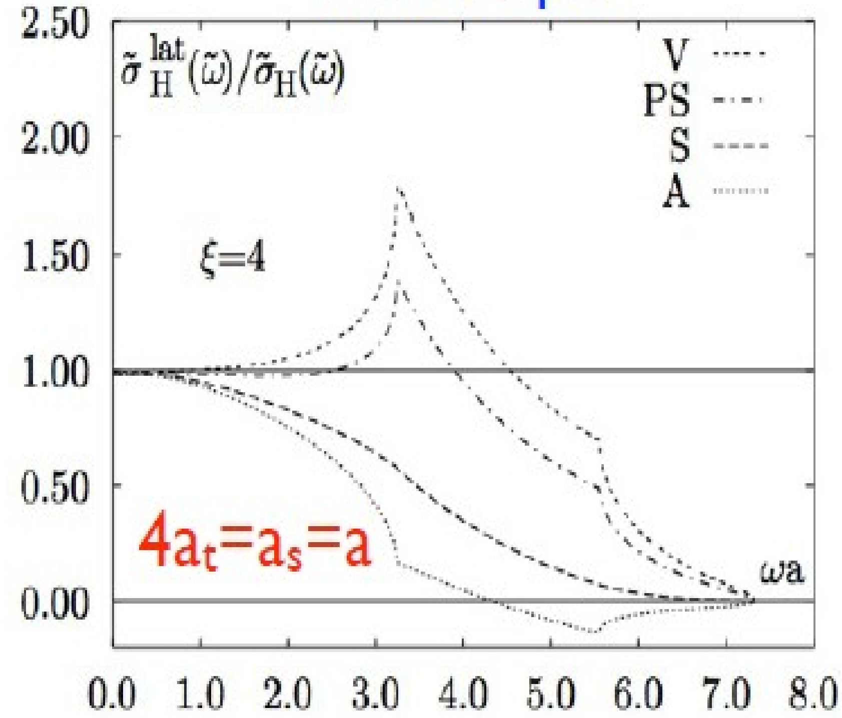
Isotropic vs. anisotropic lattices

isotropic



$\omega/T=\omega a N_t$

anisotropic

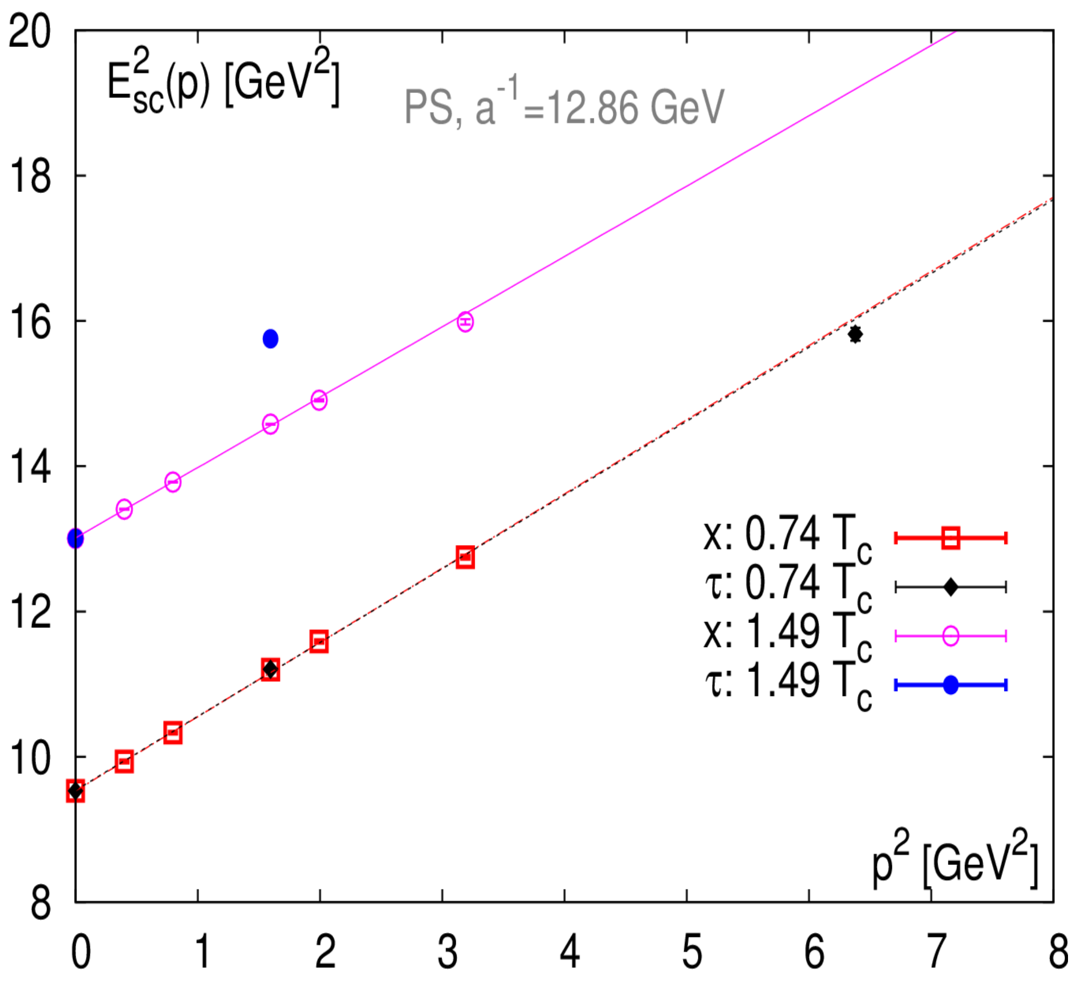


$\omega/T=\omega a N_t/4$

$1/T=a_tN_t$

On anisotropic lattices the lattice discretization effects are felt at lower frequencies than on their isotropic counterparts

Setting the mass and discretization errors



$$G(z, p_\perp, \omega_n) \sim \exp[-E_{scr} z]$$

$$E^2_{scr} = p^2_\perp + \frac{\omega_n^2}{A^2} + m^2_{scr}$$

Mass in GeV

β	J/ψ	η_c	χ_{c1}	χ_{c0}
6.872	3.1127(6)	3.048(2)	3.624(36)	3.540(25)
7.457	3.147(1)(25)	3.082(2)(21)	3.574(8)	3.486(4)
7.793	3.472(2)(114)	3.341(2)(104)	4.02(2)(23)	4.52(2)(37)

- The dispersion relation shows little deviation from continuum behavior
- Screening masses are close to the physical quarkonium masses