Universität Bielefeld

Transport and spectral properties of heavy quarks in the QGP from Lattice QCD

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in collaboration with

H.T.Ding, A.Francis, M. Laine, T.Neuhaus, H.Ohno

[arXiv:1412.6594, 1409.3724, 1311.3759, 1109.3941]

Heavy Quark Physics in Heavy Ion Collisions

ECT* Trento

17.03.2015

Motivation - Transport Coefficients

Transport Coefficients are important ingredients into **hydro/transport models for the evolution of the system.**

Usually determined by matching to experiment (see right plot)

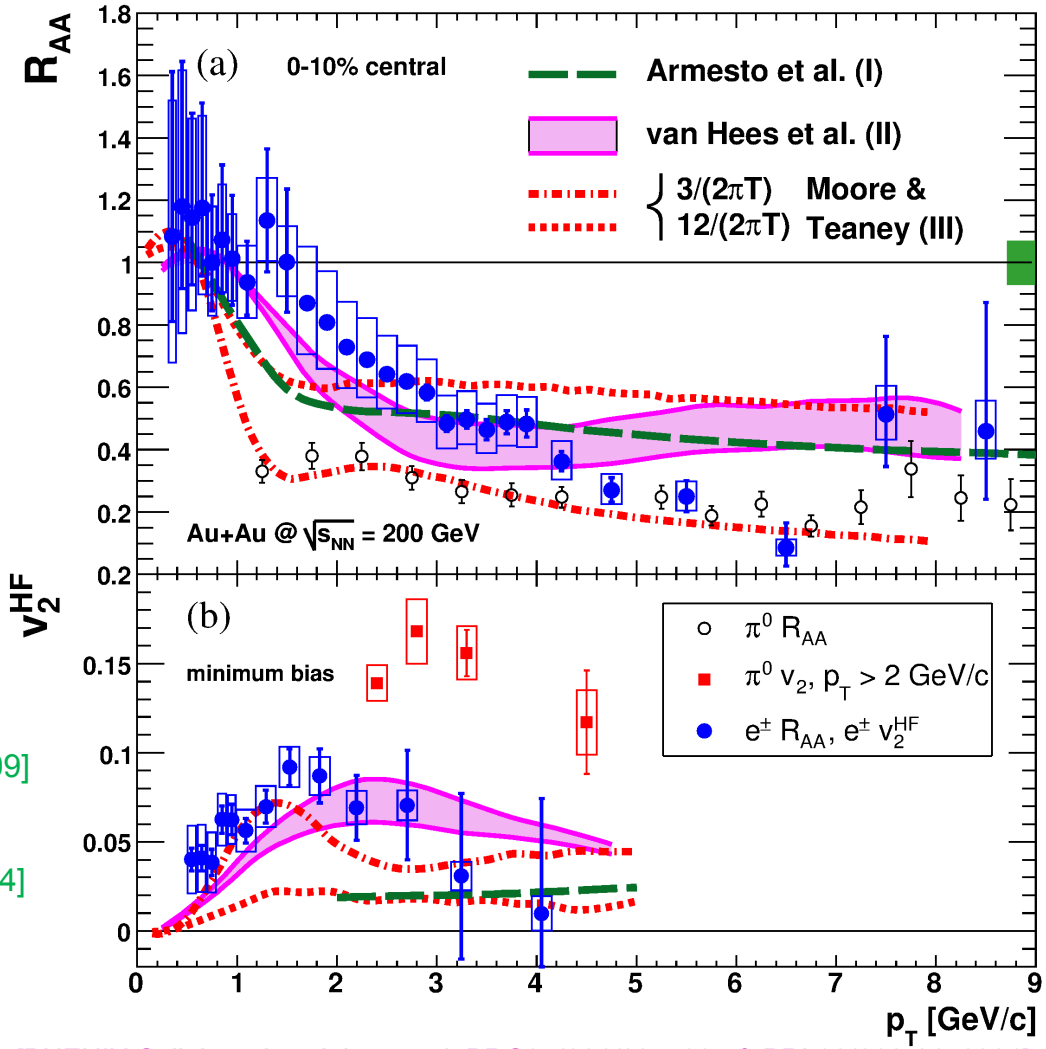
Need to be determined from QCD using first principle lattice calculations!

here heavy flavour:

- Heavy Quark Diffusion Constant D
  [H.T.Ding, OK et al., PRD86(2012)014509]
- Heavy Quark Momentum Diffusion κ
  [OK, arXiv:1409.3724]

or for light quarks:

- Light quark flavour diffusion
- Electrical conductivity
  [A.Francis, OK et al., PRD83(2011)034504]



[PHENIX Collaboration, Adare et al.,PRC84(2011)044905 & PRL98(2007)172301]

Transport coefficients from Lattice QCD – Flavour Diffusion

Transport coefficients usually calculated using correlation function of conserved currents

$$G(\tau, \mathbf{p}, T) = \int_0^\infty \frac{d\omega}{2\pi} \rho(\omega, \mathbf{p}, T) K(\tau, \omega, T)$$

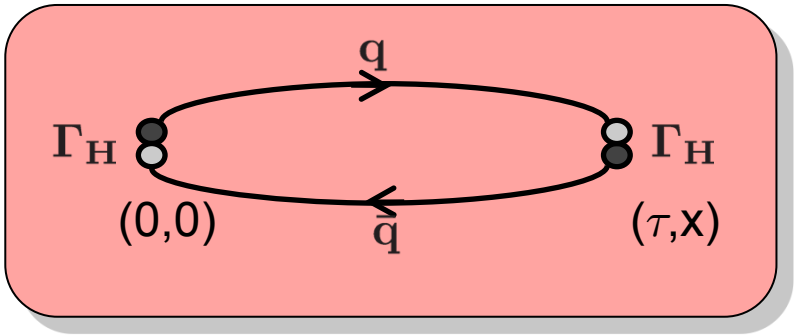
$$K(\tau, \omega, T) = \frac{\cosh\left(\omega(\tau - \frac{1}{2T})\right)}{\sinh\left(\frac{\omega}{2T}\right)}$$

Lattice observables:

$$G_{\mu\nu}(\tau, \vec{x}) = \langle J_\mu(\tau, \vec{x}) J_\nu^\dagger(0, \vec{0}) \rangle$$

$$J_\mu(\tau, \vec{x}) = 2\kappa Z_V \bar{\psi}(\tau, \vec{x}) \Gamma_\mu \psi(\tau, \vec{x})$$

$$G_{\mu\nu}(\tau, \vec{p}) = \sum_{\vec{x}} G_{\mu\nu}(\tau, \vec{x}) e^{i\vec{p}\vec{x}}$$



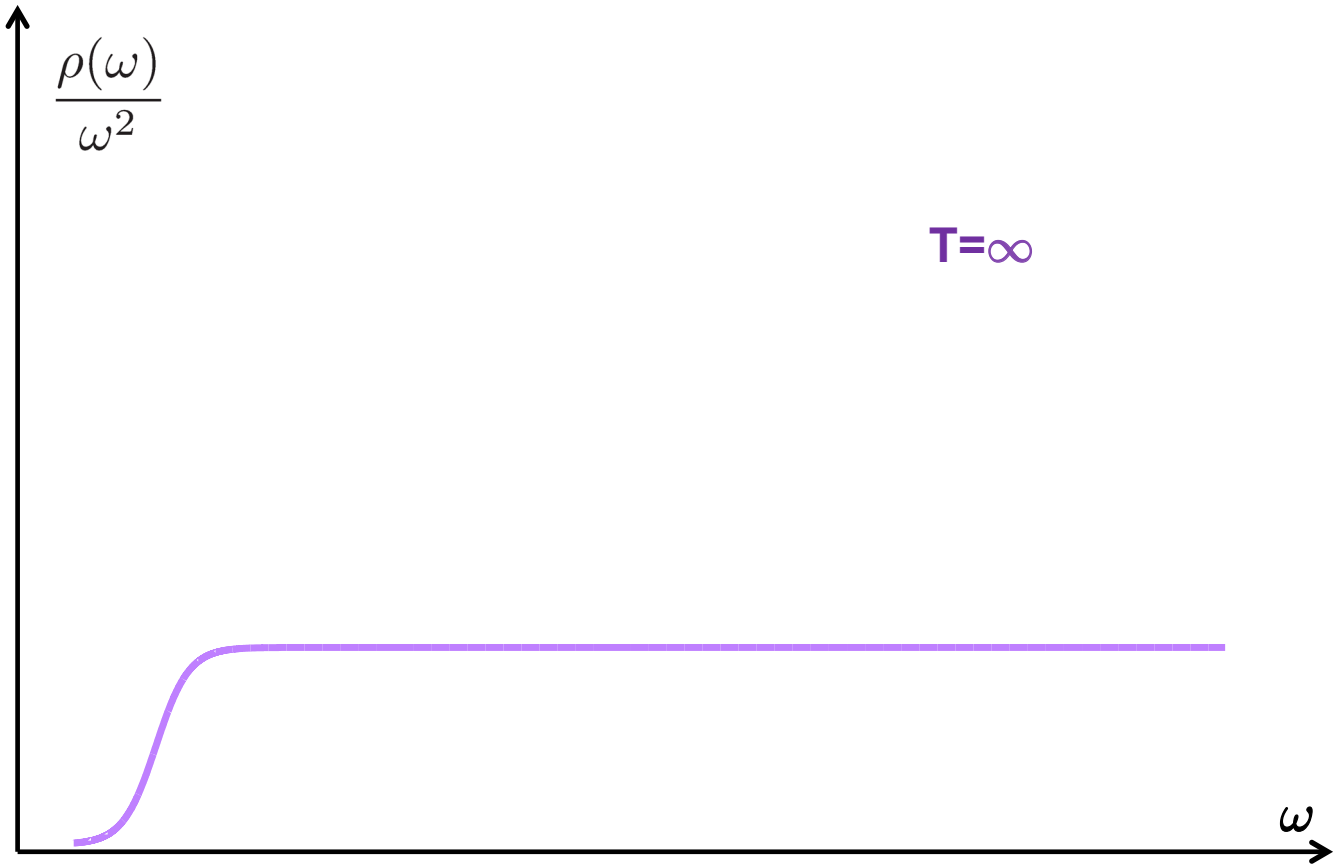
related to a conserved current

only correlation functions calculable on lattice but

Transport coefficient determined by slope of spectral function at ω=0 (Kubo formula)

$$D = \frac{\pi}{3\chi_{00}} \lim_{\omega \to 0} \frac{\rho_{ii}(\omega, \vec{p} = 0, T)}{\omega T}$$

Quarkonium spectral function – What do we expect!?



+ zero-mode contribution at ω=0: $\rho(\omega) = 2\pi\chi_{00}\ \omega\delta(\omega)$

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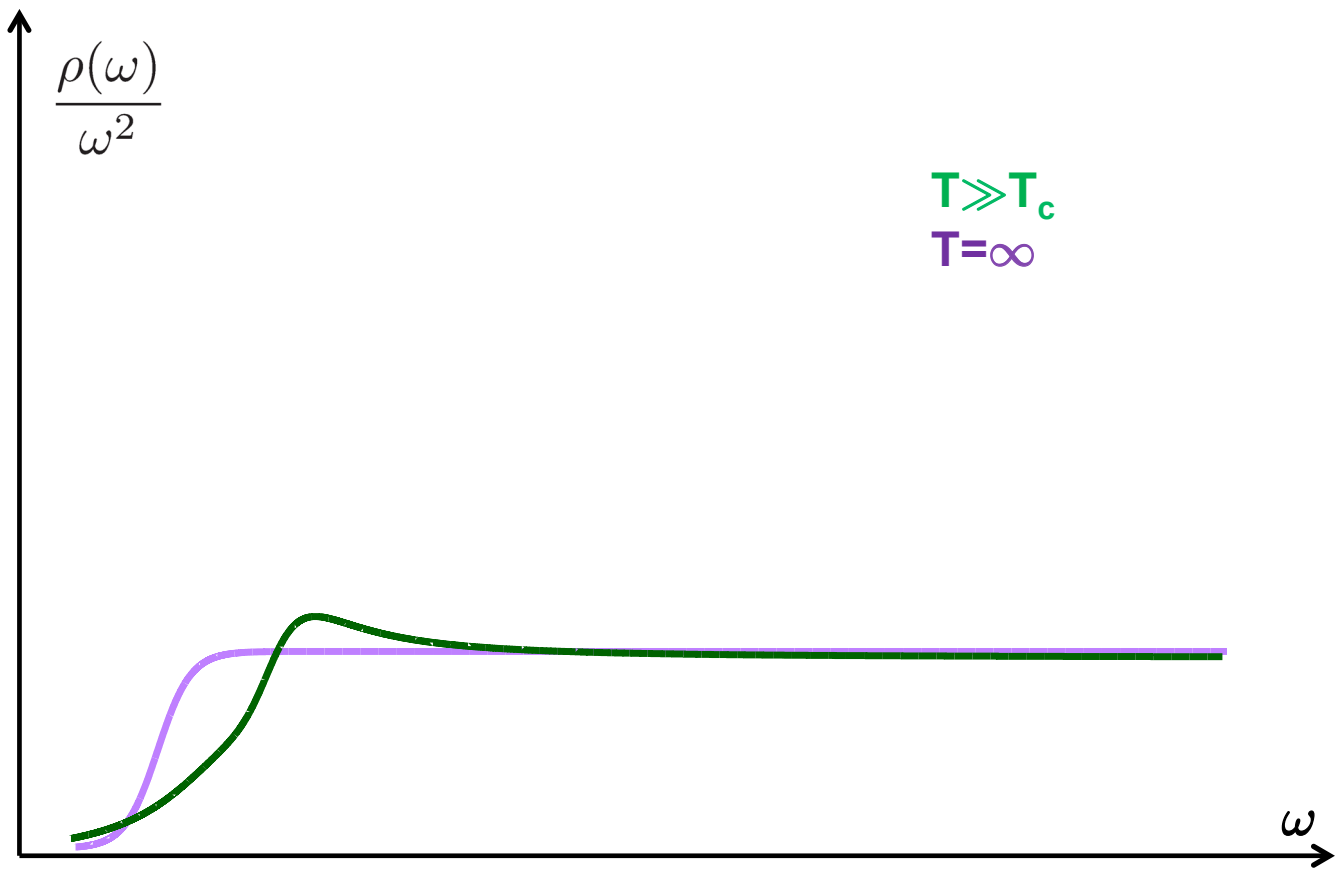

+ zero-mode contribution at ω=0: $\rho(\omega) = 2\pi\chi_{00}\ \omega\delta(\omega)$

+ transport peak at small ω: $\rho(\omega \ll T) \simeq 2\chi_{00}\frac{T}{M}\frac{\omega\eta}{\omega^2+\eta^2}\,, \qquad \eta = \frac{T}{MD}$

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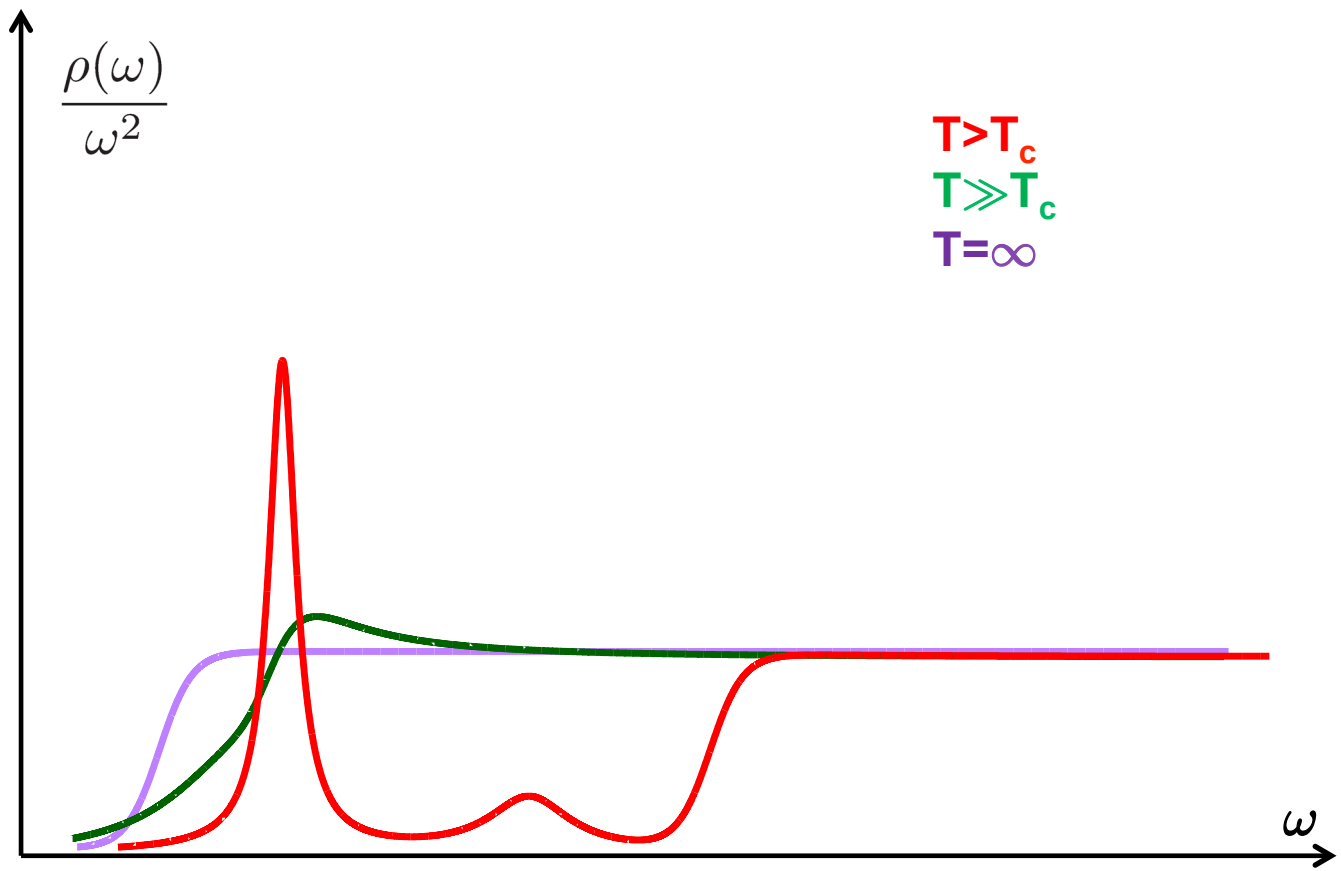

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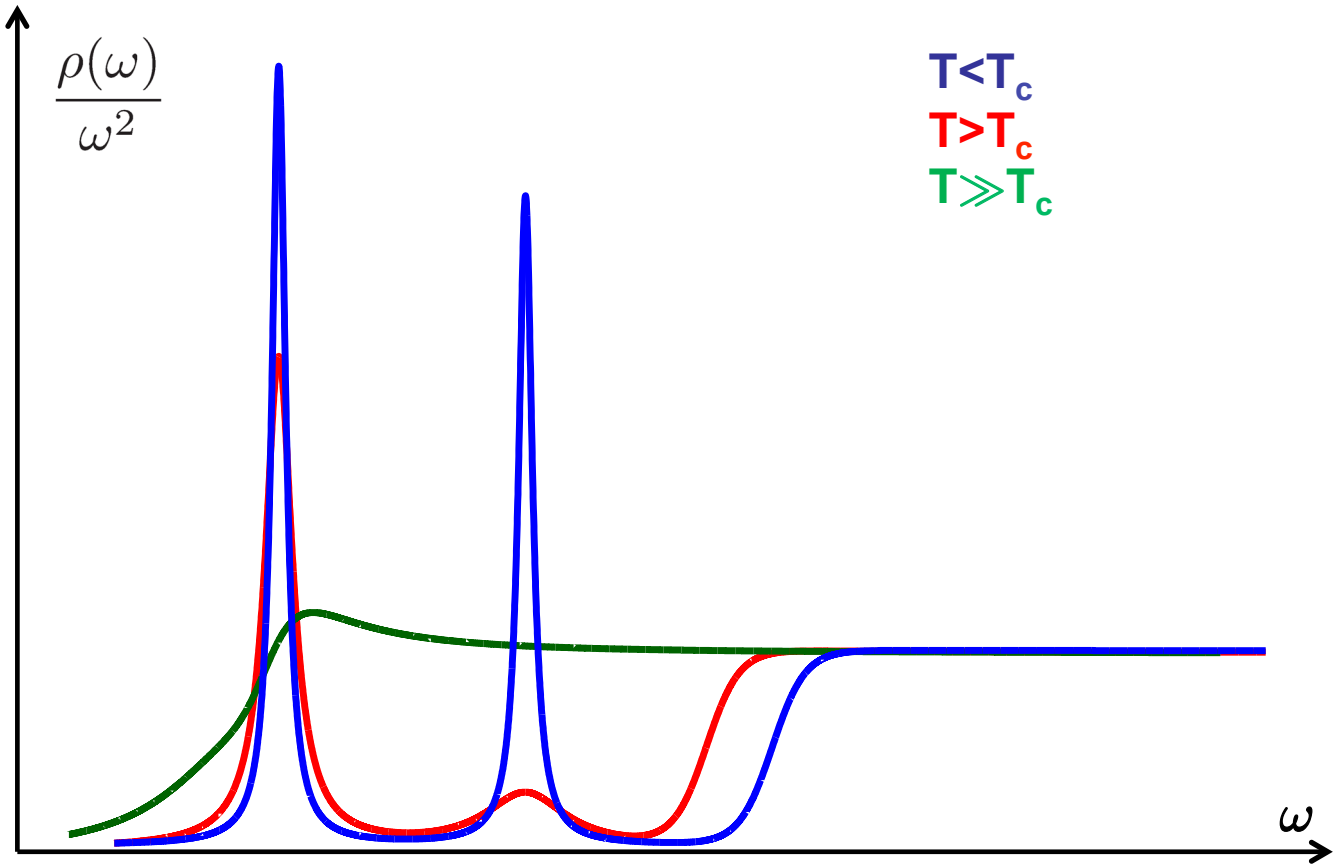

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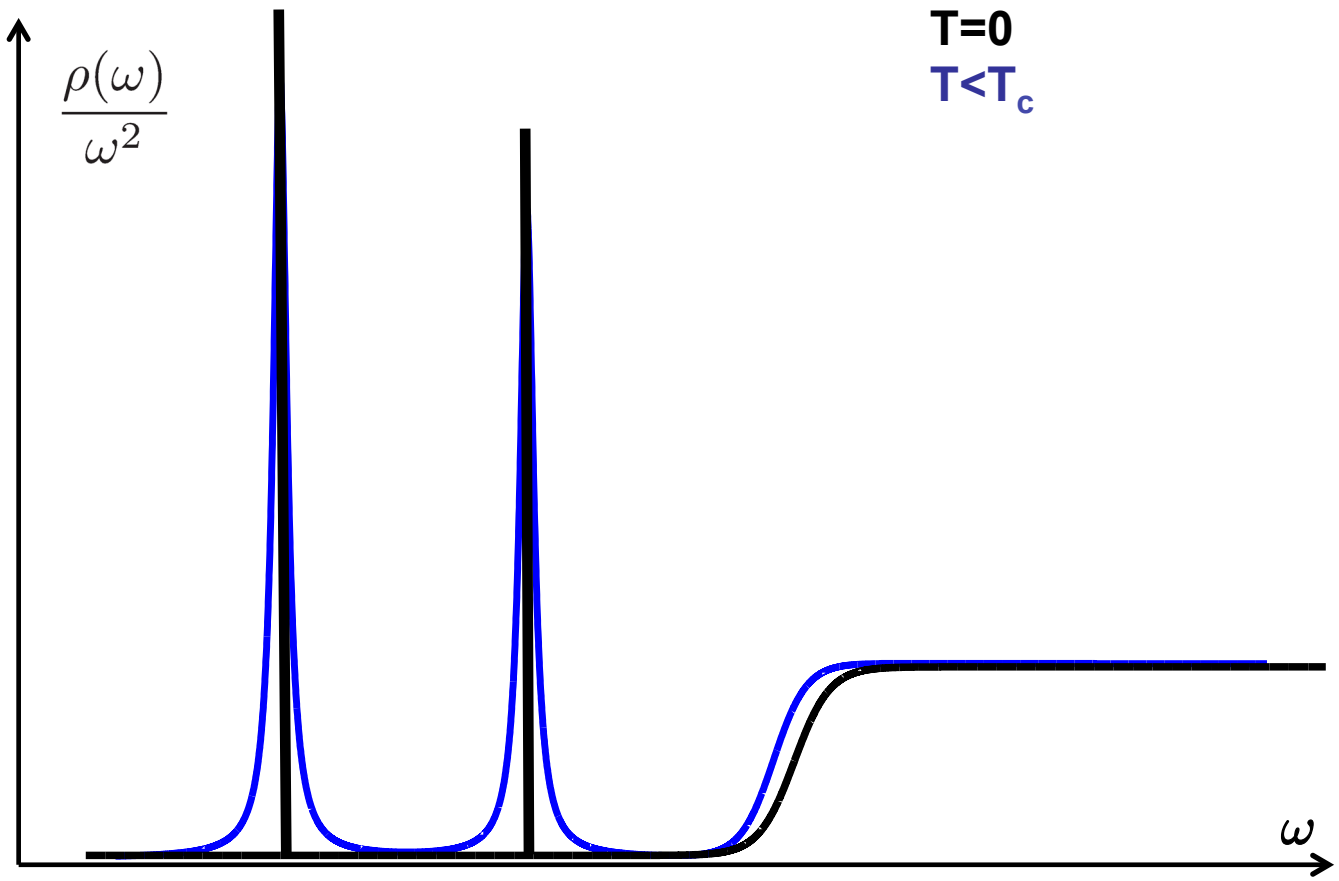

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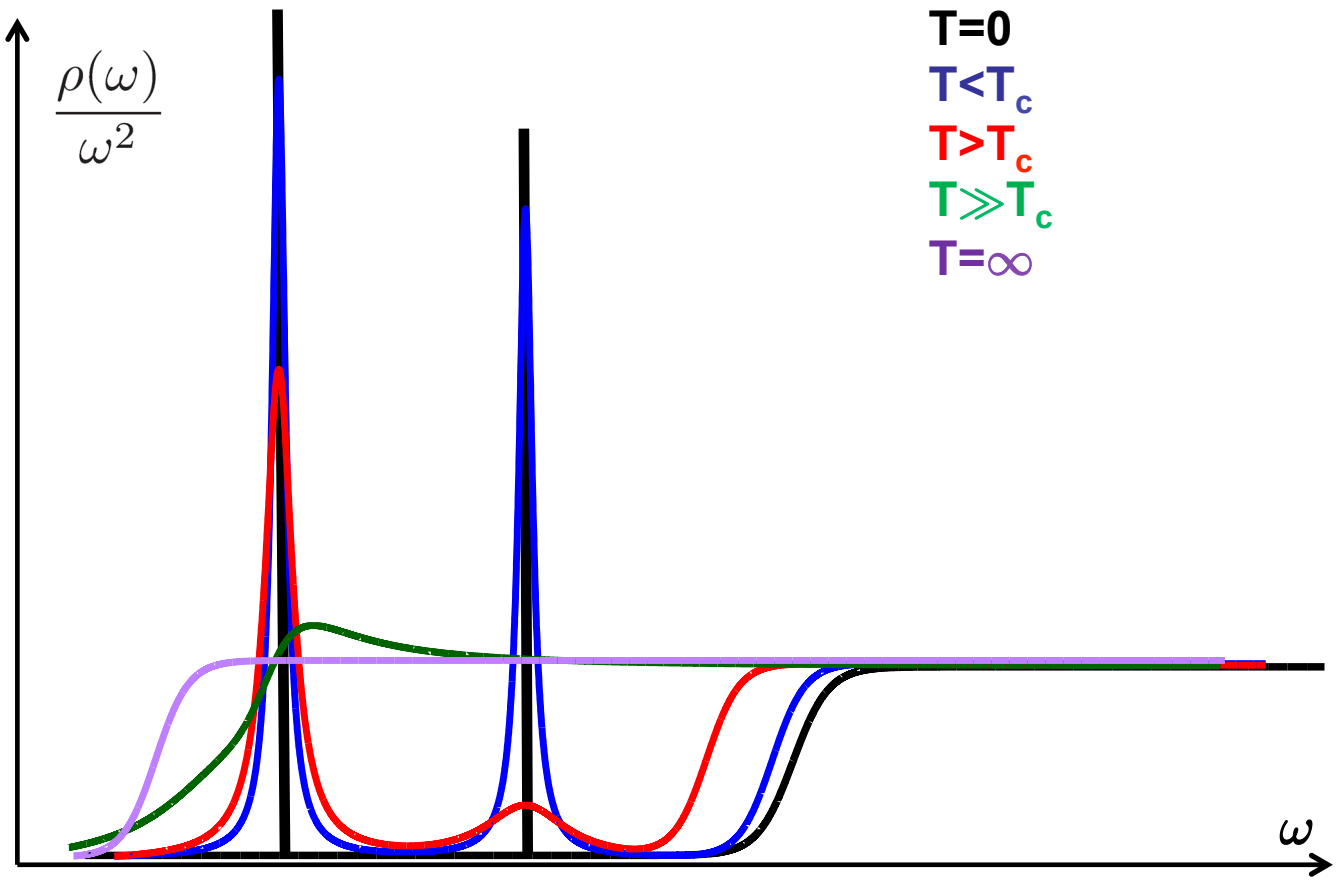

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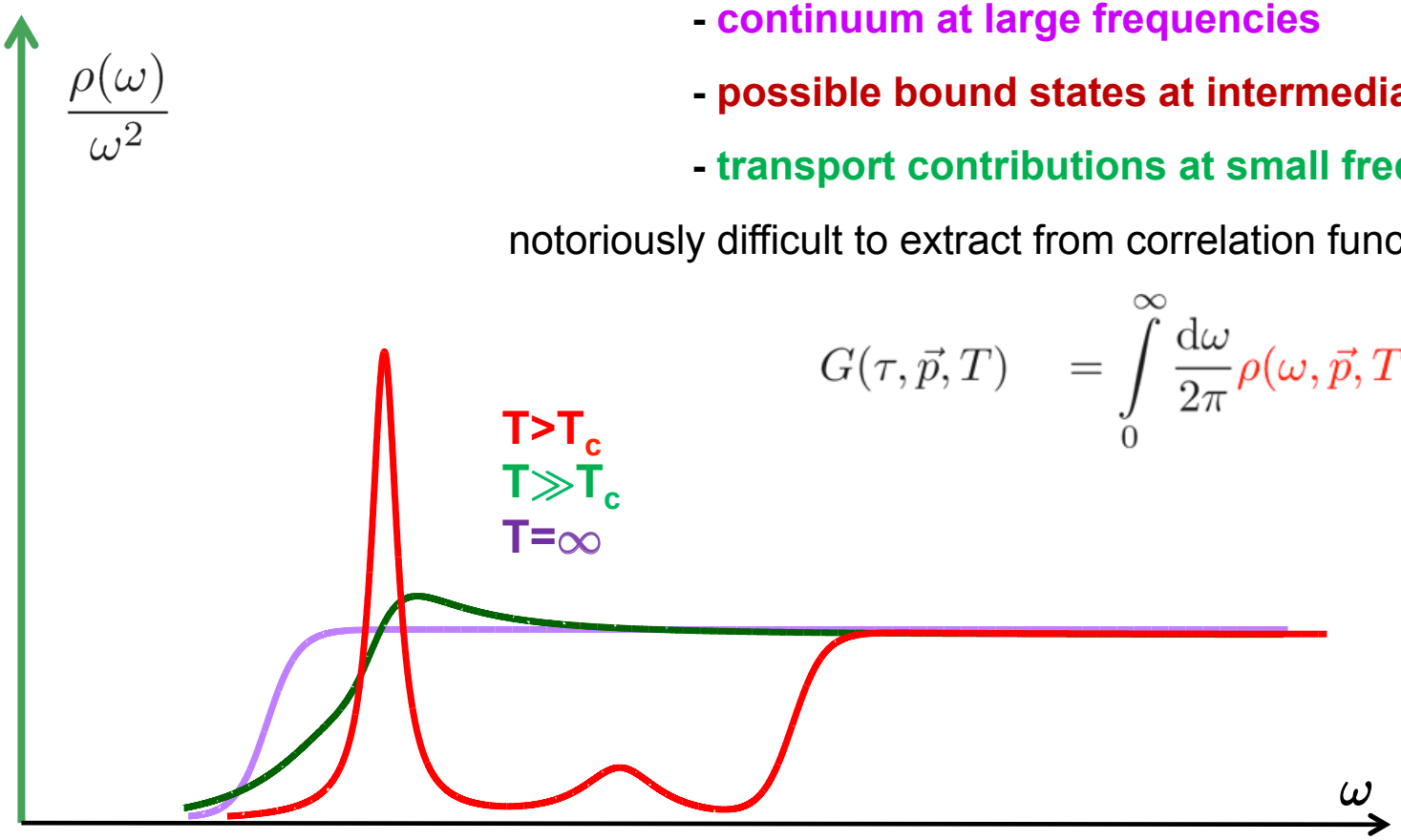
Quarkonium spectral function – hard to separate different scales

Different contributions and scales enter in the spectral function

- **continuum at large frequencies**
- **possible bound states at intermediate frequencies**
- **transport contributions at small frequencies**

notoriously difficult to extract from correlation functions

$$G(\tau,\vec{p},T) = \int_0^\infty \frac{d\omega}{2\pi}\rho(\omega,\vec{p},T)K(\tau,\omega,T)$$



+ zero-mode contribution at ω=0: $\rho(\omega) = 2\pi\chi_{00}\,\omega\delta(\omega)$

+ (narrow) transport peak at small ω: $\rho(\omega \ll T) = 2\chi_{00}\frac{T}{M}\frac{\omega\eta}{\omega^2+\eta^2}\,, \qquad \eta = \frac{T}{MD}$

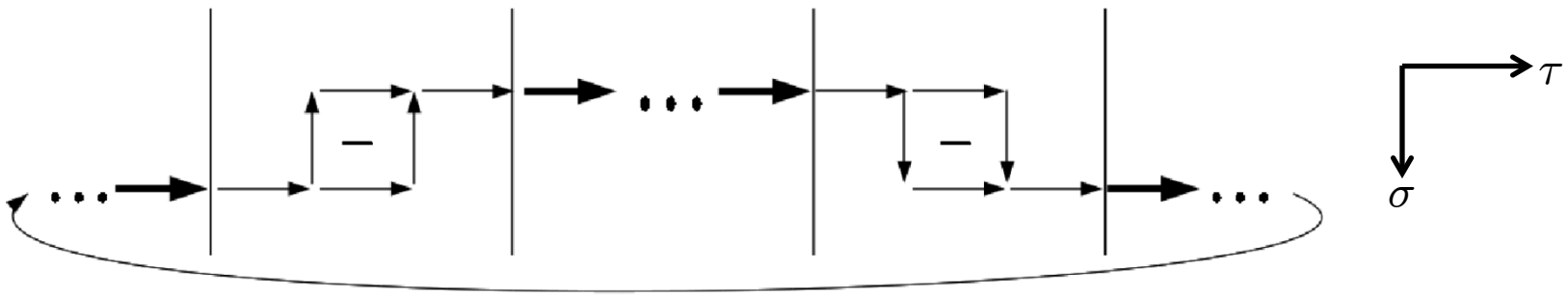
Heavy Quark Momentum Diffusion Constant – Single Quark in the Medium

Heavy Quark Effective Theory (HQET) in the large quark mass limit

for a single quark in medium

leads to a (pure gluonic) "color-electric correlator"

[J.Casalderrey-Solana, D.Teaney, PRD74(2006)085012,
S.Caron-Huot,M.Laine,G.D. Moore,JHEP04(2009)053]



$$G_{\mathrm{E}}(\tau) \equiv -\frac{1}{3}\sum_{i=1}^{3} \frac{\left\langle \mathrm{Re\,Tr}\left[U(\frac{1}{T};\tau)\, gE_i(\tau,\mathbf{0})\, U(\tau;0)\, gE_i(0,\mathbf{0})\right]\right\rangle}{\left\langle \mathrm{Re\,Tr}[U(\frac{1}{T};0)]\right\rangle}$$

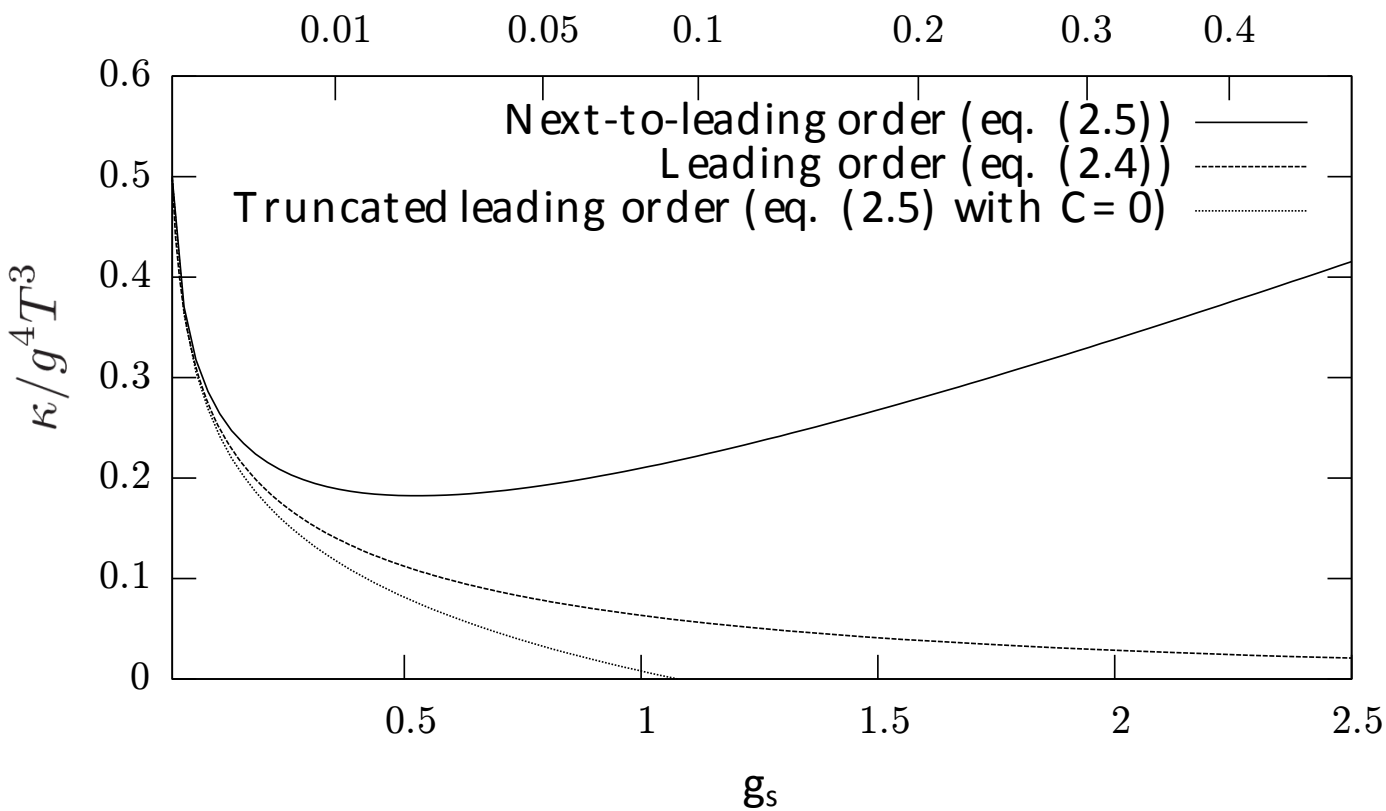
Heavy quark (momentum) diffusion:

$$\kappa = \lim_{\omega\to 0} \frac{2T\rho_{\mathrm{E}}(\omega)}{\omega} \qquad D = \frac{2T^2}{\kappa}$$

Heavy Quark Momentum Diffusion Constant – Perturbation Theory

can be related to the thermalization rate: $$\eta_D = \frac{\kappa}{2M_{kin}T}\left(1 + O\left(\frac{\alpha_s^{3/2}T}{M_{kin}}\right)\right)$$

NLO in perturbation theory: [Caron-Huot, G.Moore, JHEP 0802 (2008) 081]

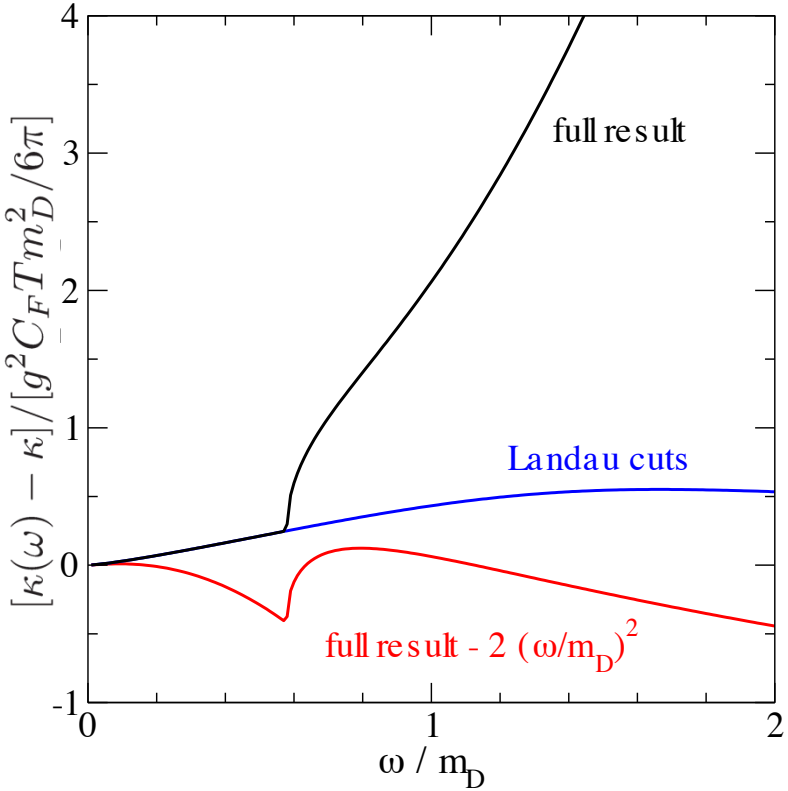


very poor convergence

→ **Lattice QCD study required in the relevant temperature region**

Heavy Quark Momentum Diffusion Constant – Perturbation Theory

NLO spectral function in perturbation theory: [Caron-Huot, M.Laine, G.Moore, JHEP 0904 (2009) 053]



in contrast to a narrow transport peak, from this a smooth limit

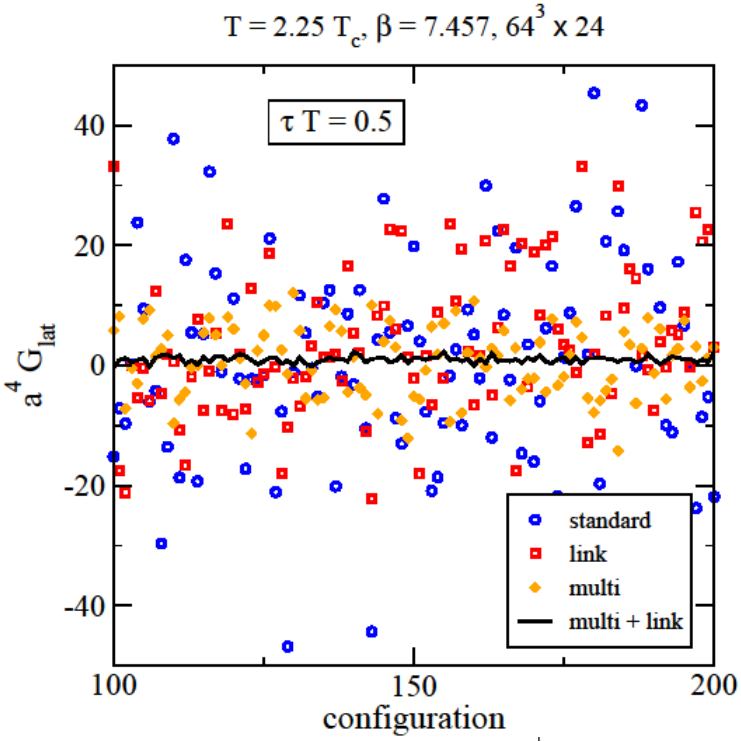
$$\kappa/T^3 = \lim_{\omega\to 0} \frac{2T\rho_{\rm E}(\omega)}{\omega}$$

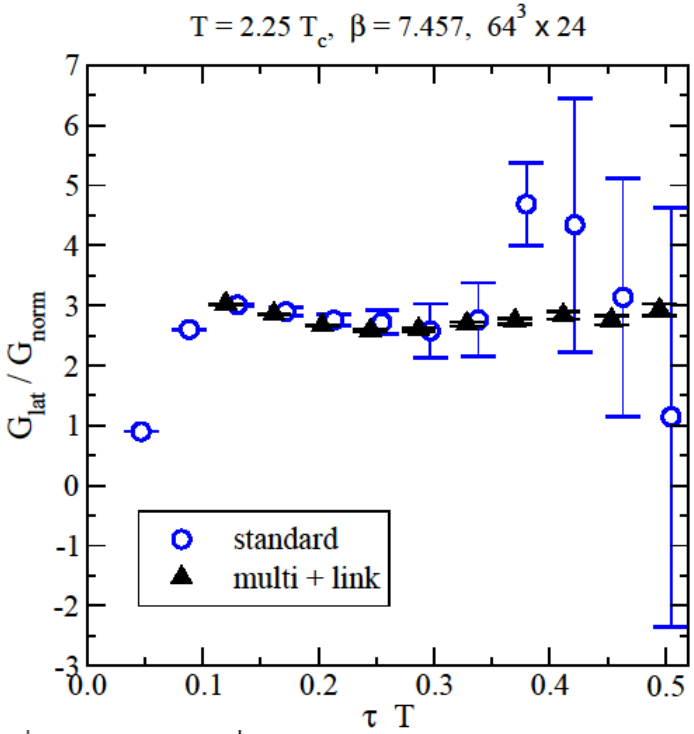
is expected

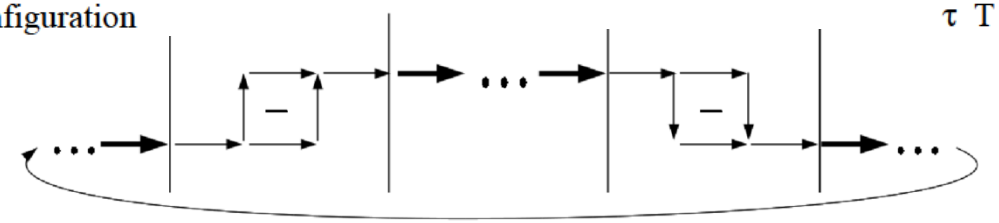
Qualitatively similar behaviour also found in AdS/CFT [S.Gubser, Nucl.Phys.B790 (2008)175]

Heavy Quark Momentum Diffusion Constant – Lattice algorithms

[A.Francis,OK,M.Laine,J.Langelage, arXiv:1109.3941 and arXiv:1311.3759]







due to the gluonic nature of the operator, signal is extremely noisy

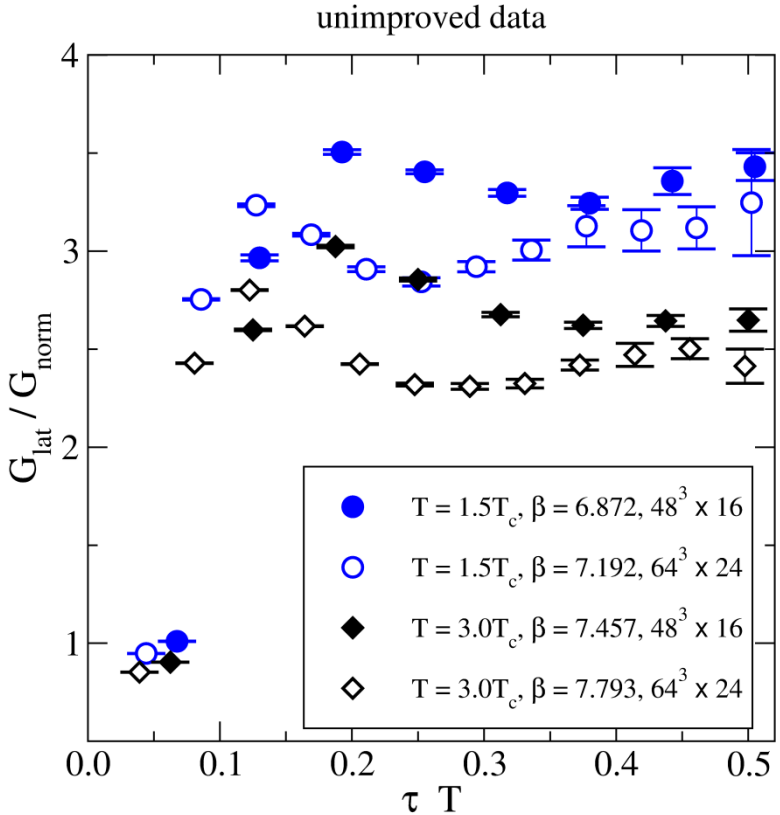
→ **multilevel combined with link-integration techniques to improve the signal**

[Lüscher,Weisz JHEP 0109 (2001)010 and H.B.Meyer PRD (2007) 101701]

[Parisi,Petronzio,Rapuano PLB 128 (1983) 418, and de Forcrand PLB 151 (1985) 77]

Heavy Quark Momentum Diffusion Constant – Tree-Level Improvement

[A.Francis,OK,M.Laine,J.Langelage, arXiv:1109.3941 and arXiv:1311.3759]



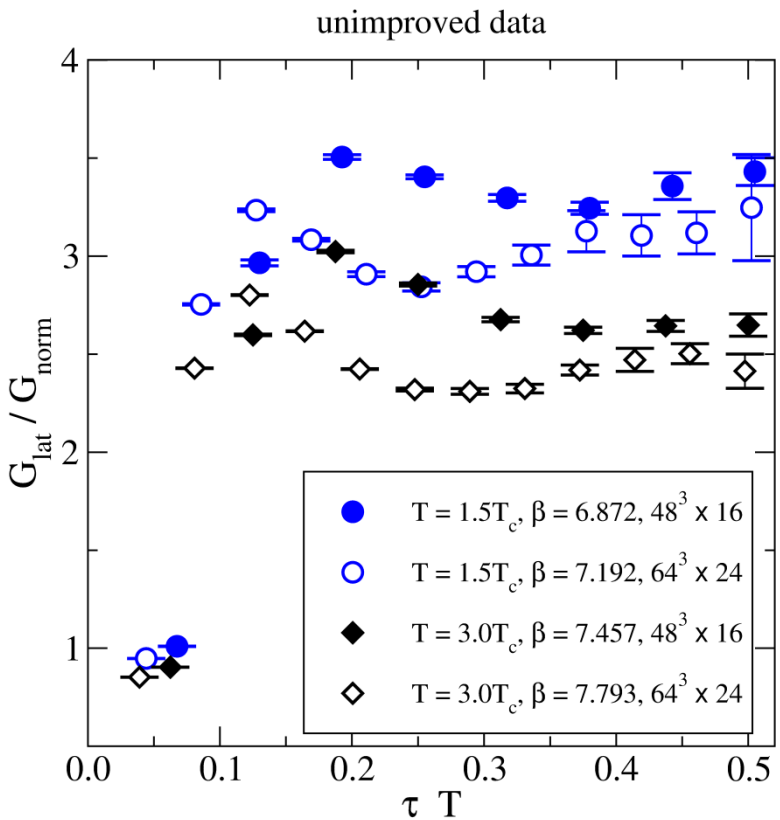
normalized by the LO-perturbative correlation function:

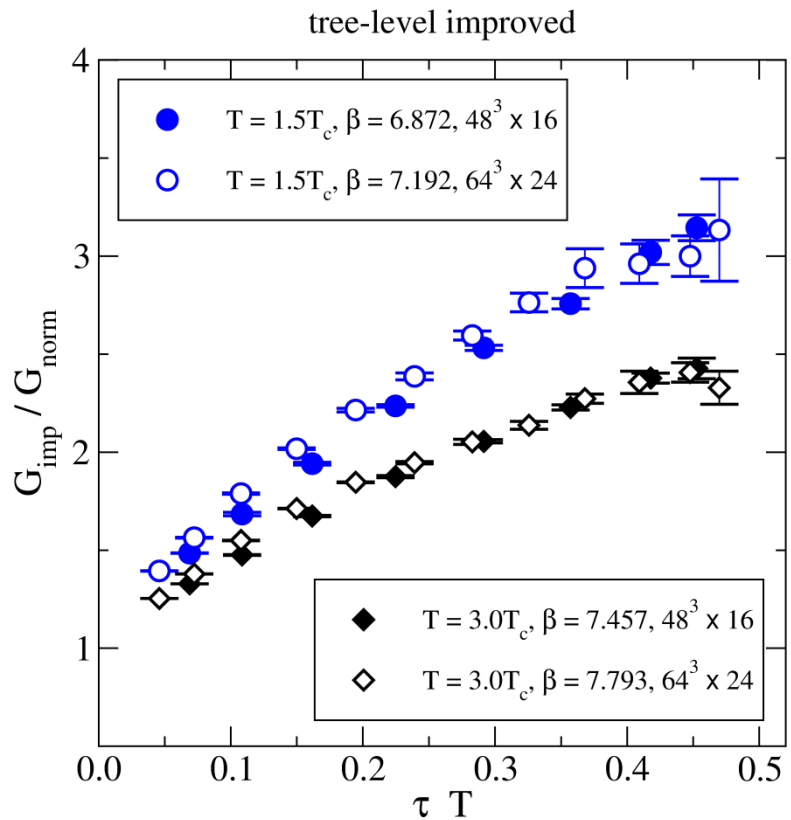
$$G_{\rm norm}(\tau T) \equiv \frac{G^{\rm LO}_{\rm cont}(\tau T)}{g^2 C_F} = \pi^2 T^4 \left[\frac{\cos^2(\pi\tau T)}{\sin^4(\pi\tau T)} + \frac{1}{3\sin^2(\pi\tau T)} \right] \qquad C_F \equiv \frac{N_c^2 - 1}{2N_c}$$

and renormalized using NLO renormalization constants $Z(g^2)$

Heavy Quark Momentum Diffusion Constant – Tree-Level Improvement

[A.Francis,OK,M.Laine,J.Langelage, arXiv:1109.3941 and arXiv:1311.3759]





lattice cut-off effects visible at small separations (left figure)

→ **tree-level improvement** (right figure) to reduce discretization effects

$$G^{\mathrm{LO}}_{\mathrm{cont}}(\overline{\tau T}) = G^{\mathrm{LO}}_{\mathrm{lat}}(\tau T)$$

leads to an effective reduction of cut-off effect for all τT

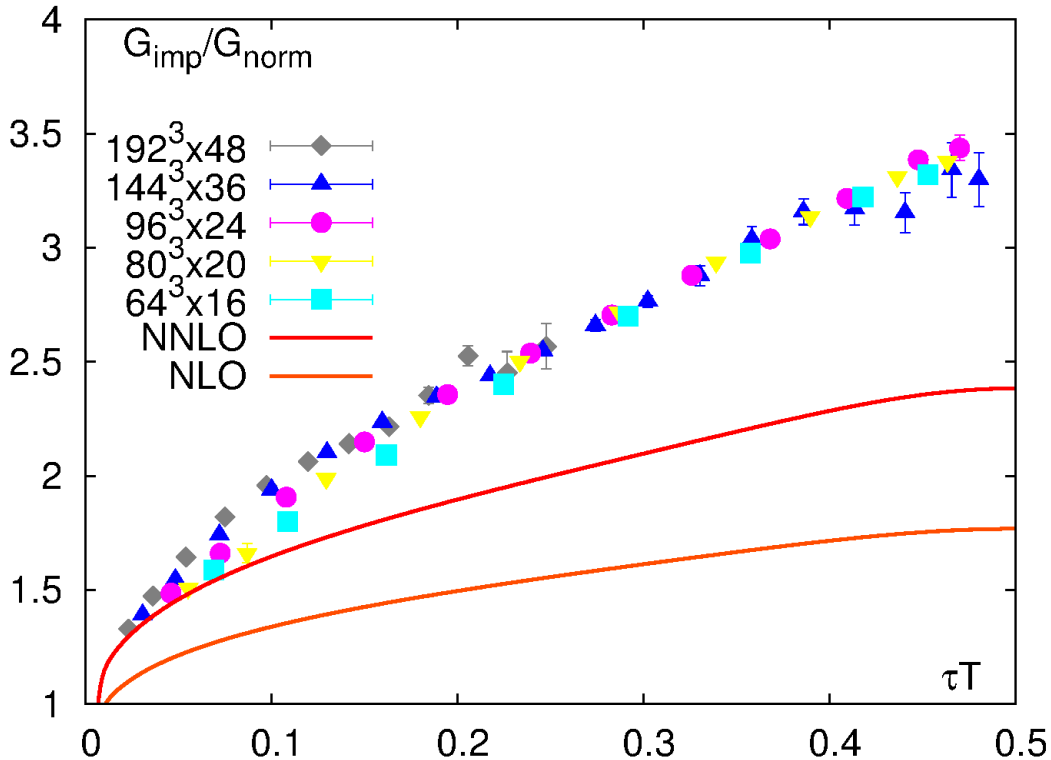
Heavy Quark Momentum Diffusion Constant – Lattice results

Quenched Lattice QCD on large and fine isotropic lattices at $T \simeq 1.4\ T_c$

- standard Wilson gauge action
- algorithmic improvements to enhance signal/noise ratio
- fixed aspect ration $N_s/N_t = 4$, i.e. fixed physical volume $(2\text{fm})^3$
- perform the continuum limit, $a \to 0 \ \leftrightarrow\ N_t \to \infty$
- determine κ in the continuum using an Ansatz for the spectral fct. $\rho(\omega)$

N_σ	N_τ	β	$1/a[\text{GeV}]$	$a[\text{fm}]$	#Confs
64	16	6.872	7.16	0.03	172
80	20	7.035	8.74	0.023	180
96	24	7.192	10.4	0.019	160
144	36	7.544	15.5	0.013	693
192	48	7.793	20.4	0.010	223

Heavy Quark Momentum Diffusion Constant – Lattice results



finest lattices still quite noisy at large τT

but only

small cut-off effects at intermediate τT

cut-off effects become visible at small τT

need to extrapolate to the continuum

perturbative behavior in the limit $\tau T \to 0$

N_σ	N_τ	β	$1/a$[GeV]	a[fm]	#Confs
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96	24	7.192	10.4	0.019	160
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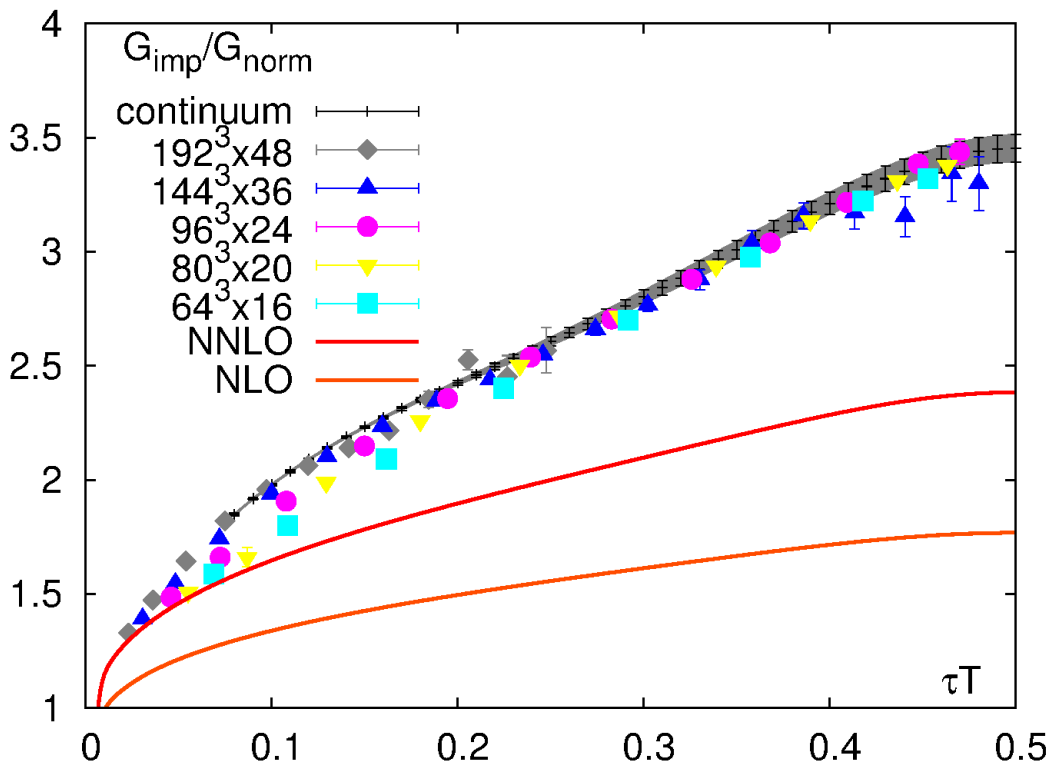
allows to perform continuum extrapolation, $a \to 0 \leftrightarrow N_t \to \infty$ **, at fixed** $T=1/a\,N_t$

Heavy Quark Momentum Diffusion Constant – Continuum extrapolation



finest lattices still quite noisy at large τT

but only

small cut-off effects at intermediate τT

cut-off effects become visible at small τT

need to extrapolate to the continuum

perturbative behavior in the limit $\tau T \to 0$

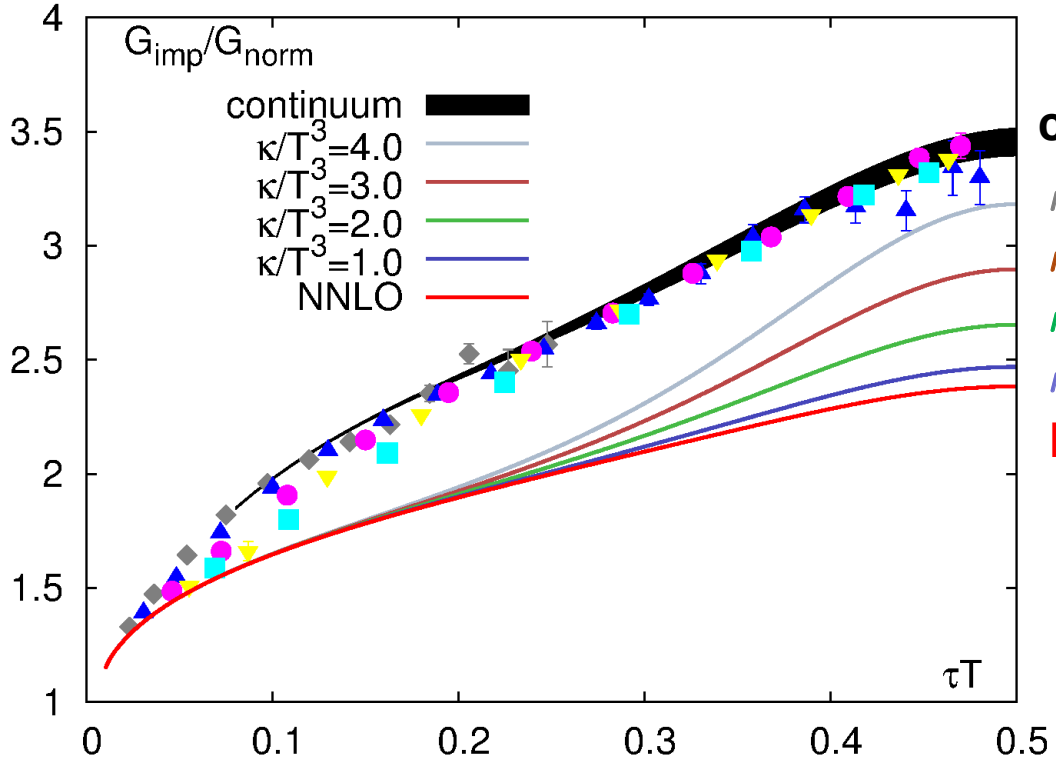
well behaved continuum extrapolation for $0.05 \leq \tau T \leq 0.5$

finest lattice already close to the continuum

coarser lattices at larger τT close to the continuum

how to extract the spectral function from the correlator?

Heavy Quark Momentum Diffusion Constant – Model Spectral Function



continuum extrapolation

κ/T^3 = 4.0

κ/T^3 = 3.0

κ/T^3 = 2.0

κ/T^3 = 1.0

NNLO perturbation theory

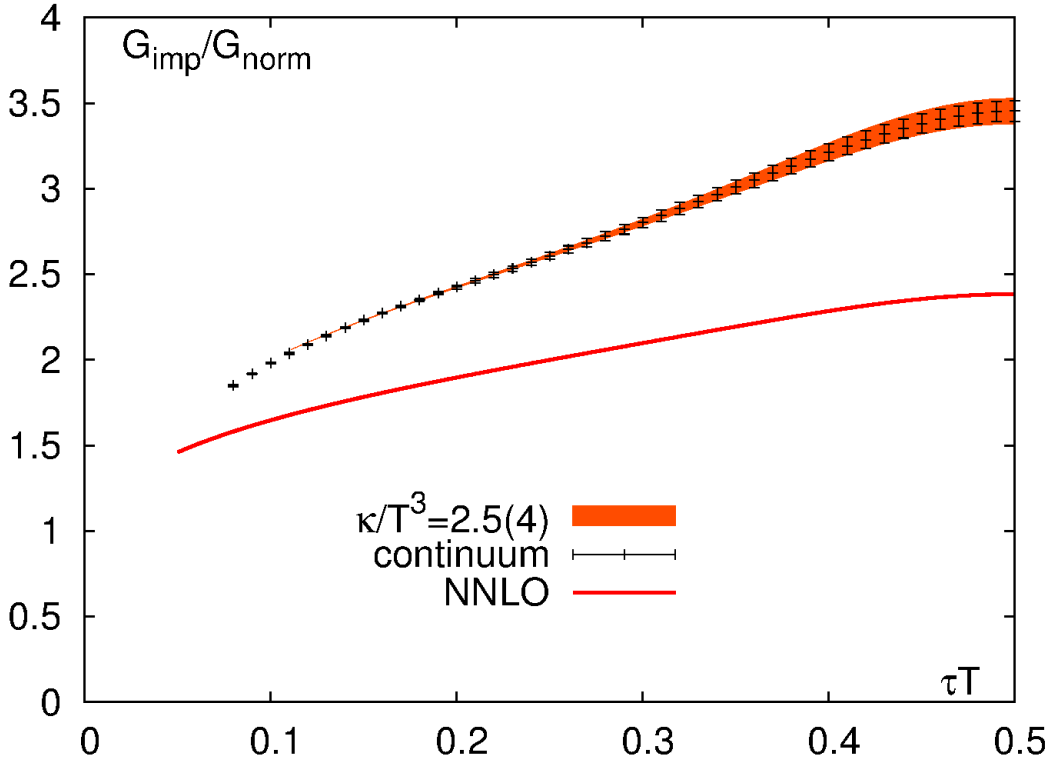
Model spectral function: transport contribution + NNLO [Y.Burnier et al. JHEP 1008 (2010) 094)]

$$\rho_{\rm model}(\omega) \equiv \max\left\{\rho_{\rm NNLO}(\omega), \frac{\omega\kappa}{2T}\right\}$$

$$G_{\rm model}(\tau) \equiv \int_0^\infty \frac{{\rm d}\omega}{\pi}\rho_{\rm model}(\omega)\frac{\cosh\left(\frac{1}{2}-\tau T\right)\frac{\omega}{T}}{\sinh\frac{\omega}{2T}}$$

some contribution at intermediate distance/frequency seems to be missing

Heavy Quark Momentum Diffusion Constant – Model Spectral Function



result of the fit to $\rho_{model}(\omega)$

with three parameters: κ,A,B

Model spectral function: transport contribution + NNLO + correction

$$\rho_{\rm model}(\omega) \equiv \max\left\{ A\rho_{\rm NNLO}(\omega) + B\omega^3, \frac{\omega\kappa}{2T} \right\}$$

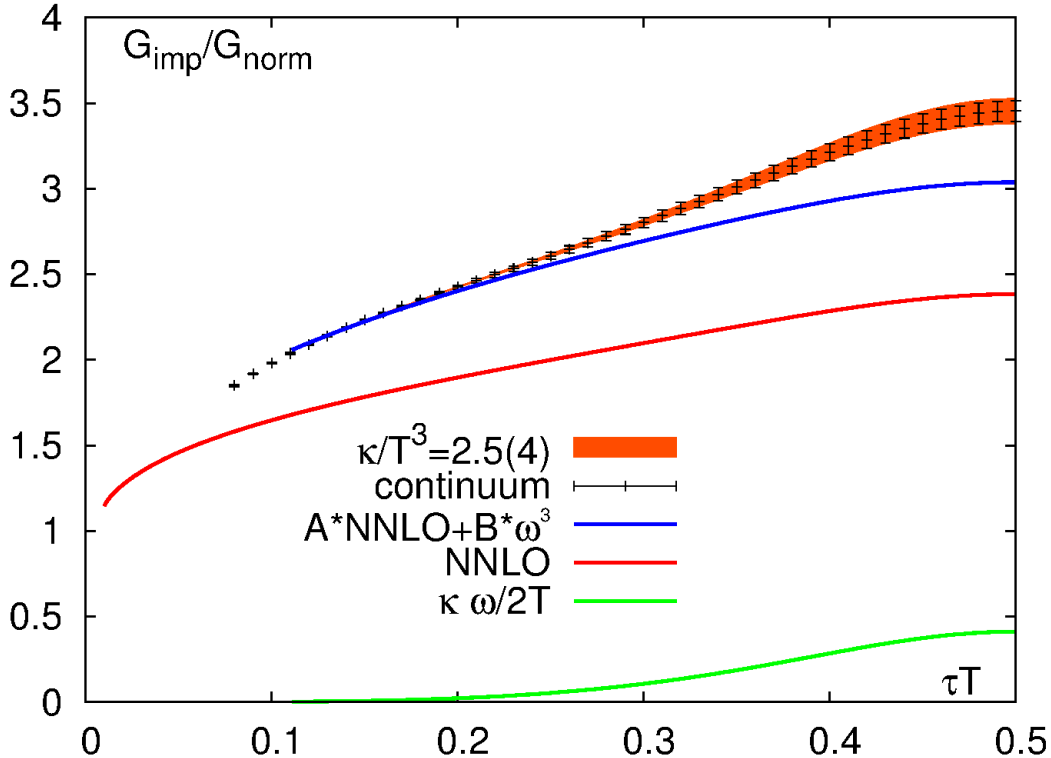
$$G_{\rm model}(\tau) \equiv \int_0^\infty \frac{{\rm d}\omega}{\pi} \rho_{\rm model}(\omega) \frac{\cosh\left(\frac{1}{2} - \tau T\right)\frac{\omega}{T}}{\sinh\frac{\omega}{2T}}$$

used to fit the continuum extrapolated data

→ **first continuum estimate of κ :**

$$\kappa/T^3 = \lim_{\omega\to 0} \frac{2T\rho_{\rm E}(\omega)}{\omega} \simeq 2.5(4)$$

Heavy Quark Momentum Diffusion Constant – Model Spectral Function



result of the fit to $\rho_{model}(\omega)$

A $\rho_{NNLO}(\omega)$ + B w^3

NNLO perturbation theory

$\frac{\omega\kappa}{2T}$ small but relevant contribution at τT > 0.2 !

Model spectral function: transport contribution + NNLO + correction

$$\rho_{\rm model}(\omega) \equiv \max\left\{A\rho_{\rm NNLO}(\omega) + B\omega^3, \frac{\omega\kappa}{2T}\right\}$$

$$G_{\rm model}(\tau) \equiv \int_0^\infty \frac{{\rm d}\omega}{\pi}\rho_{\rm model}(\omega)\frac{\cosh\left(\frac{1}{2}-\tau T\right)\frac{\omega}{T}}{\sinh\frac{\omega}{2T}}$$

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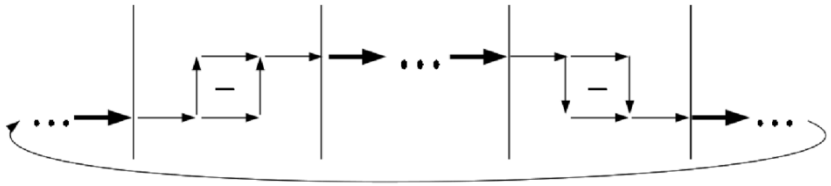
Conclusions and Outlook

$$G_{\mathrm{E}}(\tau) \equiv -\frac{1}{3}\sum_{i=1}^{3}\frac{\left\langle \mathrm{Re}\,\mathrm{Tr}\left[U(\frac{1}{T};\tau)\,gE_i(\tau,\mathbf{0})\,U(\tau;0)\,gE_i(0,\mathbf{0})\right]\right\rangle}{\left\langle \mathrm{Re}\,\mathrm{Tr}[U(\frac{1}{T};0)]\right\rangle}$$



Continuum extrapolation for the color electric correlation function

extracted from Quenched Lattice QCD

- **using noise reduction techniques to improve signal**
- **and an Ansatz for the spectral function**

→ first continuum estimate for the Heavy Quark Momentum Diffusion Coefficient κ

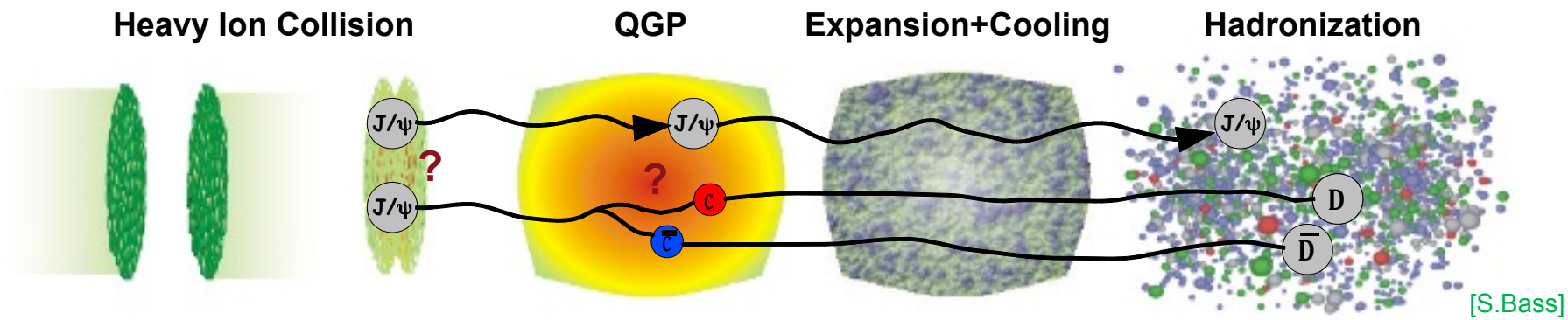
- **still based on a simple Ansatz for the spectral function**

More detailed analysis of the systematic uncertainties needed

- **Different Ansätze for the spectral function**
- **Other techniques to extract the spectral function**

Other Transport coefficients from Effective Field Theories?

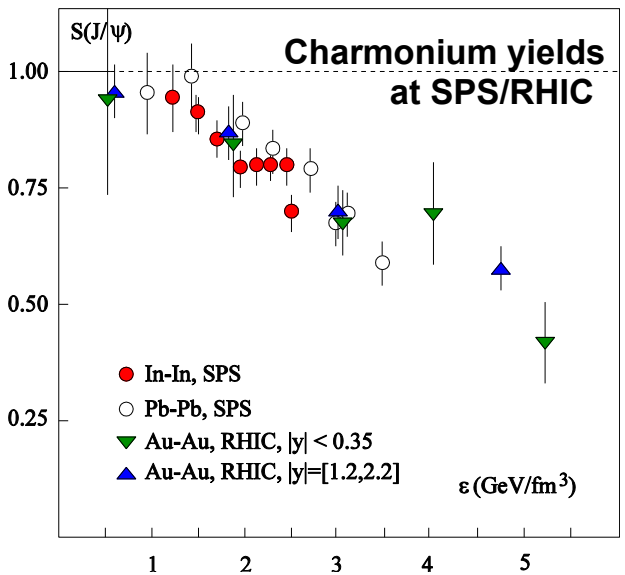
Motivation - Quarkonium in Heavy Ion Collisions



Charmonium+Bottmonium is produced (mainly) in the early stage of the collision

Depending on the Dissociation Temperature

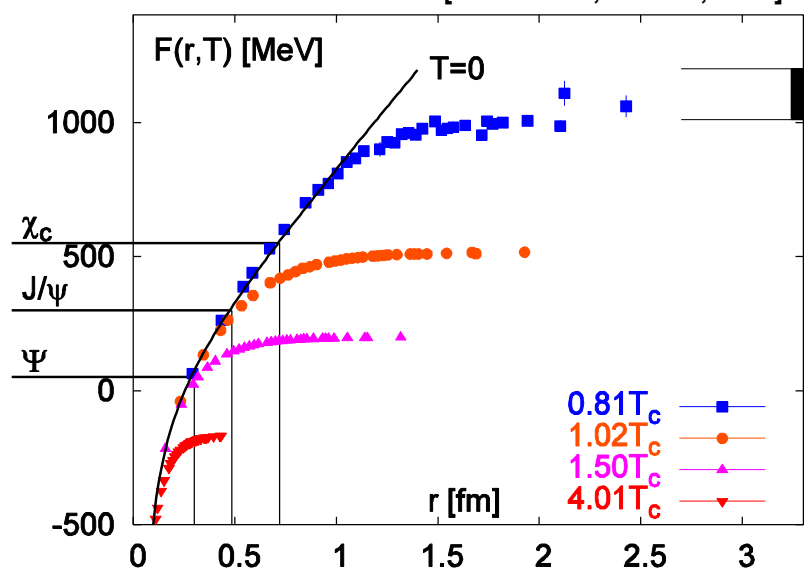
- **remain as bound states in the whole evolution**
- **release their constituents in the plasma**



First estimates on Dissociation Temperatures

from detailed knowledge of Heavy Quark Free Energies and Potential Models

[Kaczmarek, Zantow, 2005]



Quarkonium Spectral Functions – HQ Diffusion and Dissociation

In the following: Meson Correlation Functions

$$G(\tau, \mathbf{p}, T) = \int_0^\infty \frac{d\omega}{2\pi} \rho(\omega, \mathbf{p}, T) K(\tau, \omega, T)$$

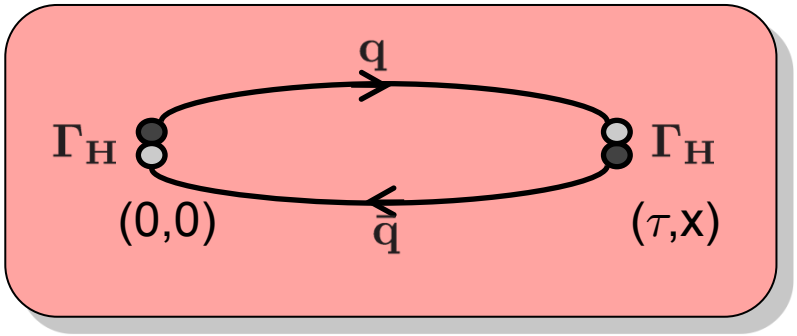
$$K(\tau, \omega, T) = \frac{\cosh\left(\omega(\tau - \frac{1}{2T})\right)}{\sinh\left(\frac{\omega}{2T}\right)}$$

Lattice observables:

$$G_{\mu\nu}(\tau, \vec{x}) = \langle J_\mu(\tau, \vec{x}) J_\nu^\dagger(0, \vec{0}) \rangle$$

$$J_\mu(\tau, \vec{x}) = 2\kappa Z_V \bar{\psi}(\tau, \vec{x}) \Gamma_\mu \psi(\tau, \vec{x})$$

$$G_{\mu\nu}(\tau, \vec{p}) = \sum_{\vec{x}} G_{\mu\nu}(\tau, \vec{x}) e^{i\vec{p}\vec{x}}$$



related to a conserved current

Channel	Γ_H	$^{2S+1}L_J$	J^{PC}	Quarkonia
Pseudoscalar (PS)	γ_5	$^1S_0$	0^{-+}	η_c, η_b
Vector (V)	γ_i	$^3S_1$	1^{--}	J/ψ, Υ
Scalar (S)	$\mathbf{1}$	$^1P_0$	0^{++}	χ_{c0}, χ_{b0}
Axialvector (AV)	$\gamma_i\gamma_5$	$^3P_1$	1^{++}	χ_{c1}, χ_{b1}

Quarkonium Spectral Functions – HQ Diffusion and Dissociation

In the following: Meson Correlation Functions

$$G(\tau, \mathbf{p}, T) = \int_0^\infty \frac{d\omega}{2\pi} \rho(\omega, \mathbf{p}, T) K(\tau, \omega, T)$$

$$K(\tau, \omega, T) = \frac{\cosh\left(\omega(\tau - \frac{1}{2T})\right)}{\sinh\left(\frac{\omega}{2T}\right)}$$

Lattice observables:

$$G_{\mu\nu}(\tau, \vec{x}) = \langle J_\mu(\tau, \vec{x}) J_\nu^\dagger(0, \vec{0}) \rangle$$

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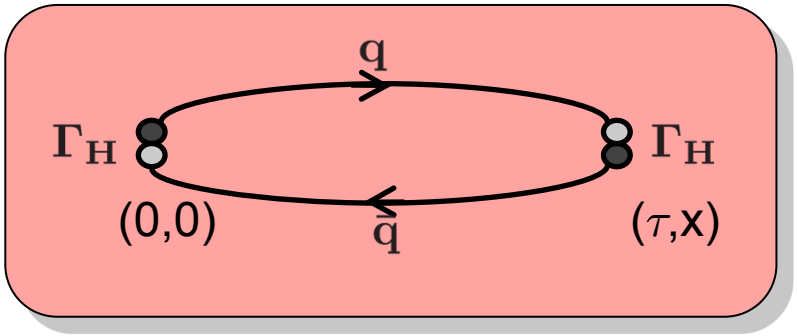


related to a conserved current

only correlation functions calculable on lattice but

Transport coefficient determined by slope of spectral function at ω=0 (Kubo formula)

$$D = \frac{\pi}{3\chi_{00}} \lim_{\omega \to 0} \frac{\rho_{ii}(\omega, \vec{p} = 0, T)}{\omega T}$$

Charmonium and Bottomonium correlators

[H.T.Ding, H.Ohno, OK, M.Laine, T.Neuhaus, work in progress]

- standard plaquette gauge & O(a)-improved Wilson quarks
- quenched gauge field configurations
- on fine and large isotropic lattices
- $T = 0.7 - 1.4 T_c$
- 2 different lattice spacing

  analysis of cut-off effects

  continuum limit (in the future)
- both charm & bottom

  tuned close to their physical masses

β	N_σ	N_τ	T/T_c	# confs.
7.192	96	48	0.7	259
		32	1.1	476
		28	1.2	336
		24	1.4	336
7.793	192	96	0.7	66
		56	1.2	66
		48	1.4	217

β	a [fm]	a^{-1} [GeV]	$\kappa_{\rm charm}$	$\kappa_{\rm bottom}$	$m_{J/\Psi}$ [GeV]	m_Υ [GeV]
7.192	0.0190	10.4	0.13194	0.12257	3.105(3)	9.468(3)
7.793	0.00968	20.4	0.13221	0.12798	3.092(5)	9.431(5)

Experimental values: $m_{J/\Psi}$ = 3.096.916(11) GeV, m_Υ = 9.46030(26) GeV

Spatial Correlation Function and Screening Masses

["Signatures of charmonium modification in spatial correlation functions", F.Karsch, E.Laermann, S.Mukherjee, P.Petreczky, (2012) arXiv:1203.3770]

Correlation functions along the **spatial direction**

$$G(z,T) = \int dxdy \int_0^{1/T} d\tau \langle J(x,y,z,\tau) J(0,0,0,0) \rangle$$

are related to the meson spectral function at **non-zero spatial momentum**

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

exponential decay defines **screening mass M_{scr} :** $\mathbf{G(z,T)} \underset{z \gg 1/T}{\longrightarrow} \mathbf{e^{-M_{scr} z}}$

bound state contribution

$$\sigma(\omega, p_z, T) \sim \delta(\omega^2 - p_z^2 - M^2)$$

high-T limit (non-interacting free limit)

$$\sigma(\omega, p_z, T) \sim \sigma_{free}(\omega, p_z, T)$$

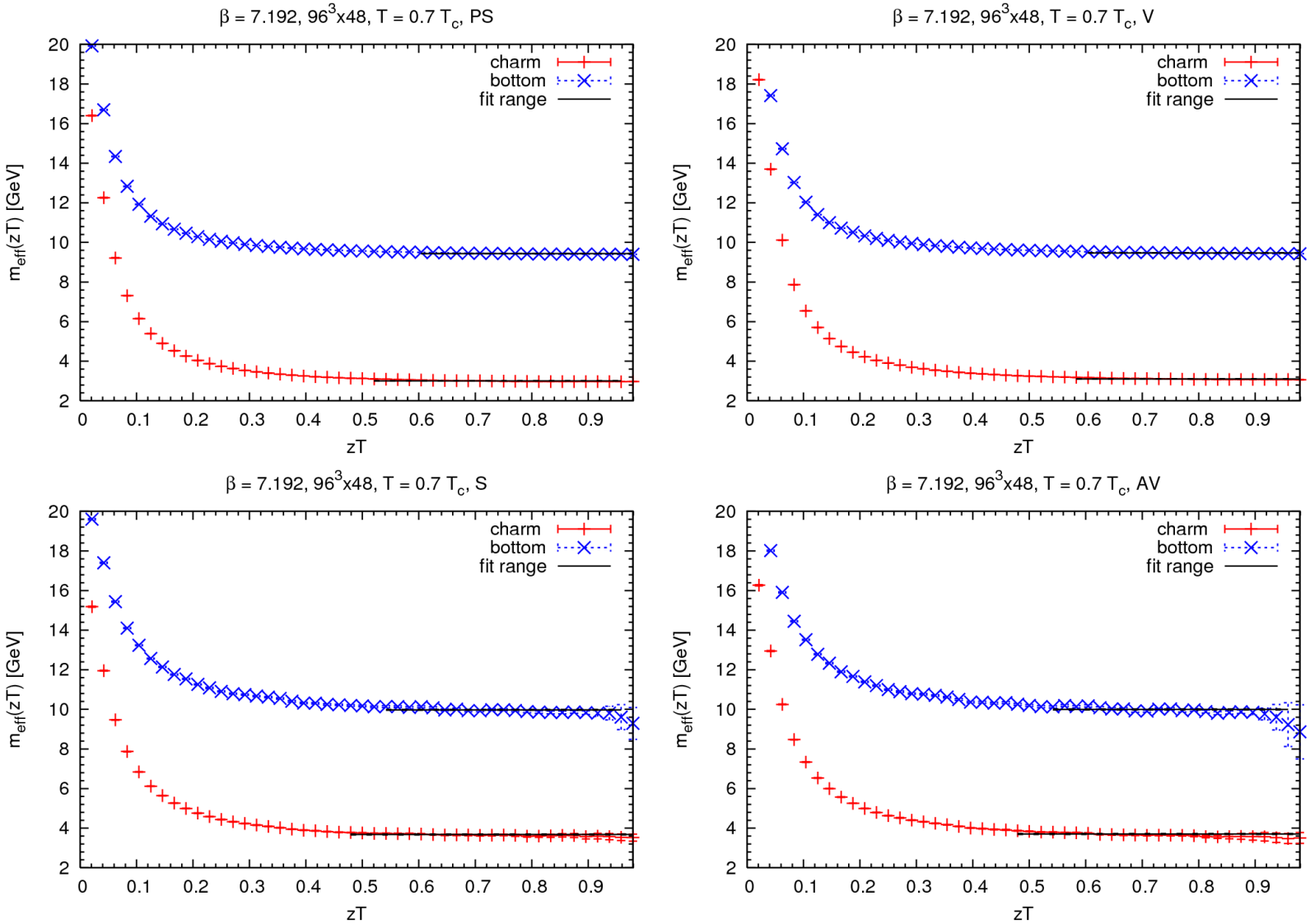
$$M_{scr} = M \longrightarrow$$

indications for medium modifications/dissociation

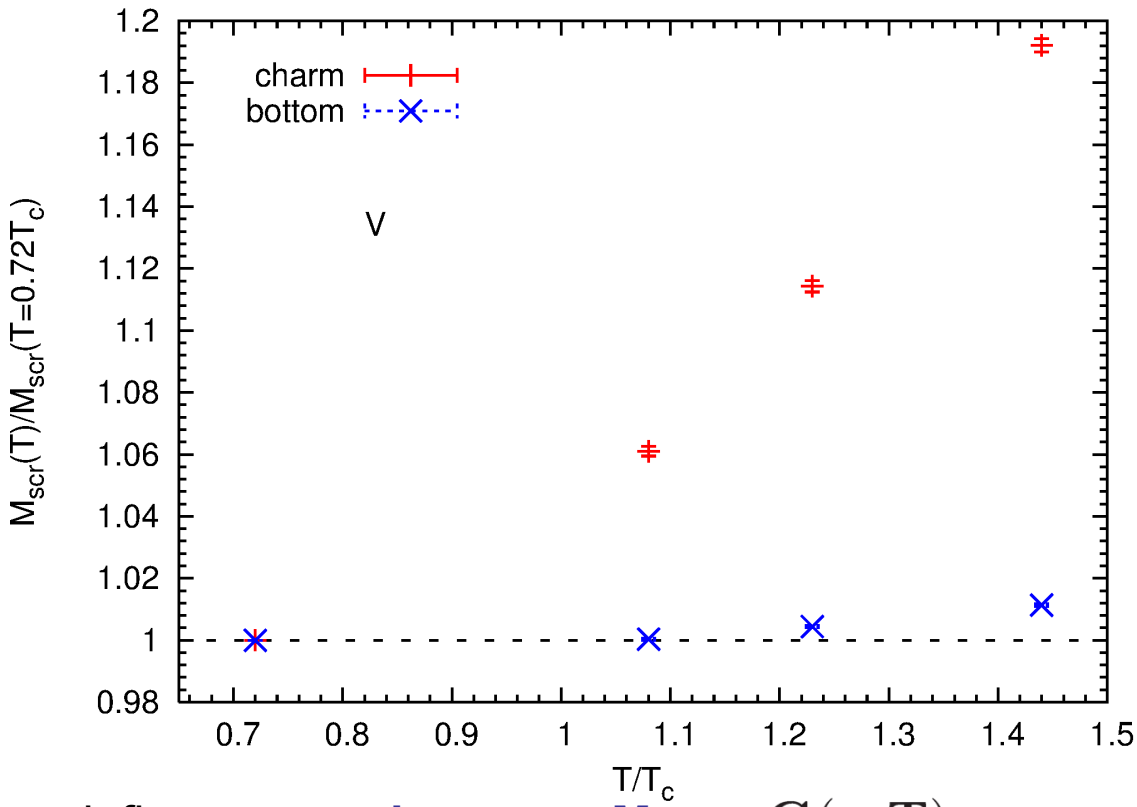
$$\longleftarrow M_{scr} = 2\sqrt{(\pi T)^2 + m_c{}^2}$$

Spatial Correlation Function and Screening Masses

$$m_{eff}(zT) = \log\left(\frac{G(zT)}{G((z+1)T)}\right)$$



Spatial Correlation Function and Screening Masses



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$$\sigma(\omega, p_z, T) \sim \delta(\omega^2 - p_z^2 - M^2)$$

high-T limit (non-interacting free limit)

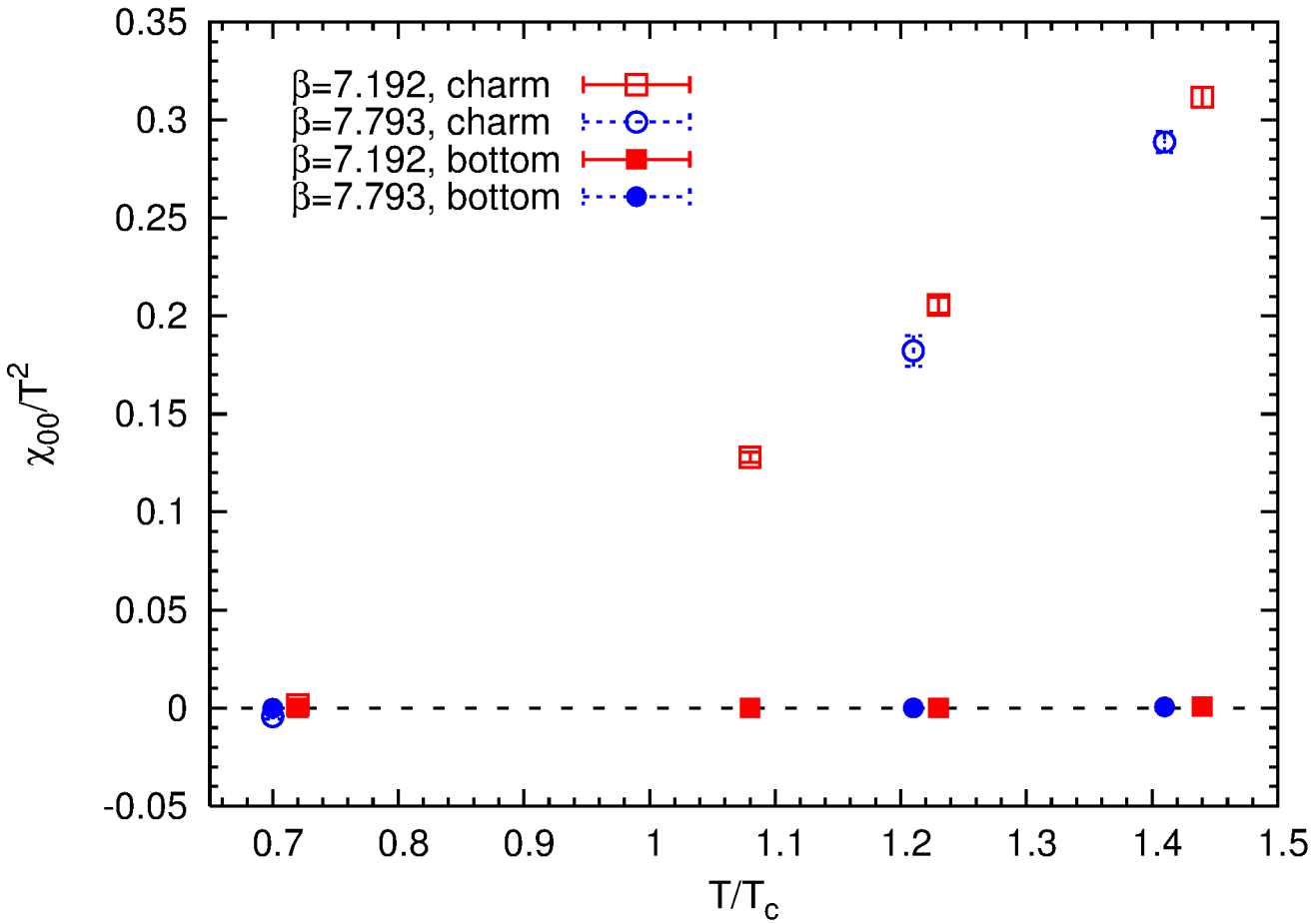
$$\sigma(\omega, p_z, T) \sim \sigma_{free}(\omega, p_z, T)$$

$M_{scr} = M$ $\longrightarrow$ indications for medium modifications/dissociation $\longleftarrow$ $M_{scr} = 2\sqrt{(\pi T)^2 + m_c{}^2}$

Charmonium and Bottomonium correlators

Quark number susceptibility:

$$\rho_{00}^{V}(\omega) = 2\pi\chi_{00}\omega\delta(\omega)$$
$$G_{00}^{V}(\tau) = T\chi_{00}$$



Reconstructed correlation function

$$G_{\rm rec}(\tau, T; T') \equiv \int_0^\infty d\omega \rho(\omega, T') K(\omega, \tau, T)$$

$$\frac{G(\tau, T)}{G_{\rm rec}(\tau, T; T')}$$ equals to unity at all τ

if the spectral function doesn't vary with temperature

S. Datta *et al.*, PRD 69 (2004) 094507

can be calculated directly from correlation function
for suitable ratios of N'_τ / N_τ without knowledge of spectral function:

$$\frac{\cosh[\omega(\tau - N_\tau/2)]}{\sinh[\omega N_\tau/2]} = \sum_{\tau'=\tau;\Delta\tau'=N_\tau}^{N'_\tau - N_\tau + \tau} \frac{\cosh[\omega(\tau' - N'_\tau/2)]}{\sinh[\omega N'_\tau/2]}$$

$$T = 1/(N_\tau a) \qquad N'_\tau = m N_\tau \qquad m = 1, 2, 3, \cdots$$

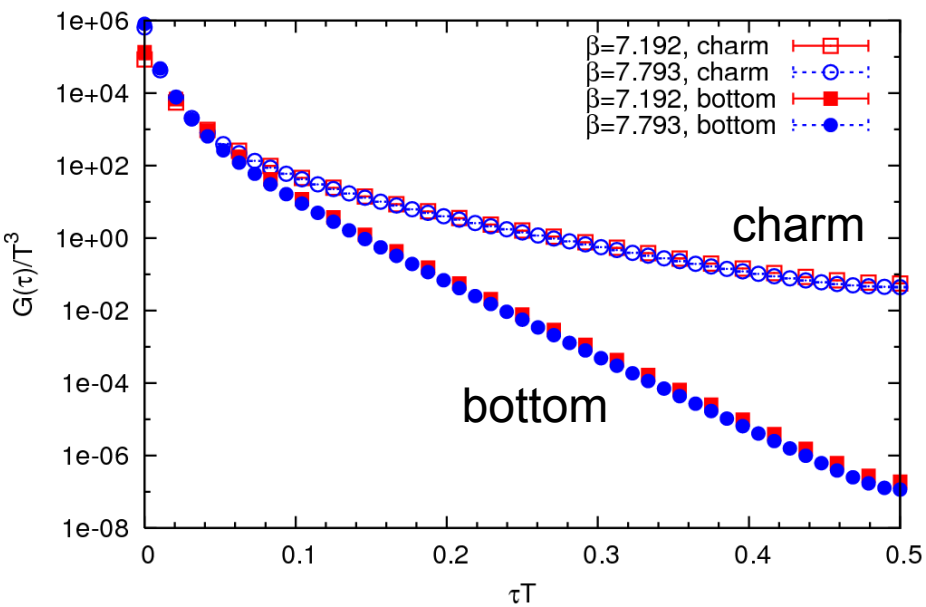
$$\boxed{G_{\rm rec}(\tau, T; T') = \sum_{\tau'=\tilde{\tau};\Delta\tau'=N_\tau}^{N'_\tau - N_\tau + \tau} G(\tau', T')}$$

H.-T. Ding *et al.*, PRD 86 (2012) 014509

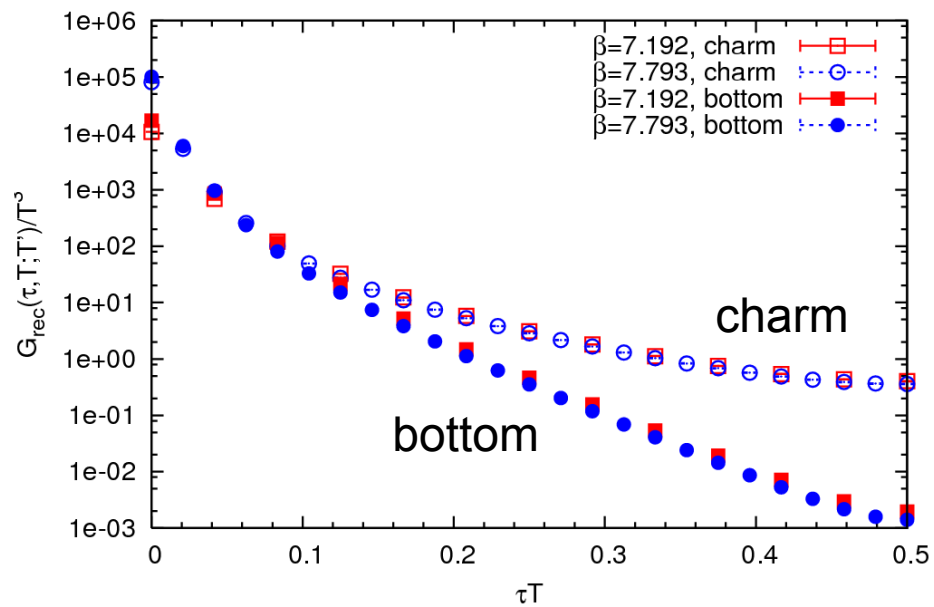
Charmonium and Bottomonium correlators

$$G_{\rm rec}(\tau, T; T') \equiv \int_0^\infty d\omega \rho(\omega, T') K(\omega, \tau, T)$$

$G(\tau, 0.7T_c)/T^3$

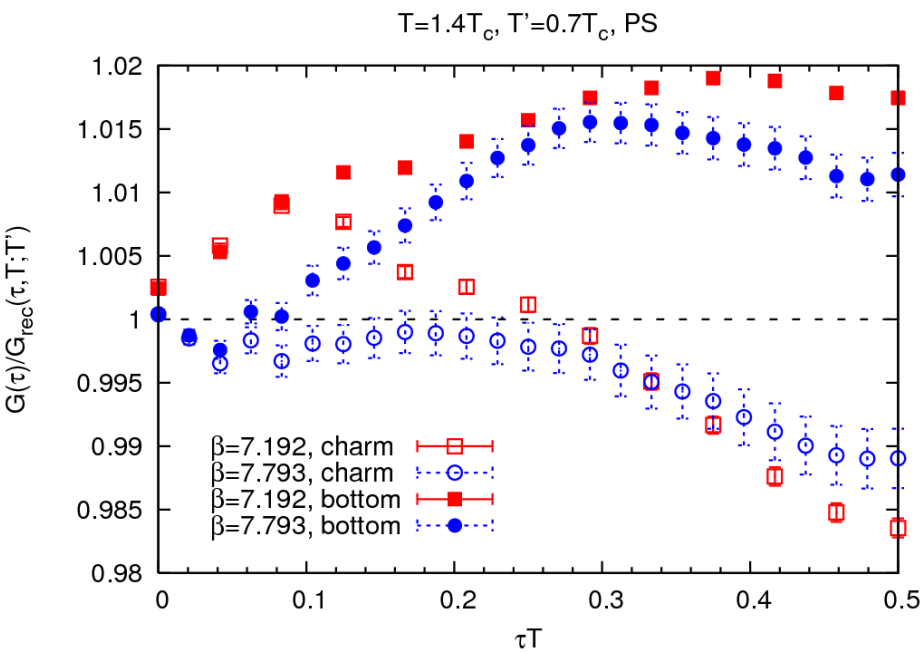


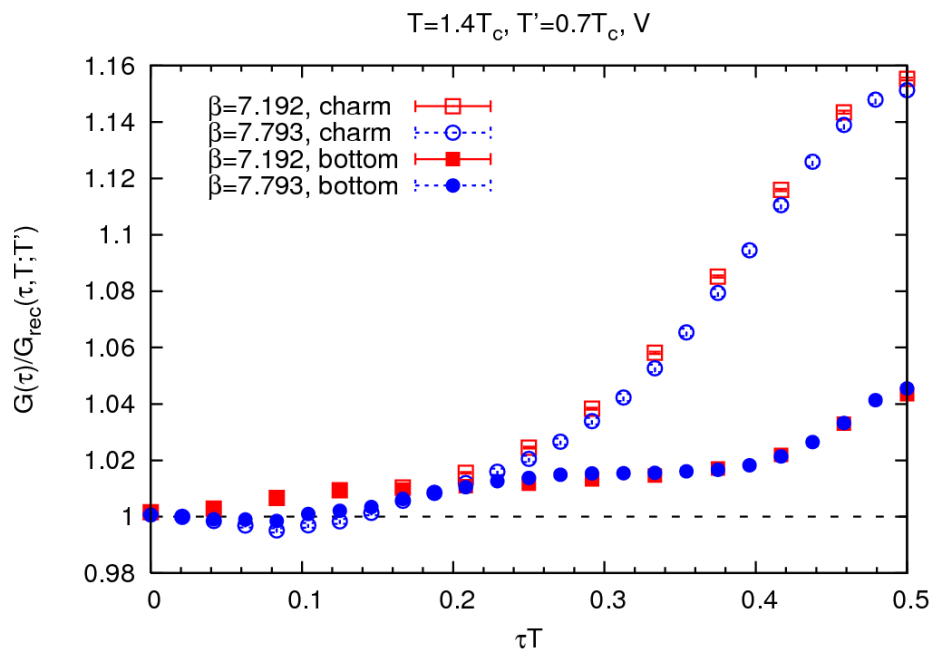
$G_{rec}(\tau, 1.4T_c; 0.7T_c)/T^3$



Charmonium and Bottomonium correlators – S-wave channels

$$G_{\rm rec}(\tau,T;T') \equiv \int_0^\infty d\omega\rho(\omega,T')K(\omega,\tau,T)$$





different behavior in pseudo-scalar (left) and vector (right) channel

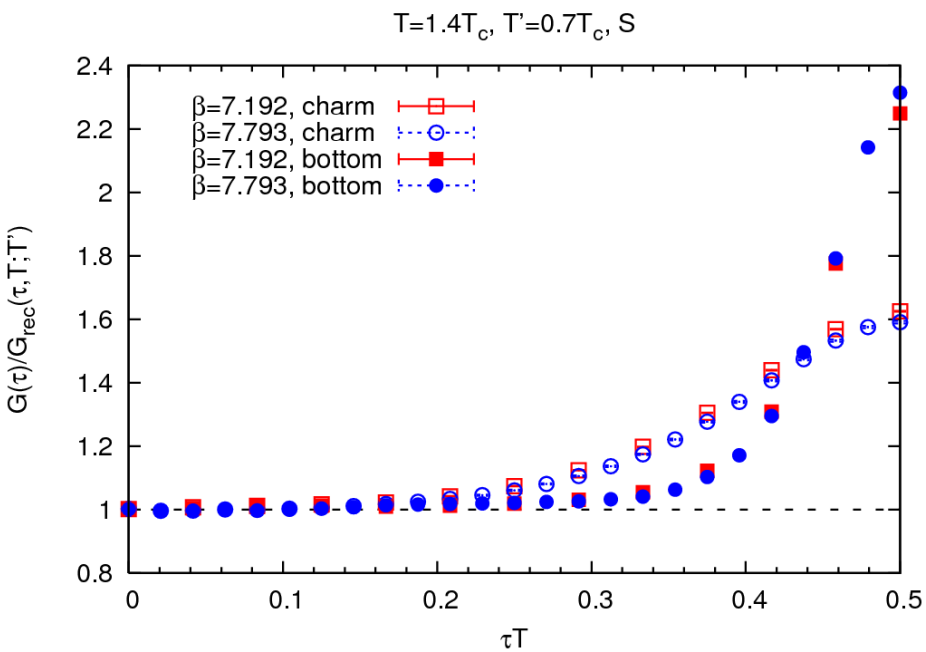
strong modification at large τ in vector channel

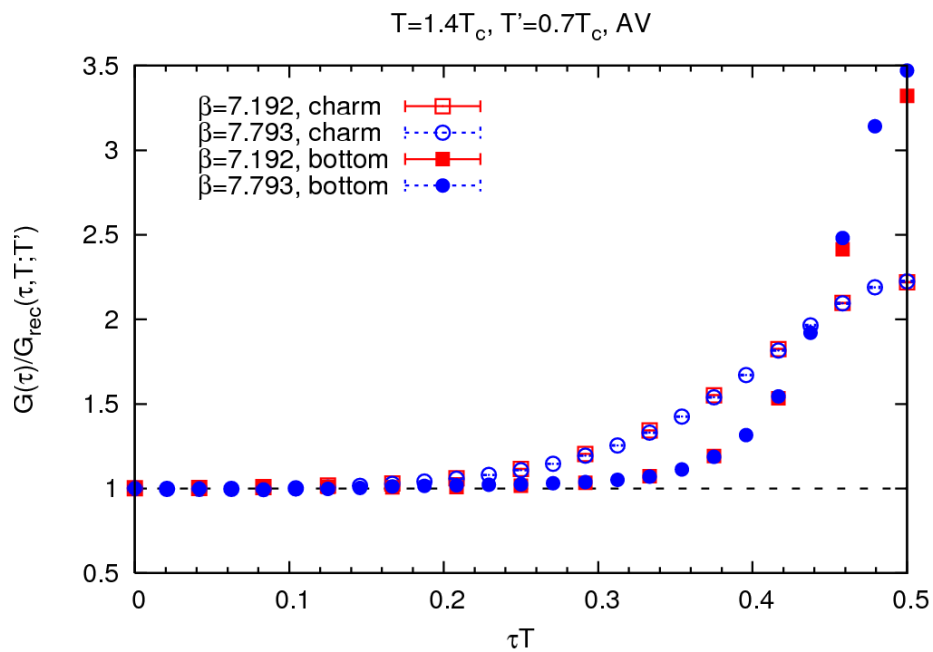
stronger for charm compared to bottom

related to transport contribution

Charmonium and Bottomonium correlators – P-wave channels

$$G_{\rm rec}(\tau,T;T') \equiv \int_0^\infty d\omega\,\rho(\omega,T')K(\omega,\tau,T)$$





comparable behavior in scalar (left) and axial-vector (right) channel

strong modification at large τ in both channels

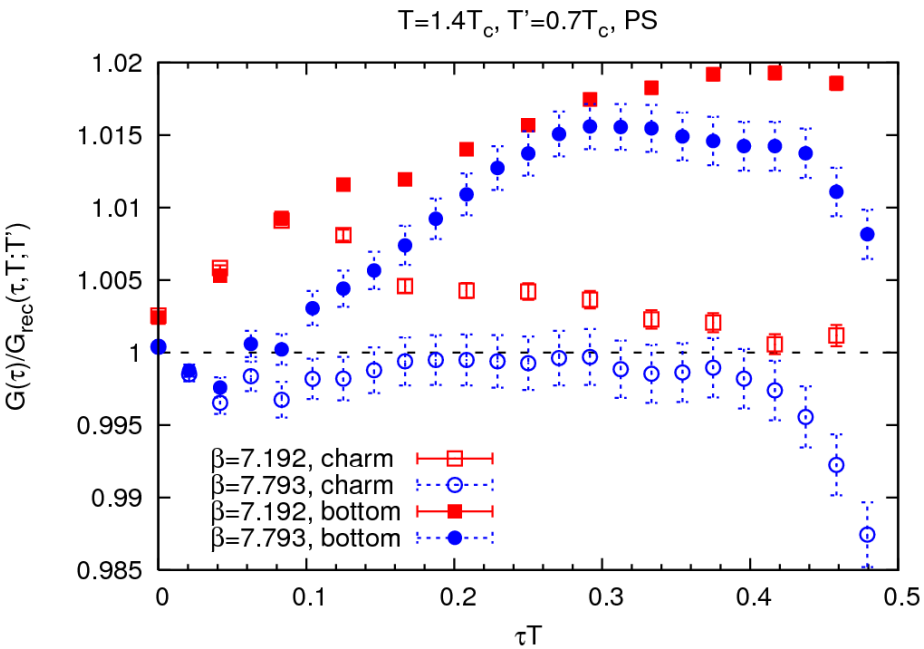
stronger for bottom compared to charm

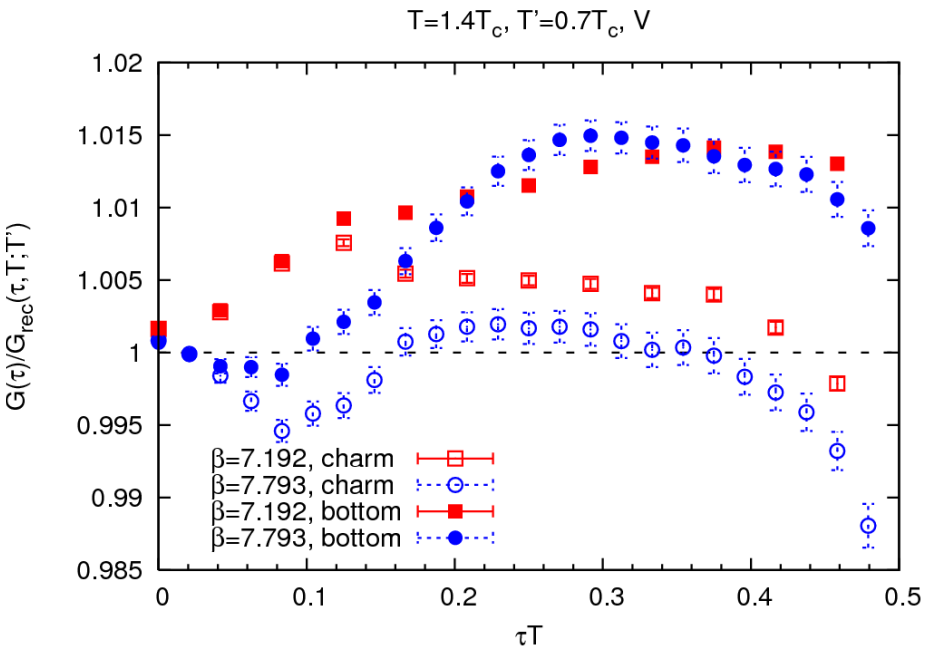
related to transport/constant contribution

Mid-point subtracted correlators – P-wave channels

$$\bar{G}(\tau) \equiv G(\tau) - G(1/2T)$$

mid-point subtracted correlator





small ω region gives (almost) constant contribution to correlators

effectively removed by mid-point subtraction

pseudo-scalar (left) and vector (right) very comparable

need to understand cut-off effects and quark-mass effects

Outlook

work is still in progress

continuum extrapolation for the quarkonium correlators still needed

detailed analysis of the systematic uncertainties

Extract spectral properties (on continuum correlators) by

- comparing to perturbation theory
- Fits using Ansätze for the spectral function
- Bayesian techniques to extract the spectral function

Final goal:

understand the temperature and quark mass dependence of

heavy quark diffusion coefficient

dissociation temperatures for different states