PROBING THE QGP:
HEAVY QUARKONIUM ON THE LATTICE

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QUARKONIA AND THE QGP

MATSUI & SATZ 86

quarkonia as a thermometer for the quark-gluon plasma

- tightly bound states (J/ψ, Υ) survive to higher temperatures
- broader states melt at lower temperatures

melting pattern informs about temperature of the QGP

- relevant for heavy-ion collisions
- quantitative predictions required

OUTLINE

- reminder: hierarchy of scales and EFTs
- complex potentials

this talk: lattice QCD

- thermal boundary conditions / constant contribution
- how they are avoided here

results:

- S and P waves in two-flavour QGP, $0.4 < T/T_c < 2.1$

outlook:

- repeated lattices
- spectral functions

QUARKONIA AND THE QGP

PREDICTIONS

how to find the response of quarkonia to the QGP?

- potential models
- lattice QCD

at $T > 0$:

- plethora of potential models: (seemingly) conflicting results
- interpretation of lattice correlators hindered by thermal (periodic) boundary conditions

re-addressed recently using first-principle approach:

- effective field theories (EFTs) and separation of scales

QUARKONIA AND EFTs

$M \gg T > \dots$

hierarchy of scales:

- heavy quark mass M
- temperature T
- inverse size $g^2 M$
- Debye mass gT
- binding energy $g^4 M$

$\longrightarrow$ weak coupling

corresponding EFTs:

- NRQCD
- NRQCD + HTL
- pNRQCD
- pNRQCD + HTL
- $\dots$

Laine, Philipsen, (Romatschke) & Tassler 07
Laine 07-08 Burnier, Laine & Vepsäläinen 08-09
Beraudo, Blaizot & Ratti 08 Escobedo & Soto 08
Brambilla, Ghiglieri, Vairo & Petreczky 08
Brambilla, Escobedo, Ghiglieri, Soto & Vairo 10

...

Quarkonia and EFTs

$$M \gg T > \ldots$$

some results:

- potential obtains an imaginary part

  Laine, Philipsen, Romatschke & Tassler

- thermal corrections to energy and width

  Brambilla, Escobedo, Ghiglieri, Soto & Vairo

- use complex potential models

  Laine et al, Strickland et al, Miao, Mocsy & Petreczky, ...

nonperturbative:

- determine imaginary part of potential in classical limit

  Laine, Philipsen & Tassler

- extract potential from Wilson loop in lattice QCD

  Rothkopf, Hatsuda & Sasaki

NON-RELATIVISTIC QCD

THIS TALK

- use NRQCD, one of the EFTs, nonperturbatively
- no potential model / no weak coupling

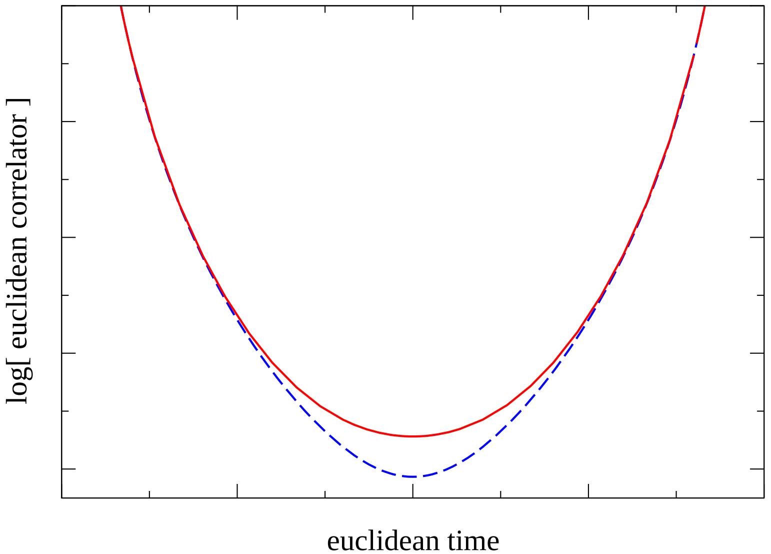
lattice QCD:

- heavy quarks with NRQCD
  requirement $M \gg T$
  bottomonium: $M \simeq 4.2$ GeV $\gg$ a few T_c
- two-flavour QGP with $0.4 < T/T_c < 2.1$

QUARKONIA AT FINITE TEMPERATURE

WELL-KNOWN OBSTACLES

- in equilibrium: thermal boundary conditions
- euclidean correlators periodic
- spectral relation



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

$$K(\tau,\omega) = \frac{\cosh[\omega(\tau - 1/2T)]}{\sinh(\omega/2T)}$$

- problematic small ω region: constant contribution

  transport, susceptibilities

G.A. & Martinez Resco 02, Petreczky & Teaney 05

QUARKONIA AT FINITE TEMPERATURE

BENEFITS OF NRQCD

relativistic formulation:

- melting of quarkonia obscured by constant contribution

Umeda 07, Petreczky et al 07-09

NRQCD:

- constant contribution absent
- no thermal boundary condition
- simple spectral relation $G(\tau) = \int d\omega\, e^{-\omega\tau}\rho(\omega)$

why?

- factor out heavy quark mass scale: $\omega = 2M + \omega'$
- $M \gg T$: thermal effects exponentially suppressed

QUARKONIA AT FINITE TEMPERATURE

BENEFITS OF NRQCD

- no thermal boundary conditions
- simple spectral relation $G(\tau) = \int d\omega\, e^{-\omega\tau} \rho(\omega)$

example:

correlators for free quarks with kinetic energy $E_{\mathbf{p}} = \frac{\mathbf{p}^2}{2M}$

$$G_S(\tau) \sim \int d^3p \, \exp\left(-2E_{\mathbf{p}}\tau\right) \qquad \rho_S(\omega) \sim \int d^3p\, \delta(\omega - 2E_{\mathbf{p}})$$

$$G_P(\tau) \sim \int d^3p\, \mathbf{p}^2 \exp\left(-2E_{\mathbf{p}}\tau\right) \qquad \rho_P(\omega) \sim \int d^3p\, \mathbf{p}^2 \delta(\omega - 2E_{\mathbf{p}})$$

Burnier, Laine & Vepsäläinen 08

- temperature dependence only enters via medium !

LATTICE DETAILS

- two light flavours of Wilson-like quarks
- many time slices: highly anisotropic lattices ($a_s/a_\tau = 6$)
- lattice size: $12^3 \times N_\tau$, $N_\tau = 80, 32, 24, 16$
- lattice spacing: $a_\tau^{-1} = 7.06$ GeV, 500 configurations

N_τ	T(MeV)	T/T_c
80	90	0.42
32	221	1.05
24	294	1.40
16	441	2.09

Morrin et al 06

G.A. et al 07

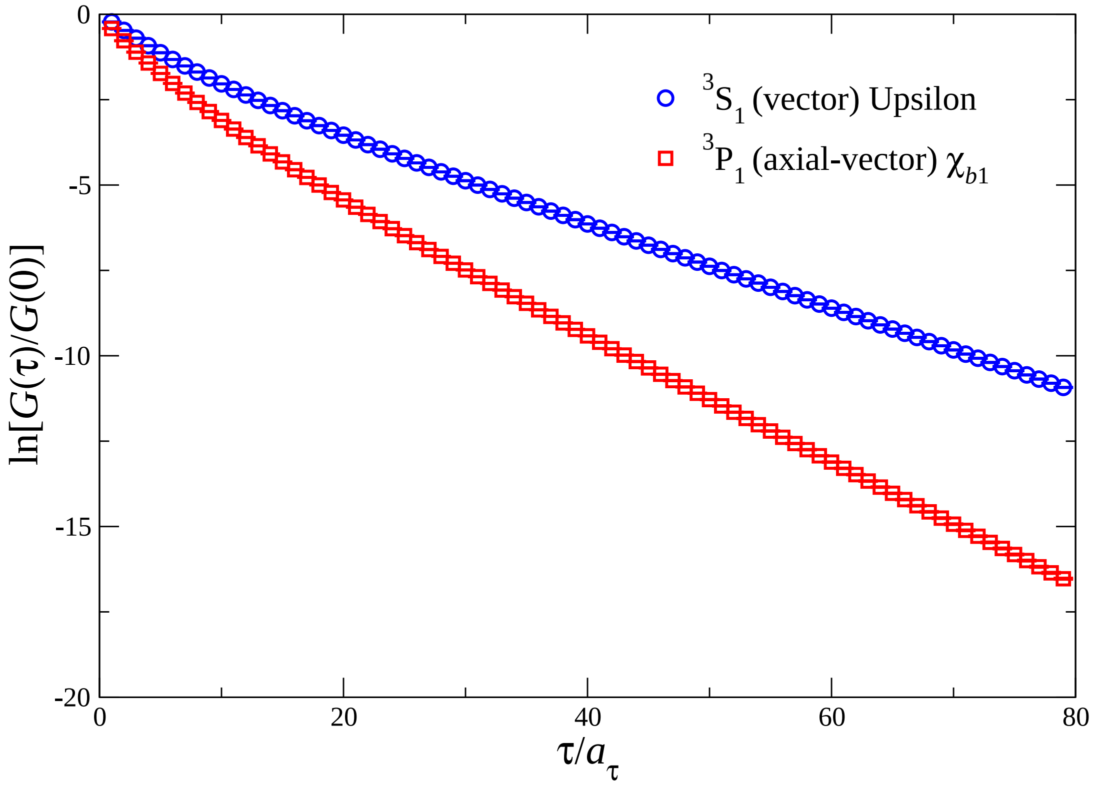
[charmonium]

- NRQCD: mean-field improved action with tree-level coefficients, including up to $\mathcal{O}(v^4)$ terms Davies et al 94

SPECTRUM

ZERO TEMPERATURE

euclidean correlators not periodic



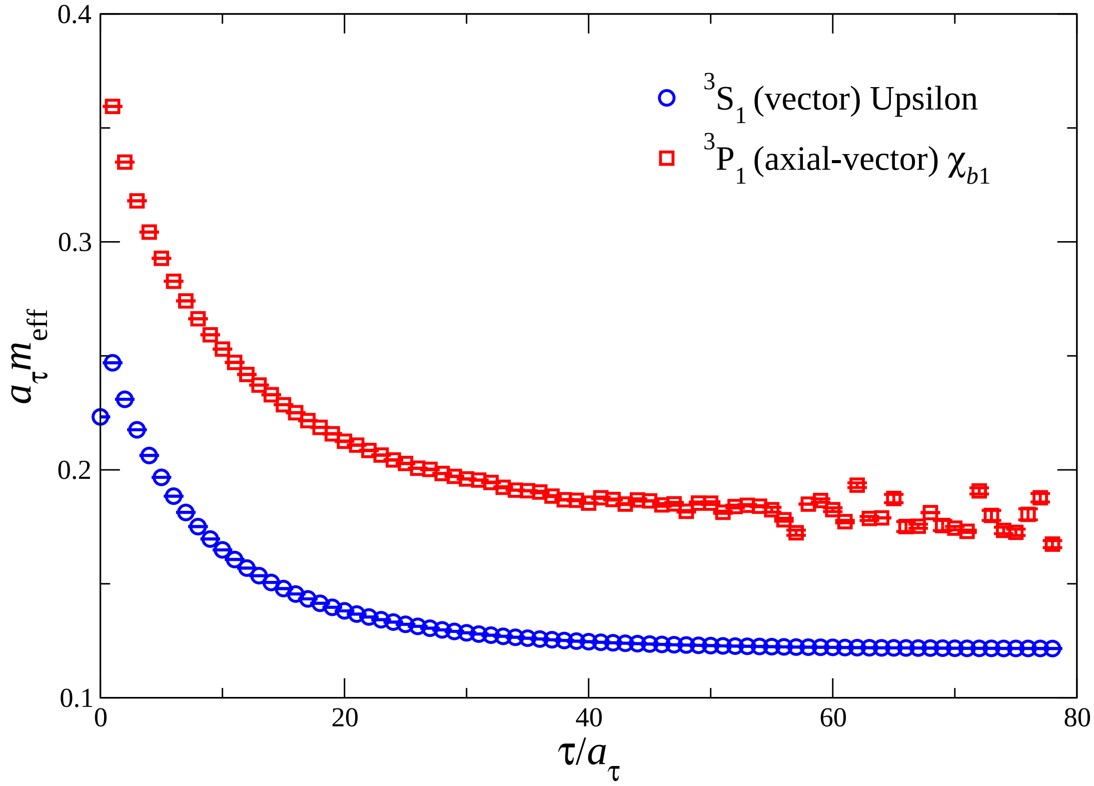
Υ (S wave) and χ_{b1} (P wave)

SPECTRUM

ZERO TEMPERATURE

exponential decay: effective mass plot

$$m_{\text{eff}} = -\log\left[G(\tau)/G(\tau - a_\tau)\right]$$



Υ (S wave) and χ_{b1} (P wave)

SPECTRUM

GROUND AND FIRST EXCITED STATES

state	$a_\tau \Delta E$	Mass (MeV)	Exp. (MeV)
$1^1S_0(\eta_b)$	0.118(1)	9438(7)	9390.9(2.8)
$2^1S_0(\eta_b(2S))$	0.197(2)	10009(14)	-
$1^3S_1(\Upsilon)$	0.121(1)	9460*	9460.30(26)
$2^3S_1(\Upsilon')$	0.198(2)	10017(14)	10023.26(31)
$1^1P_1(h_b)$	0.178(2)	9872(14)	-
$1^3P_0(\chi_{b0})$	0.175(4)	9850(28)	9859.44(42)(31)
$1^3P_1(\chi_{b1})$	0.176(3)	9858(21)	9892.78(26)(31)
$1^3P_2(\chi_{b2})$	0.182(3)	9901(21)	9912.21(26)(31)

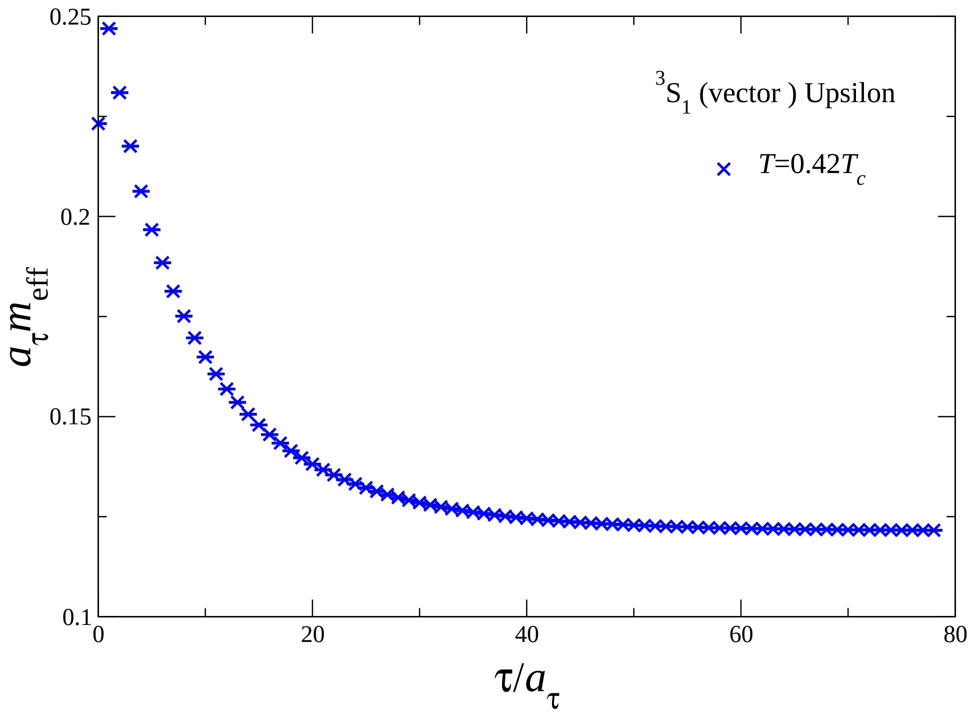
Υ used to set the scale

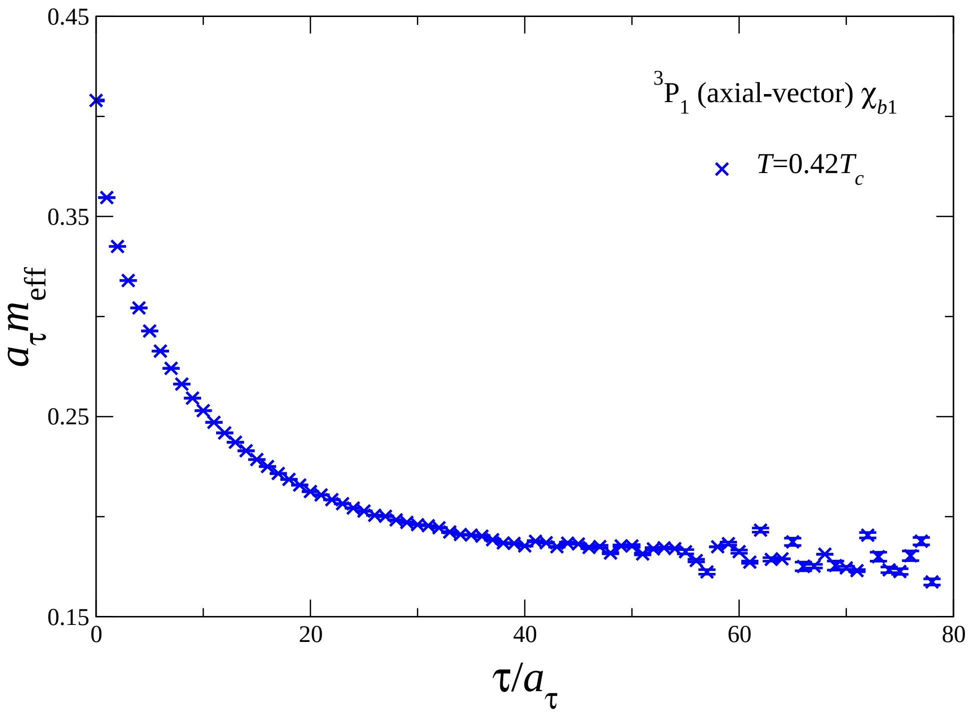
combination of point and extended sources

INCREASING THE TEMPERATURE

EFFECTIVE MASSES

Υ S wave χ_{b1} P wave





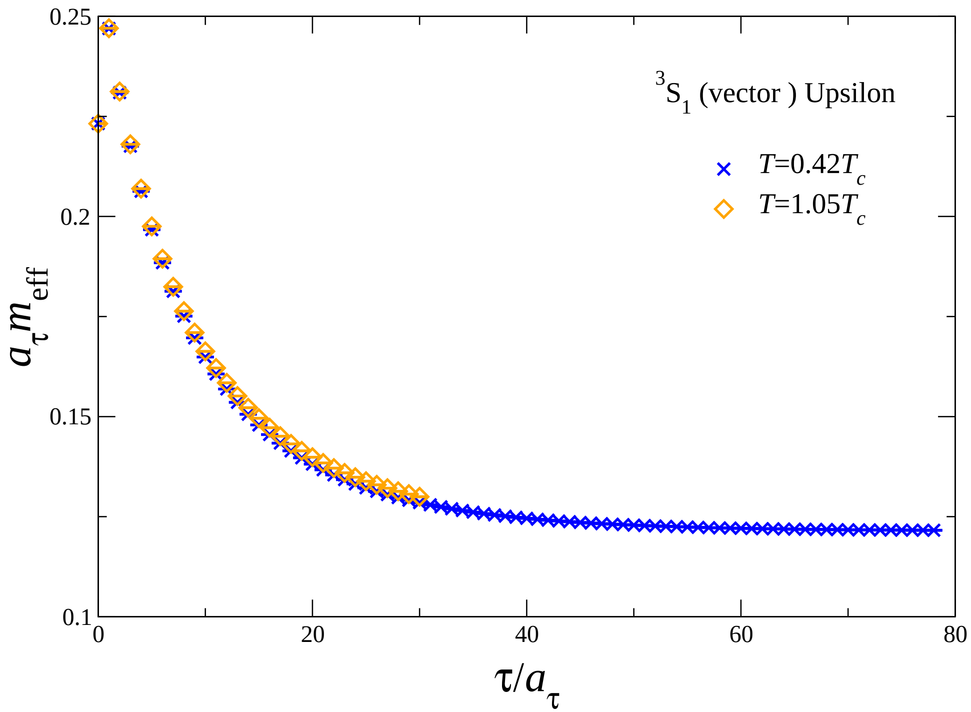
$$T/T_c = 0.42$$

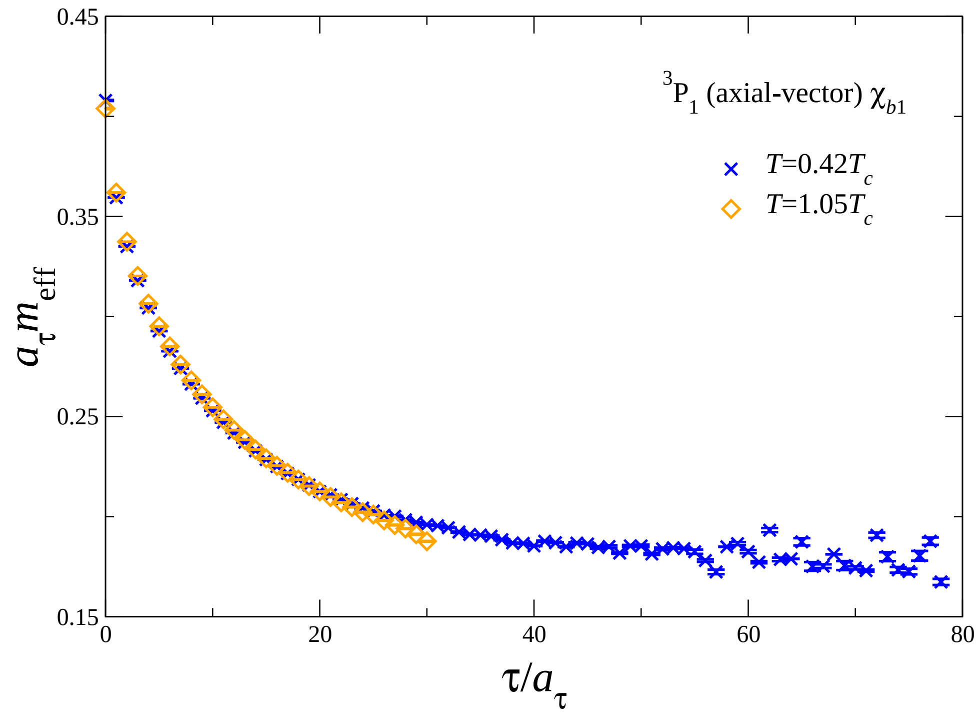
INCREASING THE TEMPERATURE

EFFECTIVE MASSES

Υ S wave

χ_{b1} P wave



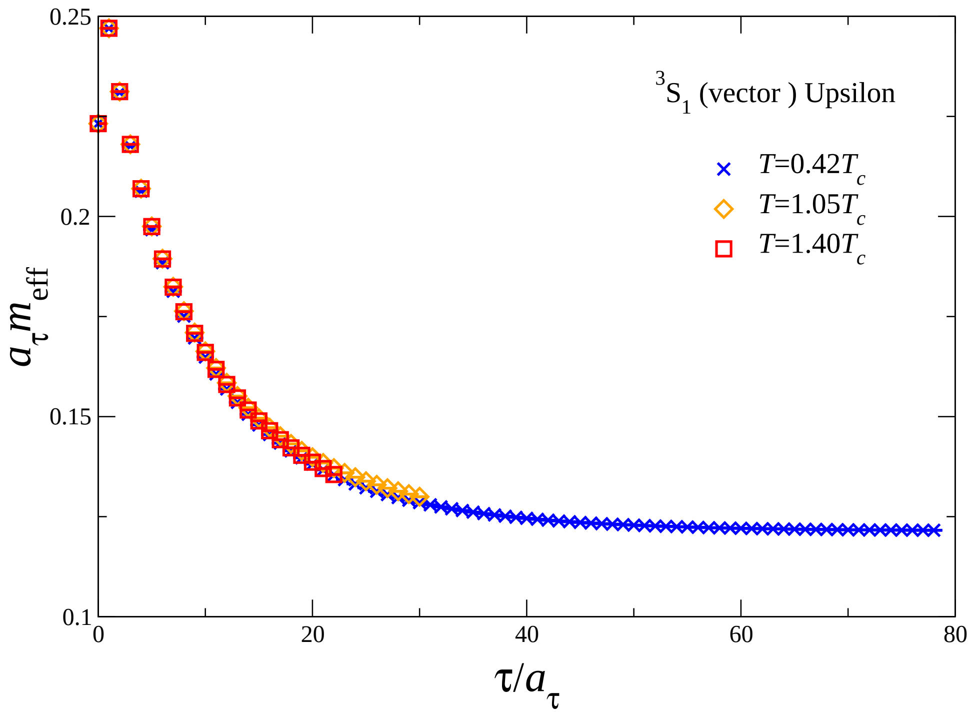


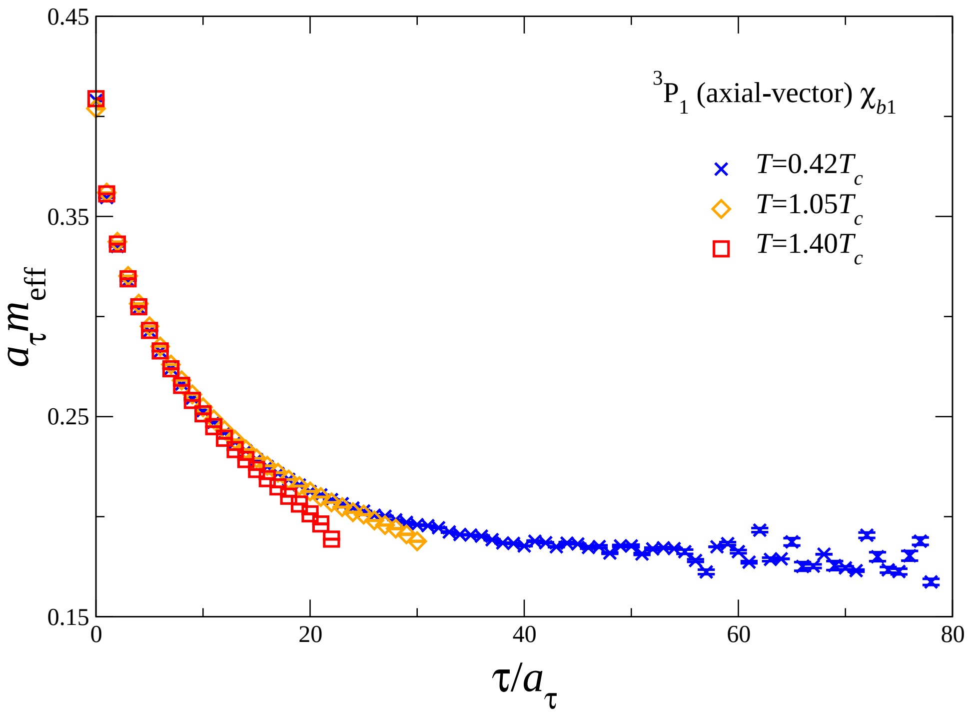
$$T/T_c = 1.05$$

INCREASING THE TEMPERATURE

EFFECTIVE MASSES

Υ S wave χ_{b1} P wave



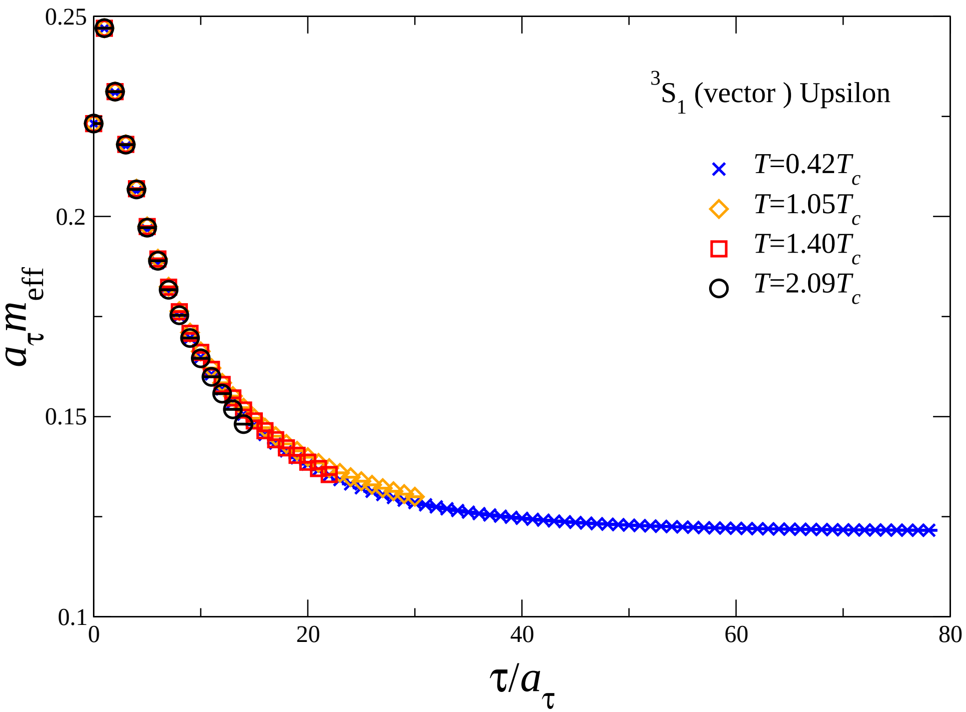


$$T/T_c = 1.40$$

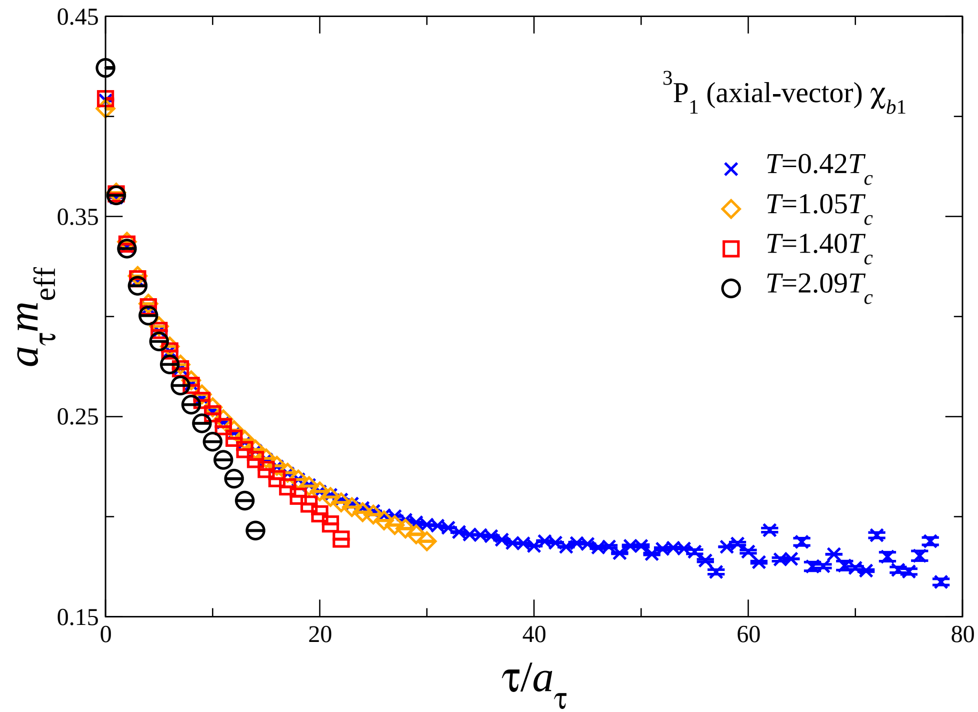
INCREASING THE TEMPERATURE

EFFECTIVE MASSES

Υ S wave



χ_{b1} P wave



$$T/T_c = 2.09$$

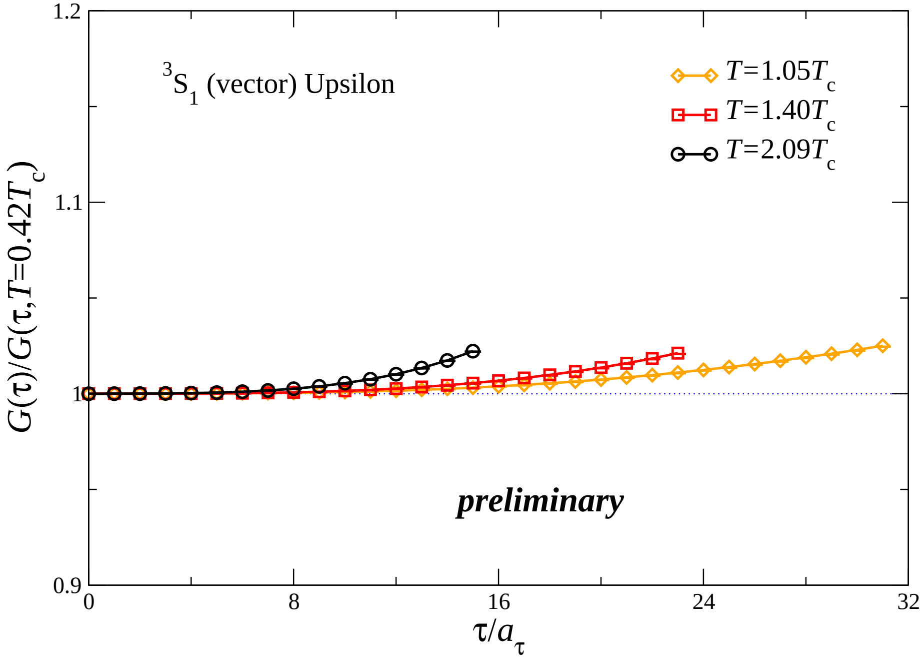
very little T dependence

substantial T dependence
no exponential decay

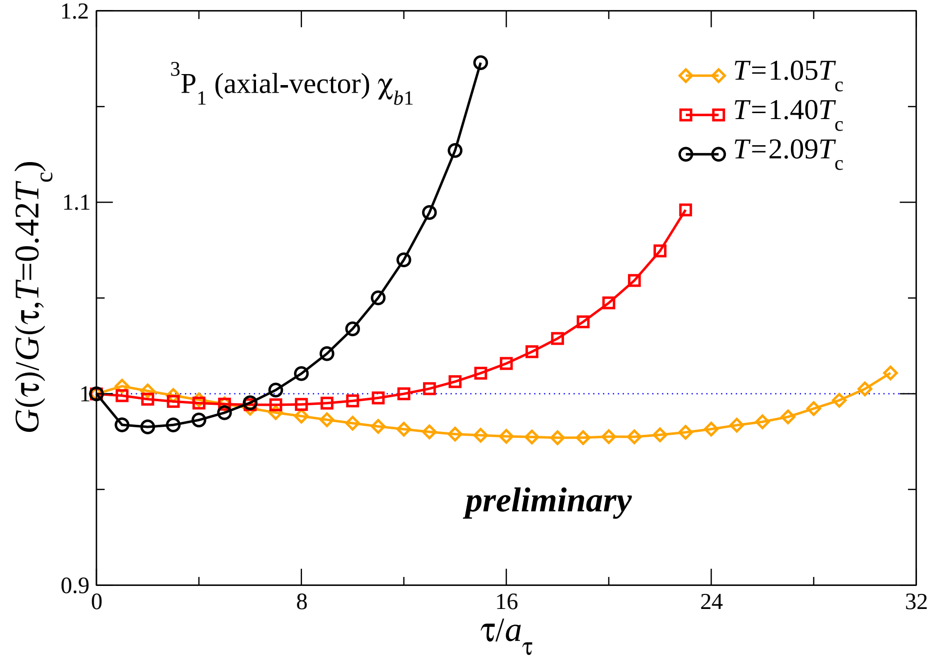
INCREASING THE TEMPERATURE

RATIO PLOT

Υ S wave



χ_{b1} P wave



$$G(\tau;T)/G(\tau;T=0.42T_c)$$

- ratio is source dependent: here point sources
- can be compared with potential model results

P WAVES

IN THE QUARK-GLUON PLASMA

- no exponential decay at high temperature, what else?
- consider free quarks with kinetic energy $E_{\mathbf{p}} = \frac{p^2}{2M}$

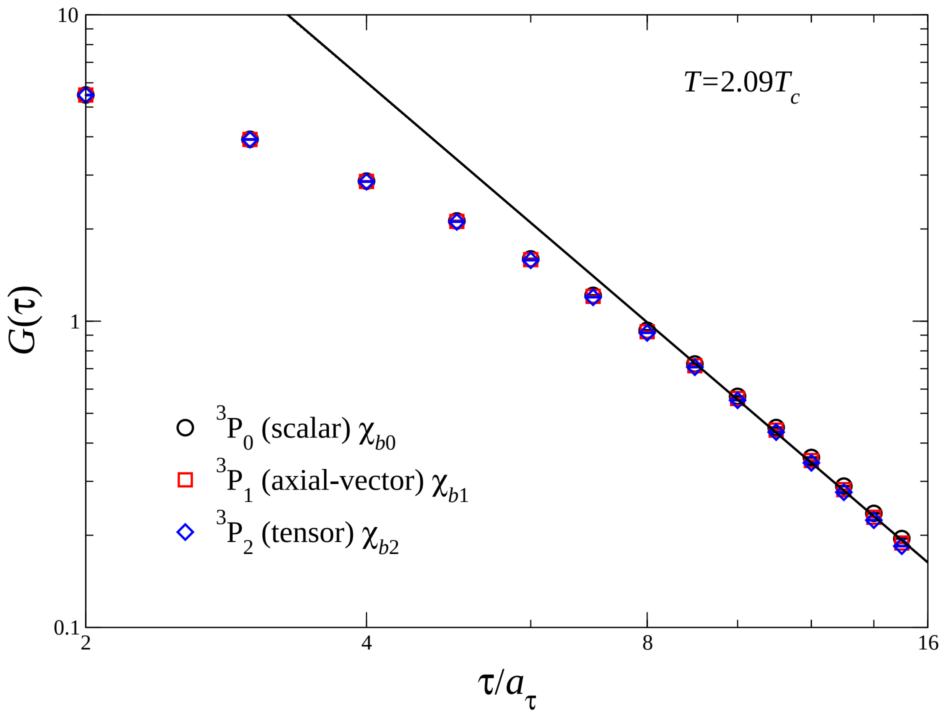
$$G_S(\tau) \sim \int d^3p \, e^{-2E_{\mathbf{p}}\tau} \sim \frac{1}{\tau^{3/2}}$$
$$G_P(\tau) \sim \int d^3p \, \mathbf{p}^2 e^{-2E_{\mathbf{p}}\tau} \sim \frac{1}{\tau^{5/2}}$$

- power decay at large euclidean times

P WAVES

IN THE QUARK-GLUON PLASMA

- no exponential decay at high temperature, what else?
- power decay at large euclidean times



- fit: $G(\tau) \sim 1/\tau^\gamma$, $\gamma = 2.605(1)$

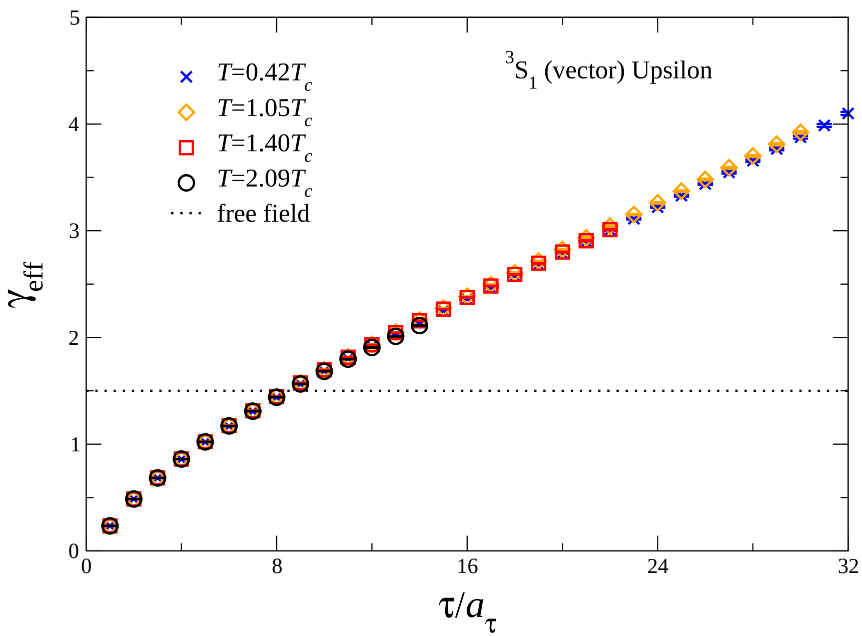
  without interactions: $\gamma = 5/2$

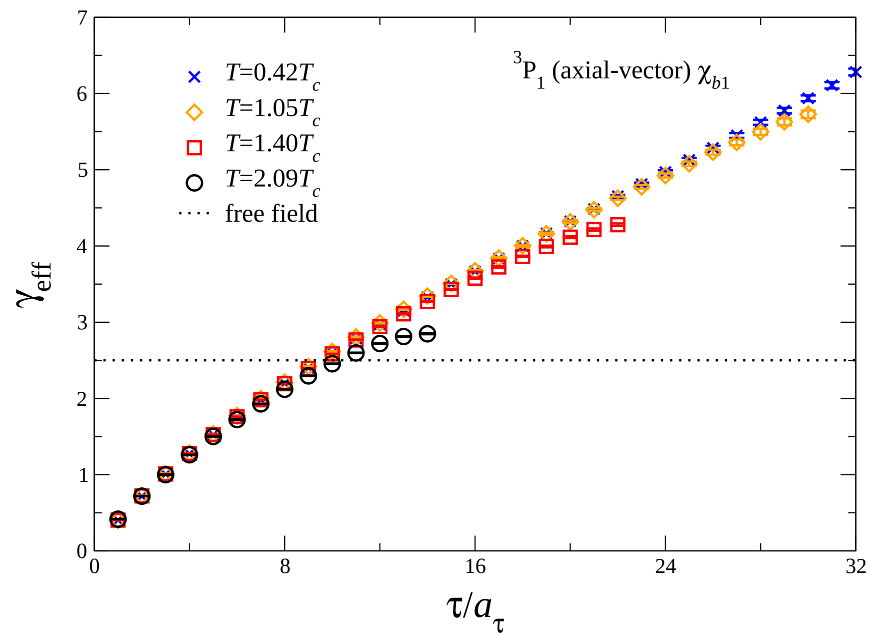
P WAVES

IN THE QUARK-GLUON PLASMA

power decay: effective power plot

$$\gamma_{\rm eff}(\tau) = -\tau \frac{G'(\tau)}{G(\tau)} \to \gamma$$





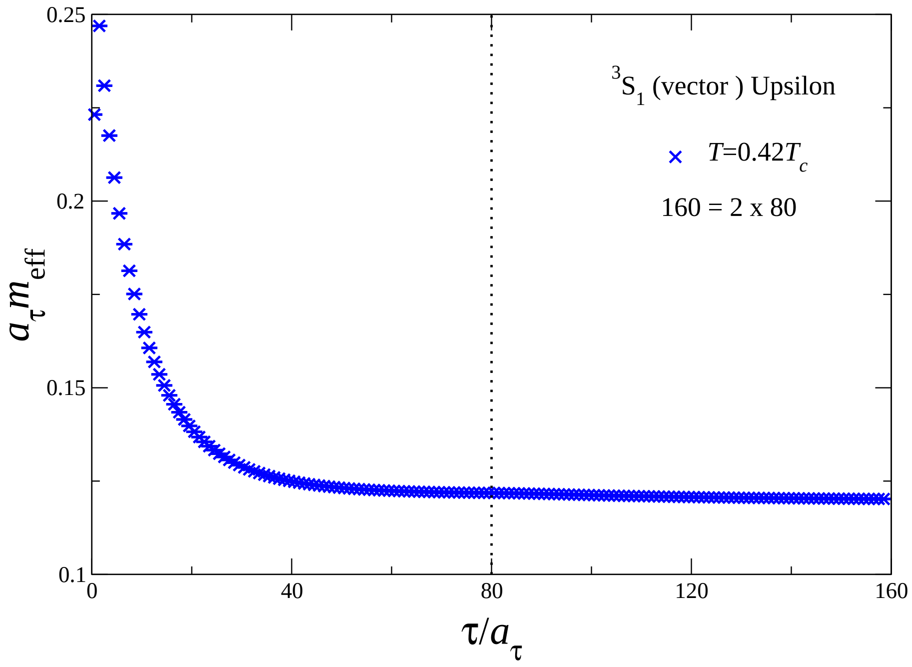
Υ S wave

χ_{b1} P wave

REPEATED LATTICES

INITIAL-VALUE PROBLEM

- NRQCD is solved as an initial-value problem
- why stop when reaching the end of the lattice?
- without interactions: no dependence on N_τ

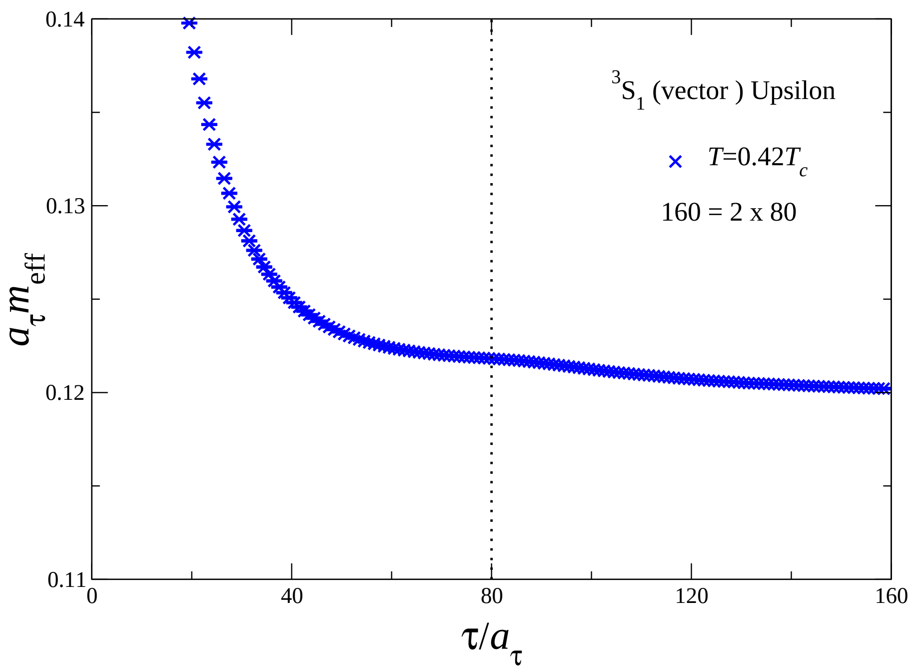


- time extent: $2 \times 80 = 160$

REPEATED LATTICES

INITIAL-VALUE PROBLEM

- NRQCD is solved as an initial-value problem
- periodic gauge field configurations
- periodicity shows up as a kink at $n_\tau = 80$!

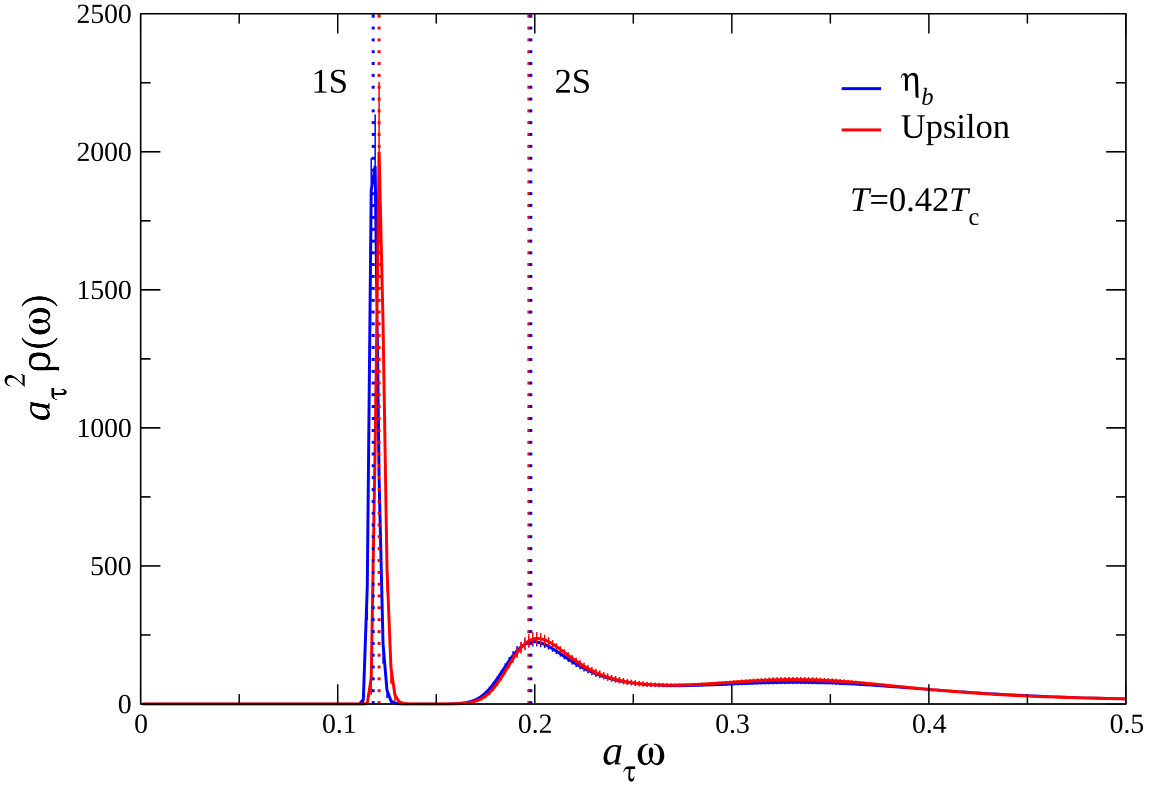


- reproduced using simple model, under investigation

SPECTRAL FUNCTIONS

MAXIMUM ENTROPY METHOD

$$G(\tau) = \int d\omega \, e^{-\omega\tau} \rho(\omega)$$



- groundstate and first excited state
- in progress

CONCLUSIONS

NRQCD avoids a number of obstacles encountered earlier:

- no thermal boundary conditions / constant contribution

$\Rightarrow$ quarkonia as a probe of the QGP

results:

- S waves: very little T dependence
- P waves: substantial T dependence, quickly after T_c
  power decay at large euclidean times

outlook:

- repeated lattices, spectral functions
- compare with potential models and EFT predictions