Quarkonium suppression in strongly coupled plasmas

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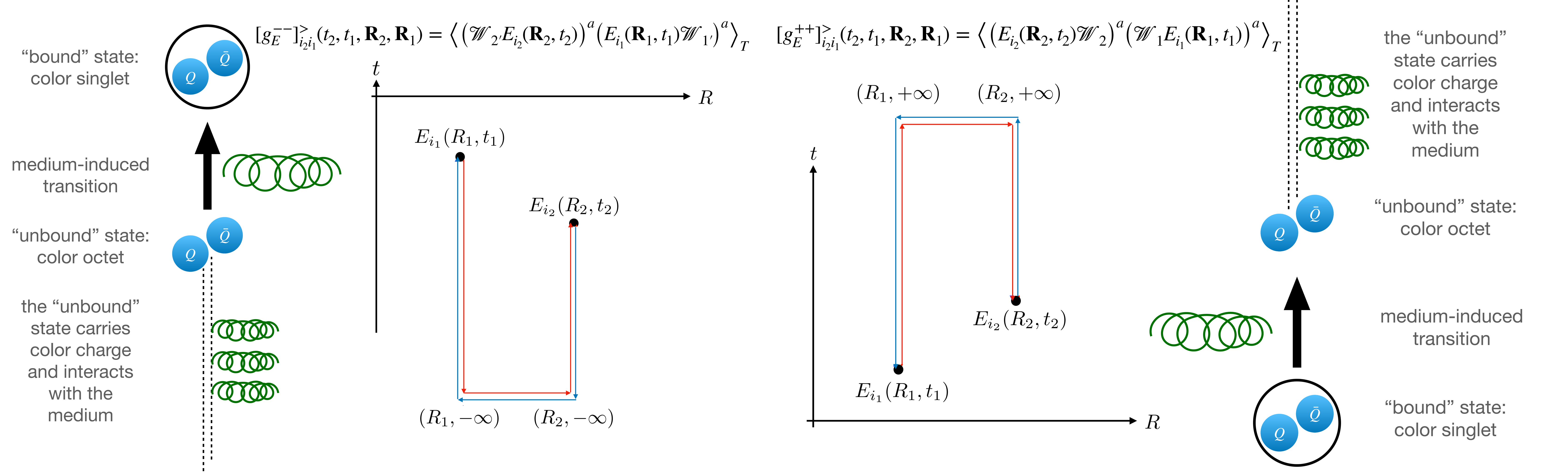
Correlation functions for quarkonium formation and dissociation in the QGP

$$[g_E^{--}]^{>}_{i_2 i_1}(t_2, t_1, \mathbf{R}_2, \mathbf{R}_1) = \left\langle \left(\mathscr{W}_{2'} E_{i_2}(\mathbf{R}_2, t_2)\right)^a \left(E_{i_1}(\mathbf{R}_1, t_1)\mathscr{W}_{1'}\right)^a \right\rangle_T$$

$$[g_E^{++}]^{>}_{i_2 i_1}(t_2, t_1, \mathbf{R}_2, \mathbf{R}_1) = \left\langle \left(E_{i_2}(\mathbf{R}_2, t_2)\mathscr{W}_{2}\right)^a \left(\mathscr{W}_{1} E_{i_1}(\mathbf{R}_1, t_1)\right)^a \right\rangle_T$$



Heavy quarks in pNRQCD

A pair of heavy quarks with mass M and relative velocity v, under the hierarchy $M \gg Mv \gg Mv^2$, and assuming that the size of their bound states is smaller than the typical energy scale of the medium $Mv \gg T$, can be described by the following Lagrangian:

$$\mathcal{L}_{\rm pNREFT} = \mathcal{L}_{\rm QCD}^{(\rm light\,d.o.f.)} + \int d^3r\, \mathrm{Tr}\Big[\mathrm{S}^\dagger(i\partial_0 - H_s)\mathrm{S} + \mathrm{O}^\dagger(iD_0 - H_{\rm adj})\mathrm{O} - V_A(\mathrm{O}^\dagger r_i gE_i \mathrm{S} + \mathrm{h.c.}) - \frac{V_B}{2}\mathrm{O}^\dagger\{r_i gE_i, \mathrm{O}\} + \cdots \Big]\,, \tag{1}$$

where S is the annihilation operator for a heavy quark pair in a color singlet state, and O that of a heavy quark pair in a color octet state. r_i is the relative position between the heavy quark pair.

Correlation functions for quarkonium transport

The above Lagrangian can be used to derive evolution equations for quarkonium using the formalism for open quantum systems. What one needs to calculate from the light QCD degrees of freedom are the following chromoelectric field correlators:

$$[g_{\rm adj}^{++}]^{>}(t) \equiv \frac{g^2 T_F}{3N_c}\langle E_i^a(t) W^{ac}_{[t,+\infty]} W^{cb}_{[+\infty,0]} E_i^b(0)\rangle_T \tag{2}$$

$$[g_{\rm adj}^{--}]^{>}(t) \equiv \frac{g^2 T_F}{3N_c}\langle W^{dc}_{[-i\beta-\infty,-\infty]} W^{cb}_{[-\infty,t]} E_i^b(t) E_i^a(0) W^{ad}_{[0,-\infty]}\rangle_T\,, \tag{3}$$

which describe quarkonium dissociation and formation processes. They can all be determined through the spectral function

$$\rho_{\rm adj}^{++}(\omega) = [g_{\rm adj}^{++}]^{>}(\omega) - [g_{\rm adj}^{--}]^{>}(-\omega)\,. \tag{4}$$

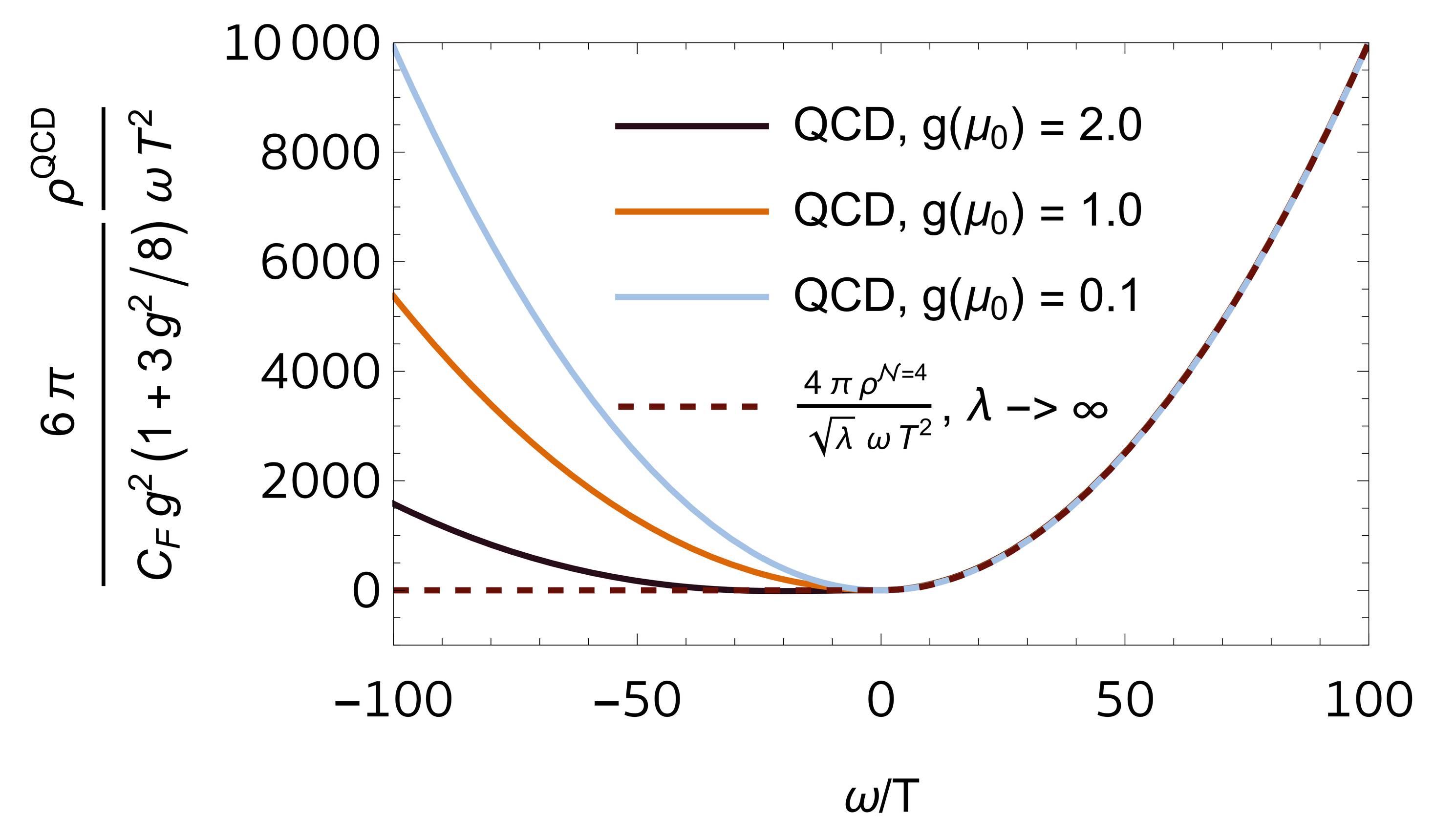


Figure 1. Spectral function $\rho_{\rm adj}^{++}$ calculated at NLO in weakly coupled QCD [1] compared with the strongly coupled calculation in $\mathcal{N}=4$ SYM [2].

References

[1] Tobias Binder, Kyohei Mukaida, B. S-H, and Xiaojun Yao. *JHEP*, 01:137, 2022.

[2] Govert Nijs, B. S-H, and Xiaojun Yao. *JHEP*, 06:007, 2023.

[3] Govert Nijs, B. S-H, and Xiaojun Yao. *Phys. Rev. D*, 109(9):094043, 2024.

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The importance of non-Markovian effects

The main feature in Figure 1 is that the spectral function becomes more asymmetric as the coupling is increased, with the extreme case showcased by the $\mathcal{N} = 4$ result, where $\rho_{\rm adj}^{++}(\omega \leq 0) = 0$. This has dramatic consequences for our understanding of currently available pNRQCD-based transport descriptions [3]:

- In the Quantum Brownian motion limit, dissociation and recombination are controlled by the value of the limit $\lim_{\omega\to 0}\rho_{\rm adj}^{++}(\omega)/\omega$. This limit vanishes in $\mathcal{N}=4$ SYM. It remains to be seen what this limit is from a lattice QCD calculation of the Euclidean counterpart of $[g_{\rm adj}^{++}]^{>}$ [4].
- In the Quantum Optical limit, dissociation and recombination are controlled by the value of $\rho_{\rm adj}^{++}(-|\Delta E|)$, where ΔE is the energy difference between the quarkonium states involved in the transition. This vanishes in $\mathcal{N}=4$ SYM. A lattice QCD calculation of the Euclidean counterpart of $[g_{\rm adj}^{++}]^{>}$ has the potential to characterize the asymmetry of $\rho_{\rm adj}^{++}$ [4].

Both of the above descriptions are expansions around certain kinematic limits, which assume that the dynamics of quarkonium as an open quantum system is local in time (i.e., *Markovian*), and that memory (i.e., *non-Markovian*) effects are negligible compared to them. Our strongly coupled result in $\mathcal{N}=4$ SYM shows that non-Markovian effects are not negligible at strong coupling.

Figure 2 compares the total regeneration probability of a $\Upsilon(1S)$ state using the different correlation functions we have calculated. The (weakly coupled) QCD curves contain both Markovian and non-Markovian effects, while the $\mathcal{N}=4$ curve contains only non-Markovian effects. This Figure indicates that assuming Markovian dynamics might lead one to overestimate the dissociation/recombination rates.

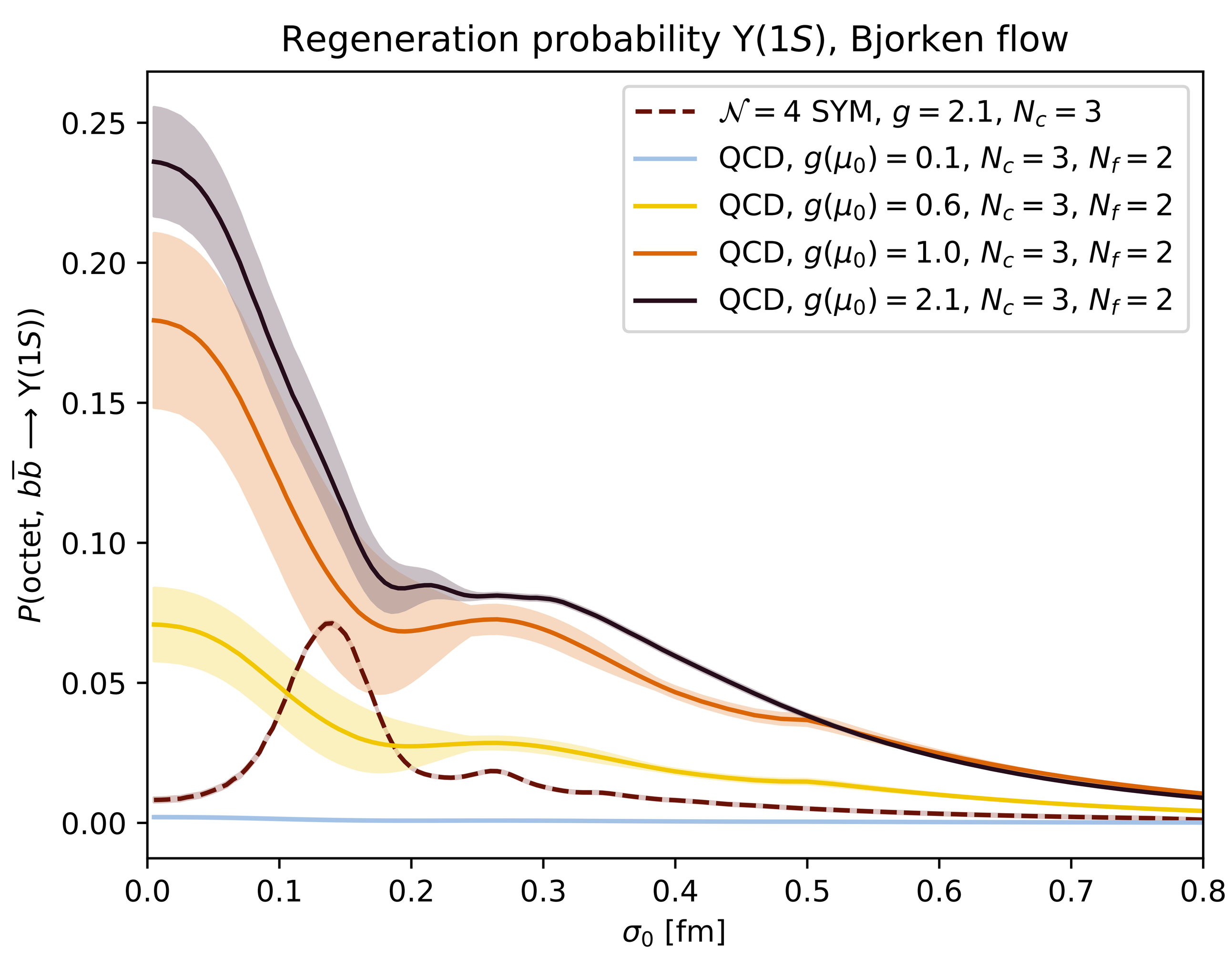

Figure 2. Regeneration probability for the $\Upsilon(1S)$ state with a Karsch-Mehr-Satz potential model on a background temperature given by Bjorken flow $T \propto \tau^{-1/3}$.

Outlook

A transport formalism that includes non-Markovian effects is needed to describe quarkonium in QGP. We are working on this. Stay tuned!

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