Charmonium above deconfinement as an open quantum system

Clint Young

SUNY Stony Brook

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Modeling charmonium with a Langevin equation

- Heavy quark and quarkonium dynamics
- Quarkonium dynamics in sQGP as a stochastic process
- Properties of the J/ψ in sQGP

Quarkonium as an open quantum system

- The path integral approach to quantum Brownian motion
- Imaginary-time correlators

Au+Au RHIC collisions

- Langevin-with-interaction simulation of charmonium
- Recombinant production
- Anomalous J/ψ suppression for two values of T_c

Conclusions and future work

Heavy quark and quarkonium dynamics

Heavy quark diffusion: $3\kappa = \int d^3q|\mathbf{q}|^2 \frac{d^3\Gamma}{dq^3}$

- HTL approximation at NLO (Caron-Huot and Moore)[1]:

$$\kappa = \frac{16\pi}{3}\alpha_s^2 T^3 \left(\log(1/g_s) + .07428 + 1.9026 g_s\right) \qquad (1)$$

- Drag force and diffusion from AdS/CFT (Gubser, Casalderrey-Solana and Teaney, Mia et al.) [2], [3], [4], [5]:

$$\kappa = \pi\sqrt{\lambda}T^3 \qquad (2)$$

- Phenomenology (Moore and Teaney) [6].

$Q\bar{Q}$ potential

- Lattice calculations of $Tr\left\langle W(\mathbf{x})W^\dagger(\mathbf{0})\right\rangle$ (Kaczmarek et al.) [7].
- Internal or Free Energy? (Shuryak and Zahed) [8].
- Potential models (Mocsy and Petreczky) [9].

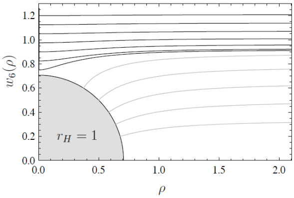
D_{HQ} vs. quarkonium diffusion

Quarkonium $\neq$ two heavy quarks!

First AdS/CFT calculations for quarkonium suggested *zero drag*, only influence of the thermal medium from a "hot wind"

Dusling, ..., Young: Fluctuations on D7 in $AdS_5 \times S_5$ dual to effective theory for dipoles

Momentum diffusion suppressed by factor of $1/N_c^2$, smaller than perturbative $\mathcal{N} = 4$ prediction by a factor of 4. Exact opposite of heavy quark situation!



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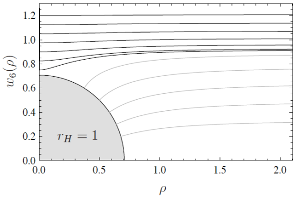


However, this treatment only valid when $E_B >> T$

Appropriate for Υ, inappropriate for J/ψ

J/ψ dynamics at RHIC somewhere between "photoelectric effect" and "Rayleigh scattering"

Quarkonium dynamics in sQGP as a stochastic process

When M_{HQ} is sufficiently larger than T, the dynamics of each heavy quark can be described by

$$\frac{dp_i}{dt} = -\eta p_i + \xi_i - \nabla_i U, \tag{3}$$

where

$$\langle \xi_i(t)\xi_j(0)\rangle = \kappa\delta_{ij}\delta(t). \tag{4}$$

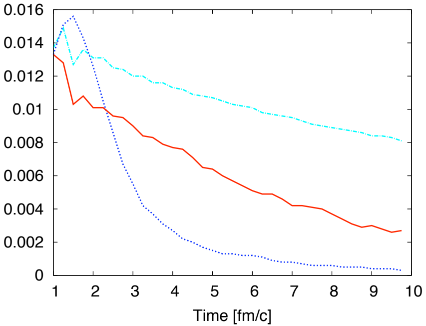
Requiring thermalization to temperature T yields the Einstein relation between noise and dissipation:

$$\eta = \frac{\kappa}{2MT}. \tag{5}$$

Evolution of an ensemble of $Q\bar{Q}$ pairs in sQGP

The probability for a $Q\bar{Q}$ pair to be bound as a function of time:

- **Green:** $2\pi TD_c = 1.5$
- **Red:** $2\pi TD_c = 3.0$
- **Blue:** $2\pi TD_c = 1.5$, no $Q\bar{Q}$ interaction



Summary of $Q\bar{Q}$ in sQGP

- Thermalization in momentum space relatively fast, spatial diffusion relatively slow.
- The $Q\bar{Q}$-potential can greatly enhance the survival probability.
- Quasi-equilibrium forms: relative abundances predicted by Boltzmann factors.

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An explanation for J/ψ survival at RHIC?

The reduced density matrix

Imagine a single degree of freedom minimally coupled to a bath:

$$\begin{aligned} L &= \frac{1}{2}M\dot{x}^2 - V(x) \\ &+ \frac{1}{2}\sum_i m_i \dot{R}_i^2 - \frac{1}{2}\sum_i m_i \omega_i^2 R_i^2 \\ &- \sum_i C_i x R_i. \end{aligned} \tag{6}$$

The *reduced* density matrix

$$\begin{aligned} \rho_{red}(x, x', \beta) &= \int dR_i \rho(x, R_i, x', R_i, \beta) \\ &= \int Dx \exp(-\int_0^\beta d\tau[\frac{1}{2}M\dot{x}^2 + V(x) \\ &- \sum_i \frac{C_i^2}{2m_i\omega_i \sinh(\omega_i\beta/2)} x(\tau) \int_0^\tau ds\, x(s) \cosh(\omega_i(\tau - s - \beta/2))]) \end{aligned} \tag{7}$$

Caldeira and Leggett, 1983

Intuitively, when the proper infinite limit is taken for the bath, the dynamics for the heavy particle may be dissipative. The density of states

$$C^2(\omega)\rho_D(\omega) = \begin{cases} \frac{2m\eta\omega^2}{\pi} & \text{if } \omega < \Omega \\ 0 & \text{if } \omega > \Omega \end{cases} \tag{8}$$

yields Langevin dynamics when $\Omega \to \infty$, with η the usual drag coefficient.

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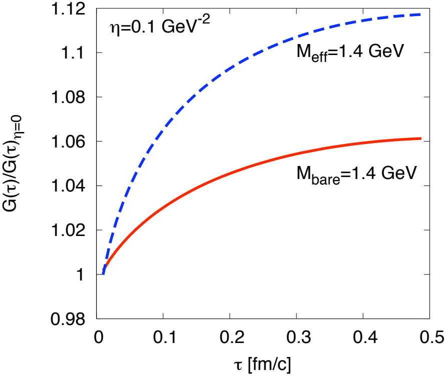
The reduced density matrix becomes, after integrating by parts and renormalizing...

The reduced density matrix for an open system

$$\begin{aligned}
\rho_{red}(x_i, x_f, \beta) &= \int_{x(0)=x_i}^{x(\beta)=x_f} \mathcal{D}x \ \exp\Bigg\{ - S_S^E[x] \\
&- \frac{\eta}{2\pi}(x_i - x_f)^2 \left[\gamma_E + \ln\left(\frac{\eta\beta}{\pi M}\right)\right] \\
&+ \frac{\eta}{\pi}(x_i - x_f) \int_0^\beta d\tau \ \dot{x}(\tau) \, \mathrm{lnsin}\left(\frac{\pi\tau}{\beta}\right) \\
&+ \frac{\eta}{\pi} \int_0^\beta d\tau \int_0^\tau ds \ \dot{x}(\tau)\dot{x}(s) \, \mathrm{lnsin}\left(\frac{\pi(\tau - s)}{\beta}\right) \Bigg\}. \quad (9)
\end{aligned}$$

The effect of dissipation on $G_{rec}(\tau)$

- $\eta = 0.1\mathrm{GeV}^{-1}$,
- $T = 1.2\,T_c$.

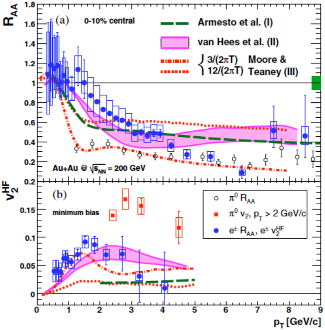


Langevin-with-interaction simulation of charmonium

LO PYTHIA event generation

2+1-dimensional hydrodynamical simulation of the plasma phase

Langevin+interaction evolution of the $c\bar{c}$ pairs



Another consideration: recombinant production

- With many hard processes per collision, the possibility of recombinant production needs to be considered.
- May lead to less suppression or even an enhancement of J/ψ yields at the LHC

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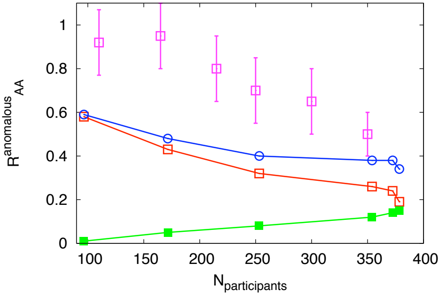
Facts about charm production at the RHIC:

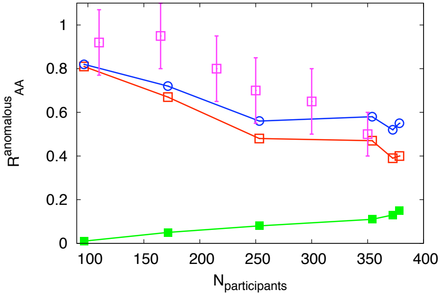
- On average 18 pairs produced in the most central Au+Au collisions.
- Only 5.5% of charm quarks produced are "neighbors" (close enough to form a bound state) with a single anti-quark. Only an additional 0.2% have more than one neighbor.

Anomalous J/ψ suppression for two values of T_c

For $T_c = 165\ \mathrm{MeV}$:

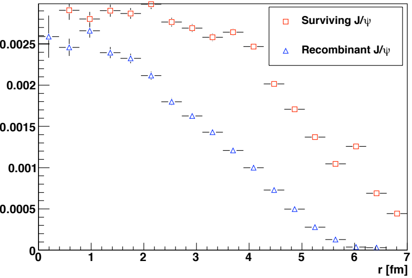


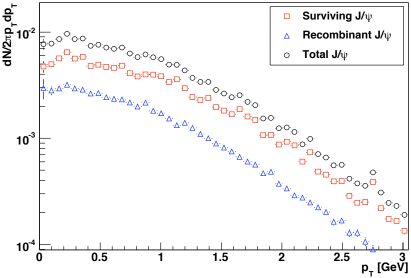
For $T_c = 190\ \mathrm{MeV}$:



Can differential p_T yields differentiate between the two components?

The surviving component in the periphery of the transverse plane, the recombinant peaked in the center.





Conclusions and future work

A model for J/ψ suppression and charmonium thermalization at the RHIC proposed which is *consistent with heavy quark dynamics in strongly-coupled gauge theory*.

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Future work

Calculate surviving and recombinant yields at the LHC

Extract spectral functions for quarkonium correlators with the maximal entropy method, *decouple "disassociation rates" in this model from hydrodynamics simulations*

Other observables at the RHIC?

What more can AdS/CFT tell us about quarkonium?

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Thanks!

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