Quarkonium and Open Quantum Systems

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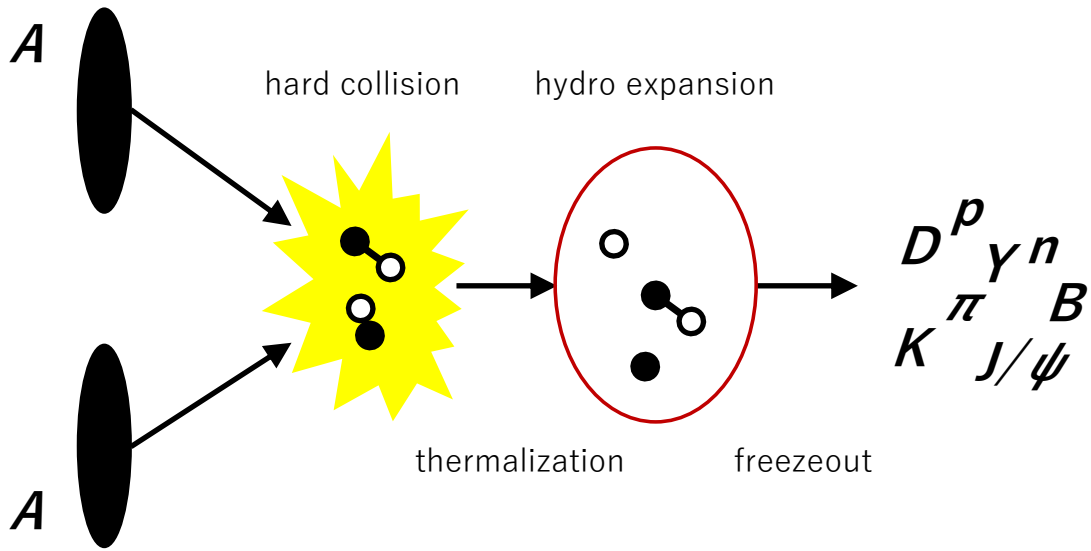
The Quantumness of Hard Probes

Refs:
Akamatsu, Prog. Part. Nucl. Phys. xxx (2022) xxxx [2009.10559]
Akamatsu-Miura, EPJ Web of Conferences 258 (2022) 01006 [2111.15402]

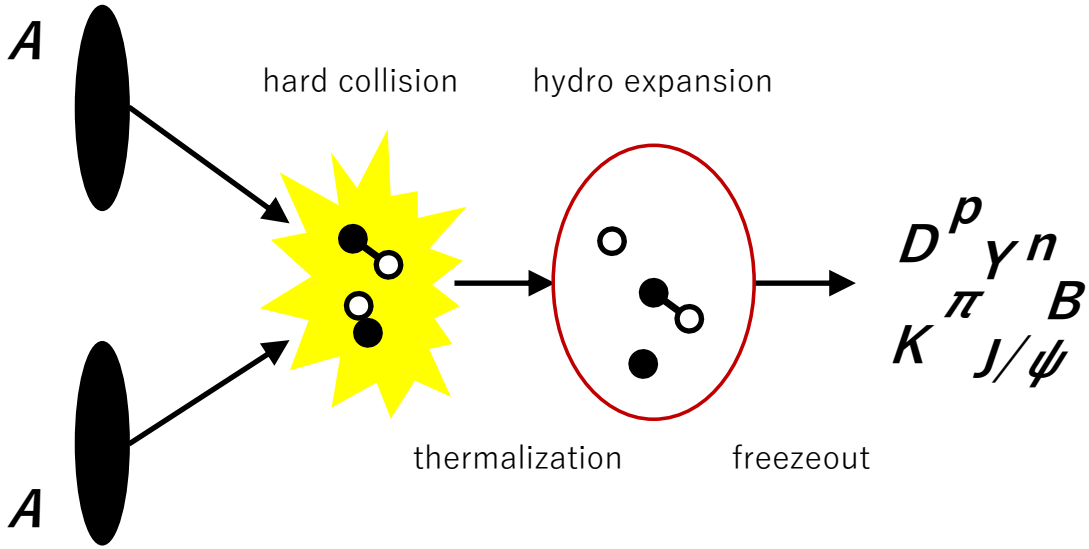
Quarkonia in heavy-ion collisions



What we are getting to know

- Non-equilibrium evolution of quarkonia in static and homogeneous medium

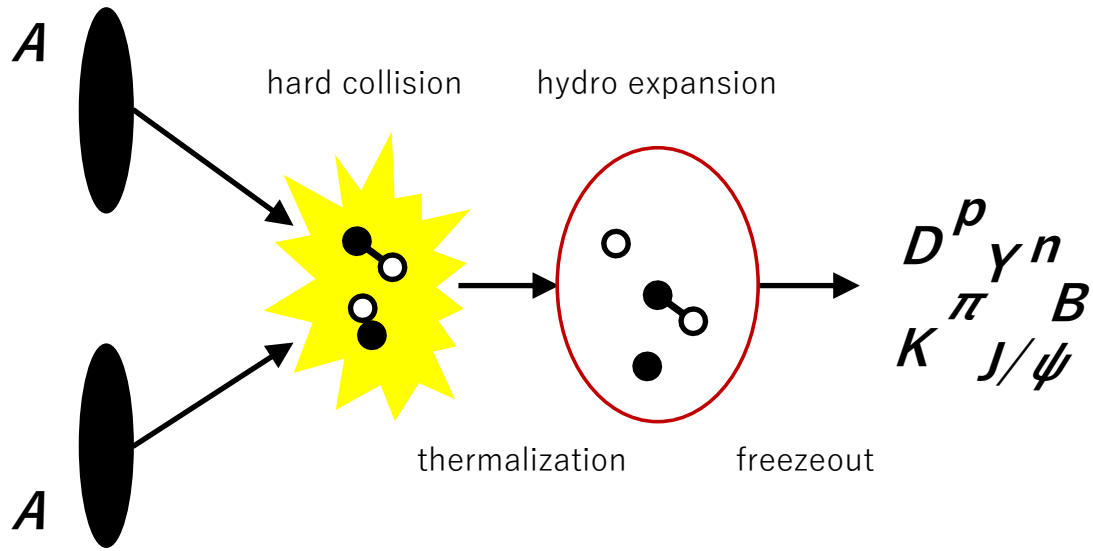
Quarkonia in heavy-ion collisions



What we ignore in this talk

- Interaction between initially uncorrelated pairs (justified for bottoms)
- Effects of non-static and inhomogeneous medium (for simplicity)
- Heavy quark pair creation in medium (suppressed by $e^{-M/T}$)
- Heavy quark pair annihilation in medium (suppressed by $1/M^2$)

Quarkonia in heavy-ion collisions



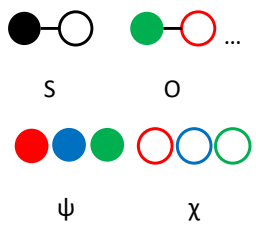
What we do not know

- Initial condition of quarkonia
  - assume singlet/octet wave packets, vacuum states, etc
- How quarkonia hadronize
  - assume evolution freezes at $T = T_f$

Quarkonia in a static and uniform medium ($T > T_c$)

Key quantities: **in-medium self-energy of a static quarkonium**

- pNRQCD description: Local correlations in the QGP
  Thermal dipole self-energy coeff./HQ mom. diffusion const.
- NRQCD description: Non-local correlations in the QGP
  Complex potential



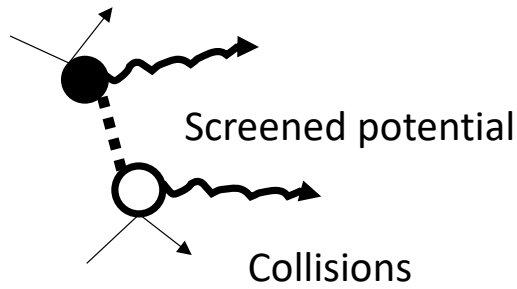
How do they determine quarkonium evolution?
$\leftrightarrow$ What can we learn from experiment, in principle?

Contents

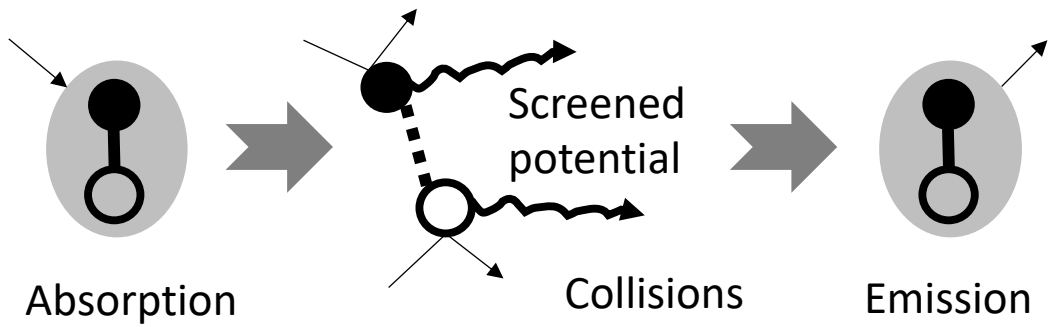
Quarkonia as an open quantum system in QGP

Quarkonium by classical kinetics

- Heavy quark and antiquark are classical particles

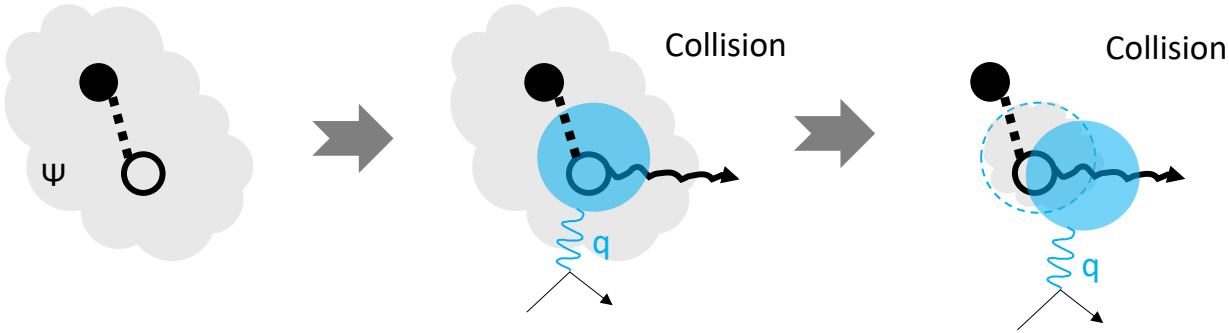


- Quarkonium is a classical molecule and unbound pairs are classical particles
  - When reaction duration $\gtrsim$ orbital period



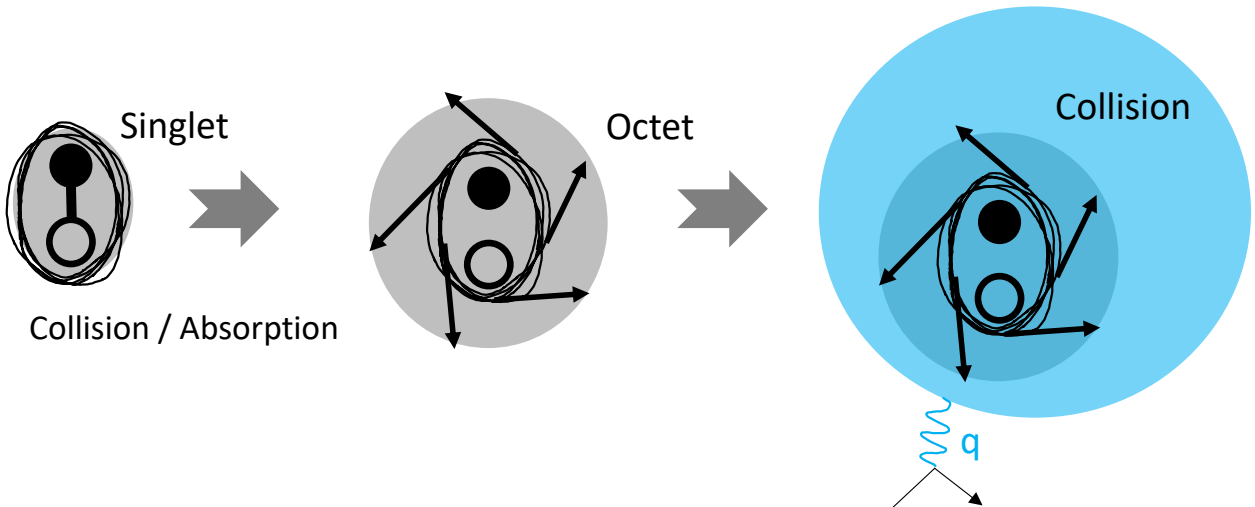
What is the quantum effect?

- Naive picture: collisions induce decoherence and classicalization



  - Decoherence proceeds rapidly if $\lambda_\Psi \gg 1/q$
  - But it is not the case for quarkonium in Coulomb potential

- Scales for quarkonium in Coulomb potential: $\lambda_\Psi \sim 1/M\alpha \ll 1/T \sim 1/q$



  - Decoherence proceeds slowly because $\lambda_\Psi \ll 1/q$
  - How long does it take for medium to distinguish different classical trajectories?

Quarkonium as an open quantum system – reference list

Key observations before the application of open quantum system:

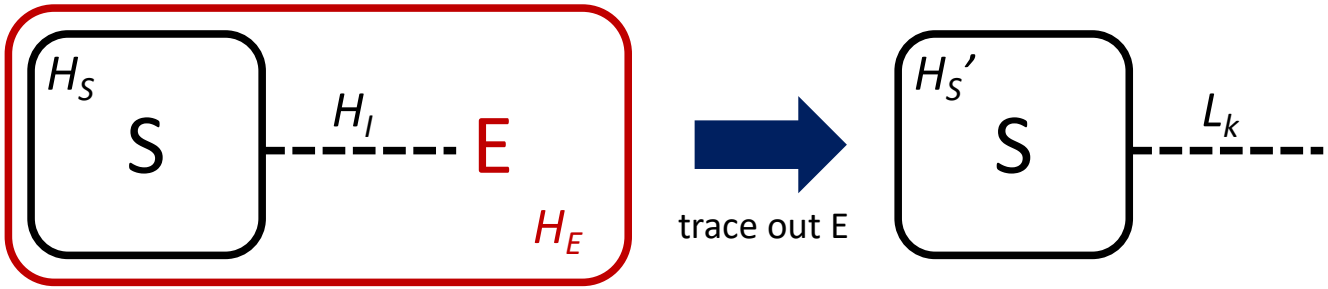
- J/ψ melting [Matsui-Satz (86)]
- J/ψ mass shift [Hashimoto+ (86)]
- J/ψ spectral function [Asakawa-Hatsuda (04)]
- Complex potential [Laine+ (07), Beraudo+ (08), Brambilla+ (08), Rothkopf+ (12)]

Personally, I was very confused by the non-unitary evolution by complex potential, which led me to take a system-environment approach, i.e. open quantum system.

Time-evolution equations using open system technique

- First applications [Young-Dusling (13) (2010 on arXiv), Borghini-Gombeaud (11,12)]
- Stochastic potential [Akamatsu-Rothkopf (12)]
- Lindblad equation from NRQCD [Akamatsu (15,22)]
- Lindblad equation from pNRQCD [Brambilla+ (17,18), Akamatsu (22)]
- Generalized Langevin equation from NRQCD [Blaizot+ (16,18,18)]
- Coupled Boltzmann equation from pNRQCD [Yao-Mehen (19)]

Minimum basics of open quantum system



Lindblad equation: evolution of reduced density matrix $\rho_S(t) \equiv \mathrm{Tr}_E \rho_{\mathrm{tot}}(t)$

$$\frac{d}{dt}\rho_S(t) = -i\,[H'_S, \rho_S] + \underbrace{\sum_k \left(L_k \rho_S L_k^\dagger - \frac{1}{2} L_k^\dagger L_k \rho_S - \frac{1}{2} \rho_S L_k^\dagger L_k \right)}_{\text{dissipator } \mathcal{D}(\rho_S)} = \mathcal{L}(\rho_S)$$

$$= -i \underbrace{\left(H_{\mathrm{eff}} \rho_S - \rho_S H_{\mathrm{eff}}^\dagger \right)}_{\text{non-Hermitian evolution}} + \underbrace{\sum_k L_k \rho_S L_k^\dagger}_{\text{transitions/scatterings}} , \quad H_{\mathrm{eff}} = \underbrace{H'_S - \frac{i}{2} \sum_k L_k^\dagger L_k}_{H_S + \text{self-energy } \Delta H_S}$$

if the evolution is Markovian, (completely) positive, and preserves probability

[Gorini-Kossakowski-Sudarshan (76), Lindblad (76)]

Lindblad equation for weak system-environment coupling

Born-Markov approximation for $H_I = V_S \otimes V_E$ (interaction picture)

$$\frac{d}{dt}\rho_S(t) = \int_0^\infty ds \; \underbrace{\langle V_E(s)V_E(0)\rangle}_{\text{environment correlator}} \left[\begin{array}{l} V_S(t-s)\rho_S(t)V_S(t) \\ -V_S(t)V_S(t-s)\rho_S(t)\end{array}\right] + h.c. + \mathcal{O}(V^3)$$

Quantum Brownian regime[1]

- Slow system time scale $\rightarrow$ derivative expansion

$$V_S(t-s) \approx V_S(t) - s\dot{V}_S(t) + \cdots = V_S(t) - is[H_S, V_S(t)] + \cdots$$

$$\rightarrow \quad L \propto \underbrace{V_S + \frac{i}{4T}\dot{V}_S}_{\tau_E/\tau_S \,\rightarrow\, 0 \text{ limit}} + \cdots \quad \text{fluctuation-dissipation theorem}$$

- Condition for derivative expansion ($\tau_{S/E}$ = system/env. timescale)

$$\tau_S \sim \underbrace{\frac{4}{M(C_F\alpha)^2}}_{\text{Coulombic}} \sim \frac{1}{[0.11-0.19]\text{GeV}} \gg \tau_E \sim \frac{1}{2\pi T}$$

[1] There is another regime "Quantum optical limit," where $H_I(t)$ has discrete spectra

Lindblad equation from potential NRQCD [Brambilla et al (17,18), Akamatsu (22)]

Color-dipole interaction (R/r = center-of-mass/relative coordinates)

$$H_I = -\Big[\underbrace{\frac{|s\rangle\langle a| + |a\rangle\langle s|}{\sqrt{2N_c}}}_{\text{singlet}\leftrightarrow\text{octet}} + \underbrace{\frac{d_{abc}}{2}|b\rangle\langle c|}_{\text{octet}\leftrightarrow\text{octet}}\Big]\underbrace{\vec{r}\otimes g\vec{E}^a(R)}_{\text{dipole at } R} \sim \vec{r}\cdot g\vec{E}(R)$$

- For small dipole, gauge-invariant and non-perturbative expansion possible
- Expansion coefficients are physical quantities

Self-energy and Lindblad operator

$$\Delta H_S = \frac{1}{2}(\gamma - i\kappa)\Big[r^2 + \underbrace{\mathcal{O}(\dot{r})}_{\text{derivative exp.}}\Big]\Big[|s\rangle\langle s| + \#|a\rangle\langle a|\Big] + \underbrace{\mathcal{O}(r^3)}_{\text{small-r exp.}}$$

$$L \sim \underbrace{\sqrt{\kappa}}_{\text{transport coeff.}}\Big[r + \underbrace{\mathcal{O}(\dot{r})}_{\text{derivative exp.}}\Big]\Big[\text{color transitions}\Big] + \underbrace{\mathcal{O}(r^2)}_{\text{small-r exp.}}$$

- γ: thermal dipole self-energy coefficient, in-medium mass shift of quarkonia
- κ: heavy quark momentum diffusion constant, in-medium width of quarkonia

Reduction of Lindblad operators

1. Lindblad operators (#=24)

$$L_{ai} \propto r_i \Big(\underbrace{\sqrt{\frac{1}{2N_c}}|a\rangle\langle s|}_{\text{singlet}\to\text{octet}} + \underbrace{\sqrt{\frac{1}{2N_c}}|s\rangle\langle a|}_{\text{octet}\to\text{singlet}} + \underbrace{\frac{1}{2}d^{abc}|b\rangle\langle c|}_{\text{octet}\to\text{octet}} \Big) + \underbrace{\mathcal{O}(\dot{r})}_{\text{derivative exp.}} + \underbrace{\mathcal{O}(r^2)}_{\text{small-r exp.}}$$

2. Singlet-octet projection (do not distinguish the octets) (#=9)

$$\tilde{C}_{+i} \propto r_i|o\rangle\langle s| + \cdots, \quad \tilde{C}_{-i} \propto r_i|s\rangle\langle o| + \cdots, \quad \tilde{C}_{di} \propto r_i|o\rangle\langle o| + \cdots$$

3. Angular momentum projection (do not distinguish ms for fixed ℓ) (#=6)

$$\begin{aligned}
&\tilde{C}_{+\uparrow} \sim r|\ell+1\rangle\langle\ell| \otimes |o\rangle\langle s|, \quad \tilde{C}_{+\downarrow} \sim r|\ell-1\rangle\langle\ell| \otimes |o\rangle\langle s|, \\
&\tilde{C}_{-\uparrow} \sim r|\ell+1\rangle\langle\ell| \otimes |s\rangle\langle o|, \quad \tilde{C}_{-\downarrow} \sim r|\ell-1\rangle\langle\ell| \otimes |s\rangle\langle o|, \\
&\tilde{C}_{d\uparrow} \sim r|\ell+1\rangle\langle\ell| \otimes |o\rangle\langle o|, \quad \tilde{C}_{d\downarrow} \sim r|\ell-1\rangle\langle\ell| \otimes |o\rangle\langle o|
\end{aligned}$$

- $|\ell\rangle\langle\ell|$ is prohibited by the parity selection rule
- See [Akamatsu (22), in Appendix C] for complete expressions including $\mathcal{O}(\dot{r})$ terms

Lindblad equation from NRQCD [Akamatsu (15,22)]

Color-eletric interaction

$$H_I = \underbrace{gA_0(x_Q) - gA_0^*(x_{Q_c})}_{\text{fluctuating scalar potential}} = \int_k \underbrace{\left(e^{ikx_Q} t_Q^a - e^{ikx_{Q_c}} t_{Q_c}^{a*}\right)}_{\text{momentum transfer } k} \otimes \underbrace{g\tilde{A}_0^a(k)}_{\text{mode } k}$$

Self-energy and Lindblad operator ($r \sim 1/gT$)

$$\Delta H_S = V(r)[t_Q^a t_{Q_c}^{a*}] + i\Big(D(r)[t_Q^a t_{Q_c}^{a*}] - C_F D(0)\Big) + \underbrace{\cdots}_{\text{expansions } (\partial_t,\, g)}$$

$$V(r) = -\frac{\alpha}{r} e^{-m_D r}, \quad D(r) = \int_k e^{ik\cdot r} \tilde{D}(k), \quad \tilde{D}(k) = g^2 T \frac{\pi m_D^2}{k(k^2+m_D^2)^2}$$

$$L_k \sim \underbrace{\sqrt{\tilde{D}(k)}}_{\text{rate}^{1/2} \propto g} \Big[e^{ikx_Q} t_Q^a - e^{ikx_{Q_c}} t_{Q_c}^{a*} + \underbrace{\mathcal{O}(\dot{x}_Q, \dot{x}_{Q_c})}_{\text{derivative exp.}}\Big] + \underbrace{\mathcal{O}(g^2)}_{\text{perturbative exp.}}$$

- Singlet complex potential ($[t_Q^a t_{Q_c}^{a*}]|_{\text{singlet}} = C_F$)
  [Laine+(07), Beraudo+(08), Brambilla+(08)]

$$V_{\text{complex}}^{(\text{singlet})}(r) = C_F\Big[V(r) - i(D(0) - D(r))\Big]$$

Classical limit of the Lindblad equations – kinetics

[Blaizot-Escobedo (18), Akamatsu (22)]

Langevin equation with correlated noise $\rightarrow$ drag force is also correlated

- Singlet pair

$$\overline{\xi_{Qi}(t)\xi_{Qj}(t')} = \overline{\xi_{Q_c i}(t)\xi_{Q_c j}(t')} = -C_F \partial_i \partial_j D(0)\delta(t-t') > 0,$$
$$\overline{\xi_{Qi}(t)\xi_{Q_c j}(t')} = \underbrace{C_F \partial_i \partial_j D(r)\delta(t-t') < 0}_{\text{singlet} \sim \text{opposite charges}}$$

- Octet pair

$$\overline{\xi_{Qi}(t)\xi_{Qj}(t')} = \overline{\xi_{Q_c i}(t)\xi_{Q_c j}(t')} = -C_F \partial_i \partial_j D(0)\delta(t-t') > 0,$$
$$\overline{\xi_{Qi}(t)\xi_{Q_c j}(t')} = \underbrace{-\frac{1}{2N_c} \partial_i \partial_j D(r)\delta(t-t') > 0}_{\text{octet} \sim \text{same charges}}$$

For pNRQCD, $C_F D(r) = C_F D(0) - \frac{1}{2}\kappa r^2$: infinite correlation length

Classical limit of the Lindblad equations – colors [Akamatsu (22)]

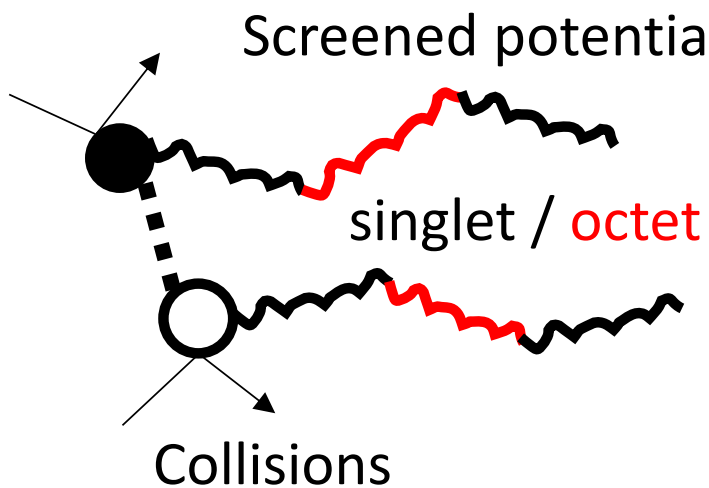
Transition rate (not quite classical)

$$\Gamma_{s\to o} = 2C_F \left[1 - \frac{V_o(r) - V_s(r)}{4T}\right]^2 \frac{D(0) - D(r)}{\hbar^2}$$

$$\Gamma_{o\to s} = \frac{1}{N_c} \left[1 + \frac{V_o(r) - V_s(r)}{4T}\right]^2 \frac{D(0) - D(r)}{\hbar^2}$$

- Approximate detail balance between singlet and octet

$$\frac{\Gamma_{o\to s}}{\Gamma_{s\to o}} = \frac{1}{N_c^2 - 1} \left(\frac{1 + [V_o(r) - V_s(r)]/4T}{1 - [V_o(r) - V_s(r)]/4T}\right)^2 \simeq \frac{1}{N_c^2 - 1} \exp\left[\frac{V_o(r) - V_s(r)}{T}\right]$$



Simulation of Lindblad equation (from NRQCD)

Numerical simulations

Most simulations use stochastic unravelling = sampling wave functions

	NRQCD	pNRQCD
Inter-quark distance r	can be long	short
Coupling g	weak	can be large
Simulation cost	heavier	lighter

NRQCD	Dissipation	Method
1D, U(1)	no	Stochastic Potential [Akamatsu-Rothkopf (12), Kajimoto+ (18)]
3D, U(1)	no	Stochastic Potential [Rothkopf (14)]
1D, SU(3)	no	Stochastic Potential [Sharma-Tiwari (20), Kajimoto+ (21)]
1D, U(1)	yes	Quantum State Diffusion [Akamatsu+ (19), Miura+ (20)]
1D, SU(3)	yes	Quantum State Diffusion [Akamatsu-Miura (22), Miura+ (in prog.)]
1D, U(1)	yes	Direct evolution [Alund+ (21)]

pNRQCD	Dissipation	Method
1_+D, SU(3)	no	Direct evolution for S and P waves [Brambilla+ (17,18)]
3D, SU(3)	no	Quantum Jump [Brambilla+ (20,21)]
1D, SU(3)	yes	Quantum State Diffusion [Miura+ (in prog.)]

Numerical Method for solving the Lindblad equation

Stochastic unravelling of ρ_S: give a mixed-state wave-function ensemble

$$\rho_S(t) = \underbrace{\overline{|\psi(t)\rangle\langle\psi(t)|}}_{\text{ensemble average}} = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} |\psi_i(t)\rangle\langle\psi_i(t)|$$

Method 1: Quantum State Diffusion [Gisin-Percival (92)]

- Nonlinear stochastic equation with complex white noises ($\overline{d\xi_k^* d\xi_\ell} = 2\delta_{k\ell}dt$)

$$\begin{aligned} |d\tilde{\psi}\rangle &= |\tilde{\psi}(t+dt)\rangle - |\psi(t)\rangle \\ &= \underbrace{\left[\mathcal{L}(|\psi\rangle\langle\psi|) - \langle\mathcal{L}(|\psi\rangle\langle\psi|)\rangle_\psi\right]|\psi(t)\rangle dt}_{\text{closest pure state to Lindblad evolution}} + \underbrace{\frac{1}{\sqrt{2}}\sum_k L_k|\psi(t)\rangle d\xi_k}_{\text{mixed state}} \end{aligned}$$

$$|\psi(t+dt)\rangle = \text{normalize } |\tilde{\psi}(t+dt)\rangle \quad \rightarrow \quad \text{repeat}$$

Method 2: Quantum Jump [Plenio-Knight (98)] → Nora's talk

Numerical Method for solving the Lindblad equation

Stochastic unravelling of ρ_S: give a mixed-state wave-function ensemble

$$\rho_S(t) = \underbrace{\overline{|\psi(t)\rangle\langle\psi(t)|}}_{\text{ensemble average}} = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} |\psi_i(t)\rangle\langle\psi_i(t)|$$

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$$\begin{aligned} |d\tilde{\psi}\rangle &= |\tilde{\psi}(t+dt)\rangle - |\psi(t)\rangle \\ &= \underbrace{\left[-iH_{\text{eff}}|\psi(t)\rangle + \sum_k \langle L_k^\dagger\rangle_\psi L_k|\psi(t)\rangle\right]dt}_{\text{nonlinear Schrödinger equation}} + \underbrace{\frac{1}{\sqrt{2}}\sum_k L_k|\psi(t)\rangle d\xi_k}_{\text{mixed state}} \end{aligned}$$

$$|\psi(t+dt)\rangle = \text{normalize } |\tilde{\psi}(t+dt)\rangle \quad \rightarrow \quad \text{repeat}$$

Method 2: Quantum Jump [Plenio-Knight (98)] → Nora's talk

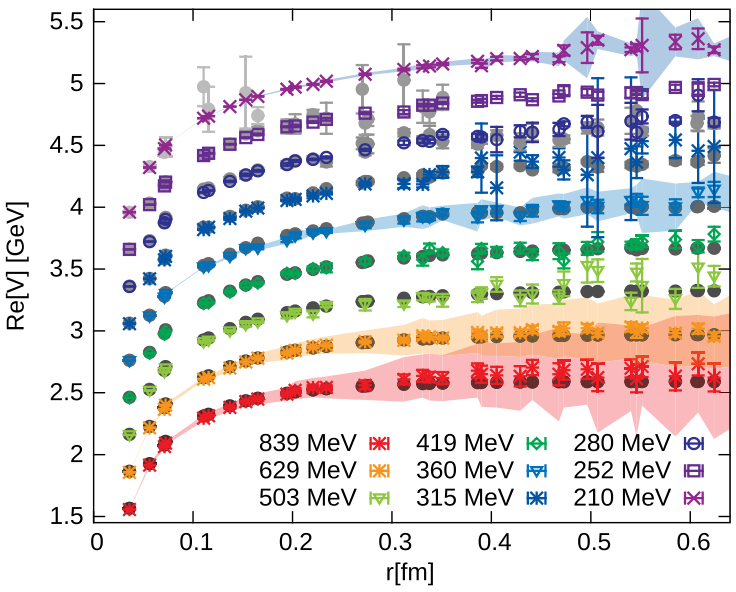
QSD simulation (NRQCD) [Akamatsu-Miura (22)]

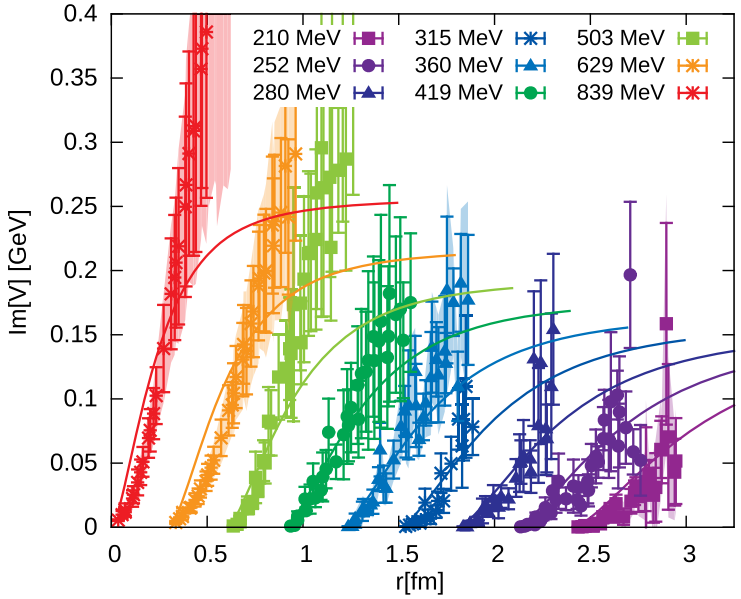
Modeling the Lindblad equation from singlet complex potential

$$V_{\rm complex}^{(\rm singlet)}(r) = C_F \Big[\underbrace{V(r)}_{\text{screening}} \; -i \underbrace{(D(0) - D(r))}_{0 \nearrow D(0)} \Big]$$

Complex potential from non-perturbative thermal Wilson loop

[Rothkopf+ (12,15), see also Bala+ (20)]





- Plateau $\mathrm{Im}V(r \to \infty)$ yet to be seen

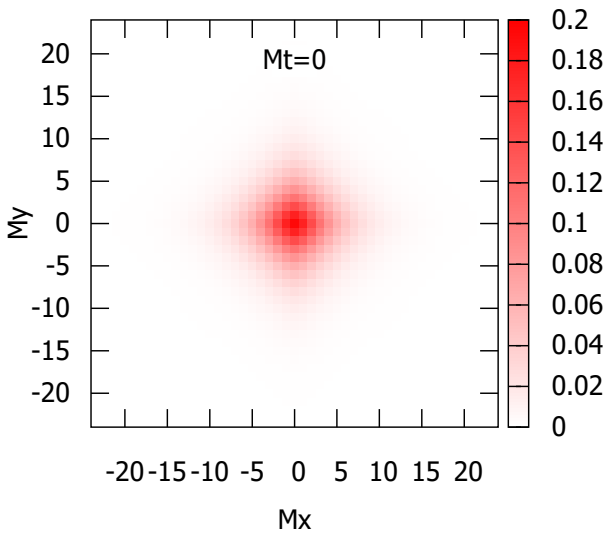
QSD simulation (NRQCD): density matrix [Akamatsu-Miura (22)]

Model complex potential: $V_{\rm complex}^{(\rm singlet)}(r) = C_F V(r) - iC_F(D(0) - D(r))$

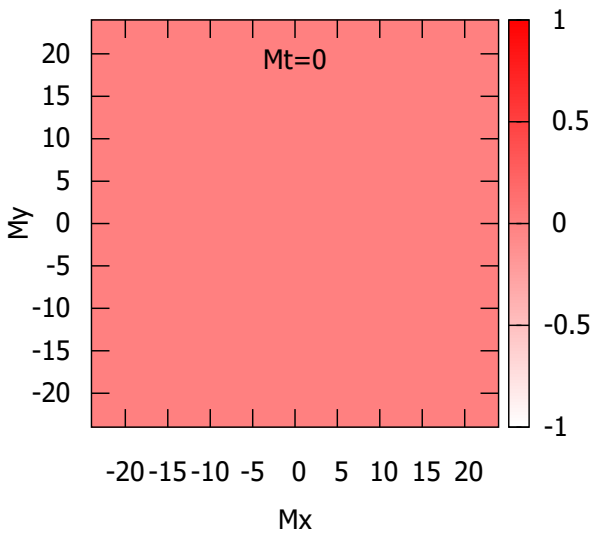
$$C_F V(r) = -\frac{0.3}{r}e^{-2Tr}, \quad C_F D(r) = \frac{T}{\pi}e^{-(Tr)^2}, \quad T = 0.1M$$

$\rightarrow$ Color resolution scale of QGP $\ell \sim 1/T = 10/M$

Singlet $|\rho_s(x,y)|^2$



Octet $|\rho_o(x,y)|^2$



Singlet ground state

QSD simulation (NRQCD): density matrix [Akamatsu-Miura (22)]

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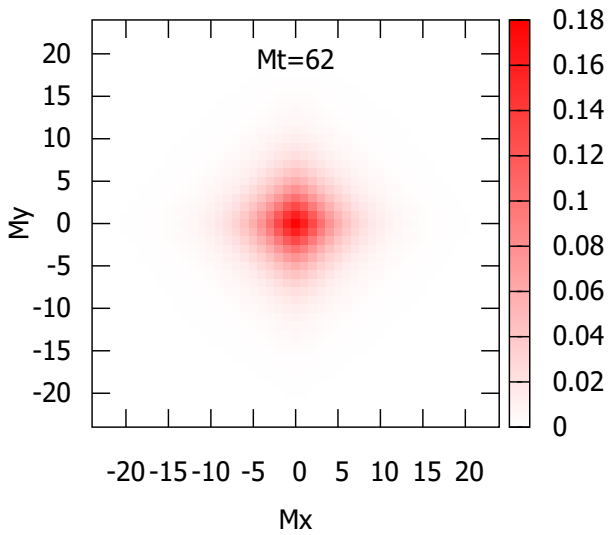

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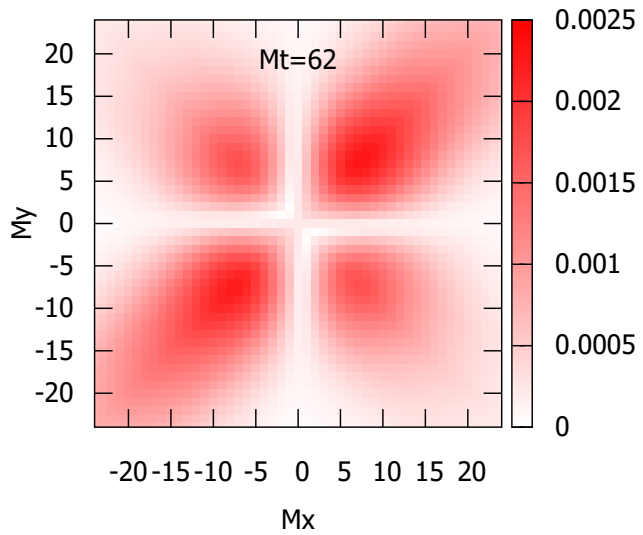

Dipole excitation to octet

QSD simulation (NRQCD): density matrix [Akamatsu-Miura (22)]

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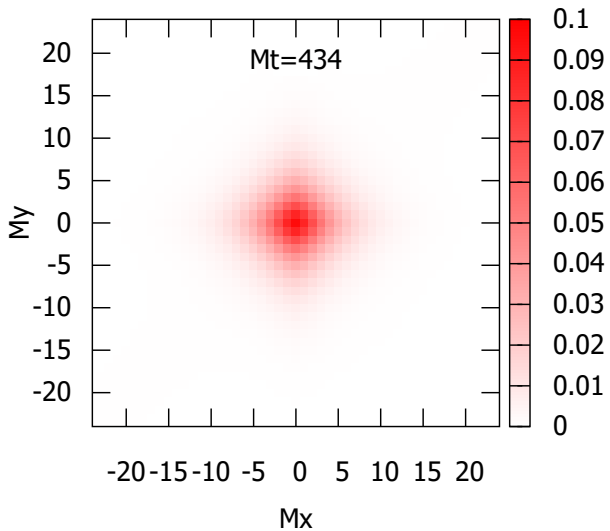
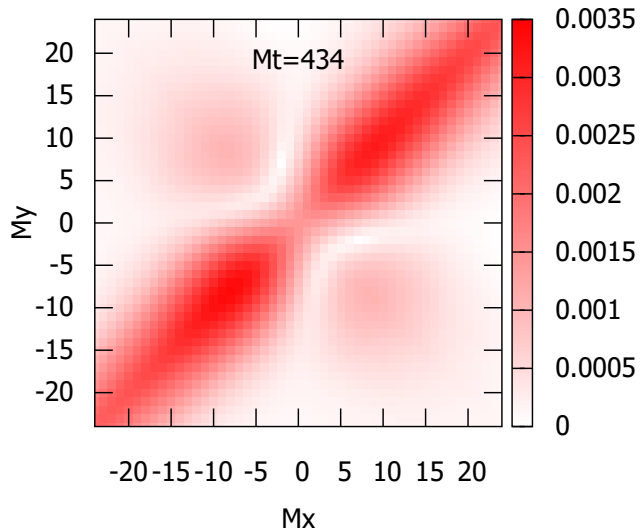


Octet $|\rho_o(x,y)|^2$



Decoherence in octet[2]

[2]For color $\mathrm{SU}(2)$ case, density matrix does not get diagonalized. [Kajimoto+ 2021]

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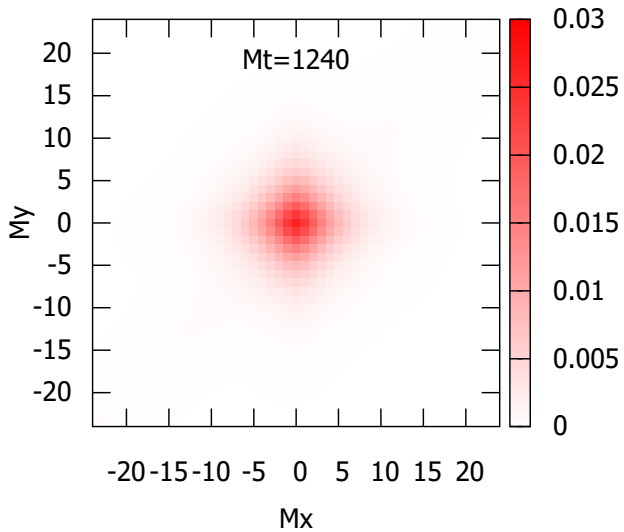
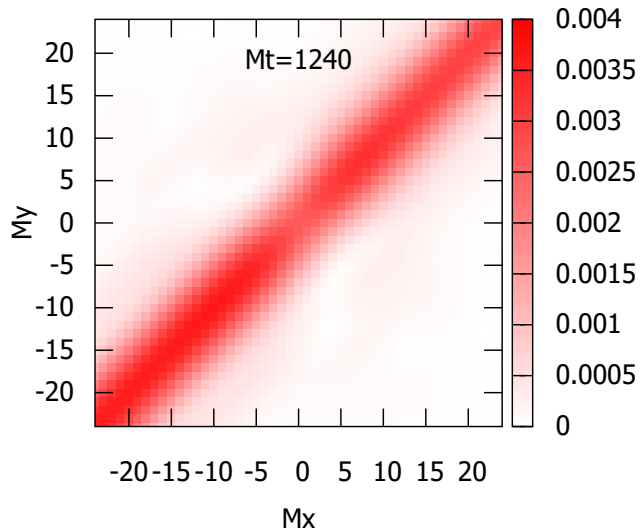
$\rightarrow$ Color resolution scale of QGP $\ell \sim 1/T = 10/M$

Singlet $|\rho_s(x,y)|^2$



Octet $|\rho_o(x,y)|^2$



Decoherence in octet[2]

[2]For color $\mathrm{SU}(2)$ case, density matrix does not get diagonalized. [Kajimoto+ 2021]

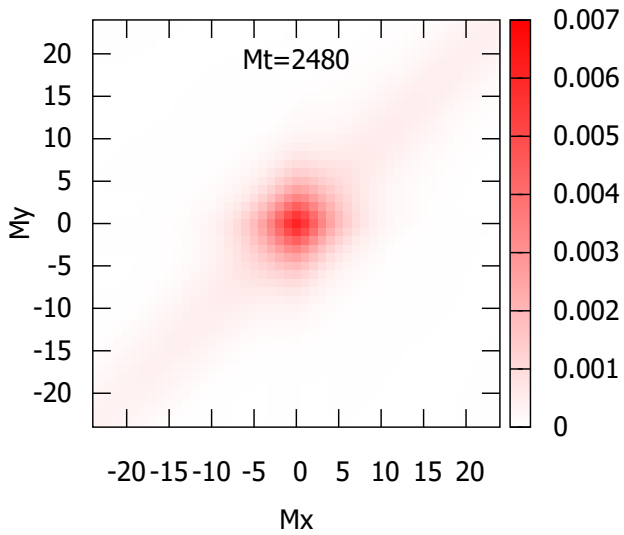
QSD simulation (NRQCD): density matrix [Akamatsu-Miura (22)]

Model complex potential: $V_{\rm complex}^{(\rm singlet)}(r) = C_F V(r) - iC_F(D(0) - D(r))$

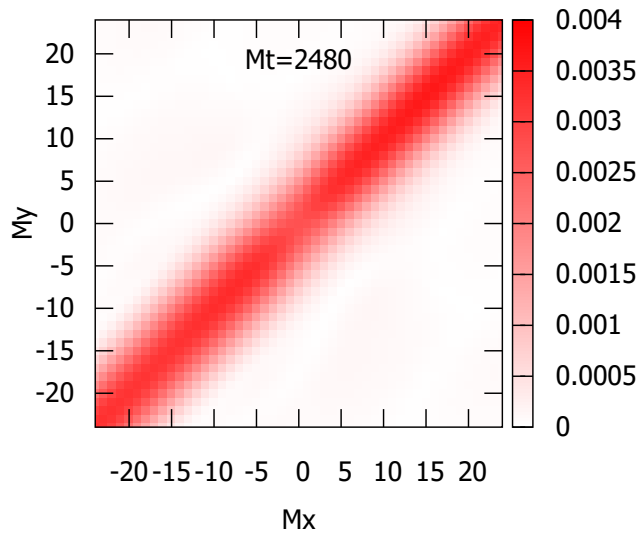
$$C_F V(r) = -\frac{0.3}{r}e^{-2Tr}, \quad C_F D(r) = \frac{T}{\pi}e^{-(Tr)^2}, \quad T = 0.1M$$

$\rightarrow$ Color resolution scale of QGP $\ell \sim 1/T = 10/M$

Singlet $|\rho_s(x,y)|^2$



Octet $|\rho_o(x,y)|^2$



De-excitation to singlet

QSD simulation (NRQCD): density matrix [Akamatsu-Miura (22)]

Model complex potential: $V_{\rm complex}^{(\rm singlet)}(r) = C_F V(r) - iC_F(D(0) - D(r))$

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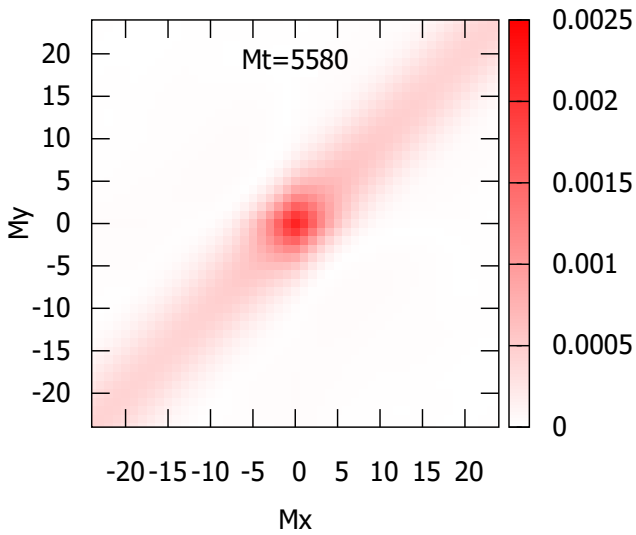
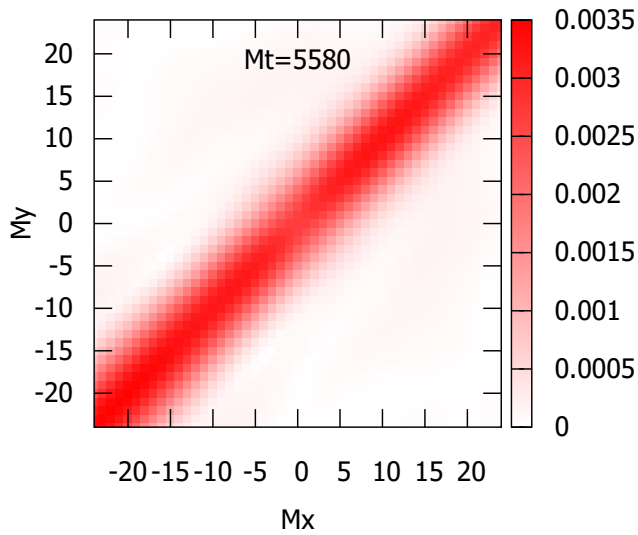
$\rightarrow$ Color resolution scale of QGP $\ell \sim 1/T = 10/M$

Singlet $|\rho_s(x,y)|^2$



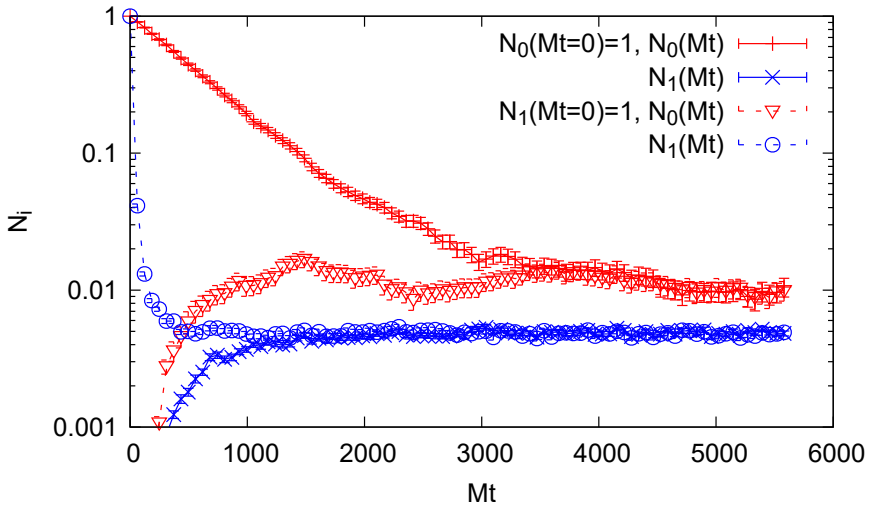
Octet $|\rho_o(x,y)|^2$



De-excitation to singlet $\rightarrow$ equilibrated?

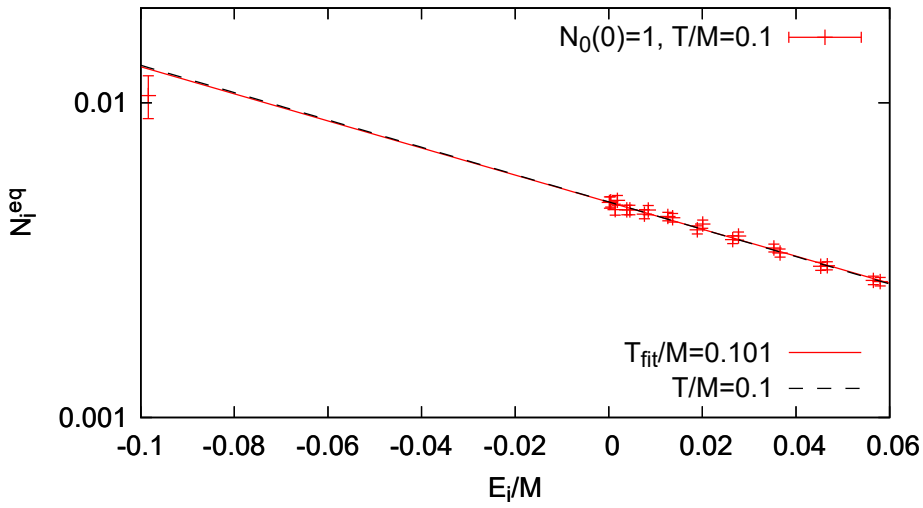
QSD simulation (NRQCD): equilibration [Akamatsu-Miura (22)]

Evolution of eigenstate occupation



Steady state is independent of initial conditions

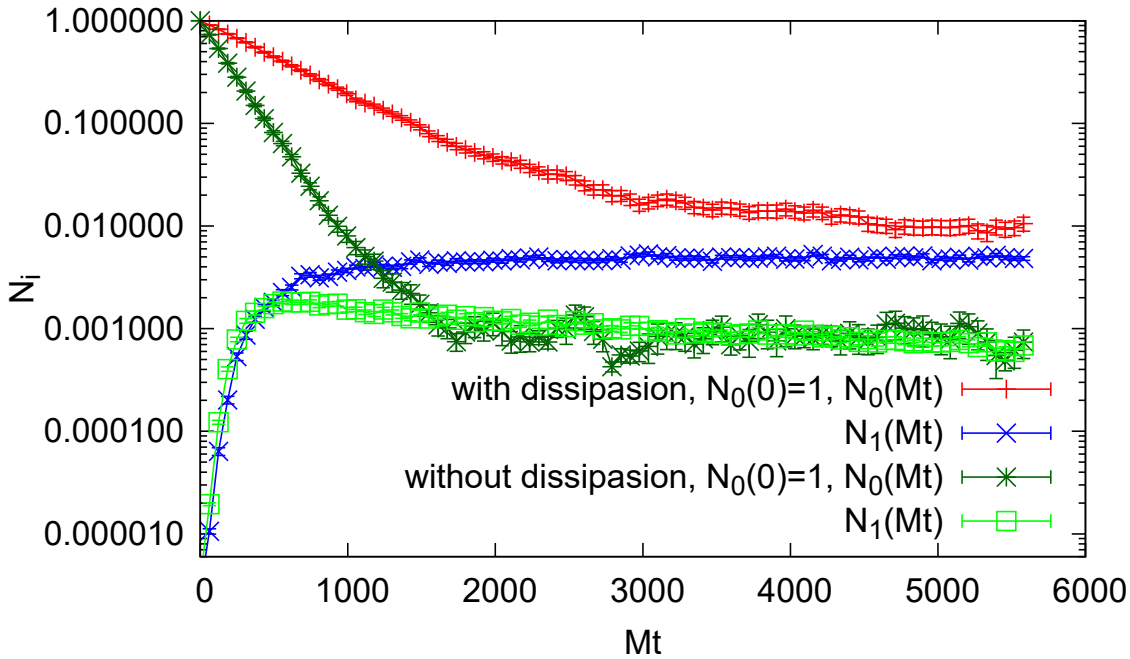
Eigenstate occupation in the steady state



Approach to the Boltzmann distribution with environment temperature

QSD simulation (NRQCD): role of dissipation [Akamatsu-Miura (22)]

Evolution of eigenstate occupation



Without dissipation, all states get equally occupied
Dissipation is non-negligible from early time

Decoherence is not effective for a localized bound state
$\rightarrow$ Need to take account of heavy quark's motion during decoherence (=dissipation)

Summary – theory

Quarkonium Lindblad equations carry information of QGP

- pNRQCD: local coefficients γ and κ
- NRQCD: complex potential

Quarkonium Lindblad equation is yet to be complete

- pNRQCD: valid in non-perturbative regime and in the dipole limit
- NRQCD: valid in weak-coupling regime and can be modeled for any size
- For $T \lesssim 0.2\mathrm{GeV}$, quantum Brownian regime may cease to hold [Yao+ (19)]

$$\text{QGP corr. time} \sim \frac{1}{(2\pi?)T} \ll \text{orbital period} \sim \frac{1}{[0.11 - 0.19]\mathrm{GeV}}$$

Summary – phenomenology

Simulation of Lindblad equation

- pNRQCD: phenomenological application has started
- NRQCD: equilibration achieved by balancing decoherence and dissipation
- Need to check the validity of dipole approximation [Miura+ (in prog.)]
- Quantum simulation? [Hu-Zia-Kais (20), de Jong+ (20)]

Initial condition

- Complete positivity derives from uncorrelated initial condition – when is it?

$$\rho_{\rm tot}(t_0) = \rho_S(t_0) \otimes \rho_E(t_0), \quad t_0 \sim \underbrace{1/M}_{\text{pair creation}}, \quad \underbrace{1/M\alpha^2}_{\text{formation}}, \quad \underbrace{\tau_{\rm hydro}}_{\text{thermalization}}$$

- If initial condition mainly consists of octet wave packet

$$R_{AA} = \text{survival probability?}$$

Freezeout process

- Is projection onto singlet wave function enough? Octet component?