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The Osaka/Stavanger stochastic Schrödinger approach

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References:

S. Kajimoto, Y. Akamatsu, M. Asakawa, A.R. in progress
T. Miura, Y. Akamatsu, M. Asakawa, A.R. arXiv:1908.06293
Y. Akamatsu, Phys.Rev. D91 (2015) no.5, 056002
Y. Akamatsu, A.R. Phys.Rev. D85 (2012) 105011

Motivation: Osaka/Stavanger approach

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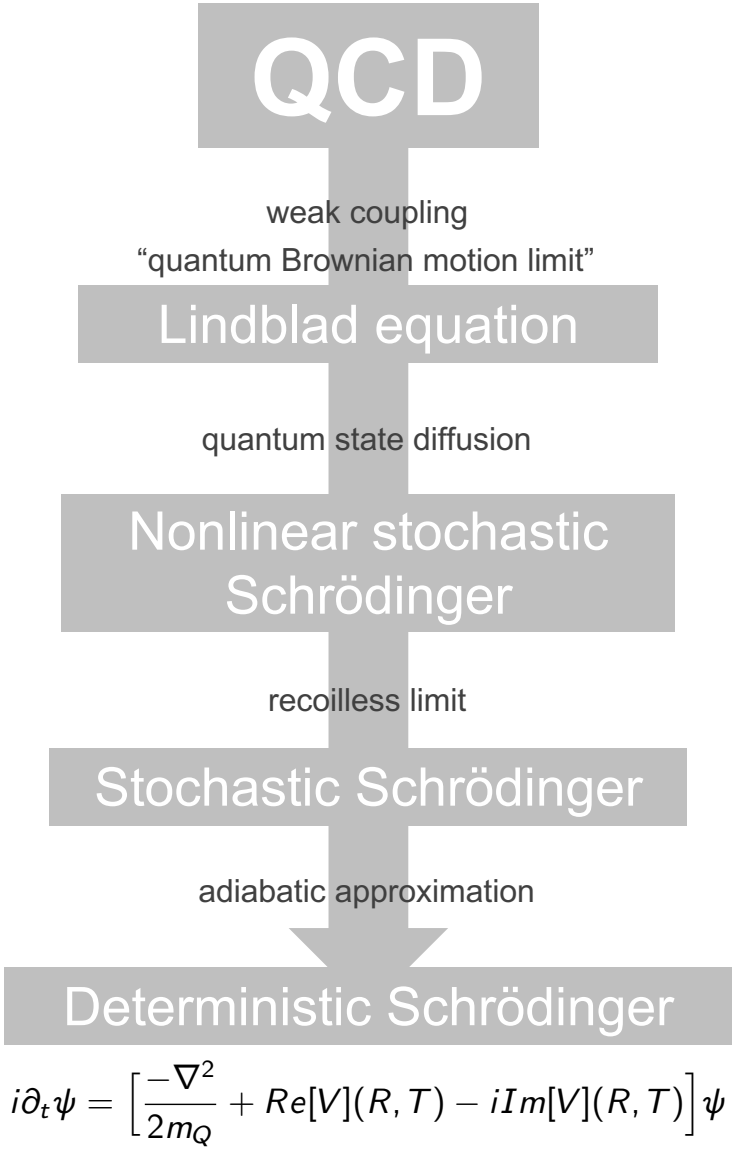
- Main goal: derive a **potential based** e.o.m. for quarkonium wavefunctions from QCD

$$i\partial_t \psi(t) = F[\psi, Re[V], Im[V], \ldots]$$

  - **conceptual**: connect imaginary part of the EFT potential to microscopic quarkonium dynamics
  - **technical**: range of validity of phenomenological models
  - **practical**: provide path for incremental improvement of current approaches

- Based on **open-quantum-systems** picture (avoid semiclassical approximation)



$$i\partial_t \psi = \left[\frac{-\nabla^2}{2m_Q} + Re[V](R,T) - iIm[V](R,T)\right]\psi$$

Why quantum dynamics?

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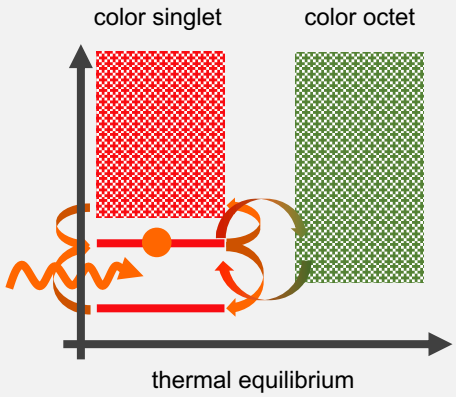
Stochastic SE in the **recoilless limit** including SU(3) color d.o.f.:

$$H(\mathbf{r},t) = -\frac{1}{2\mu}\nabla_{\mathbf{r}}^2 + V(\mathbf{r})(t^a \otimes t^{a*}) + \Theta(\mathbf{r},t)$$

$$\Theta(\mathbf{r},t) = \theta^a(\mathbf{R}+\mathbf{r}/2,t)(t^a \otimes 1) - \theta^a(\mathbf{R}-\mathbf{r}/2,t)(1 \otimes t^{a*})$$

$$\langle \theta^a(\mathbf{x},t)\theta^b(\mathbf{x}',t')\rangle = D(\mathbf{x}-\mathbf{x}')\delta(t-t')\delta^{ab}$$

Based on single gluon exchange: noise governed by D function always corresponds to a singlet <-> octet transition.

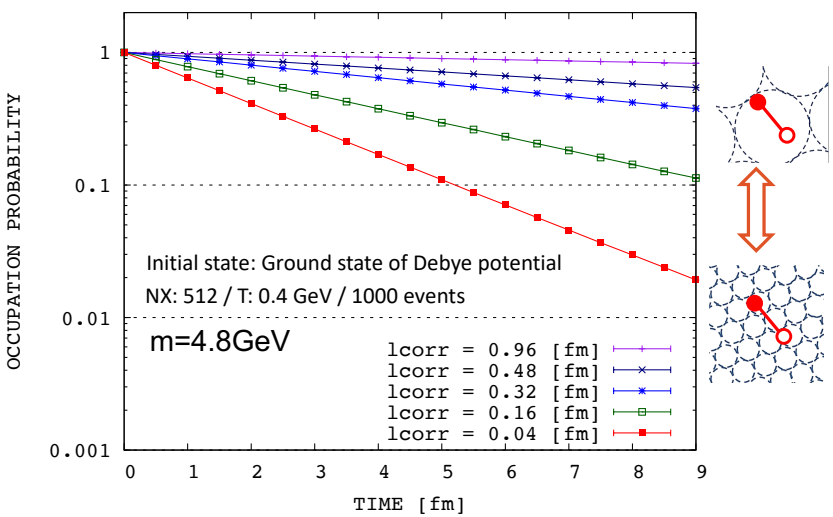


$$V(x) = -\frac{\alpha_S}{\sqrt{x^2+x_c^2}}e^{-m_D|x|}$$

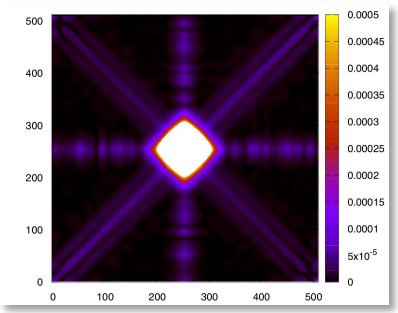
$$D(x) = \gamma \exp\left[-x^2/\ell_{\text{corr}}^2\right]$$

$$\alpha = \frac{g^2}{4\pi}, \quad m_D = gT\sqrt{\frac{N_c}{3}+\frac{N_f}{6}} \simeq \frac{2}{\ell_{\text{corr}}}$$

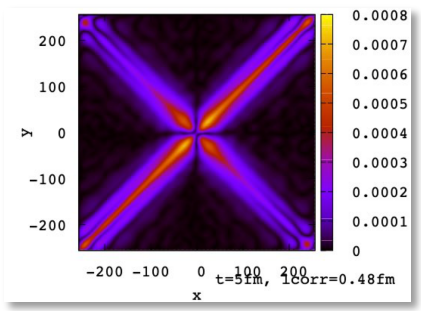
$$\gamma = D(0) = \frac{g^2 T}{4\pi}$$



color singlet density matrix



color octet density matrix



$$W(R,p) = \int dr\rho(x,y)e^{-ipr}$$

Wigner distribution around origin shows **non-positive contributions**

Genuine **quantum nature** of quarkonium **remains relevant**

Towards Lindblad based dynamics

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- Lindblad Equation for the quantum Brownian motion regime at high temperature

$$\frac{d}{dt}\rho_{Q\bar{Q}}(t) = -i\left[H_{Q\bar{Q}}, \rho_{Q\bar{Q}}\right] + \sum_{i=1}^{N_{LB}} \gamma_i \left(\hat{L}_i \rho_{Q\bar{Q}} \hat{L}_i^\dagger - \frac{1}{2}\hat{L}_i \hat{L}_i^\dagger \rho_{Q\bar{Q}} - \frac{1}{2}\rho_{Q\bar{Q}} \hat{L}_i \hat{L}_i^\dagger\right)$$

$H_{Q\bar{Q}}\left[Re[V]\right]$

$L\left[Im[V]\right]$

- Derivation in weak-coupling: phenomenology possible with a lattice vetted potential

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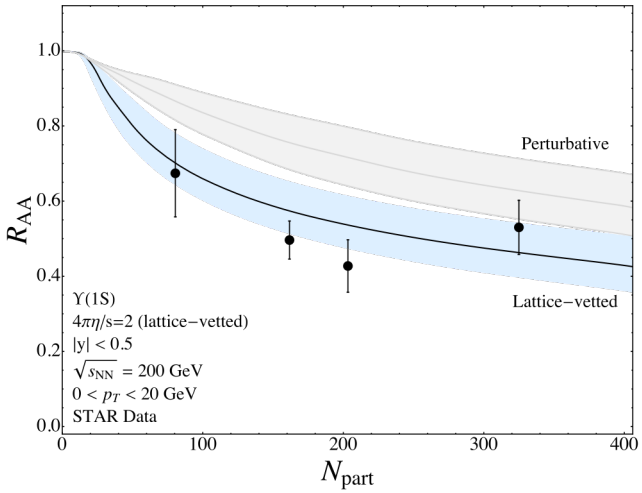
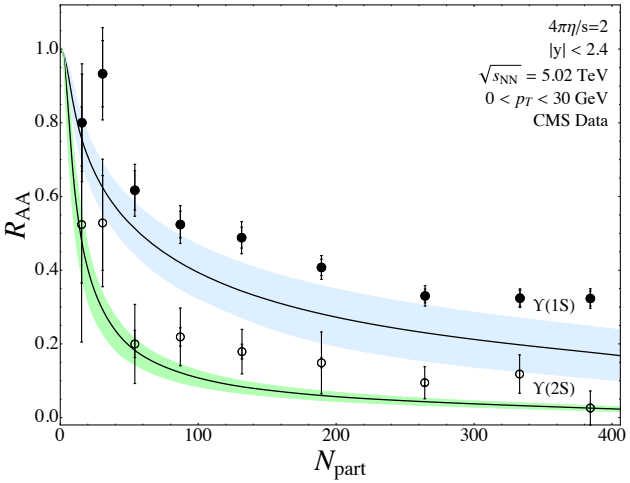
Krouppa et. al., PRDD97 (2018) 016017
[STAR Collaboration] Z. Ye
Nucl.Part.Proc. 289-290 (2017) 401





- At RHIC: bottom not equilibrated & good agreement. At LHC: underestimates yields

The stochastic potential

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- Include the effects of fluctuations by taking the **first order gradient expansion**

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$$U = \exp\Big[-i\int dt\Big(\underbrace{-\frac{\nabla^2}{m_Q} + V(r)}_{S_{\text{pot}}} + \underbrace{\eta(t,\frac{\mathbf{r}}{2}) - \eta(t,-\frac{\mathbf{r}}{2})}_{\Theta(r,t)}\Big)\Big]$$

$$\langle \eta(t,\mathbf{x})\eta(t',\mathbf{y})\rangle = \delta(t-t')D(\mathbf{x}-\mathbf{y})$$

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$$i\partial_t \psi_{Q\bar{Q}}(t) = \Big(-\frac{\nabla^2}{2m_Q} + V(r) + \Theta - \frac{i}{2}\Theta^2\Big)\psi_{Q\bar{Q}}(t)$$

- Fully unitary microscopic dynamics, no thermalization

The stochastic potential

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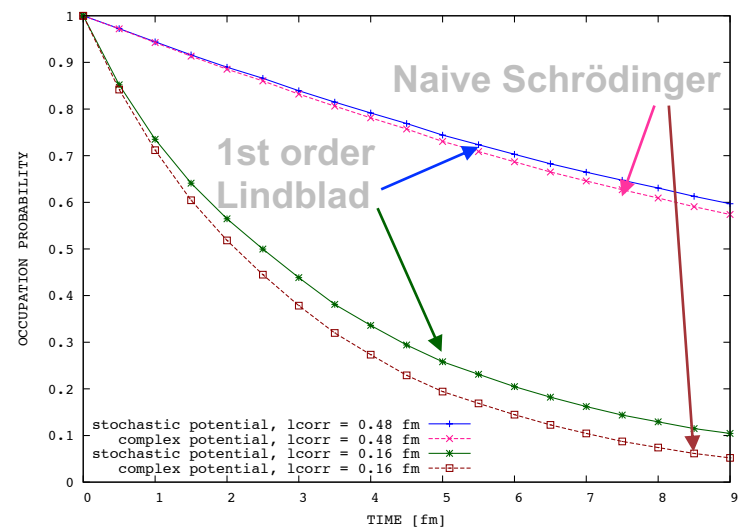

S.Kajimoto, Y.Akamatsu, M. Asakawa, A.R., PRD97 (2018) 014003

The stochastic potential

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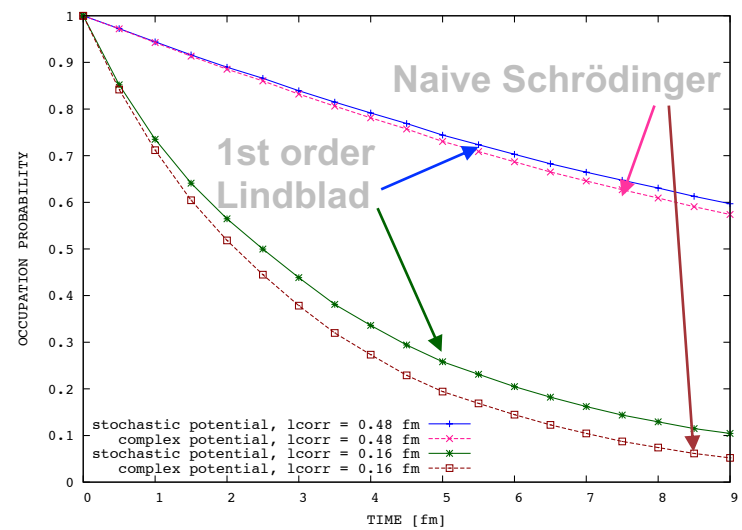

S.Kajimoto, Y.Akamatsu, M. Asakawa, A.R., PRD97 (2018) 014003

- Fully unitary microscopic dynamics, no thermalization

$$i\partial_t \langle\psi_{Q\bar{Q}}(t)\rangle = \Big(-\frac{\nabla^2}{M} + Re[V] - i|Im[V]|\Big)\langle\psi_{Q\bar{Q}}(t)\rangle$$

Towards full Lindblad dynamics (I)

University of Stavanger

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- Unravel dynamics in wavefunction stochastic dynamics: **Quantum State Diffusion**

T. Miura, Y.Akamatsu, M. Asakawa, A.R., arXiv:1908.06293

$$|d\psi\rangle = |\psi(t+dt)\rangle - |\psi(t)\rangle$$
$$= -iH|\psi(t)\rangle dt + \sum_n \begin{pmatrix} 2\langle L_n^\dagger\rangle_\psi L_n - L_n^\dagger L_n \\ -\langle L_n^\dagger\rangle_\psi \langle L_n\rangle_\psi \end{pmatrix} |\psi(t)\rangle dt$$
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$$L_{\mathbf{k},a} = \sqrt{\frac{D(\mathbf{k})}{2}}\left[1 - \frac{\mathbf{k}}{4m_Q T}\cdot\left(\frac{1}{2}\mathbf{P}_{\mathrm{CM}} + \mathbf{p}\right)\right] e^{i\mathbf{k}\cdot\mathbf{r}/2}\left(T^a \otimes 1\right)$$
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weak coupling parameters, V(r) Debye form

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weak coupling parameters, V(r) Debye form

- First derivation of a stochastic nonlinear SE – how to connect to Schrødinger-Langevin?

c.f. e.g. R. Katz, P. Gossiaux Annals Phys. 368 (2016) 267

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c.f. e.g. R. Katz, P. Gossiaux Annals Phys. 368 (2016) 267

- First genuine Lindblad implementation: previous works could not maintain positivity of ρ

D. De Boni, JHEP 1708 (2017) 064

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University of Stavanger

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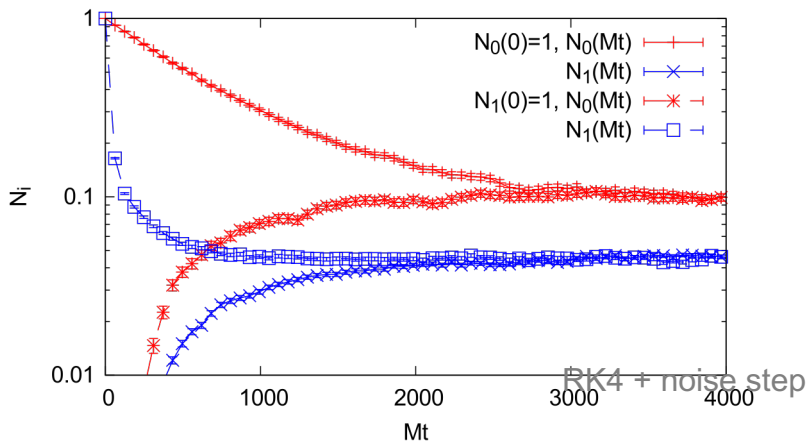

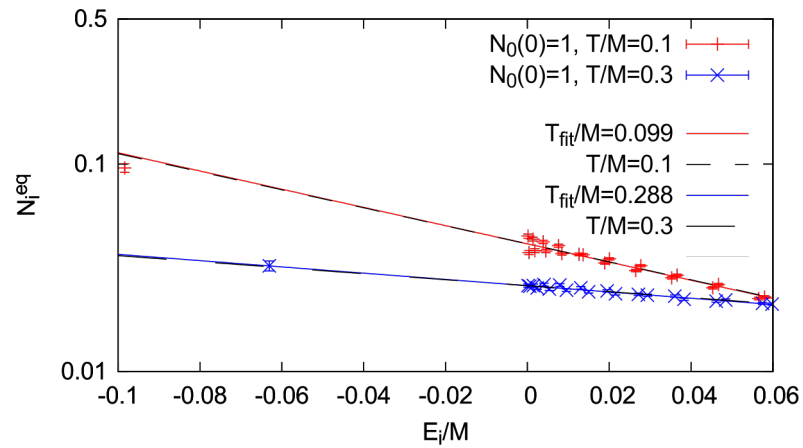

- Encouraging: admixtures become independent of initial conditions at late times
- Distribution of states at late times agrees well with Boltzmann and yields consistent T

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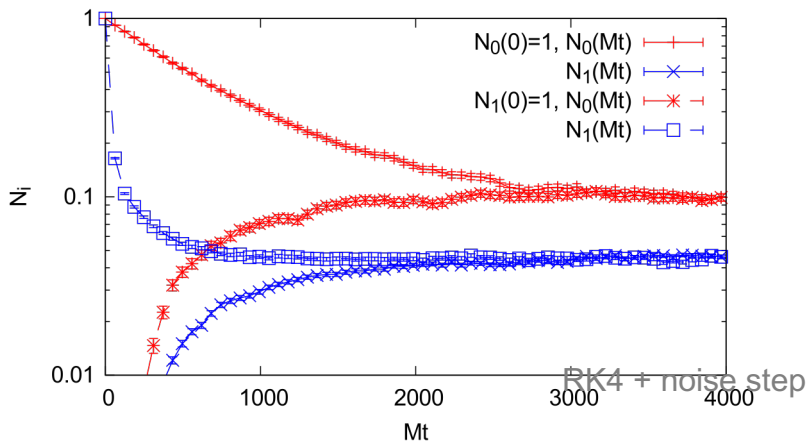
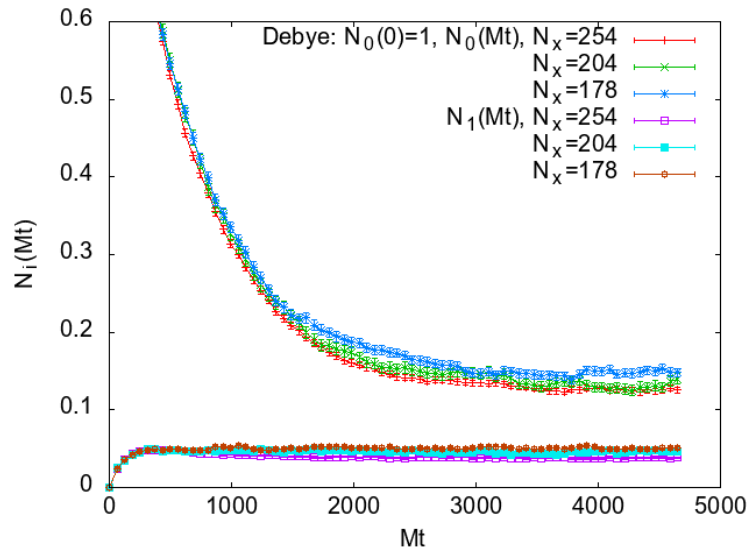
- Lindblad Equation for the quantum Brownian motion regime at high temperature

$$\frac{d}{dt}\rho_{Q\bar{Q}}(t) = -i\left[H_{Q\bar{Q}}, \rho_{Q\bar{Q}}\right] + \sum_{i=1}^{N_{LB}} \gamma_i \left(\hat{L}_i \rho_{Q\bar{Q}} \hat{L}_i^\dagger - \frac{1}{2}\hat{L}_i \hat{L}_i^\dagger \rho_{Q\bar{Q}} - \frac{1}{2}\rho_{Q\bar{Q}} \hat{L}_i \hat{L}_i^\dagger\right)$$

- Unravel dynamics in wavefunction stochastic dynamics: **Quantum State Diffusion**

T. Miura, Y.Akamatsu, M. Asakawa, A.R., arXiv:1908.06293





- Encouraging: admixtures become independent of initial conditions at late times
- Distribution of states at late times agrees well with Boltzmann and yields consistent T

Conclusion

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- Indications that quantum coherence remains relevant over time
- Adiabatic approximation may overestimate suppression
- Inclusion of fluctuation and dispersion lead to increasing survival
- Currently only proof-of-principle dissipative QSD computation
- Ongoing work: beyond the adiabatic approximation in full dynamic model