Variational Multiconfigurational Gaussian Wavepacket Dynamics: Interpolating between Accurate Quantum Dynamics and the Quantum-Classical Limit

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Topics

1. Gaussian-based MCTDH (G-MCTDH)
   - Preamble: MCTDH
   - Quantum-Semiclassical MCTDH: G-MCTDH, vMCG
   - GWP/Langevin Dynamics & Density Matrices

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2. Two-Layer/Multi-Layer G-MCTDH
   - Two-Layer Extension – Concept
   - Equations of Motion
   - Applications: Energy Transport in a Molecular Chain, Spin-Boson System

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2. Two-Layer/Multi-Layer G-MCTDH
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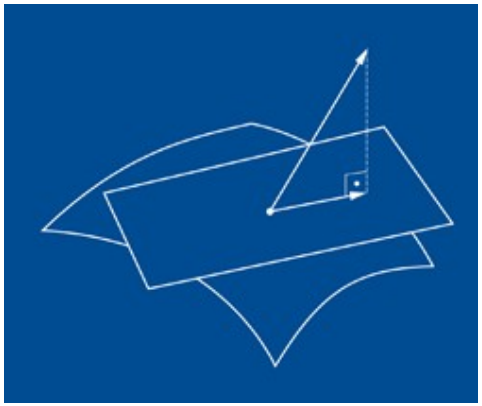
   - Equations of Motion
   - Applications: Energy Transport in a Molecular Chain, Spin-Boson System
3. Quantum-Classical Limit of G-MCTDH
   - Semiclassically Scaled G-MCTDH
   - Quantum-Classical Dynamics
   - Variational Multiconfigurational Ehrenfest Dynamics

Approximate Wavefunctions from the Dirac-Frenkel Variational Principle



C. Lubich, From Quantum to Classical Molecular Dynamics: Reduced Models and Numerical Analysis, Zürich (2008)

Dirac-Frenkel variational principle (DFVP):

$$\langle \delta\Psi | \hat{H} - i\frac{\partial}{\partial t} | \Psi \rangle = 0 \quad \longrightarrow \quad \text{dynamical equation for } \dot{\Psi}$$

where $\delta\Psi \in \mathscr{T}_\Psi \mathscr{M}$ (tangent space wrt the approximate manifold $\mathscr{M}$ on which the wavefunction is defined)

Dirac 1930, Frenkel 1934, McLachlan 1964

- the time derivative is then given by
  $\dot{\Psi} = \mathscr{P}(\Psi)\frac{1}{i}\hat{H}\Psi$
  where $\mathscr{P}(\Psi)$ projects onto the tangent space
- the residual is minimized: $||\dot{\Psi} - \frac{1}{i}\hat{H}\Psi|| = \min$
- interpretation as action principle:
  $\delta S(\Psi) = \delta \int_{t_0}^{t_1} \langle \Psi(t) | i\frac{\partial}{\partial t} - \hat{H} | \Psi(t) \rangle dt = 0$
- symplectic flow: norm and energy conservation

Unitary Dynamics in Many Dimensions: MCTDH

$$\Psi(r,t) = \sum_J A_J(t)\ \Phi_J(r,t) \equiv \sum_{j_1=1}^{n_1} \dots \sum_{j_f=1}^{n_f} A_{j_1 \dots j_f}(t) \prod_\kappa \varphi_{j_\kappa}^{(\kappa)}(r_\kappa,t)$$

- Multi-Configuration Time-Dependent Hartree
  Meyer, Manthe, Cederbaum, Chem. Phys. Lett. **165**, 73 (1990), Beck et al., Phys. Rep. **324**, 1 (2000)
- EoM's from the Dirac-Frenkel variational principle: $\langle \delta\Psi | \hat{H} - i\frac{\partial}{\partial t} | \Psi \rangle = 0$
- MCTDH takes one to 50-100 modes; exponential scaling alleviated
- restriction on the form of the potential: sums over products

- related multi-layer variant (ML-MCTDH) goes up to 1000 modes
  Wang, Thoss, J. Chem. Phys. 119, 1289 (2003), Manthe, J. Chem. Phys. 128, 164116 (2008), Vendrell, Meyer, *ibid* 134, 044135 (2011)
- related MCTDH-F (fermion) and MCTDH-B (boson) methods
  Kato, Kono, Chem. Phys. Lett. 392, 533 (2004), Nest, Klamroth, Saalfrank, J. Chem. Phys. 122, 124102 (2005)
  Alon, Streltsov, Cederbaum, Phys. Lett. A 362, 453 (2007)
- density matrix variant
  Raab, Burghardt, Meyer, J. Chem. Phys. 111, 8759 (1999)
- hybrid approaches: e.g., Gaussian-based variant (G-MCTDH, vMCG)
  Burghardt, Meyer, Cederbaum, J. Chem. Phys. 111, 2927 (1999), Worth, Burghardt, Chem. Phys. Lett. 368, 502 (2003)

Unitary Dynamics in Many Dimensions: MCTDH

MCTDH: optimal, compact time-dependent SPF basis

Meyer, Manthe, Cederbaum, Chem. Phys. Lett. **165**, 73 (1990), Beck et al., Phys. Rep. **324**, 1 (2000)

$$\begin{aligned}\Psi(r,t) &= \sum_J A_J(t)\ \Phi_J(r,t) \\ &= \sum_{j_1=1}^{n_1} \dots \sum_{j_f=1}^{n_f} A_{j_1 \dots j_N}(t)\, \varphi_{j_1}^{(1)}(r_1,t) \dots \varphi_{j_f}^{(f)}(r_f,t)\end{aligned}$$

A_J: coefficient vector

Φ_J: configurations

$\varphi_{j_\kappa}^{(\kappa)}$: single-particle functions (SPFs) – to be represented in a primitive basis $\{\chi_{i_\kappa}\}$

Another convenient notation:

$$\Psi(r,t) = \sum_{j_\kappa=1}^{n_\kappa} \varphi_{j_\kappa}^{(\kappa)}(r_\kappa,t)\, \psi_{j_\kappa}^{(\kappa)}(r_1,\dots,r_{\kappa-1},r_{\kappa+1},\dots,r_N,t)$$

$\psi_{j_\kappa}^{(\kappa)}$: single-hole functions (SHFs) $\longrightarrow$ $\rho_{ij}^{(\kappa)} = \langle \psi_j^{(\kappa)} | \psi_i^{(\kappa)} \rangle$ reduced density

MCTDH as Low-Rank Tensor Approximation Scheme

MCTDH: Tucker format representation of coefficient tensor

Consider $\Psi(r,t)$ in terms of the primitive basis (typically DVR[1] grid):

$$\Psi(r,t) \quad = \quad \sum_{i_1=1}^{N_1} \dots \sum_{i_f=1}^{N_f} Y_{i_1 \dots i_f}(t) \prod_{\kappa=1}^{f} \chi_{i_\kappa}^{(\kappa)}(r_\kappa)$$

Tucker format of the coefficient tensor $Y_{i_1 \dots i_f}(t)$:

$$Y_{i_1 \dots i_f}(t) = \sum_{j_1=1}^{n_1} \dots \sum_{j_f=1}^{n_f} A_{j_1 \dots j_f}(t) \prod_{\kappa=1}^{f} U_{i_\kappa j_\kappa}^{(\kappa)}(t)$$

noting that $n_\kappa \ll N_\kappa$

A_J: core tensor

$U_{i_\kappa j_\kappa}^{(\kappa)} = \langle \chi_{i_\kappa}^{(\kappa)} | \varphi_{j_\kappa}^{(\kappa)} \rangle$ representation of SPFs in the primitive basis

$\varphi_{j_\kappa}^{(\kappa)}$: single-particle functions (SPFs)

$\chi_{i_\kappa}^{(\kappa)}$: primitive basis functions

[1] DVR = Discrete Variable Representation

Bachmayr, Schneider, Uschmajew, Found. Comp. Math. 16, 1423 (2016)

MCTDH – Equations of Motion

Coupled system of coefficient equations and low-dimensional non-linear equations for single-particle functions (SPFs) $\varphi^{(\kappa)}$:

coefficients:
$$i\frac{dA_J}{dt} = \sum_L \langle \Phi_J | H | \Phi_L \rangle A_L$$

SPFs:
$$i\frac{\partial \varphi^{(\kappa)}}{\partial t} = \left(\hat{1} - \hat{P}^{(\kappa)}\right)\left[\rho^{(\kappa)}\right]^{-1} \hat{H}^{(\kappa)} \varphi^{(\kappa)}$$

Meyer, Manthe, Cederbaum, CPL **165**, 73 (1990), Beck et al., Phys. Rep. **324**, 1 (2000)

- $\hat{P}^{(\kappa)} = \sum_j |\varphi_j^{(\kappa)}\rangle\langle\varphi_j^{(\kappa)}|$ is the time-dependent projector on the κth subspace
- $\hat{H}_{ij}^{(\kappa)} = \langle \psi_i^{(\kappa)} | \hat{H} | \psi_j^{(\kappa)} \rangle$ are mean-field Hamiltonian matrix elements
- $\rho_{ij}^{(\kappa)} = \langle \psi_i^{(\kappa)} | \psi_j^{(\kappa)} \rangle$ are reduced density matrix elements in the κth subspace
- recent approaches to "repair" singularity problem ($[\rho^{(\kappa)}]^{-1}$)

Manthe, J. Chem. Phys. **142**, 244109 (2015), Wang, Meier, J. Chem. Phys. **148**, 124105 (2018),
Lubich, Appl. Math. Res. Express 2, 311-328 (2015), Kloss, Burghardt, Lubich. J. Chem. Phys., 146, 174107 (2017)

Derivation of MCTDH Equations of Motion: Two Procedures

- standard procedure: construct explicit form of wavefunction variation:

$$\delta\Psi = \sum_J \delta A_J \, \Phi_J + \sum_\kappa \left(\sum_{l_\kappa} \delta\varphi_{l_\kappa}^{(\kappa)} \Psi_{l_\kappa}^{(\kappa)} \right)$$

and insert independent variations δA_J and $\delta\varphi_{l_\kappa}^{(\kappa)}$ into the DFVP:

$$\langle \delta\Psi | \hat{H} - i\frac{\partial}{\partial t} | \Psi \rangle = 0$$

- alternative procedure: obtain tangent-space projector

$$\mathscr{P}(\Psi) = \mathscr{P}_0(\Psi) + \sum_\kappa \mathscr{P}_\kappa(\Psi)$$

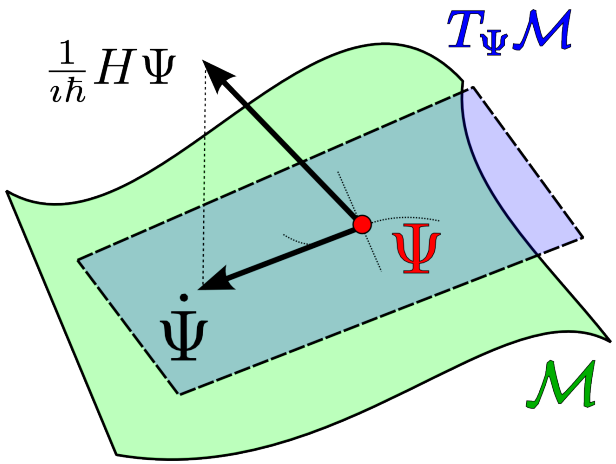
and insert component projectors into the projected TDSE:

$$i\frac{\partial}{\partial t} | \Psi \rangle = \mathscr{P}(\Psi) \hat{H} | \Psi \rangle$$

C. Lubich, From Quantum to Classical Molecular Dynamics: Reduced Models and Numerical Analysis, Zürich (2008)

Tangent Space Projector for MCTDH

$$\mathscr{P}(\Psi) = \mathscr{P}_0(\Psi) + \sum_\kappa \mathscr{P}_\kappa(\Psi)$$



$$\mathscr{P}_0(\Psi) = \sum_J |\Phi_J\rangle\langle\Phi_J| \quad \text{and} \quad \mathscr{P}_\kappa(\Psi) = \left(1 - P^{(\kappa)}\right) \otimes \bar{P}^{(\kappa)}$$

$P^{(\kappa)} = \sum_i |\varphi_i^{(\kappa)}\rangle\langle\varphi_i^{(\kappa)}|$: SPF subspace projector

$\bar{P}^{(\kappa)} = \sum_{l,l'} |\Psi_l^{(\kappa)}\rangle (\rho^{(\kappa)})^{-1}_{l'l} \langle\Psi_{l'}^{(\kappa)}|$: SHF projector (noting non-orthogonality!)

Koch, Lubich, SIAM J. Matrix Anal. Appl. 31, 2360 (2010), Kloss, Burghardt, Lubich. J. Chem. Phys., 146, 174107 (2017)
Bonfanti, Burghardt, Chem. Phys., in press (2018), arXiv:1802.01058 [physics.chem-ph]

Advantage of using this route: new concepts of how to split $\mathscr{P}$

New Projector Splitting Scheme for MCTDH

concept: split subspace projectors $\mathscr{P}_\kappa = \mathscr{P}^+_\kappa(\Psi) - \mathscr{P}^-_\kappa(\Psi)$ such that:

$$\mathscr{P}(\Psi) = \mathscr{P}_0(\Psi) + \sum_\kappa \left(\mathscr{P}^+_\kappa(\Psi) - \mathscr{P}^-_\kappa(\Psi) \right)$$

where

$$\mathscr{P}_0(\Psi) = \sum_J |\Phi_J\rangle\langle\Phi_J| \quad \text{and} \quad \mathscr{P}^+_\kappa(\Psi) = \bar{P}^{(\kappa)} \quad \mathscr{P}^-_\kappa(\Psi) = P^{(\kappa)} \otimes \bar{P}^{(\kappa)}$$

$P^{(\kappa)} = \sum_i |\varphi^{(\kappa)}_i\rangle\langle\varphi^{(\kappa)}_i|$: SPF subspace projector

$$\bar{P}^{(\kappa)} = \sum_{l,l'} |\Psi^{(\kappa)}_{l'}\rangle \, (\rho^{(\kappa)})^{-1}_{l'l} \, \langle\Psi^{(\kappa)}_l| = \sum_l |\tilde{\Psi}^{(\kappa)}_l\rangle\langle\tilde{\Psi}^{(\kappa)}_l|$$

- use a complementary representation where the SHFs are orthogonal
- two sets of coupled EoMs for SPFs where $[\rho^{(\kappa)}]^{-1}$ does not appear!

Lubich, Appl. Math. Res. eXpress 2015, 311 (2015), Kloss, Burghardt, Lubich, J. Chem. Phys., 146, 174107 (2017)
Bonfanti, Burghardt, Chem. Phys., in press (2018), arXiv:1802.01058 [physics.chem-ph]

Implementation of Projector Splitting Integrator for MCTDH

Lubich, Appl. Math. Res. eXpress 2015, 311 (2015), Kloss, Burghardt, Lubich, J. Chem. Phys. 146, 174107 (2017).

MCTDH equations in tensor notation:

$$i\dot{C} = \sum_q a_q C \times_{n=1}^{d} \mathbf{H}^q_{spf,n} \tag{1}$$

$$\dot{\mathbf{U}}_n = \sum_q a_q \left(\mathbf{I} - \mathbf{P}_n\right) \mathbf{H}^q_{prim,n} \mathbf{U}_n \mathscr{H}^q_n \rho_n^{-1} \tag{2}$$

To obtain Lubich's projector-splitting scheme, replace (2) with the following, where $\mathbf{K}_n = \mathbf{U}_n \mathbf{S}_n$ can be understood as modified SPFs that are *not* orthonormal – while the single-hole functions (SHFs) have been orthogonalized,

$$i\dot{\mathbf{K}}_n = \sum_q a_q \mathbf{H}^q_{prim,n} \mathbf{U}_n \mathbf{S}_n \mathscr{H}^q_n$$

$$i\dot{\mathbf{S}}_n = \sum_q a_q \mathbf{H}^q_{SPF,n} \mathbf{S}_n \tilde{\mathscr{H}}^q_n$$

- The inverse of the density matrix no longer appears!

Gaussian-based MCTDH (G-MCTDH)

Burghardt, Meyer, Cederbaum, J. Chem. Phys. 111, 2927 (1999)

$$\Psi(r,t) = \sum_J A_J(t)\Phi_J(r,t) \quad ; \quad \Phi_J(r,t) = \underbrace{\prod_{\kappa=1}^{M} \varphi_{j_\kappa}^{(\kappa)}(r_\kappa,t)}_{\text{SPFs}} \underbrace{\prod_{\kappa=M+1}^{P} g_{j_\kappa}^{(\kappa)}(r_\kappa,t)}_{\text{GWPs}}$$

Gaussian wavepackets (GWP)

- on-the-fly ("direct") dynamics
- system-bath type dynamics

$\Psi(r,t) = \sum_j A_j(t) g_j(r,t)$ (vMCG)

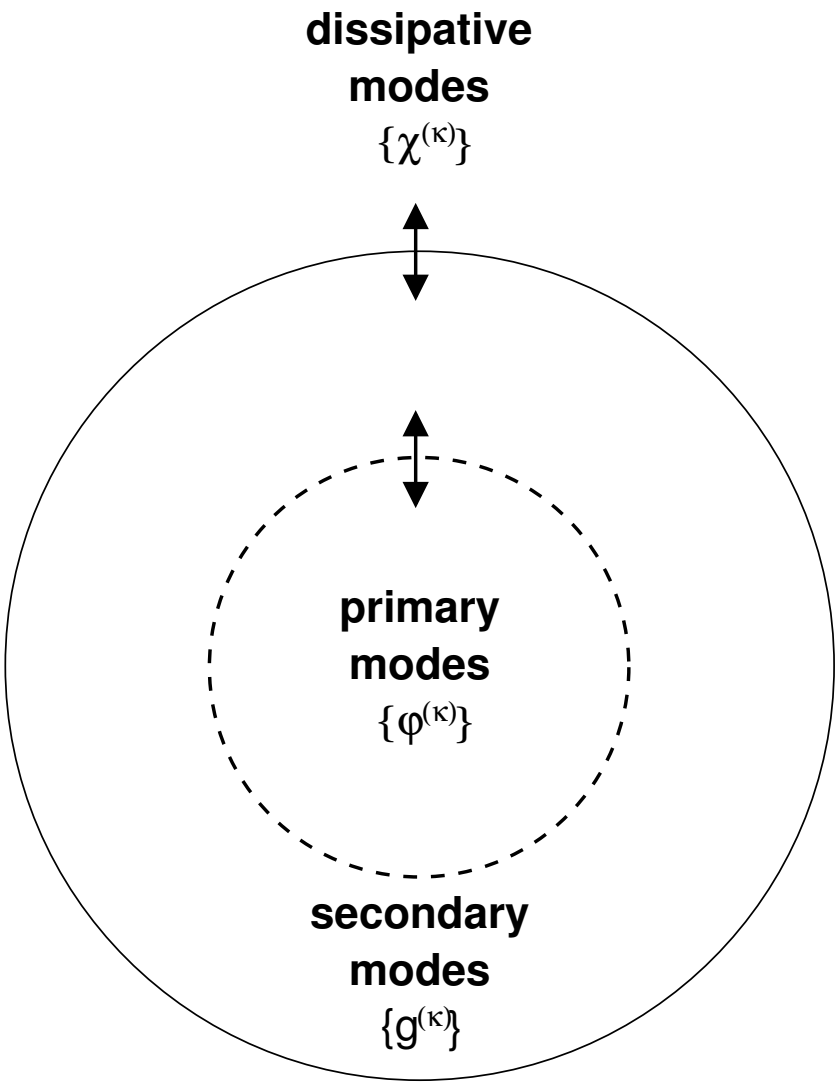
variational Multi-Configurational Gaussians

Burghardt et al., JCP 119, 5364 (2003), 129, 174104 (2008)

Worth, Burghardt, Chem. Phys. Lett. 368, 502 (2003), Richings et al., Int. Rev. Phys. Chem., 34, 265 (2015)

- key precursors: Heller's Frozen and Thawed GWPs (1975, 1981 etc.)
- variational GWPs: Metiu & co (1985), Martinazzo & co (2007): LCSA (Local Coherent State Approximation)
- non-variational GWPs: Martínez & co (1996): FMS (Full Multiple Spawning); Shalashilin & co (2000): CCS (Coupled Coherent States); Batista & co (2003): MP/SOFT (Matching Pursuit)

G-MCTDH = Quantum-Semiclassical MCTDH



$$\Psi(r,t) = \sum_J A_J(t)\ \Phi_J(r,t)$$

$$\text{with } \Phi_J(r,t) = \prod_{\kappa=1}^{M} \varphi_{j_\kappa}^{(\kappa)}(r_\kappa,t)$$

Multi-Configuration Time-Dependent Hartree

Meyer et al., CPL **165**, 73 (1990), Beck et al., Phys. Rep. **324**, 1 (2000)

Gaussian-based hybrid method: G-MCTDH

$$\Phi_J(r,t) = \underbrace{\prod_{\kappa=1}^{M} \varphi_{j_\kappa}^{(\kappa)}(r_\kappa,t)}_{\text{primary nodes}} \quad \underbrace{\prod_{\kappa=M+1}^{P} g_{j_\kappa}^{(\kappa)}(r_\kappa,t)}_{\text{secondary modes}}$$

Burghardt, Meyer, Cederbaum, J. Chem. Phys. **111**, 2927 (1999)
Burghardt, Giri, Worth J. Chem. Phys. **129**, 174104 (2008)

Variational Dynamics

$$\Psi(r_1,\ldots,r_P,t) = \sum_{j_1}\cdots\sum_{j_P} A_{j_1\ldots j_P}(t) \prod_{\kappa=1}^{M} \varphi_{j_\kappa}^{(\kappa)}(r_\kappa,t) \prod_{\kappa=M+1}^{P} g_{j_\kappa}^{(\kappa)}(r_\kappa,t)$$

$$g_j^{(\kappa)}(r_\kappa,t) = \exp\left[r_\kappa \cdot a_j^{(\kappa)}(t) r_\kappa + \xi_j^{(\kappa)}(t)\cdot r_\kappa + \eta_j^{(\kappa)}(t)\right]$$

multidimensional Gaussian functions:

- "thawed" (TG) vs. "frozen" (FG)
- quasi-classical motion for $\xi_j = -2a_j q_j + i p_j$
- analytical integrals

Dirac-Frenkel variational principle:

$$\langle \delta\Psi | H - i\frac{\partial}{\partial t} | \Psi \rangle = 0 \longrightarrow \text{dynamical equations for } \Lambda_j^{(\kappa)} = (a_j^{(\kappa)}, \xi_j^{(\kappa)}, \eta_j^{(\kappa)})$$

- up to 50-100 modes – exponential scaling problem ($\sim f N^{f+1}$) is alleviated

Dynamical Equations

Burghardt, Meyer, Cederbaum, JCP 111, 2927 (1999)

coefficients: $$iS\dot{A} = \left[H - i\tau\right]A$$

SPFs (primary modes): $$i\dot{\varphi}^{(\kappa)} = \left(\hat{1} - \hat{P}^{(\kappa)}\right)\left[\rho^{(\kappa)}\right]^{-1}\hat{H}^{(\kappa)}\varphi^{(\kappa)}$$

GWPs (secondary modes): $$iC^{(\kappa)}\dot{\Lambda}^{(\kappa)} = Y^{(\kappa)}$$

$$S_{jl}^{(\kappa)} = \langle g_j^{(\kappa)} | g_l^{(\kappa)} \rangle \quad ; \quad \tau_{jl}^{(\kappa)} = \langle g_j^{(\kappa)} | \frac{\partial g_l^{(\kappa)}}{\partial t} \rangle$$

$$C_{j\alpha,l\beta}^{(\kappa)} = \rho_{jl}^{(\kappa)} \langle \frac{\partial g_j^{(\kappa)}}{\partial \lambda_{j\alpha}^{(\kappa)}} \Big| (\hat{1} - \hat{P}^{(\kappa)}) \Big| \frac{\partial g_l^{(\kappa)}}{\partial \lambda_{l\beta}^{(\kappa)}} \rangle \quad ; \quad Y_{j\alpha}^{(\kappa)} = \sum_l \langle \frac{\partial g_j^{(\kappa)}}{\partial \lambda_{j\alpha}^{(\kappa)}} \Big| (\hat{1} - \hat{P}^{(\kappa)}) \hat{H}_{jl}^{(\kappa)} \Big| g_l^{(\kappa)} \rangle$$

- evolution under multiconfigurational mean-field Hamiltonian
- coupled, variational equations for Gaussian parameters
- correlations between primary vs. secondary subspace
- analogous equations for density matrix evolution Burghardt, Meyer, Cederbaum, JCP 111, 2927 (1999)

Symplectic Structure of "VP Mechanics"

- variational formulation via action integral: $\delta \mathscr{S} = \delta \int dt \, \mathscr{L} = 0$

classical mechanics

$$\mathscr{L} = \sum_k p_k \dot{q}_k - H(q_k, p_k)$$

$$\dot{q}_k = \frac{\partial H}{\partial p_k}$$

$$\dot{p}_k = -\frac{\partial H}{\partial q_k}$$

VP mechanics

$$\mathscr{L} = \sum_{\alpha=1} S^{(0\alpha)} \dot{\lambda}_\alpha - \langle \Psi | H | \Psi \rangle$$

identify: $\tilde{p}_\alpha = S^{(0\alpha)} = i \langle \Psi | \frac{\partial \Psi}{\partial \lambda_\alpha} \rangle$

$$\dot{\lambda}_\alpha = \frac{\partial \langle H \rangle}{\partial \tilde{p}_\alpha}$$

$$= \sum_\beta \frac{\partial \langle H \rangle}{\partial \lambda_\beta} \frac{\partial \lambda_\beta}{\partial \tilde{p}_\alpha}$$

$$= \sum_\beta \frac{\partial \langle H \rangle}{\partial \lambda_\beta} \left(C^{-1} \right)_{\alpha\beta}$$

Kramer, Saraceno, Geometry of the time-dependent variational principle, Springer (1981), Shalashilin, Burghardt, JCP 129, 084104 (2008)

Classical Evolution as a Special Case

$$\boxed{q_j, p_j} \quad \longleftrightarrow \quad g_j(r_\kappa) = N_j \exp\left[(r_\kappa - q_j) \cdot a_j (r_\kappa - q_j) + i p_j \cdot (r_\kappa - q_j)\right]$$

where we used $\xi_j = -2a_j q_j + i p_j$

We have classical motion of $(q_j(t), p_j(t))$ if

- single Gaussian (cf. Heller)
- superposition of TGs / single-surface + harmonic potential: "decoupling effect" (Metiu & co, JCP (1985))

or

- if the classical limit is reached ($\lambda_{dB} \ll L$), such that G-MCTDH becomes a true mixed quantum-classical method for $\psi^\varepsilon = \sum_{jl} A_{jl} e^{iS_l/\varepsilon} \varphi_j g_l^\varepsilon$, see below

Römer, Burghardt, Mol. Phys. 111, 3618 (2013)

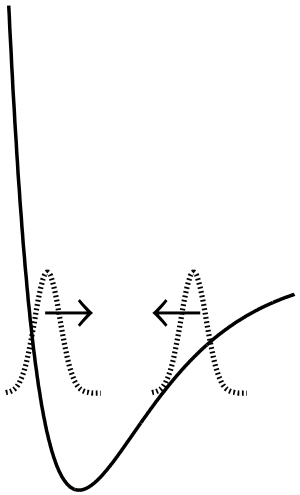
Implementation Details

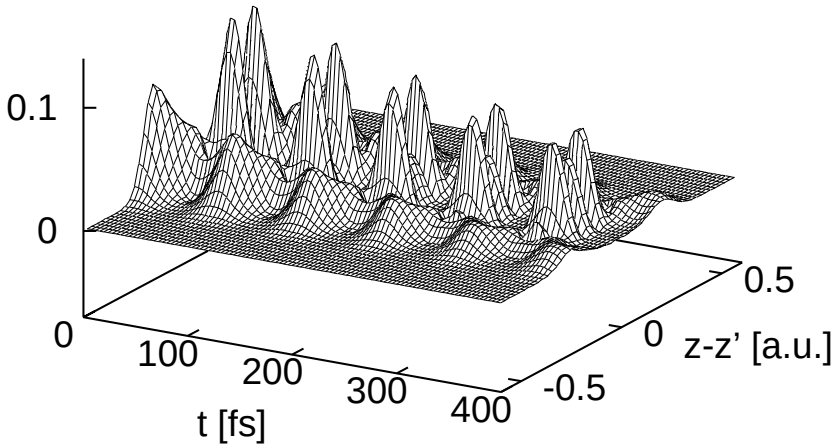
- frozen Gaussians (FGs) almost exclusively used due to numerical robustness
- however, thawed Gaussians (TGs) were successfully employed for system-bath problems
  [Burghardt, Nest, Worth (2003)]
- various conventions possible for complex GWP phase η_j: here, normalized GWPs, imaginary part of phase set to zero
- local harmonic approximation (LHA) or higher-order local expansion
- split off separable part of evolution: $i\dot{\Lambda}^{(\kappa)} = X_0^{(\kappa)} + (C^{(\kappa)})^{-1} Y_{\mathrm{corr}}^{(\kappa)}$
- Constant Mean Field (CMF) integrator used, by switching to an orthogonalized representation to match standard A coeff. propagation
- singularities of the $\boldsymbol{S}$ and $\boldsymbol{C}$ matrices (linear dependencies): standard regularization scheme
- Wigner sampling or single GWP as initial condition
- dynamic GWP allocation (G. Worth)

Example: System-Bath Correlations and Decoherence

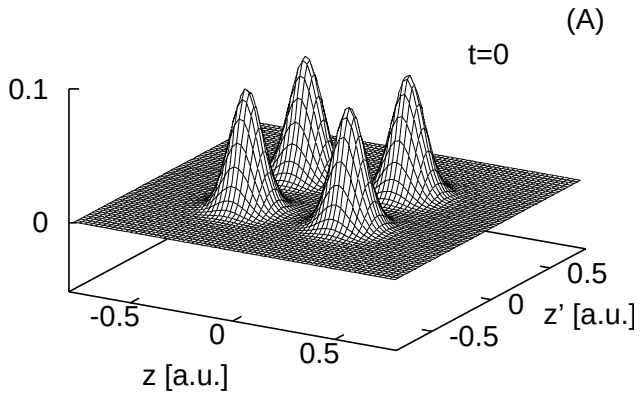
Thawed Gaussians (TGs)

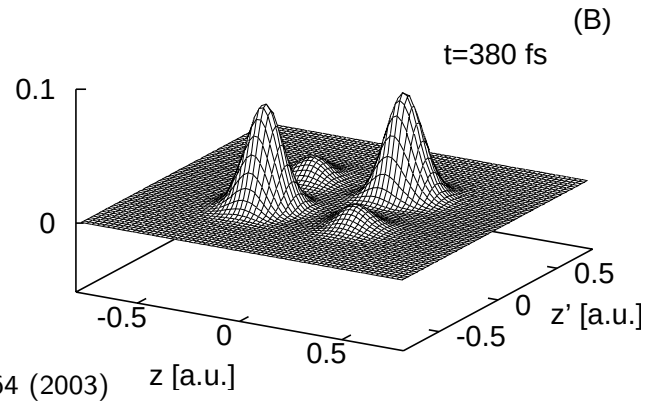
cat state + 60 HO-bath





coherence $\rho(z,z')$



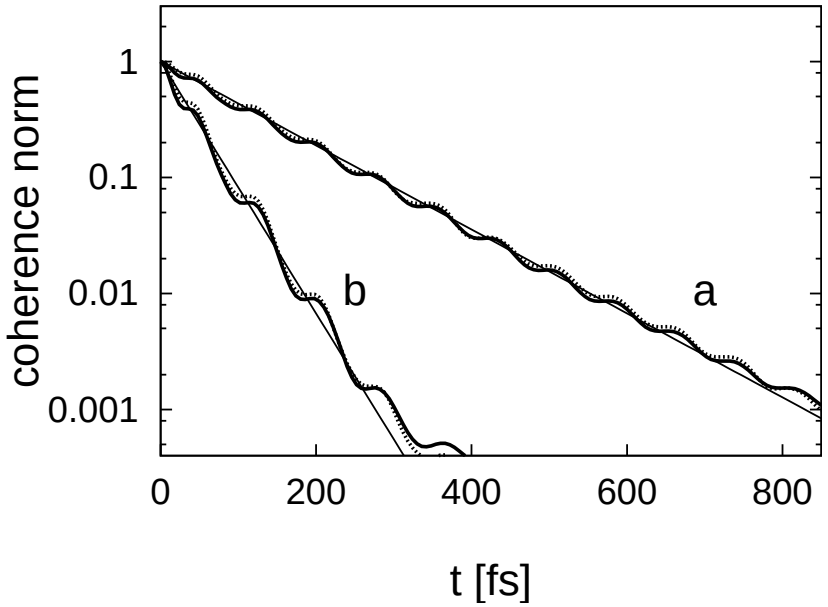


Burghardt, Nest, Worth, JCP 19, 5364 (2003)

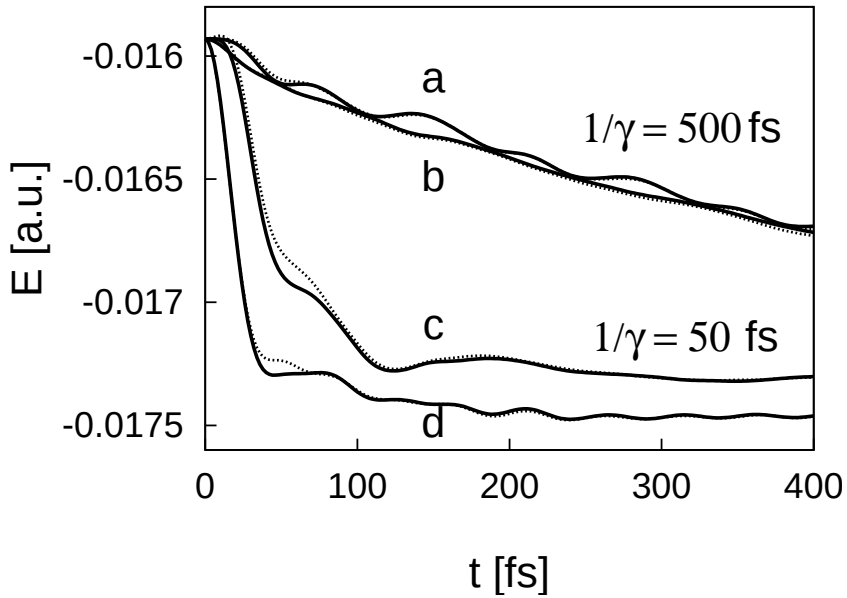
G-MCTDH: Morse Oscillator + 60-Mode Harmonic Bath

Thawed Gaussians (TGs)

decoherence



energy relaxation



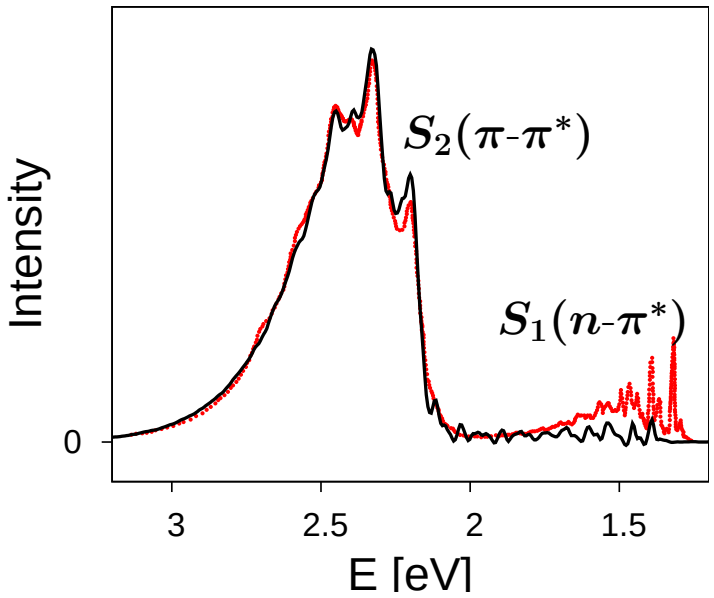
- typical configuration: $([5]_{\text{core}}, [3,3,3,4,4,3,3,3]_{\text{bath}})$

Burghardt, Nest, Worth, JCP 19, 5364 (2003)

G-MCTDH Calculation for S_2/S_1 CoIn in pyrazine

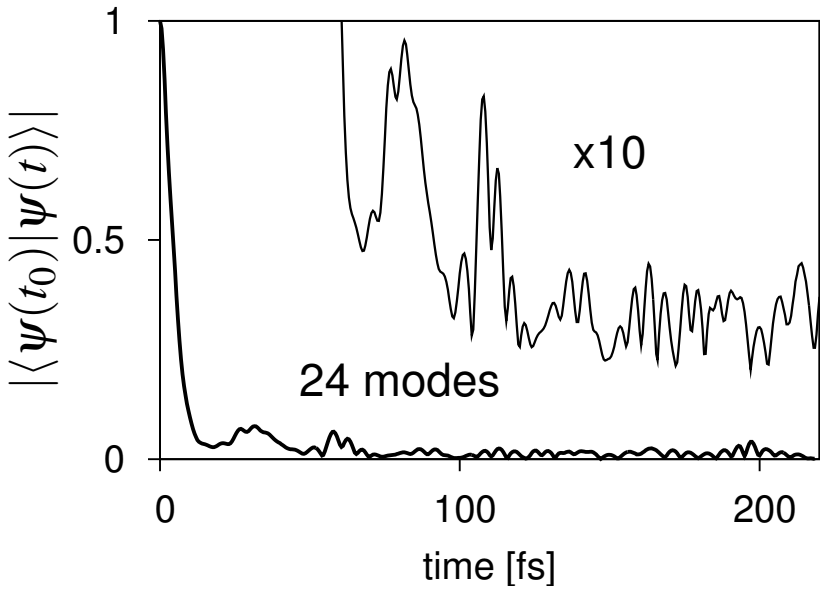
Hybrid calculation for 4+20 modes (FGs)

absorption spectrum



FT

autocorrelation function



dotted red line: experiment

Yamazaki et al., Faraday Discuss. **75**, 395 (1983)

full black line: G-MCTDH

Burghardt, Giri, Worth, JCP **129**, 174104 (2008)

state 1: $([19,10]_{\text{core}}, [18,10,18,10]_{\text{bath}})$

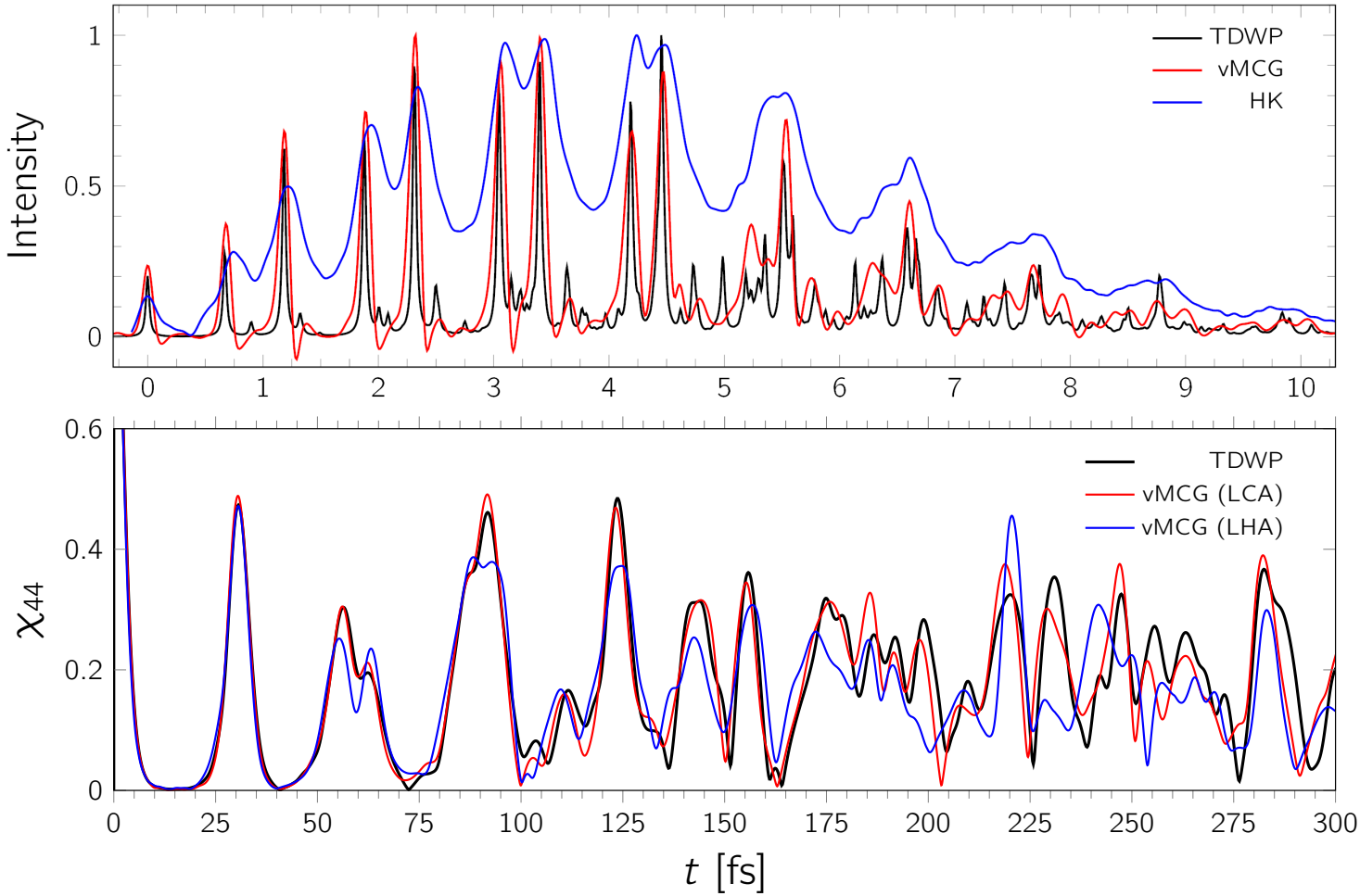
state 2: $([12,7]_{\text{core}}, [10,8,12,10]_{\text{bath}})$

150 fs / 1644 MB / 1250 hrs / 6962400 config's

MCTDH: 150 fs / 2614 MB / 279 hrs / 10966760 cf's

vMCG Calculation for Herzberg-Teller Spectrum of Formaldehyde (6 dof's) (FGs)

- up to 108 GWPs
- Local Cubic Approximation
- dominant modes: out-of-plane-bending, CO stretch
- vMCG outperforms HK-SCIVR (10^5 traj.)



Bonfanti, Petersen, Eisenbrandt, Burghardt, Pollak, JCTC, submitted (2018).

Stochastic Schrödinger Equation in GWP/Mean-Field Setting

Burghardt, Meyer, Cederbaum, J. Chem. Phys. 111, 2927 (1999), see also: Peskin, Steinberg, J. Chem. Phys. 109, 704 (1999)

For example, consider a vMCG wavefunction + Hartree bath:

$$\psi(r_1,\ldots,r_N,\{q_n\},t) = \left[\sum_j A_j(t)\, g_j(r_1,\ldots,r_N,\Lambda(t))\right] \prod_{n=1}^{\infty} \chi^{(n)}(q_n,t)$$

Take a bath acting upon the kth DOF of the GWP particle: $\hat{H}_{SB} = -\sum_n c_{kn}\hat{r}_k\hat{q}_n$, resulting in the mean-field Hamiltonian

$$\langle H\rangle_{jl}(t) \quad = \quad -\rho_{jl}(t)\,\hat{r}_k \sum_n c_{kn}\langle\chi^{(n)}(t)|\hat{q}_n|\chi^{(n)}(t)\rangle = -\rho_{jl}(t)\,\hat{r}_k \sum_n c_{kn} Q_n(t)$$

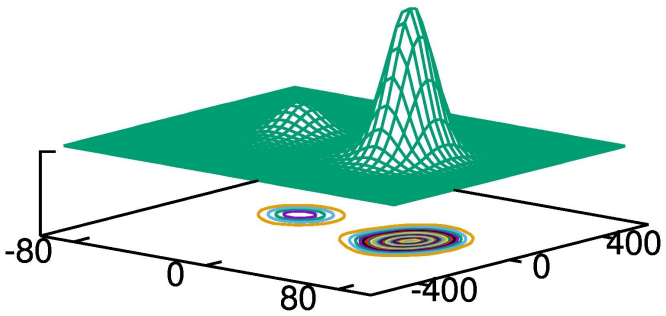
Now use: $\lim_{n\to\infty}(\sum_n c_n Q_n(t)) = f(t) - \int_0^t dt'\,\zeta(t-t')\dot{Q}_k(t') + \zeta(0)Q_k(t)$

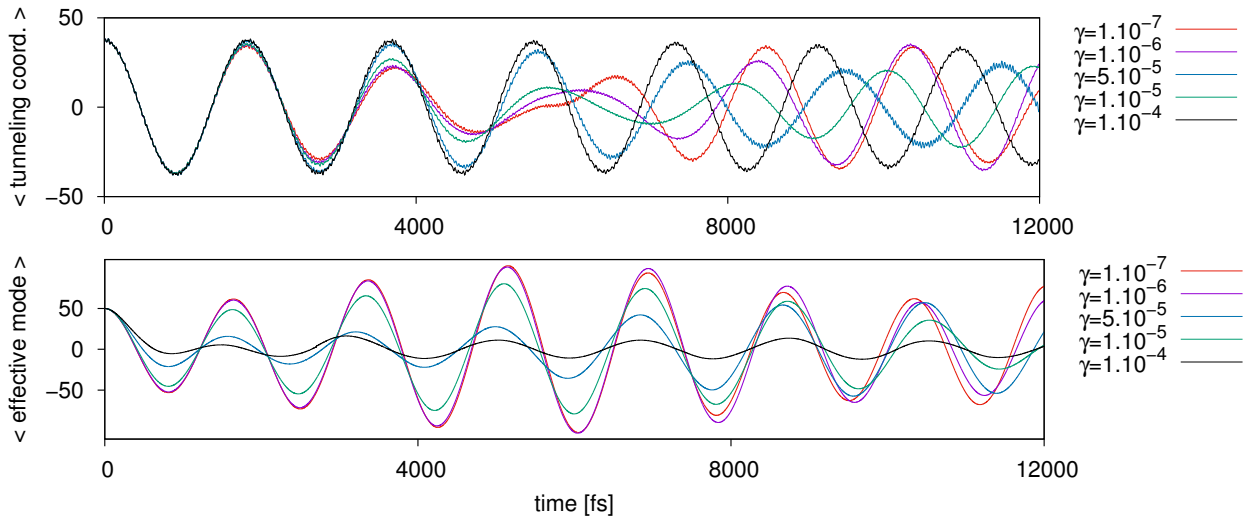
In the simplest case, we obtain a Langevin type equation for the GWPs:

$$\dot{q}_{j,k} \quad = \quad \frac{p_{j,k}}{m}$$

$$\dot{p}_{j,k} \quad = \quad -\left.\frac{\partial V_{\rm sys}}{\partial r_k}\right|_{r_k=q_k} + f(t) - \gamma\dot{Q}_k(t) + \zeta(0)\dot{Q}_k(0)$$

GWP/Langevin Dynamics: 2D Tunneling





- vMCG calculations with 20 two-dimensional GWPs (not entirely converged)
- Langevin dissipation acting on harmonic coordinate
- increasing friction destroys resonant dynamics between the two modes
- general scheme: Langevin closure of effective-mode chains
- cheap and physically intuitive way of implementing dissipation

GWP/Langevin Dynamics: 2D Tunneling

tunnel coordinate $\longleftrightarrow$ $J(\omega) = \sum_n \frac{c_n^2}{\omega_n}\delta(\omega-\omega_n) = \frac{2\gamma\omega D^2}{(\Omega^2-\omega^2)^2+4\gamma^2\omega^2}$

$\downarrow$

tunnel coordinate $\longleftrightarrow$ effective mode $\hat{X}_1$ $\longleftrightarrow$ $J^{\text{residual}}(\omega) = 2\gamma\omega$

- $\hat{H}_{SB}+\hat{H}_B = \hat{s}\sum_i c_n\hat{x}_n + \hat{H}_B \longrightarrow D\hat{s}\ \hat{X}_1$ – residual bath
- "Brownian oscillator" picture: 1 effective mode + Ohmic bath
- here, effective mode is chosen resonant with the tunneling frequency
- treat residual Ohmic bath by Langevin dynamics
- 2D system with damping of effective Brownian oscillator mode
- replaces discretized residual bath (or full discretization of SD)

MCTDH & G-MCTDH for Density Operators

- EOMs from variational principle for densities: $\langle\langle \delta\rho | \boldsymbol{L} - i\partial_t | \rho \rangle\rangle = 0$
- multiconfigurational density operators of two types:
  - density operators of *type I*:

$$\rho(x_1,\ldots,x_N;x_1',\ldots,x_N') = \sum_{\tau_1}\ldots\sum_{\tau_N} B_{\tau_1\ldots\tau_N}(t) \prod_{\kappa=1}^{N} \sigma_{\tau_\kappa}^{(\kappa)}(x_\kappa,x_\kappa',t)$$

  - density operators of *type II*:

$$\begin{aligned}\rho(x_1,\ldots,x_N;x_1',\ldots,x_N') &= \sum_{j_1}\ldots\sum_{j_N}\sum_{l_1}\ldots\sum_{l_N} B_{j_1,\ldots,j_N;l_1,\ldots,l_N}(t) \\ &\quad\times \prod_{\kappa=1}^{N} \varphi_{j_\kappa}^{(\kappa)}(x_\kappa,t)\,\varphi_{l_\kappa}^{(\kappa)*}(x_\kappa',t)\end{aligned}$$

Raab, Burghardt, Meyer, J. Chem. Phys. 111, 8759 (1999), Raab, Meyer, J. Chem. Phys. 112, 10718 (2000)

- employ, e.g., in conjunction with Markovian MEs (Lindblad, Caldeira-Leggett)

G-MCTDH for Density Operators

Burghardt, Meyer, Cederbaum, J. Chem. Phys. 111, 2927 (1999)

- density operators of *type I*:

$$\rho(\boldsymbol{r};\boldsymbol{r}') = \sum_{\tau_1} \cdots \sum_{\tau_N} B_{\tau_1 \ldots \tau_N}(t) \prod_{\kappa=1}^{N} \mathcal{G}_{\tau_\kappa}^{(\kappa)}(\boldsymbol{r}_\kappa, \boldsymbol{r}'_\kappa, t)$$

$$\mathcal{G}_{\tau}^{(\kappa)}(\boldsymbol{r},\boldsymbol{r}',t) = \exp\left(\boldsymbol{r}\cdot\alpha_\tau(t)\cdot\boldsymbol{r} + \boldsymbol{r}'\cdot\alpha'_\tau(t)\cdot\boldsymbol{r}' + \beta_\tau(t)\cdot\boldsymbol{r} + \beta'_\tau(t)\cdot\boldsymbol{r}' + \boldsymbol{r}\cdot\nu'_\tau(t)\cdot\boldsymbol{r}' + \theta(t) \right)$$

- includes thermal GWPs, e.g., as initial condition:

$$\mathcal{G}_{\tau}^{(\kappa)}(r,r',t=0) = \exp\left(-\frac{m\omega}{2\sinh(\omega/kT)} \left[(r^2 + r'^2)\cosh(\omega/kT) - 2rr' \right] \right)$$

- density operators of *type II*: adjoint pairs of component densities

$$\mathcal{G}_{jl}^{(\kappa)}(\boldsymbol{r},\boldsymbol{r}',t) = g_j^{(\kappa)}(\boldsymbol{r}) g_l^{(\kappa)*}(\boldsymbol{r}') = \mathcal{G}_{lj}^{(\kappa)*}(\boldsymbol{r},\boldsymbol{r}',t)$$

Topics

Two-Layer G-MCTDH – Motivation

- original G-MCTDH concept: combined, correlated TG modes (correlations through off-diagonal elements of the width matrix)
- in practice: G-MCTDH or vMCG using combined FG modes
  - factorizable, uncorrelated FG configurations
  - despite the separability, the C matrix is *not* block-diagonal
  - hence, expensive inversion step $\propto (\tilde{n}d)^3$
- alternative concept: replace high-dimensional FG's by superpositions of FG configurations $\longrightarrow$ two-layer approach

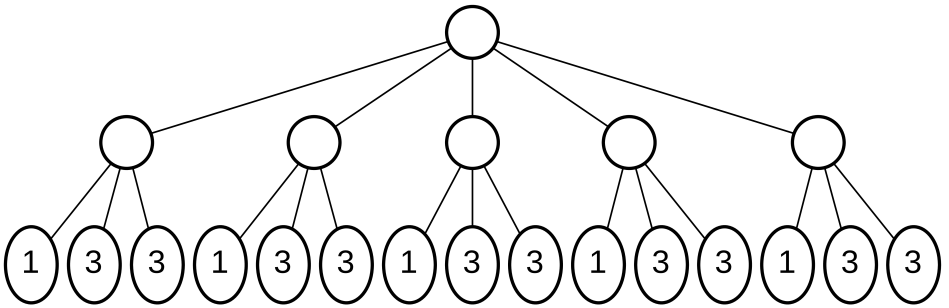
Two-Layer (2L)-G-MCTDH Scheme

Römer, Ruckenbauer, Burghardt, J. Chem. Phys. 138, 064106 (2013)

$$\Psi(r,t) = \sum_J A_J(t)\Phi_J(r,t) \;\; = \sum_J A_J(t) \prod_{\kappa=1}^{M} \varphi_{j_\kappa}^{(\kappa)}(r_\kappa,t)$$

where the single-particle functions (SPFs) $\varphi_{j_\kappa}^{(\kappa)}$ are now built as superpositions of Frozen Gaussian (FG) configurations,

$$\begin{aligned} \varphi_{j_\kappa}^{(\kappa)}(r_\kappa,t) &= \sum_L B_{j,L}^{(\kappa)}(t) G_L^{(\kappa)}(r_\kappa,t) \\ &= \sum_L B_{j,L}^{(\kappa)}(t) \prod_\mu g_{l_\mu}^{(\kappa,\mu)}(r_{\kappa_\mu},t) \end{aligned}$$



- hierarchical Tucker format
- intra-SPF correlations are carried by B coefficients
- GWP parameter dynamics in small (κ,μ) subspaces
- first-layer SPFs can be chosen to be orthogonal: $\langle \varphi_j^{(\kappa)}(t) | \varphi_{j'}^{(\kappa)}(t) \rangle = \delta_{jj'}$

Two-Layer G-MCTDH – Equations of Motion

1st layer coefficients: $$i\dot{A} = HA$$

2nd layer coefficients: $$iS^{(\kappa)}\dot{B}^{(\kappa)} = \left[\tilde{H}^{(\kappa)} - i\tilde{\tau}^{(\kappa)}\right] B^{(\kappa)}$$

GWPs (2nd layer): $$iC^{(\kappa,\mu)}\dot{\Lambda}^{(\kappa,\mu)} = Y^{(\kappa,\mu)}$$

where $\tilde{S}^{(\kappa)}_{jL,j'L'} = \delta_{jj'}\langle G^{(\kappa)}_L | G^{(\kappa)}_{L'}\rangle$, $\tilde{\tau}^{(\kappa)}_{jL,j'L'} = \delta_{jj'}\langle G^{(\kappa)}_L | \partial_t G^{(\kappa)}_{L'}\rangle$

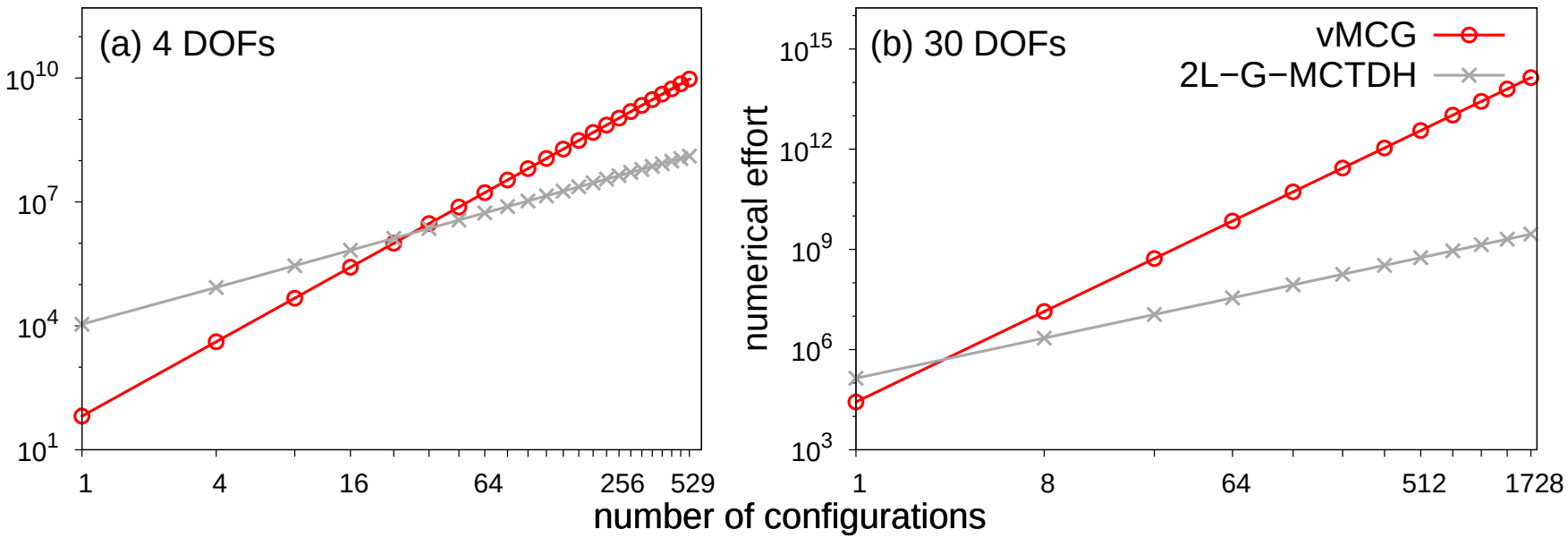
and the 1st layer mean field term: $\tilde{H}^{(\kappa)}_{jL,j'L'} = \langle G^{(\kappa)}_L | (1-\hat{P}^{(\kappa)}) \left[(\rho^{(\kappa)})^{-1}\hat{H}^{(\kappa)}\right]_{jj'} G^{(\kappa)}_{L'}\rangle$

and for the parameter equations: $C^{(\kappa,\mu)}_{j\alpha,l\beta} = \rho^{(\kappa,\mu)}_{jl}\langle \partial_\alpha g^{(\kappa,\mu)}_j | (\hat{1}-\hat{P}^{(\kappa,\mu)}) | \partial_\beta g^{(\kappa,\mu)}_l\rangle$

as well as $Y^{(\kappa,\mu)}_{j\alpha} = \sum_l \langle \partial_\alpha g^{(\kappa,\mu)}_j | (\hat{1}-\hat{P}^{(\kappa,\mu)})\hat{H}^{(\kappa,\mu)}_{jl} | g^{(\kappa,\mu)}_l\rangle$

Römer, Ruckenbauer, Burghardt, J. Chem. Phys. 138, 064106 (2013)

Two-Layer G-MCTDH – Scaling



effort$^{\text{G-MCTDH}} \sim m f^2 n^{f+1} + f(\tilde{d}n)^3$

calculation of mean fields + C matrix inversion

effort$^{\text{2L-G-MCTDH}} \sim m_1 f_1^2 n_1^{f_1+1} + m_1 m_2 f_1 f_2 n_1 n_2^{f_2+1}(f_2 + n_1) + f_1 f_2 (d_2 n_2)^3$

calculation of 1st and 2nd-layer mean fields + C matrix inversion

2L-G-MCTDH for Coupled Electronic States: Three Variants

— single-set: shared basis

$$\Psi_S(r,t) = \sum_{J,s} A_{Js}(t)\Phi_J(r,t)|s\rangle = \sum_{J,s} A_{Js}(t)\prod_{\kappa=1}^{N}\varphi_{j_\kappa}^{(\kappa)}(r_\kappa,t)|s\rangle$$

$$\varphi_{j_\kappa}^{(\kappa)}(r_\kappa,t) = \sum_L B_{j,L}^{(\kappa)}(t)G_L^{(\kappa)}(r_\kappa,t) = \sum_L B_{j,L}^{(\kappa)}(t)\prod_\mu g_{l_\mu}^{(\kappa,\mu)}(r_{\kappa_\mu},t)$$

— multi-set: state-specific basis

$$\Psi_M(r,t) = \sum_{J,s} A_J^{(s)}(t)\Phi_J^{(s)}(r,t)|s\rangle = \sum_{J,s} A_J^{(s)}(t)\prod_{\kappa=1}^{N}\varphi_{j_\kappa}^{(\kappa,s)}(r_\kappa,t)|s\rangle$$

$$\varphi_{j_\kappa}^{(\kappa,s)}(r_\kappa,t) = \sum_L B_{j,L}^{(\kappa,s)}(t)G_L^{(\kappa,s)}(r_\kappa,t) = \sum_L B_{j,L}^{(\kappa,s)}(t)\prod_\mu g_{l_\mu}^{(\kappa,\mu,s)}(r_{\kappa_\mu},t)$$

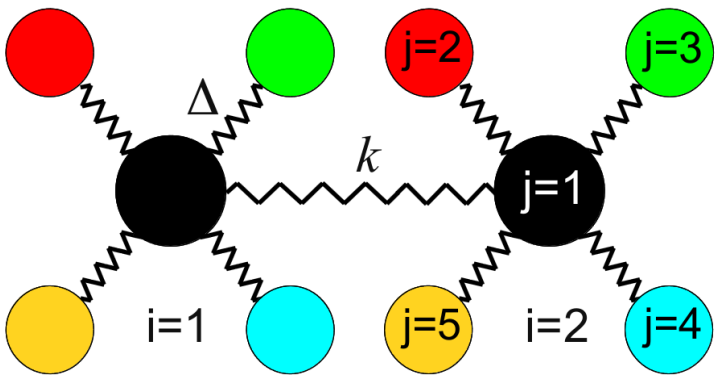
— hybrid-multi/single set ≡ hybrid-set: state-specific but shared 2nd-layer basis

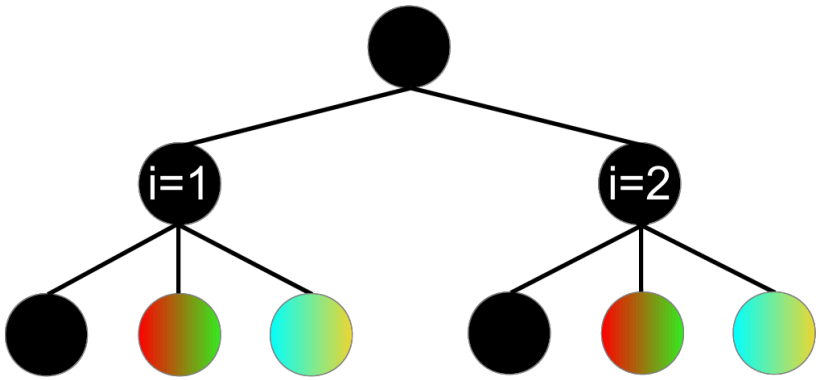
$$\Psi_H(r,t) = \sum_{J,s} A_J^{(s)}(t)\Phi_J^{(s)}(r,t)|s\rangle = \sum_{J,s} A_J^{(s)}(t)\prod_{\kappa=1}^{N}\varphi_{j_\kappa}^{(\kappa,s)}(r_\kappa,t)|s\rangle$$

$$\varphi_{j_\kappa}^{(\kappa,s)}(r_\kappa,t) = \sum_L B_{j,L}^{(\kappa,s)}(t)G_L^{(\kappa)}(r_\kappa,t) = \sum_L B_{j,L}^{(\kappa,s)}(t)\prod_\mu g_{l_\mu}^{(\kappa,\mu)}(r_{\kappa_\mu},t)$$

Model System: Intramolecular Vibrational Redistribution (IVR)

$$\hat{H} = \hat{T} + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{m}\omega_i \hat{q}_{i,\,j}^2 + \frac{1}{2}\sum_{i=1}^{n-1} k\left(\hat{q}_{i,1} - \hat{q}_{i+1,1}\right)^2 + \Delta\sum_{i=1}^{n}\sum_{j=2}^{m}\hat{q}_{i,1}^2\hat{q}_{i,j}$$



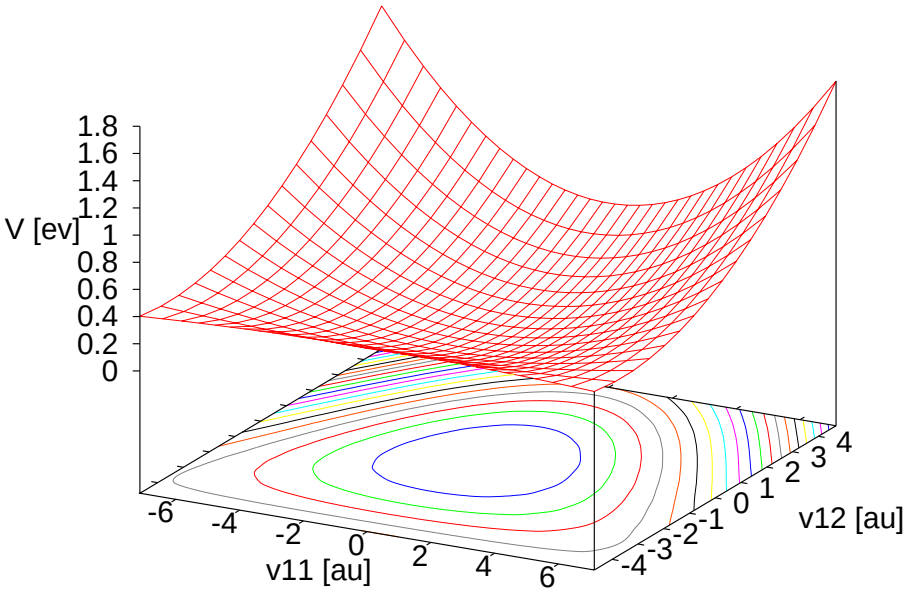


Schade, Hamm, J. Chem. Phys. **131**, 044511 (2009), Eisenbrandt, Ruckenbauer, Römer, Burghardt, to be submitted (2018)

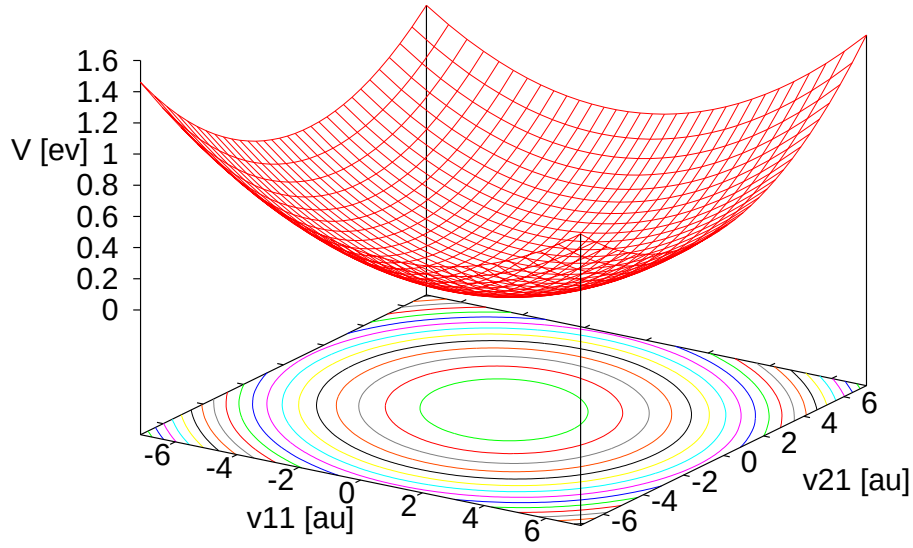
- low-frequency transporting modes + high-frequency local modes
- transporting/local modes communicate via Fermi resonances
- IVR efficiency is controlled by parameters k and Δ
- consider regime of "ballistic" transport along the chain
- $i = 1, \ldots f_1$ 1st-layer modes , $j = 1, \ldots f_2$ 2nd-layer modes/site

Model System: PES Cuts

$$\hat{H} = \hat{T} + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{m}\omega_i \hat{q}_{i,\,j}^2 + \frac{1}{2}\sum_{i=1}^{n-1} k\left(\hat{q}_{i,1} - \hat{q}_{i+1,1}\right)^2 + \Delta\sum_{i=1}^{n}\sum_{j=2}^{m}\hat{q}_{i,1}^2\hat{q}_{i,j}$$



intra-site PES cut (q_{11}, q_{12})

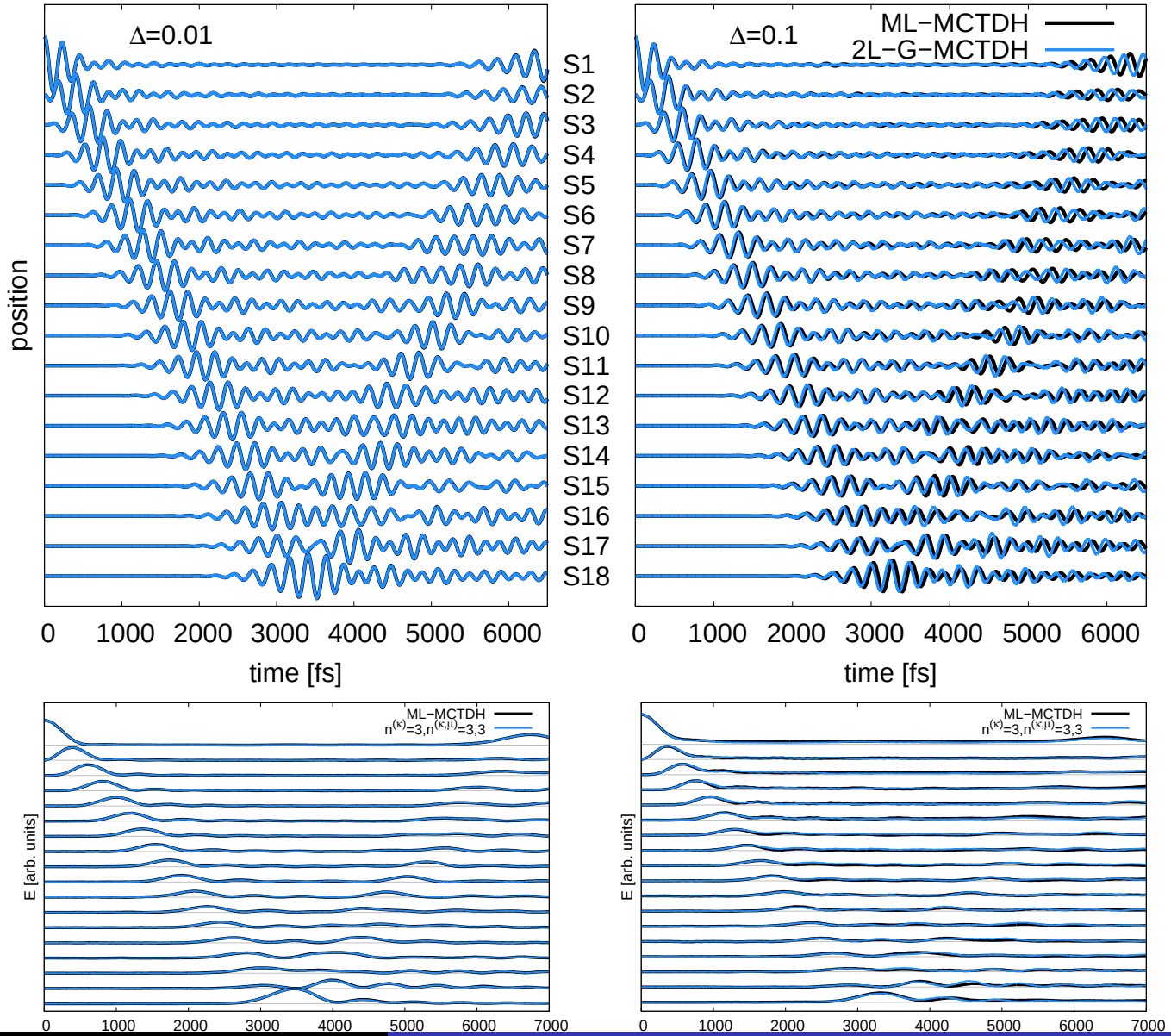


PES cut for transporting modes (q_{11}, q_{21})

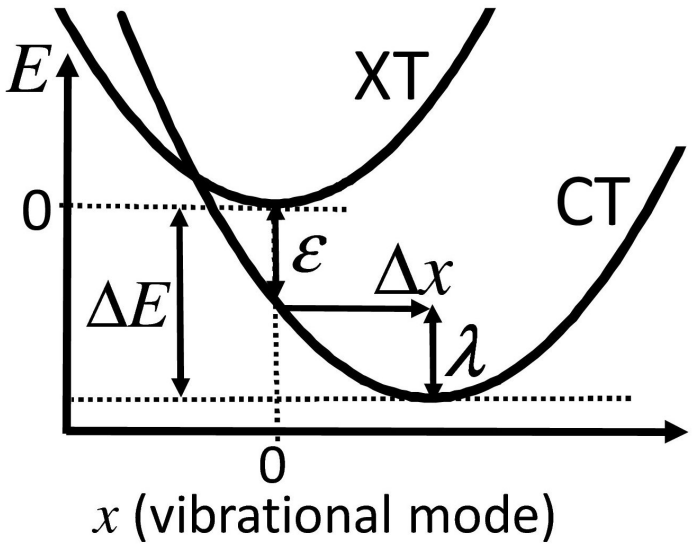
Results & Benchmarks

18 sites
90 DOFs
1st/2nd layer modes:
$f_1 = 6, f_2 = 6$
1st/2nd layer SPFs:
$n_1 = 3, n_2 = 3$

[140 hrs/36 MB]
in-house code
(vs. [136 hrs/215 MB]
2L-MCTDH
HD package)



Benchmarks for 2-State Donor-Acceptor Model



$$\hat{H} = \hat{H}_0 + \hat{H}_R + \hat{H}_B$$

$\hat{H}_0$: electronic part
$\hat{H}_R$: inter-fragment coordinate part
$\hat{H}_B$: phonon bath part

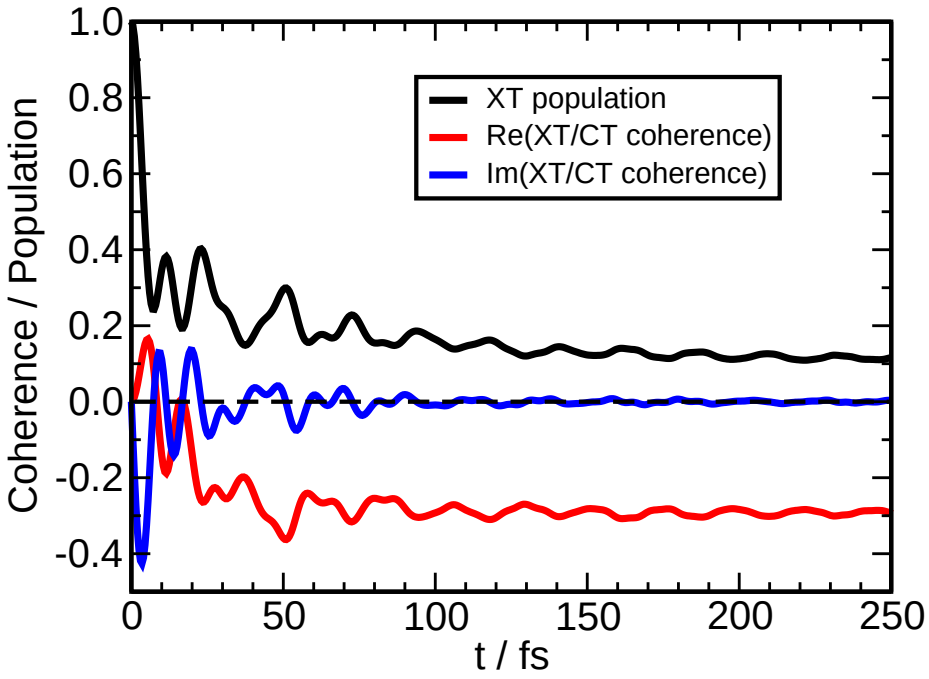
$$\hat{H}_0 = \Delta_{\mathrm{XT-CT}} |\mathrm{CT}\rangle\langle\mathrm{CT}| + \gamma\left(|\mathrm{XT}\rangle\langle\mathrm{CT}| + |\mathrm{CT}\rangle\langle\mathrm{XT}|\right)$$

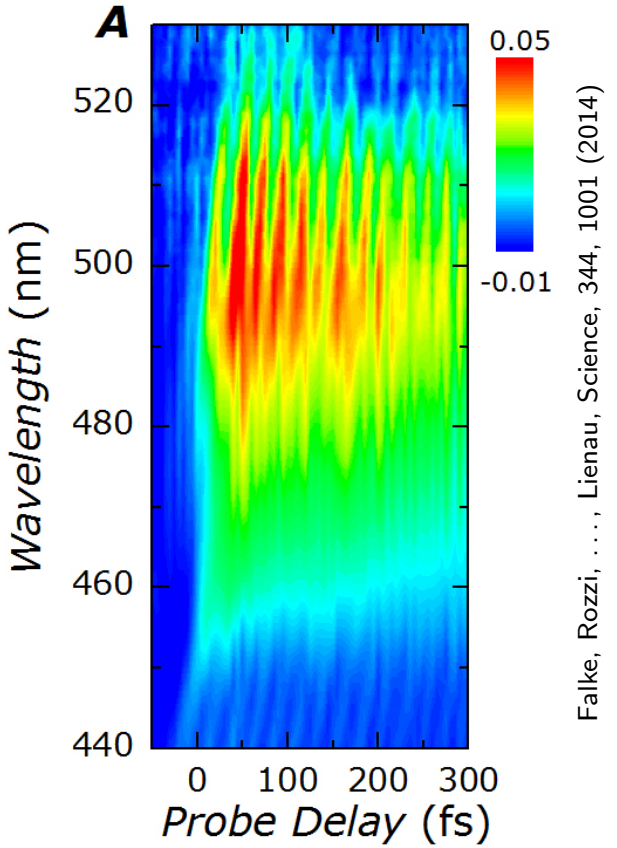
$$\begin{aligned}\hat{H}_R \quad = \quad & \frac{\omega_R}{2}(\hat{R}^2 + \hat{P}^2) + \kappa_R \hat{R}\,|\mathrm{CT}\rangle\langle\mathrm{CT}| \\ & + \gamma_R \hat{R}\left(|\mathrm{XT}\rangle\langle\mathrm{CT}| + |\mathrm{CT}\rangle\langle\mathrm{XT}|\right)\end{aligned}$$

$$\hat{H}_B = \sum_{i=1}^{N} \frac{\omega_i}{2}(\hat{x}_i^2 + \hat{p}_i^2) + \sum_{i=1}^{N} \kappa_i x_i\,|\mathrm{CT}\rangle\langle\mathrm{CT}| + \sum_{i=1}^{N} \frac{\kappa_i^2}{2\omega_i}$$

Tamura, Martinazzo, Ruckenbauer, Burghardt, J. Chem. Phys., 137, 22A540 (2012)

Ultrafast Coherent Transfer Dynamics (MCTDH/60 Modes)





el. coherence: $\rho_{XT,CT}(t) = \mathrm{Tr}\{|\mathrm{CT}\rangle\langle\mathrm{XT}|\hat{\rho}(t)\}$

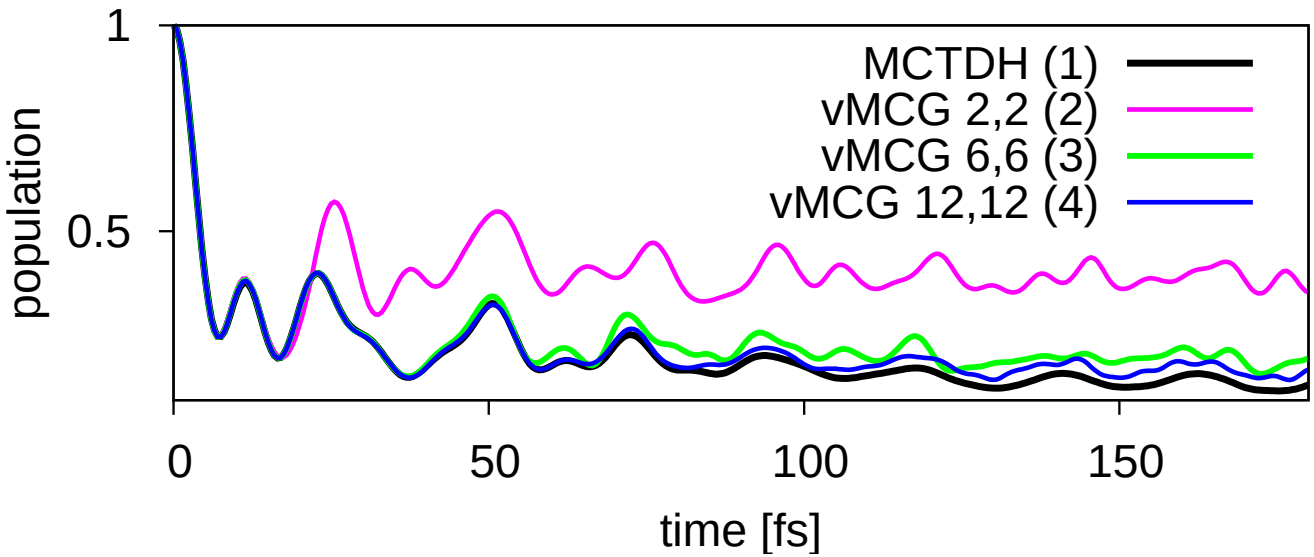
- imaginary part $(-2\gamma/\hbar)\mathrm{Im}\rho_{XT,CT}$ ⟷ population flux
- real part ⟷ stationary coherent superposition ($P_{\mathrm{XT}} \sim 0.1$, $P_{\mathrm{CT}} \sim 0.9$)
- experiment: ultrafast ET (~ 50 fs), oscillatory features [Brabec et al., CPL (2001)]) confirmed by recent pump-probe experiments by Lienau group [Science (2014)])

Benchmarks – 41D Spin-Boson System

Frozen Gaussians (FGs)

- 2 el. states, 1 subsystem mode, 40 bath modes
- qualitative agreement even of "cheap" calculations
- memory requirements favorable
- vMCG very expensive even for few config's

	calc. type	mode combination	# configs	memory [mb]	CPU time [hh:mm]	C inversion avg/tot time
1	MCTDH	[6,8],[6,8],[3,5],[2,3] [2,2],[2,2],[2,2],[2,2],[6,8]	143616	754	1:36	- -
2	vMCG 2,2	[2,2]	4	2	0:47	5.10 ms 0:03:60
3	vMCG 6,6	[6,6]	12	15	7:10	136.38 ms 1:29:18
4	vMCG 12,12	[12,12]	24	55	47:56	1758.71 ms 23:21:38

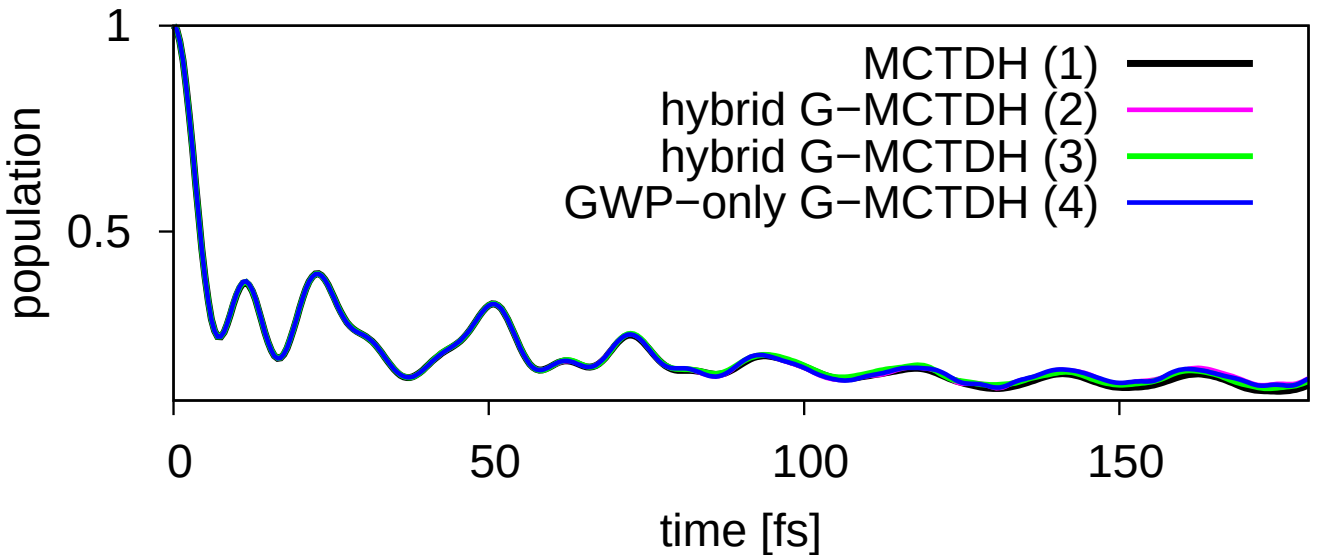


Benchmarks – 41D Spin-Boson System

Frozen Gaussians (FGs)

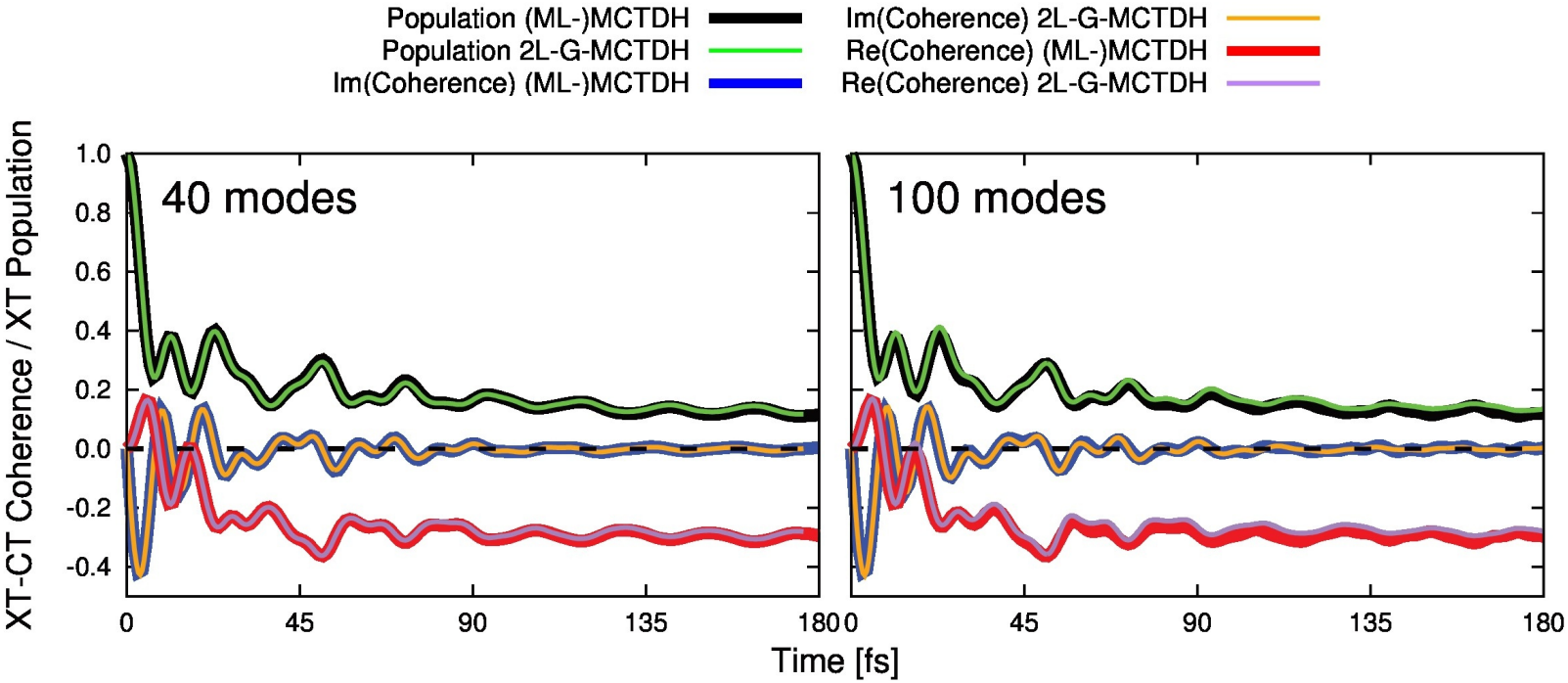
- different mode combinations and #'s of GWP config's
- C inversion in smaller subspaces
- all G-MCTDH calculations have reasonable timings
- memory requirements favorable

	calc. type	mode combination	# configs	memory [mb]	CPU time [hh:mm]	C inversion avg/tot time
1	MCTDH	[6,8],[6,8],[3,5],[2,3] [2,2],[2,2],[2,2],[2,2],[6,8]	143616	754	1:36	- -
2	G-MCTDH hybrid	[6,8],[6,8],[3,5],[2,3] [2,2],[2,2],[2,2],[2,2],[6,8]	143616	28	0:12	0.21 ms 0:01:48
3	G-MCTDH hybrid	[8,10],[8,10],[5,7],[4,5] [3,3],[3,3],[3,3],[3,3],[6,8]	2890080	521	3:56	7.65 ms 0:12:03
4	G-MCTDH all-GWP	[6,8],[6,8],[3,5],[2,3] [2,2],[2,2],[2,2],[2,2],[6,8]	143616	28	0:26	0.19 ms 0:06:13



Results & Benchmarks: Spin-Boson System

calc type	# L1 modes	# L1 SPFs	# L2 modes	# L2 SPFs	timing [s]
small	6	[4,4,4,4,4,7]	[4,4,4,4,4,1]	[3,3,3,3,3,7]	[8252]
medium	6	[6,6,5,5,5,7]	[4,4,4,4,4,1]	[5,5,5,5,5,8]	[122636]
large	6	[7,7,8,8,7,8]	[4,4,4,4,4,1]	[5,6,6,7,6,9]	[286980]



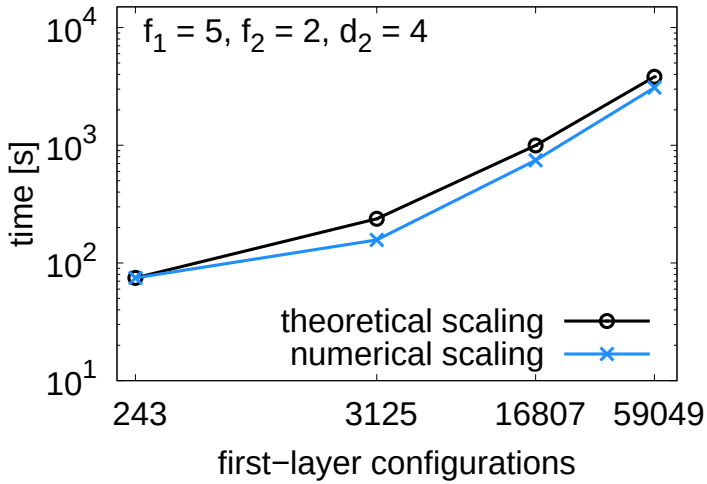
Eisenbrandt, Ruckenbauer, Römer, Burghardt, to be submitted (2018)

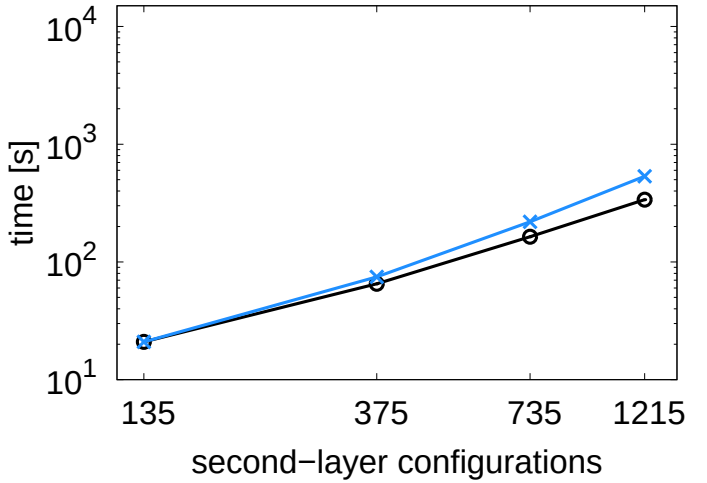
- single-set calculations for rediscretized SDs for 40 / 100 modes
- convergence properties are similar for single(S)/hybrid(H)/multi(M)-set

Implementation & Scaling

- in-house code (M. Ruckenbauer, P. Eisenbrandt)
- general polynomial potentials
- Hamiltonian given as sum-over-products
- initial condition: shell-like spatial distribution (here, initially unoccupied GWPs narrower than central GWP)
- conventional regularization of $\boldsymbol{S}$ and $\boldsymbol{C}$ matrices
- ABM integrator (time step typically $\sim 10^{-2}$ fs)
- scaling in good agreement with theory

- NB: joint standard G-MCTDH/vMCG code with G. A. Worth now available within QUANTICS package at `http://ccpforge.cse.rl.ac.uk/`.





Multi-Layer Form

$$\Psi(t) = \sum_J A_J^{[1]}(t)\Phi_J^{[1]}(t) := \sum_J A_J^{[1]}(t) \prod_{\kappa_1=1}^{f^{[1]}} \chi_{j_{\kappa_1}}^{[1](\kappa_1)}(t)$$

with the spf's of the first $M-1$ layers ($m \in \{2,3,\ldots,M\}$),

$$\chi_j^{[m-1](\mu_m-1)}(t) \quad = \quad \sum_J A_{j,J}^{[m](\mu_m-1)}(t)\Phi_J^{[m](\mu_m-1)}(t) = \sum_J A_{j,J}^{[m](\mu_m-1)}(t) \prod_{\kappa_m=1}^{f_{\mu_{m-1}}^{[m]}} \chi_{j_{\kappa_m}}^{[m]}(t)$$

and the final (Mth) layer composed of FG's,

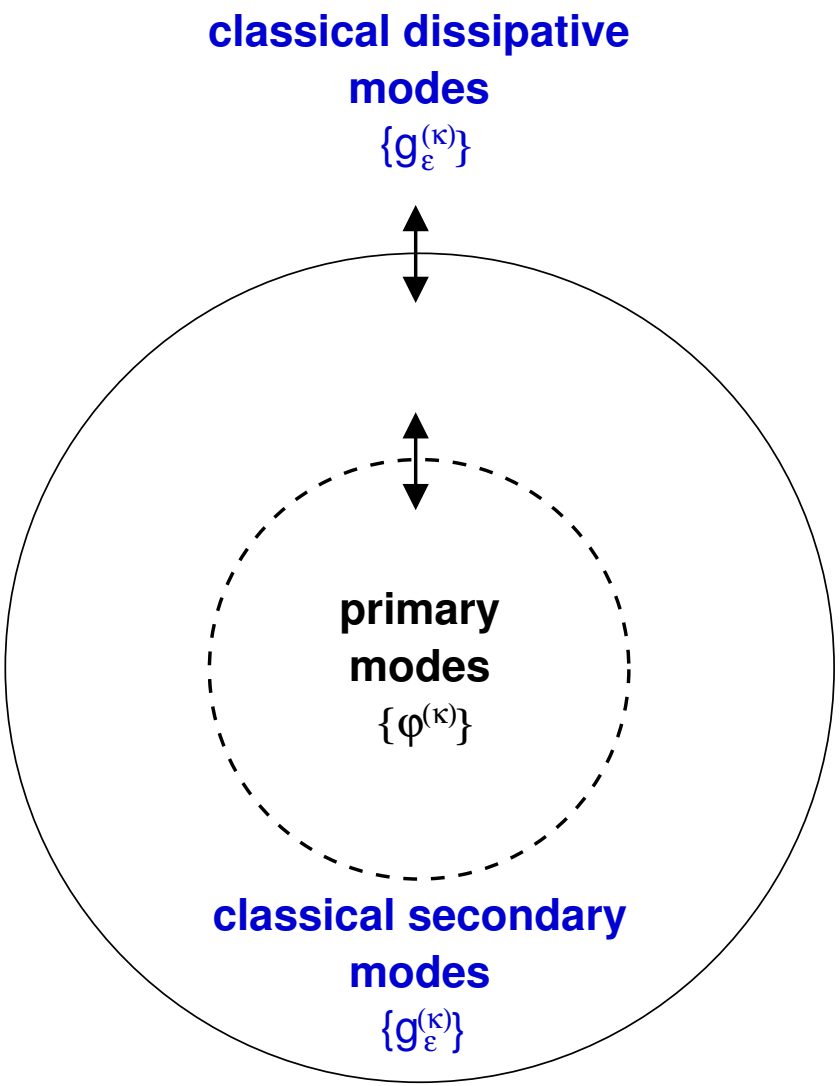
$$\chi_j^{[M](\mu_M)}(t) = g_j^{(\mu_M)}(\Lambda_j^{(\mu_M)}(t))$$

can be straightforwardly combined with existing ML-MCTDH approaches

Römer, Ruckenbauer, Burghardt, J. Chem. Phys. 138, 064106 (2013)

Topics

Quantum-Classical Limit of G-MCTDH



take GWP subspace to classical limit:

$$\Psi^{\mathrm{qc}}(r,t) = \sum_J A_J(t)\ \Phi_J^{\mathrm{qc}}(r,t)$$

$$\Phi_J^{\mathrm{qc}}(r,t) = \underbrace{\prod_{\kappa=1}^{M} \varphi_{j_\kappa}^{(\kappa)}(r_\kappa,t)}_{\text{primary nodes}}\ \underbrace{\prod_{\kappa=M+1}^{P} g_{\varepsilon,j_\kappa}^{(\kappa)}(r_\kappa,t)}_{\text{secondary modes}}$$

Römer, Burghardt, Mol. Phys. 111, 3618 (2013)

use "narrow" semiclassical GWPs:

$$g_{\varepsilon,j_\kappa}^{(\kappa)}(r_\kappa) = N_\varepsilon \exp\left[-\frac{1}{2\varepsilon}(r_\kappa - q_{j_\kappa})\cdot a(r_\kappa - q_{j_\kappa}) + \frac{i}{\varepsilon} p_{j_\kappa}^{(\kappa)}(t)\cdot(r_\kappa - q_{j_\kappa})\right]$$

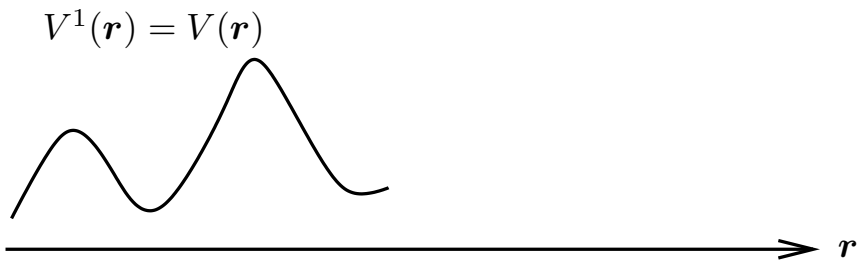
Classical Limit as Scaling Limit

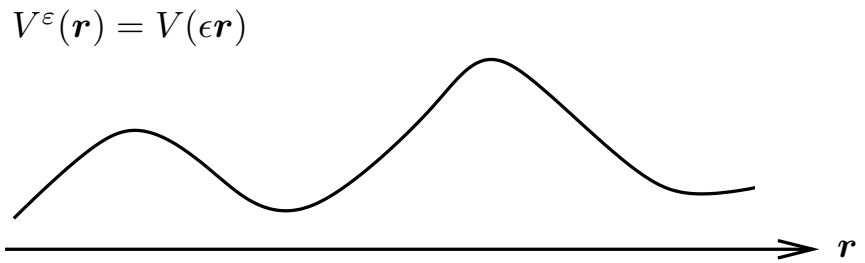
- condition for classicality:

  $\lambda_{dB} \ll L$

  λ_{dB} = de Broglie wave length; L = scale of variation of the potential V
- rescale potential: $V^\varepsilon(r) := V(\varepsilon r)$ such that $\varepsilon \to 0$ corresponds to the limit of slow variation of V^ε
- switch to macroscopic coordinates: $(\tilde{r}, \tilde{t}) = (\varepsilon r, \varepsilon t)$ such that the Schrödinger Equation reads ($\hbar = 1$, $m = 1$):

$$i\varepsilon \frac{\partial}{\partial \tilde{t}} \Psi(\tilde{r}, \tilde{t}) = \left[-\frac{\varepsilon^2}{2} \Delta_{\tilde{r}} + V(\tilde{r}) \right] \Psi(\tilde{r}, \tilde{t})$$





Classical-Limit Gaussian Wavepackets

$$g_{\varepsilon,j}(\tilde{r}) = N_\varepsilon \exp\left[-\frac{1}{2\varepsilon}(\tilde{r}-q_j)\cdot a(\tilde{r}-q_j) + \frac{i}{\varepsilon}p_j\cdot(\tilde{r}-q_j)\right]$$

- "narrow" wavepackets centered around position and momentum (q_j, p_j),
  $\|(\hat{r}-q_j)g_{\varepsilon,j}\| \sim \sqrt{\varepsilon} \qquad \|(\hat{p}-p_j)g_{\varepsilon,j}\| \sim \sqrt{\varepsilon}$
- move along classical trajectories (up to an error of order $\sqrt{\varepsilon}$)
  $g_{\varepsilon,j}(\tilde{r},\tilde{t}) \sim \exp\left(\frac{i}{\varepsilon}S^{\mathrm{cl}}(\tilde{t})\right) g_{\varepsilon,j}(\tilde{r}, q_j^{\mathrm{cl}}(\tilde{t}), p_j^{\mathrm{cl}}(\tilde{t}))$
- in this limit, the Gaussian wavepackets are decoupled from each other

G. Hagedorn, Ann. Inst. H. Poincaré Phys. Théor. **42** (1985), no. 4, 363, G. Hagedorn, Ann. Physics **269** (1998), 77

Mixed Quantum-Classically Evolved Wavefunction

$$\Psi^{\mathrm{qc}}(r,t) = \sum_{j_1} \cdots \sum_{j_M} \sum_{l} A^{\mathrm{qc}}_{j_1 \cdots j_M, l} \left(\prod_{\kappa=1}^{M} \varphi^{(\kappa)}_{j_\kappa}(r_\kappa, t) \right) \exp\left(\frac{i}{\varepsilon} S^{\mathrm{cl}}_l \right) g^{(f)}_{\varepsilon,l}(r_f; q^{(f)}_l, p^{(f)}_l)$$

coefficients: $i\dot{A}_l = H A_l$

SPFs (primary modes): $i\dot{\varphi}^{(\kappa)} = \left(\hat{1} - \hat{P}^{(\kappa)} \right) \left[\rho^{(\kappa)} \right]^{-1} \hat{H}^{(\kappa)} \varphi^{(\kappa)}$

classical secondary modes: $\dot{q}^{(f)}_l = p^{(f)}_l \qquad \dot{p}^{(f)}_l = -\nabla_{q_l} H^{(f)}_l$

- the resulting quantum-classical dynamics corresponds to a multiconfigurational Ehrenfest (MCE) approach
- the trajectories are still coupled through the primary-mode mean fields

Römer, Burghardt, Mol. Phys. 111, 3618 (2013)

MCE Nonadiabatic Dynamics (Diabatic Representation)

$$\hat{H} = -\frac{\varepsilon^2}{2}\nabla_r^2 \hat{1} + \hat{V} \qquad \hat{V}(r) = \begin{pmatrix} V_{11}(r) & V_{12}(r) \\ V_{12}(r) & V_{22}(r) \end{pmatrix}$$

$$|\Psi^{\mathrm{qc}}(r,t)\rangle = \sum_{n=1}^{n_{\mathrm{states}}} \sum_{l=1}^{n_G} A_{nl}(t) \exp\left(\frac{i}{\varepsilon} S_l^{\mathrm{cl}}(t)\right) g_{\varepsilon,l}(r; q_l(t), p_l(t)) \, |n\rangle \qquad (\text{“single-set”})$$

coefficients: $i\dot{\boldsymbol{A}}_l = \boldsymbol{H}(q_l)\boldsymbol{A}_l$

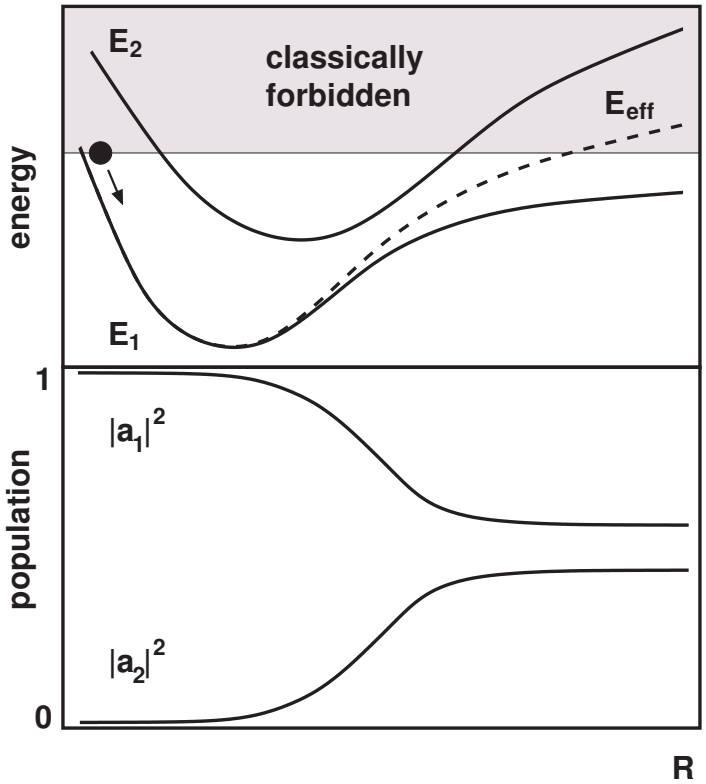
classical modes: $\dot{q}_l = p_l \qquad \dot{p}_l = -\nabla_{q_l} \bar{V}_l(q_l)$

with the mean-field potential $\bar{V}_l = \left[\sum_n |A_{nl}|^2\right]^{-1} \sum_n \sum_{n'} A_{nl}^* A_{n'l} \langle n|\hat{V}(r = q_l)|n'\rangle$

- Ψ^{qc} evolves along a superposition of Ehrenfest trajectories
- similarly for adiabatic representation (kinetic energy couplings)

see also Shalashilin, J. Chem. Phys. 130, 244101 (2009), 132, 244111 (2010)

Ehrenfest & Beyond



N. L. Doltsinis, in: Quantum Simulations of Complex Many-Body Systems: From Theory to Algorithms NIC Series, Jülich, 10, p. 377 (2002)

- single Ehrenfest trajectory: mean field
  $\bar{V}(q) = \sum_{n,n'} A_n A_{n'} \langle n|\hat{V}(q)|n'\rangle$

  Delos, Thorson, Knudson, Phys. Rev. A 6, 709 (1972)
  Billing, Chem. Phys. Lett. 100, 535 (1983)

- multiconfigurational Ehrenfest: coherent superposition of trajectories (q_l, p_l) with mean fields
  $\bar{V}_l(q_l) = [\sum_n |A_{nl}|^2]^{-1} \sum_{n,n'} A^*_{nl} A_{n'l} \langle n|\hat{V}(q_l)|n'\rangle$

  Shalashilin, J. Chem. Phys. 130, 244101 (2009), 132, 244111 (2010)
  Römer, Burghardt, Mol. Phys. 111, 3618 (2013)

- different from statistical Ehrenfest approach

  Alonso et al., J. Chem. Phys. 137, 054106 (2012)

MCE-like Dynamics for Non-Scaled GWPs

- important in practice, in view of GWP-based sampling of initial conditions and guaranteeing norm conservation
- two-layer ansatz required to restrict electronic coupling to lth subspace:

$$|\Psi^{\mathrm{qc}}(r,t)\rangle = \sum_{l=1}^{n_G} \tilde{A}_l(t)|\Phi_l^{\mathrm{qc}}(r,t)\rangle = \sum_{l=1}^{n_G} \tilde{A}_l(t)\exp\left(\frac{i}{\hbar}S_l^{\mathrm{cl}}(t)\right) g_l(r;q_l(t),p_l(t))\,|\chi_l^{(\mathrm{el})}(t)\rangle$$

$$|\chi_l^{(\mathrm{el})}(t)\rangle = \sum_{n=1}^{n_{\mathrm{states}}} B_{nl}(t)|n\rangle$$

$\tilde{\boldsymbol{A}}$ coefficients: $i\boldsymbol{S}\dot{\tilde{\boldsymbol{A}}} = (\boldsymbol{H} - i\tau)\tilde{\boldsymbol{A}}$

$\boldsymbol{B}$ coefficients: $i\dot{\boldsymbol{B}}_l = \boldsymbol{H}(q_l)\boldsymbol{B}_l$

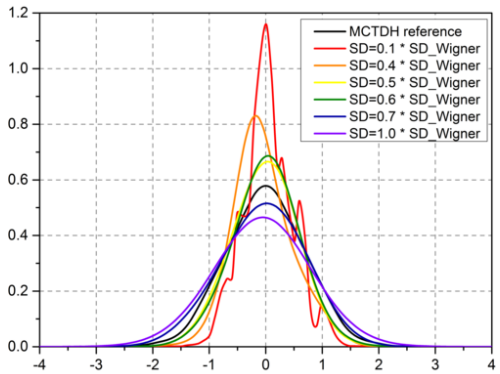
classical modes: $\dot{q}_l = p_l \quad \dot{p}_l = -\nabla_{q_l}\bar{V}_l(q_l)$

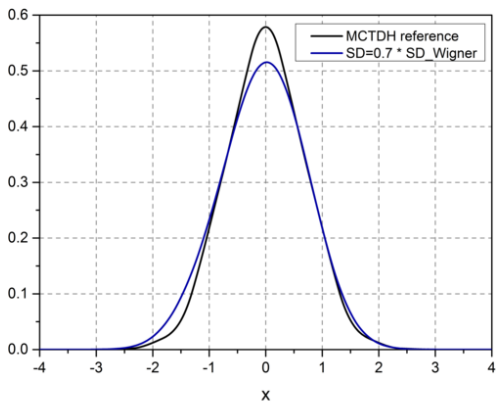
with the mean-field potential $\bar{V}_l = \left[\sum_n |B_{nl}|^2\right]^{-1} \sum_n \sum_{n'} B_{nl}^* B_{n'l} \langle n|\hat{V}(r=q_l)|n'\rangle$

see also Shalashilin, J. Chem. Phys. 132, 244111 (2010)

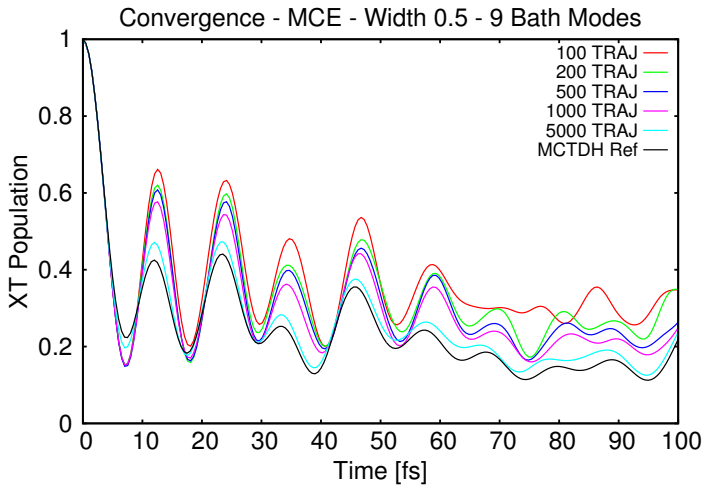
Multiconfigurational Ehrenfest Dynamics

- 4D – 40D spin-boson system
- several 1000 trajectories
- importance sampling over ρ_{Wigner}
- strong dependence on GWP width

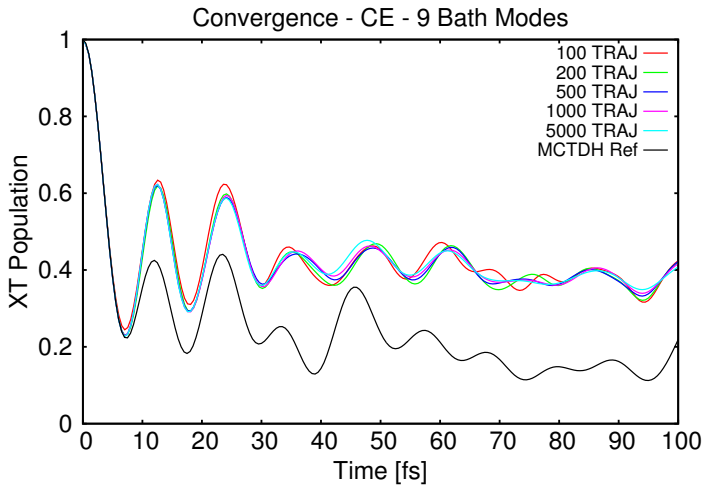




- Multiconfiguration Ehrenfest



- For Comparison: Statistical Ehrenfest



Multiconfigurational Ehrenfest System – Properties

- the quantum-classical wavefunction state carries correlations due to the multiconfigurational wavefunction form,

$$\Psi^{\mathrm{qc}}(r,t) = \sum_J \sum_l A^{\mathrm{qc}}_{J,l}(t)\Phi_J(r_\kappa,t)\exp\left(\frac{i}{\varepsilon}S^{\mathrm{cl}}_l\right) g^{(f)}_{\varepsilon,l}(r_f;q^{(f)}_l,p^{(f)}_l)$$

- the reduced density matrix of the quantum subsystem is in a mixed state,[2]

$$\rho^{sys}_{qc}(x,x',t) = \mathrm{Tr}_{cl}\left[\Psi^{\varepsilon}_{qc}(x,r,t)\Psi^{\varepsilon *}_{qc}(x',r',t)\right]$$

- statistical ensembles can be constructed as follows:

$$\rho^{\varepsilon}_{qc}(x,r,x',r',t) = \sum_n p_n \Psi^{\varepsilon}_{qc,n}(x,r,t)\Psi^{\varepsilon *}_{qc,n}(x',r',t)$$

[2] By contrast, single-trajectory Ehrenfest evolution always yields a pure subsystem state.

Is Multiconfigurational Ehrenfest Dynamics Consistent?

- the properties of the underlying wavefunction state Ψ_{qc} are preserved
- correlations between the quantum and classical subspaces are accounted for
- the dynamics is variational, hence a generalized Poisson bracket structure exists: $i\{\cdot,\cdot\}_{qc} = i\sum_n\{\langle H\rangle, A_n\} + i\sum_l\{\langle H\rangle, \xi_l\}$ where $\langle H\rangle = \langle\Psi_{qc}|\hat{H}|\Psi_{qc}\rangle$

However,

- the single-configurational (standard Ehrenfest) case is not a satisfactory quantum-classical description
- due to the non-linear structure of the equations, a direct comparison with other approaches (e.g., the QC Liouville Equation) is not straightforward

Summary

- G-MCTDH/ML-G-MCTDH/vMCG are useful due to their proximity to classical mechanics, while permitting full quantum convergence
- two-layer (or multi-layer) variant employs correlated FG-based particles; need for sampling strategies when combining with on-the-fly applications
- natural quantum-classical limit of G-MCTDH: multiconfiguration Ehrenfest
- Langevin dynamics from a stochastic Schrödinger equation picture
- next steps: statistical sampling & extension to thermal GWPs; random-phase thermal wavepackets; GWP-based correlation functions (cf. Coughtrie & Tew, JCP 140, 194106 (2014)); GWP calculations for nonlinear optical signals, transport dynamics, multiscale microscopic/mesoscopic dynamics ...

Acknowledgments & Collaborations

Group Frankfurt:

- M. Biswas
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- R. Binder
- J. Wahl
- P. Eisenbrandt
- M. Polkehn
- M. Huix-Rotllant

Former members:

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- M. Ruckenbauer
- J. Ortiz-Sánchez

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MPNS COST Action MP1006

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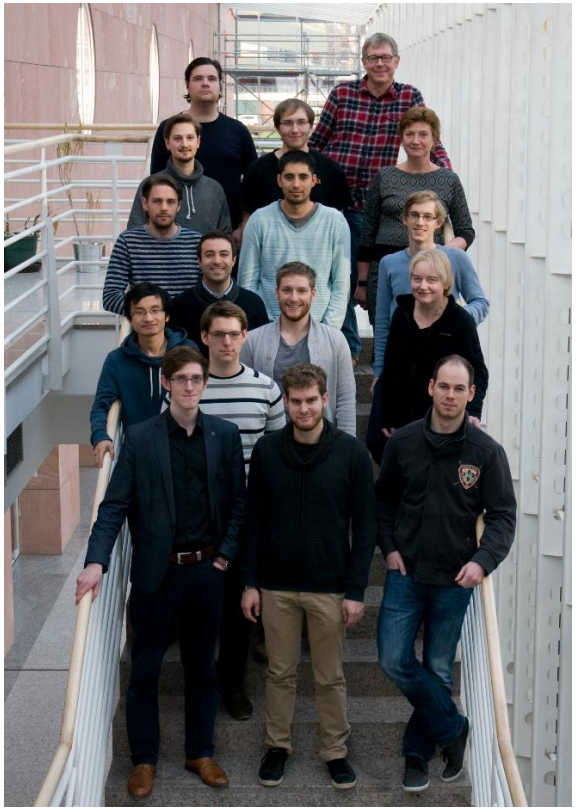


Theoretical Chemistry
of Complex Systems

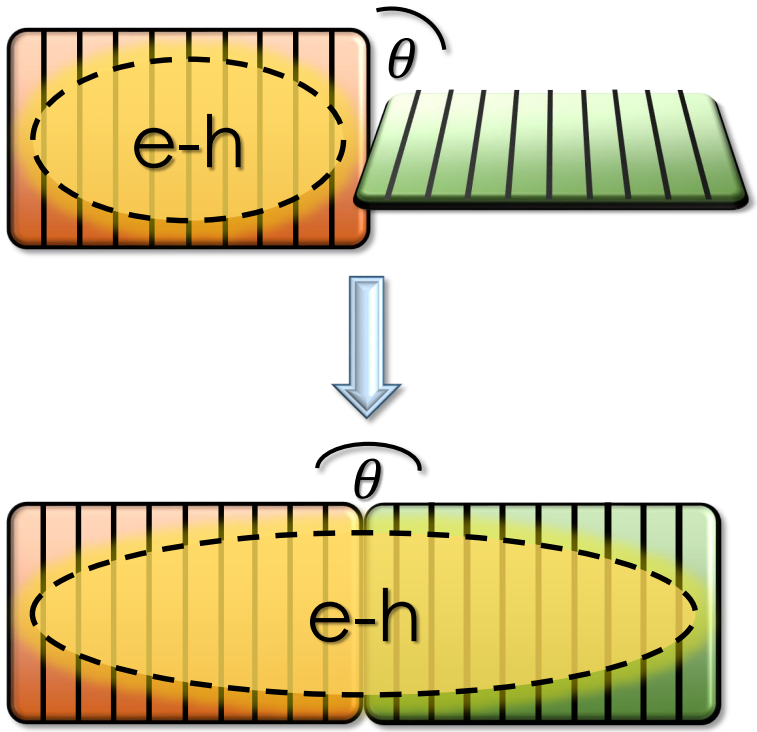
AK Burghardt

Dynamics: Test Case OT-20

- Do we see trapped exciton-polarons in the dynamics?
- How exactly does the exciton migrate as the conjugation break "heals"?
- How does the spatial extension of the exciton change as a function of conformational (torsional) fluctuations?

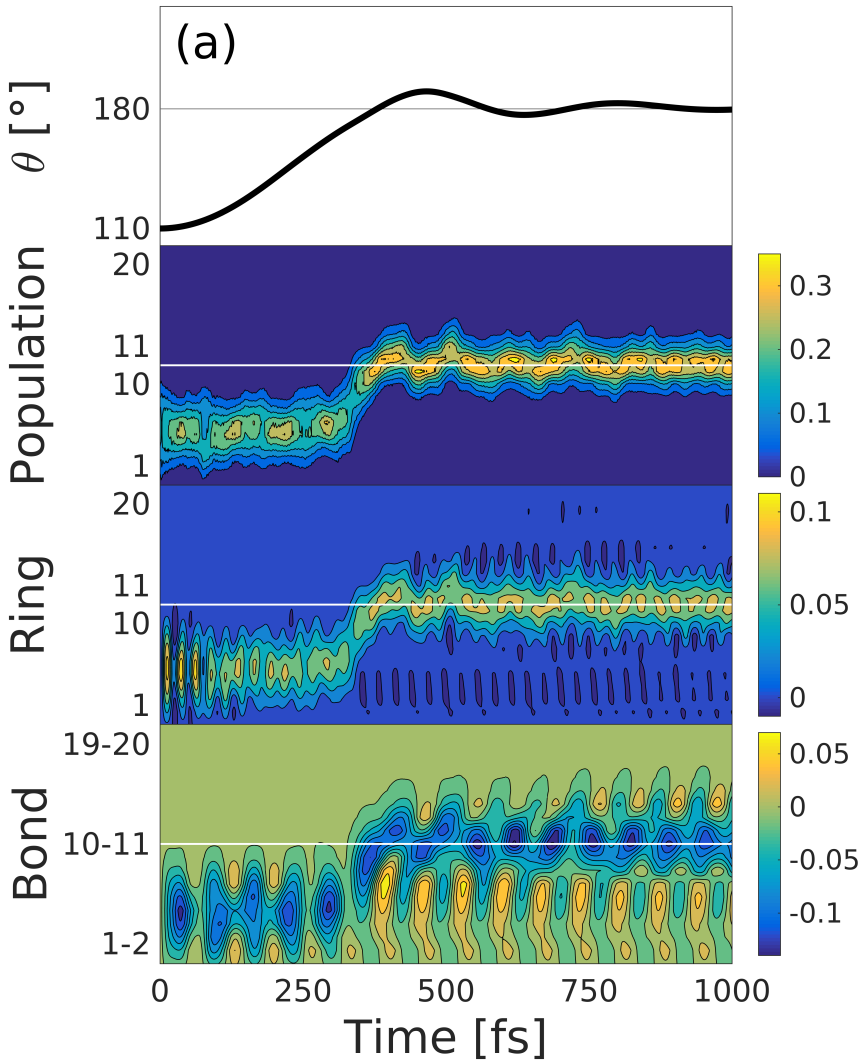
Monomer representation:
most unbiased picture to answer these questions!

Binder, Lauvergnat, Burghardt, Phys. Rev. Lett. 120, 227401 (2018)

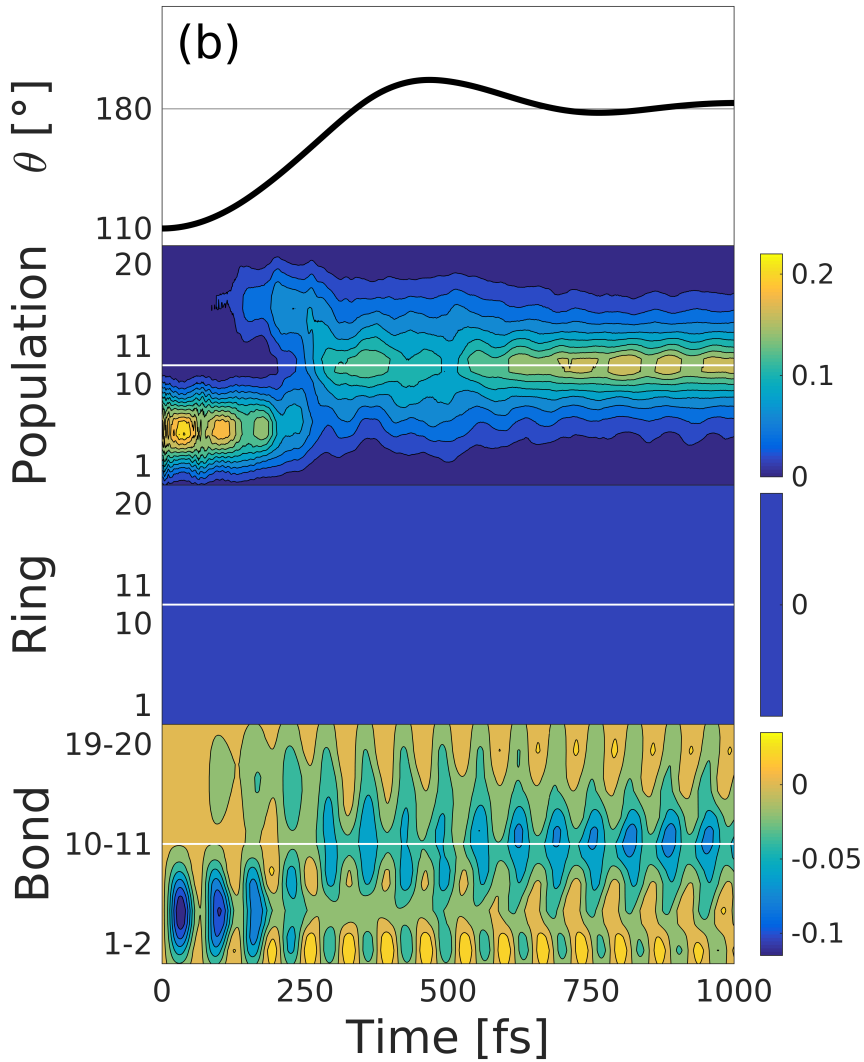


Quantum Dynamics: 20-Site J-Aggregate with Central Torsion

C-C inter-monomer mode + local C=C + torsion + bath

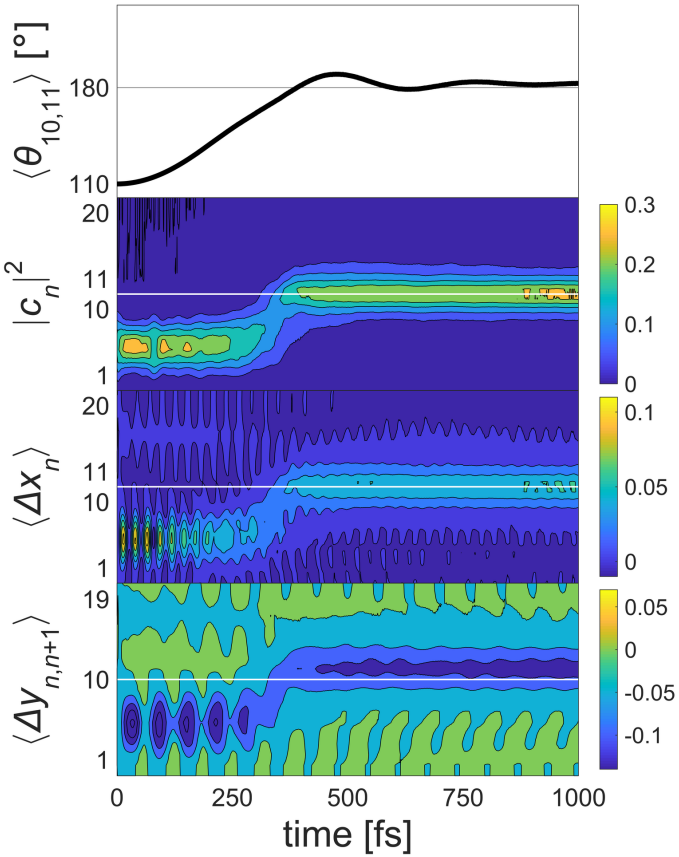


C-C inter-monomer + torsion + bath

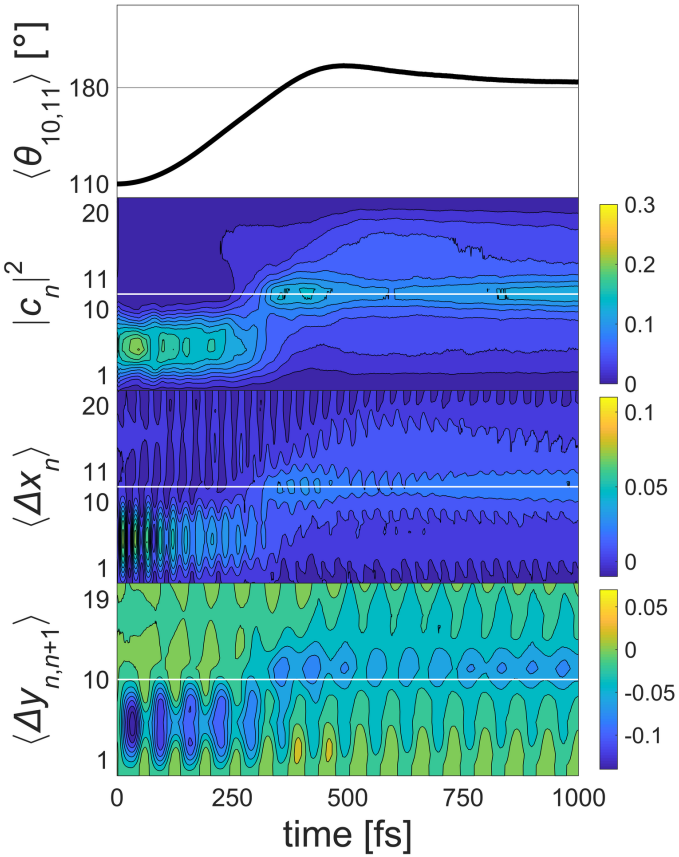


Semiclassical SQC/MM dynamics (T=0K)

SQC/MM – single trajectory



SQC/MM – Wigner average

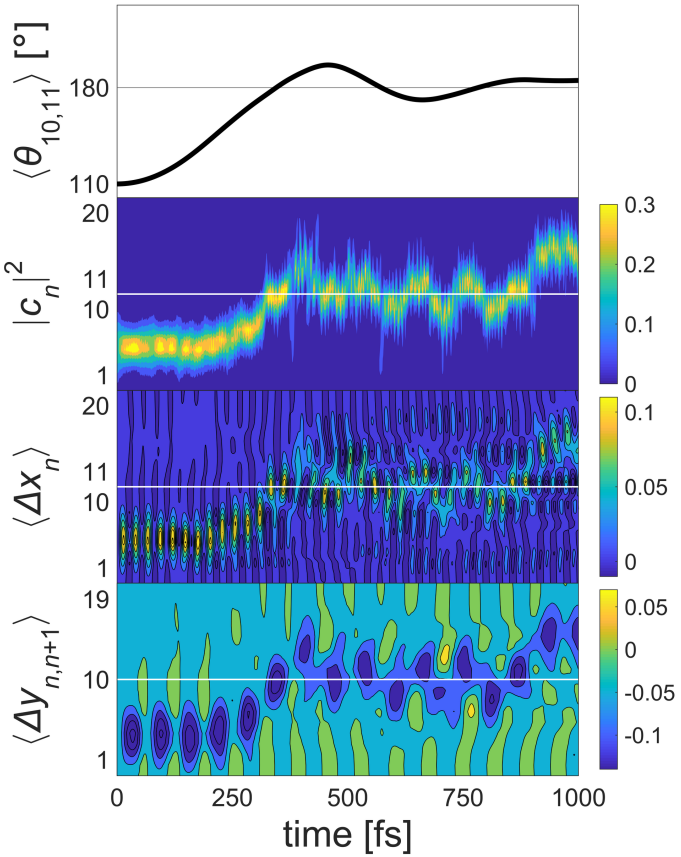


- SQC/MM = Symmetrical Quasi-Classical / Meyer-Miller model
- single-trajectory result close to MCTDH, but Wigner average "fuzzy"

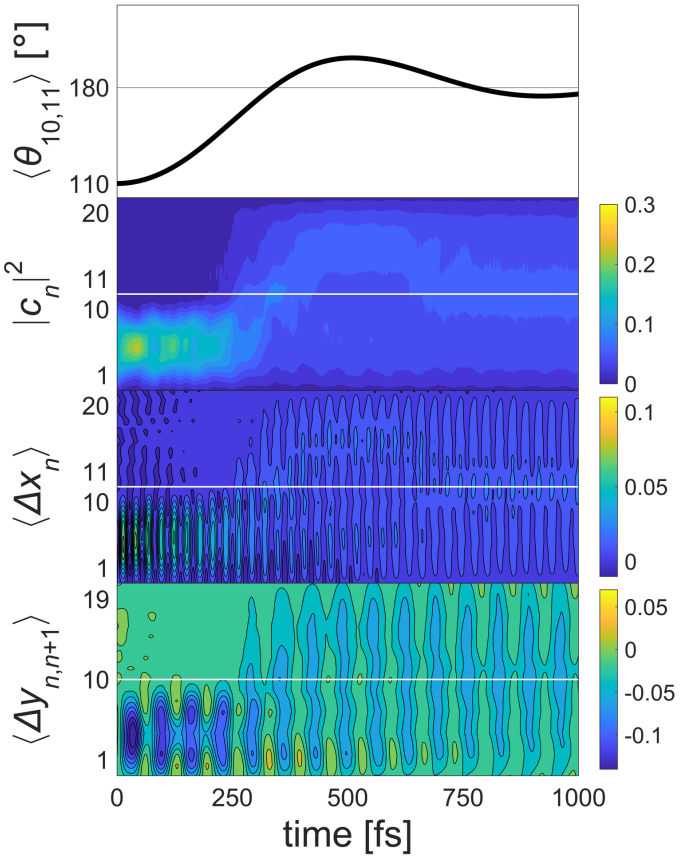
Liang, Cotton, Binder, Hegger, Burghardt, Miller, J. Chem. Phys., in press (2018)

Ehrenfest/Langevin dynamics (T=0K)

Ehrenfest – single trajectory



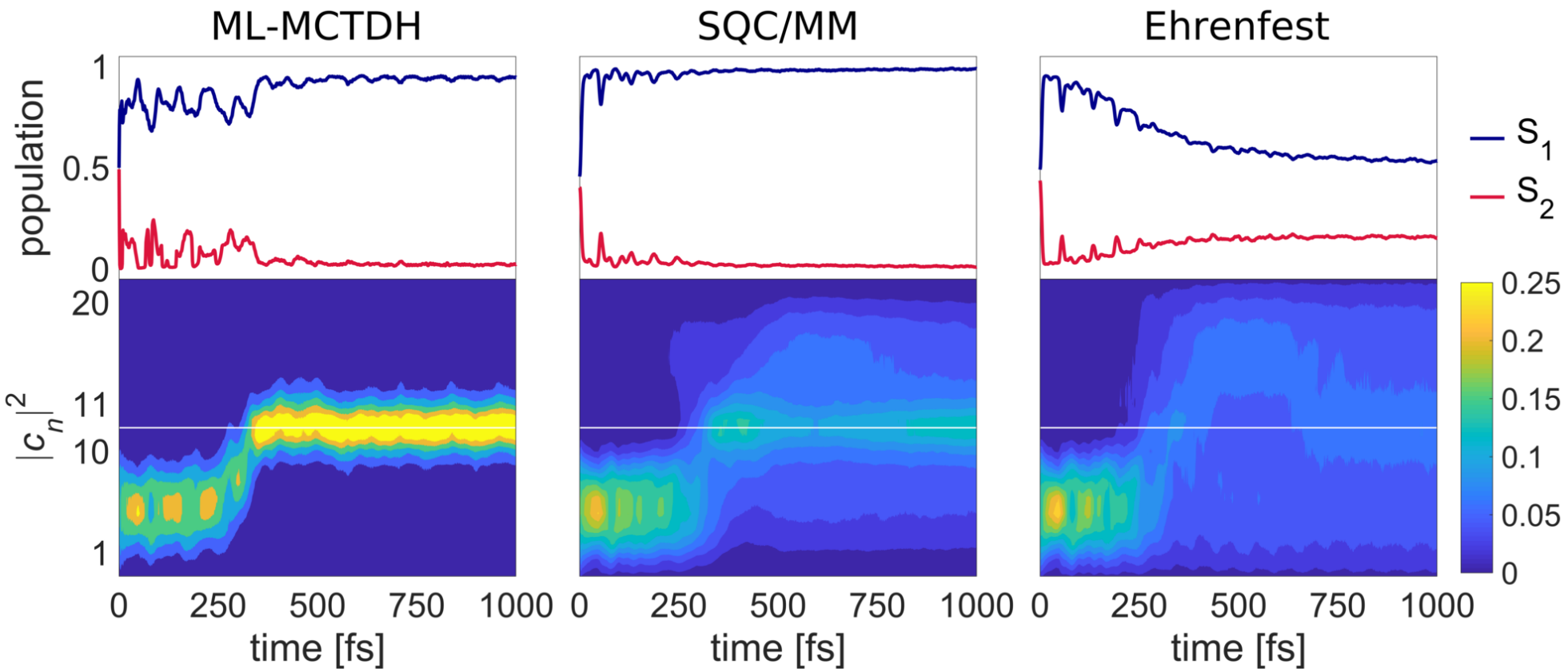
Ehrenfest – Wigner average



- single-trajectory dynamics exhibits fluctuations
- Wigner average "fuzzy" – due to Wigner sampling of high-frequency modes

Liang, Cotton, Binder, Hegger, Burghardt, Miller, J. Chem. Phys., in press (2018)

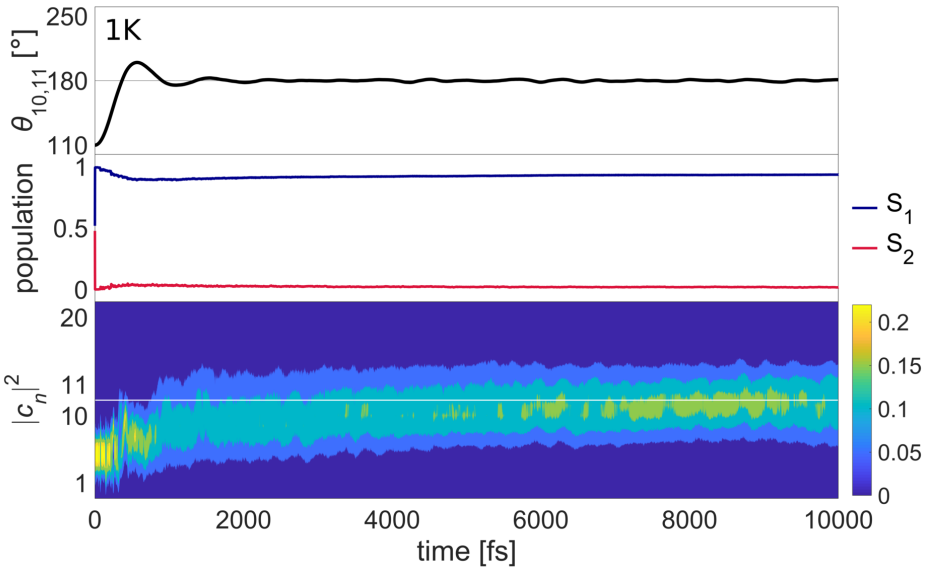
Adiabatic Populations (T=0K)

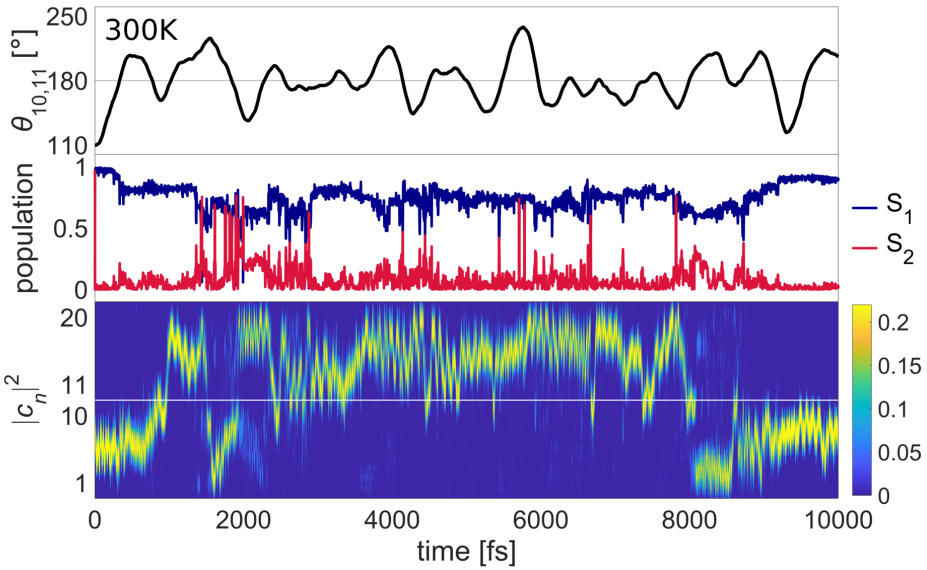


- SQC/MM reproduces the adiabatic populations quite accurately
- Ehrenfest shows severe shortcomings (related to detailed-balance problem)
- both methods incur problems due to ZPE of high-frequency modes

Liang, Cotton, Binder, Hegger, Burghardt, Miller, J. Chem. Phys., in press (2018)

Temperature Effects: Ehrenfest/Langevin dynamics

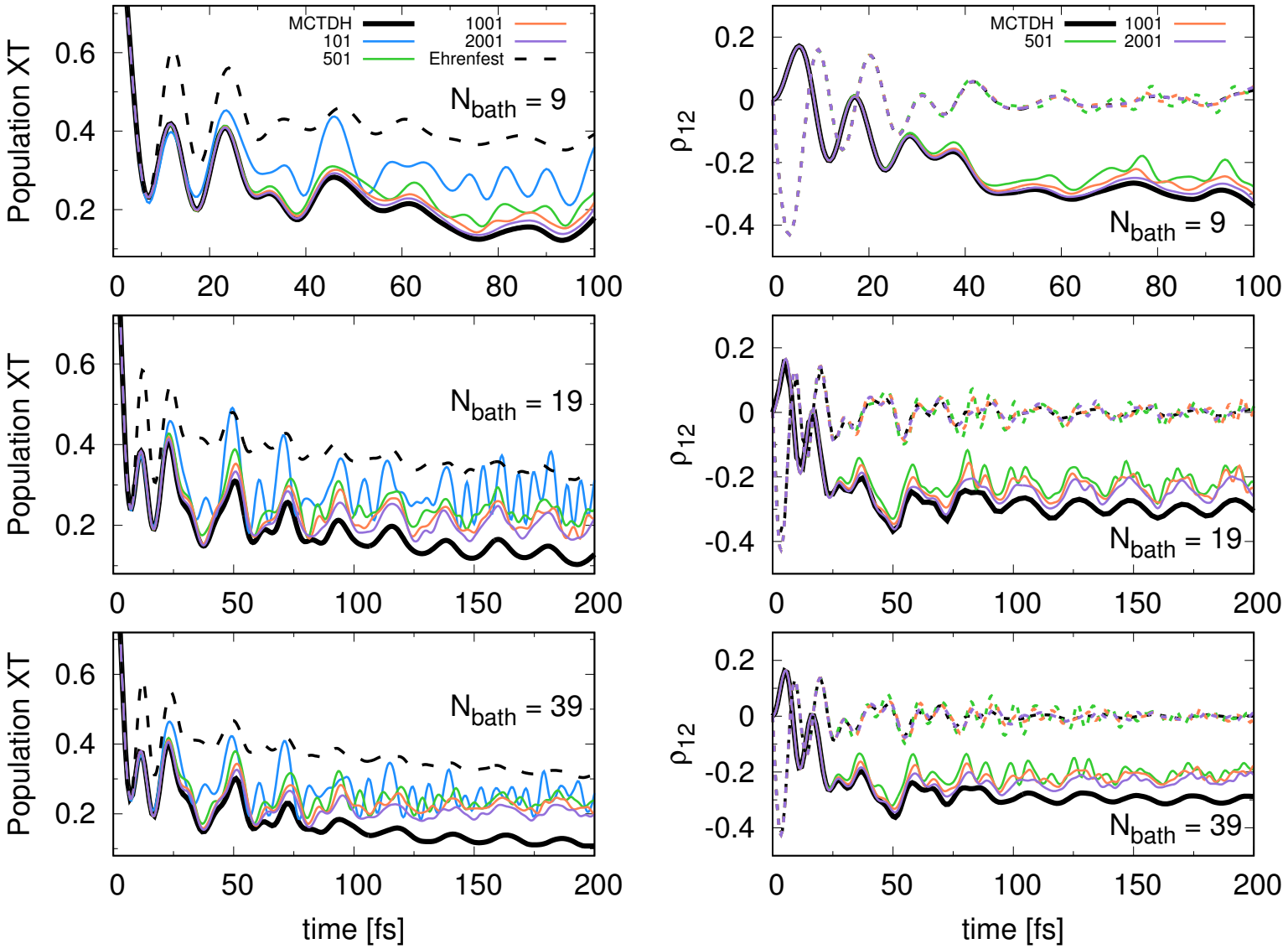




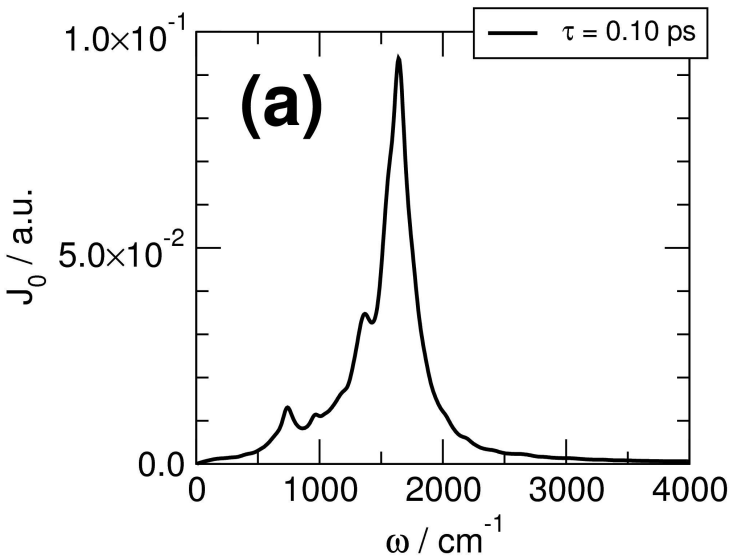
- single-trajectory simulation, with ZPE of high-frequency modes removed
- exciton migration at higher T is related to repeated non-adiabatic events
- interplay of torsional fluctuations and trapping explains observations
- quantum benchmark simulations needed (*via* random-phase wavefunctions, or thermofield method, combined with MCTDH)

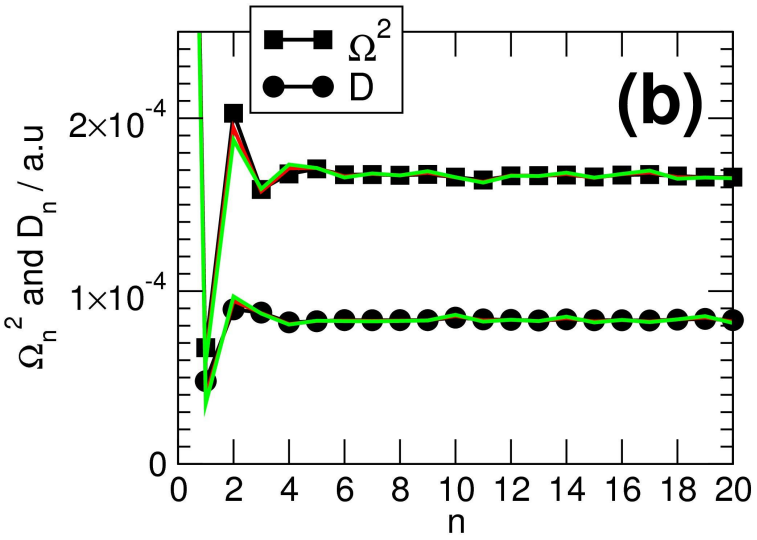
Wahl, Hegger, Binder, Burghardt, in preparation

Multiconfigurational Ehrenfest Dynamics, Cont'd



G-MCTDH: System-Bath Models





- discretized bath spectral densities (SDs) represented by "GWP bath"
- hierarchical chain representations of SDs that are (partially) represented by GWPs including Langevin closure

$$\hat{H}_{SB} + \hat{H}_B = \hat{s} \sum_i c_n \hat{x}_n + \hat{H}_B \longrightarrow D\hat{s}\hat{X}_1 + D_{12}\hat{X}_1\hat{X}_2 + \ldots + \hat{X}_M\text{–residual bath}$$

Approximate SD's: Mth Order Truncation

$$J(\omega) = \frac{\pi}{2} \sum_n \frac{c_n^2}{\omega_n} \delta(\omega - \omega_n) \quad \longleftrightarrow \quad J^{(M)}(\omega) = \lim_{\varepsilon \to 0^+} \mathrm{Im}\, K_B^{(M)}(\omega - i\varepsilon)$$

Hughes, Christ, Burghardt, JCP 131, 124108 (2009), Garg, Onuchic, Ambegaokar, JCP 83, 4491 (1985), Leggett, Phys. Rev. B 30, 1208 (1984)

$$K_B^{(M)}(z) = -\cfrac{D_{0,1}^2}{\Omega_1^2 - z^2 - \cfrac{D_{1,2}^2}{\Omega_2^2 - z^2 - \cdots \cfrac{D_{M-2,M-1}^2}{\Omega_{M-1}^2 - z^2 - \cfrac{D_{M-1,M}^2}{\Omega_M^2 - z^2 - z^2 I^M(z)}}}}$$

Ohmic closure:

$$I^M_{\mathrm{ohm}}(z) = -i\frac{\gamma}{z}$$

Rubin (quasi-Ohmic) closure:

$$I^M_{\mathrm{Rubin}}(z) = \frac{1}{2z} \frac{{\Lambda_R}^2 - 2z^2 + 2iz\sqrt{{\Lambda_R}^2 - z^2}}{z + i\sqrt{{\Lambda_R}^2 - z^2}}$$

Hughes, Christ, Burghardt, J. Chem. Phys. 131, 024109 (2009), Martinazzo, Vacchini, Hughes, Burghardt, J. Chem. Phys. 134, 011101 (2011)