Nonequilibrium Quantum Dynamics of Ultracold Bosonic and Fermionic Mixtures: from Few- to Many-Body Systems

Peter Schmelcher
Zentrum für Optische Quantentechnologien
Universität Hamburg

WORKSHOP ON 'SMALL AND MEDIUM SIZED COLD ATOM SYSTEMS'
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The Centre for Optical Quantum Technologies

Experiment and Theory
Workshop and Guest Program

in collaboration with

- Methodology: L. Cao, S. Krönke, O. Vendrell (ML-MCTDHB)
- Applications: L. Cao, S. Krönke, R. Schmitz, J. Knörzer, S. Mistakidis, L. Katsimiga, G. Koutentakis, J. Schurer, A. Negretti, J. Chen

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SFB 925: Light induced dynamics and control of strongly correlated quantum systems

Contents

1. Introduction and Motivation

Introduction and Motivation

An exquisite control over the external and internal degrees of freedom of atoms developed over decades lead to the realization of **Bose-Einstein Condensation** in dilute alkali gases at nK temperatures.

Key tools available:

- Laser and evaporative cooling
- Magnetic, electric and optical dipole traps
- Optical lattices and atom chips
- Feshbach resonances (mag-opt-conf) for tuning of interaction

Introduction and Motivation

Enormous degree of control concerning preparation, processing and detection of ultracold atoms !

Weak to strongly correlated **many-body** systems:

- BEC nonlinear mean-field physics (solitons, vortices, collective modes,...)
- Strongly correlated many-body physics (quantum phases, Kondo- and impurity physics, disorder, Hubbard model physics, high T_c superconductors,...)

Few-body regime:

- Novel mechanisms of transport and tunneling
- Atomtronics (Switches, diodes, transistors, ...)
- Quantum information processing

Introduction: Some facts

Hamiltonian: $\mathcal{H} = \sum_i \left(\frac{\mathbf{p}_i^2}{2m_i} + V(\mathbf{r}_i) \right) + \frac{1}{2} \sum_{i,j,i \neq j} W(\mathbf{r}_i - \mathbf{r}_j)$

V is the trap potential: harmonic, optical lattice, etc.

W describes interactions: contact $g\delta(\mathbf{r}_i - \mathbf{r}_j)$, dipolar, etc.

Dynamics is governed by TDSE: $i\hbar\partial_t \Psi(\mathbf{r}_1, ..., \mathbf{r}_N, t) = \mathcal{H}\Psi(\mathbf{r}_1, ..., \mathbf{r}_N, t)$

Ideal Bose-Einstein condensate: no interaction $g = 0 \Rightarrow$ Macroscopic matter wave.

$$\Phi(\mathbf{r}_1, ..., \mathbf{r}_N) = \prod_{i=1}^{N} \phi(\mathbf{r}_i)$$

Hartree product: bosonic exchange symmetry.

Interaction $g \neq 0$: Mean-field description leads to Gross-Pitaevskii equation with cubic nonlinearity, exact for $N \to \infty, g \to 0$.

Introduction: Some facts

Finite, and in particular 'stronger' interactions:

- **Correlations are ubiquitous**
- A multiconfigurational ansatz is necessary

$$\Psi(\mathbf{r}_1, ..., \mathbf{r}_N, t) = \sum_i c_i \Phi_i(\mathbf{r}_1, ..., \mathbf{r}_N, t)$$

$\Rightarrow$ Ideal laboratory for exploring the **dynamics of correlations** (beyond mean-field):

- Preparation of correlated initial states
- Spreading of localized/delocalized correlations ?
- Time-dependent 'management' and control of correlations ?
- Is there universality in correlation dynamics ?

Introduction and Motivation

Calls for a versatile tool to explore the (nonequilibrium) quantum dynamics of ultracold bosons: **Wish list**

- Take account of all correlations (numerically exact)
- Applies to different dimensionality
- Time-dependent Hamiltonian: Driving
- Weak to strong interactions (short and long-range)
- Few- to many-body systems
- Mixed systems: different species, mixed dimensionality
- Efficient and fast

Introduction and Motivation

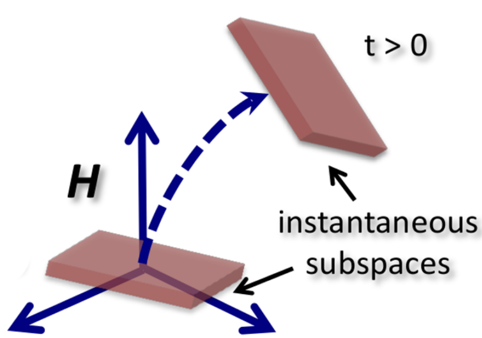
Multi-Layer Multi-Configuration Time-Dependent Hartree for Bosons (ML-MCTDHB) is a significant step in this direction !

In the following: A brief account of the methodology and then some selected diverse applications to ultracold bosonic systems.

2. Methodology: The ML-MCTDHB Approach

The ML-MCTDHB Method

- **aim:** numerically exact solution of the time-dependent Schrödinger equation
  for a quite general class of interacting many-body systems
- **history:** [H-D Meyer. *WIREs Comp. Mol. Sci.* **2**, 351 (2012).]
  MCTDH (1990): few distinguishable DOFs, quantum molecular dynamics
  ML-MCTDH (2003): more distinguishable DOFs, distinct subsystems
  MCTDHF (2003): indistinguishable fermions
  MCTDHB (2007): indistinguishable bosons
- **idea:**
  use a time-dependent, optimally moving basis in the many-body Hilbert space



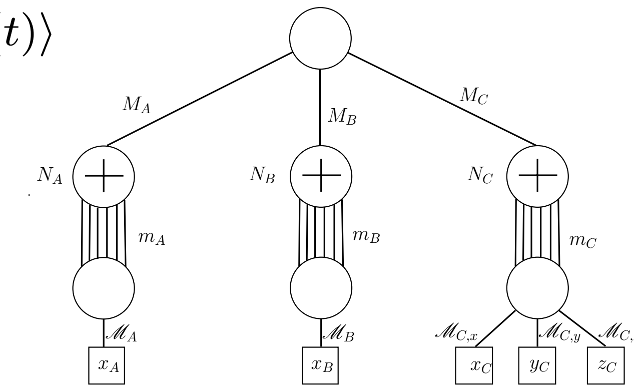
Hierarchy within ML-MCTDHB

We make an ansatz for the state of the total system $|\Psi_t\rangle$ with time-dependencies on different *layers*:

top layer $|\Psi_t\rangle = \sum_{i_1=1}^{M_1} \dots \sum_{i_S=1}^{M_S} A_{i_1,\dots,i_S}(t) \bigotimes_{\sigma=1}^{S} |\psi_{i_\sigma}^{(\sigma)}(t)\rangle$

species layer $|\psi_k^{(\sigma)}(t)\rangle = \sum_{\vec{n}|N_\sigma} C_{k;\vec{n}}^{\sigma}(t)\, |\vec{n}\rangle(t)$

particle layer $|\phi_k^{(\sigma)}(t)\rangle = \sum_{i=1}^{n_\sigma} B_{k;i}^{\sigma}(t)|u_i\rangle$



- Mc Lachlan variational principle: Propagate the ansatz $|\Psi_t\rangle \equiv |\Psi(\{\lambda_t^i\})\rangle$, $\lambda_t^i \in \mathbb{C}$ according to $i\partial_t|\Psi_t\rangle = |\Theta_t\rangle$ with $|\Theta_t\rangle \in \text{span}\{\frac{\partial}{\partial \lambda_t^k}|\Psi(\{\lambda_t^i\})\rangle\}$ minimizing the error functional $|||\Theta_t\rangle - \hat{H}|\Psi_t\rangle||^2$
[AD McLachlan. *Mol. Phys.* **8**, 39 (1963).]
- In this sense, we obtain a *variationally* optimally moving basis!
- Dynamical truncation of Hilbert space on all layers
- Single species, single orbital on particle layer $\rightarrow$ Gross-Pitaevskii equation ! (Nonlinear excitations: Solitons, vortices,...)

The ML-MCTDHB equations of motion

- top layer EOM:

$$i\partial_t A_{i_1,\dots,i_S} = \sum_{j_1=1}^{M_1} \dots \sum_{j_S=1}^{M_S} \langle \psi_{i_1}^{(1)} \dots \psi_{i_S}^{(S)} |\ \hat{H}\ | \psi_{j_1}^{(1)} \dots \psi_{j_S}^{(S)} \rangle\ A_{j_1,\dots,j_S}$$

$$\text{with} \quad |\psi_{j_1}^{(1)} \dots \psi_{j_S}^{(S)}\rangle \equiv |\psi_{j_1}^{(1)}\rangle \otimes \dots \otimes |\psi_{j_S}^{(S)}\rangle$$

$\Rightarrow$ system of coupled linear ODEs with time-dependent coefficients due to the time-dependence in $|\psi_j^{(\sigma)}(t)\rangle$ and $|\phi_j^{(\sigma)}(t)\rangle$

$\Rightarrow$ reminiscent of the Schrödinger equation in matrix representation

- species layer EOM:

$$i\partial_t C^{\sigma}_{i;\vec{n}} = \langle \vec{n}|(\mathbb{1} - \hat{P}^{spec}_{\sigma}) \sum_{j,k=1}^{M_\sigma} \sum_{\vec{m}|N_\sigma} [(\rho^{spec}_{\sigma})^{-1}]_{ij} \langle \hat{H} \rangle^{\sigma,spec}_{jk} |\vec{m}\rangle\ C^{\sigma}_{k;\vec{m}}$$

$\Rightarrow$ system of coupled non-linear ODEs with time-dependent coefficients due to the time-dependence of the $|\phi_j^{(\sigma)}(t)\rangle$ and of the top layer coefficients

The ML-MCTDHB equations of motion

- particle layer EOM:

$$i\partial_t|\phi_i^{(\sigma)}\rangle = (\mathbb{1} - \hat{P}_\sigma^{part}) \sum_{j,k=1}^{m_\sigma} [(\rho_\sigma^{part})^{-1}]_{ij} \langle\hat{H}\rangle_{jk}^{\sigma,part} |\phi_k^{(\sigma)}\rangle$$

$\Rightarrow$ system of coupled non-linear partial integro-differential equations (ODEs, if projected on $|u_k^{(\sigma)}\rangle$, respectively) with time-dependent coefficients due to time-dependence of the $C_{i;\vec{n}}^{\sigma}$ and $A_{i_1,\ldots,i_S}$

Lowest layer representations:

- **Discrete Variable Representation (DVR):**
  implemented DVRs: harmonic, sine (hardwall b.c.), exponential (periodic b.c.), radial harmonic, Laguerre
- Fast Fourier Transform

Stationary states via improved relaxation involving imaginary time propagation !

S Krönke, L Cao, O Vendrell, P S, *New J. Phys.* **15, 063018 (2013).**

L Cao, S Krönke, O Vendrell, P S, *J. Chem. Phys.* **139, 134103 (2013).**

L Cao, V Bolsinger, SI Mistakidis, GM Koutentakis, S Krönke, J Schurer and P S, *J. Chem. Phys.* **147, 044106 (2017).**

3. Tunneling mechanisms in the double and triple well

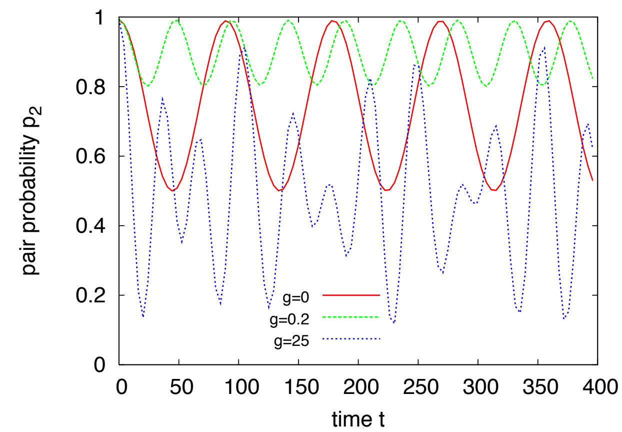
Few-boson systems - Perspectives

- Extensive experimental control of few-boson systems possible: Loading, processing and detection

  [I. Bloch *et al*, Nature **448**, 1029 (2007)]

- Bottom-up understanding of tunneling processes and mechanisms
- Atomtronics perspective providing us with controllable atom transport on individual atom level:
  - Diodes, transistors, capacitors, sources and drains
- Double well, triple well, waveguides, etc.

Few-boson systems: Double Well



- No interactions: Rabi oscillations.
- Weak interactions: Delayed tunneling.
- Intermediate interactions:
  - Tunneling comes almost to a hold in spite of repulsive interactions.
  - Pair tunneling takes over !
- Very strong interactions: Fragmented pair tunneling.

▷ $N = 2$ atoms

K. Winkler *et al.*, Nature **441**, 853 (2006); S. Fölling *et al.*, Nature **448**, 1029 (2007)

S. Zöllner, H.D. Meyer and P.S., PRL **100**, 040401 (2008); PRA **78**, 013621 (2008)

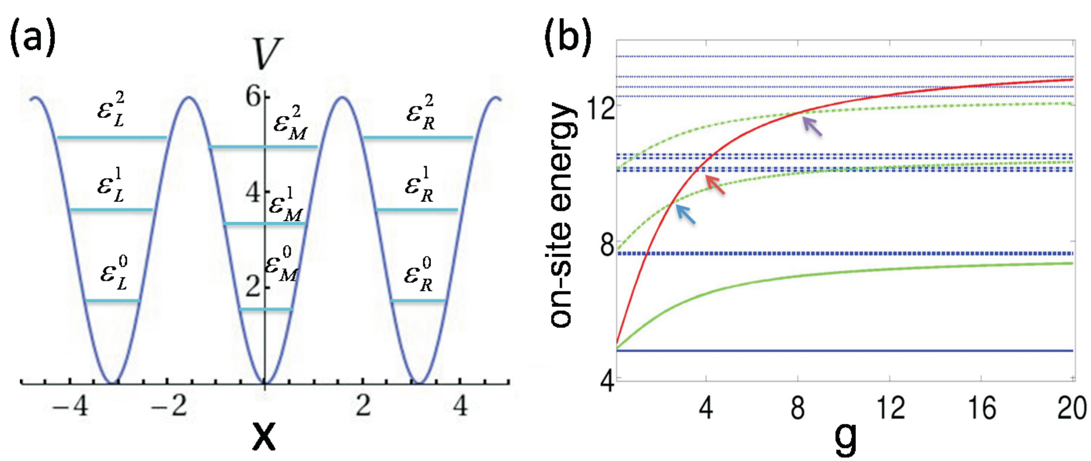
Interband Tunneling: Motivation

Here: Bottom-up approach of understanding the tunneling mechanisms !

- Triple well is minimal system analog of a source-gate-drain junction for atomtronics
- Triple well shows novel tunneling scenarios $\Leftrightarrow$ Impact on transport
- Strong correlation effects beyond single band approximation !
- Beyond the well-known suppression of tunneling: Multiple windows of enhanced tunneling i.e. revivals of tunneling: Interband tunneling involving higher bands !

Interband Tunneling: Analysis Tool

- Methodology: Multi-Layer Multi-Configuration Time-Dependent Hartree for Bosons
- Novel number-state representation including interaction effects for analysis

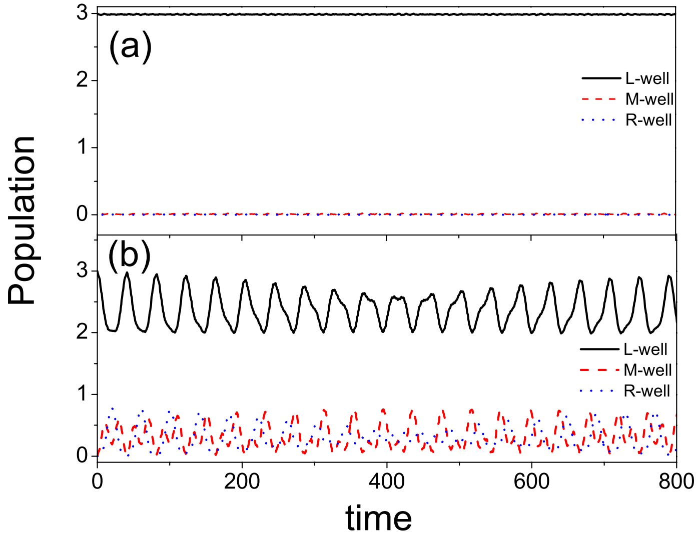


Three bosons: Single, pair and triple modes.

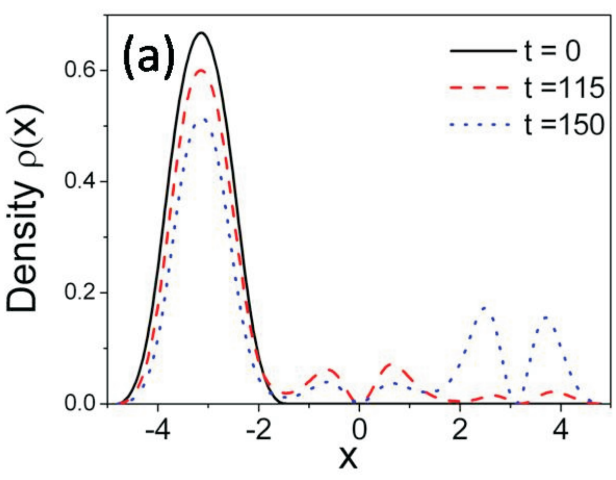
Interband Tunneling: Single boson tunneling

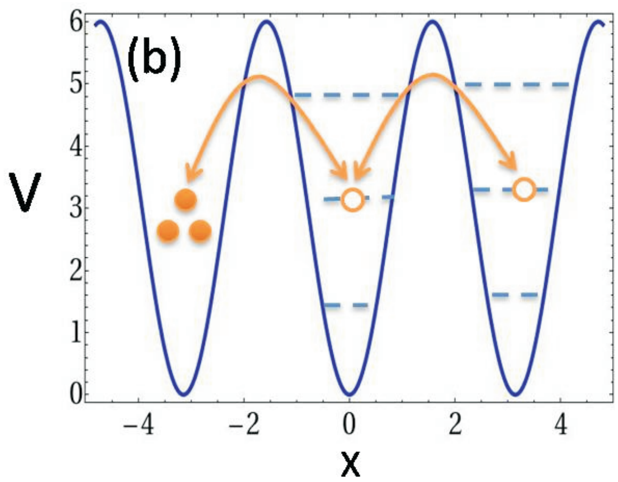
Three bosons initially in the left well: $\Psi \approx |3,0,0\rangle_0$

(a) $g = 0.1$ and (b) $g = 3.26$



Single boson tunneling to middle and right well via $|3,0,0\rangle_0 \Leftrightarrow |2,1,0\rangle_1 \Leftrightarrow |2,0,1\rangle_1$ i.e. via first-excited states !

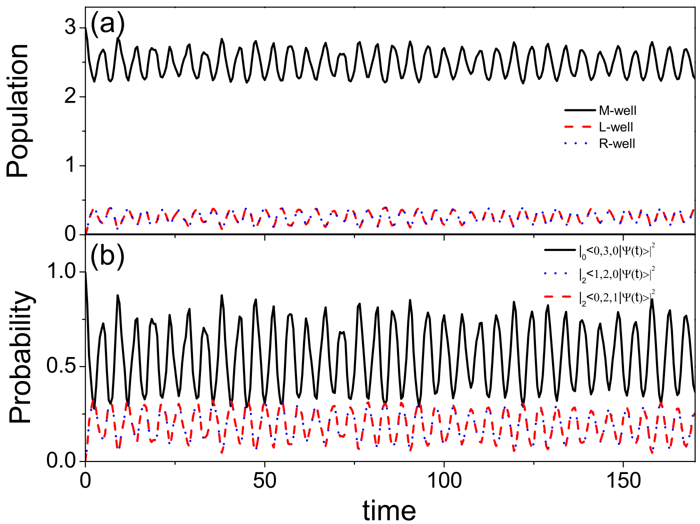




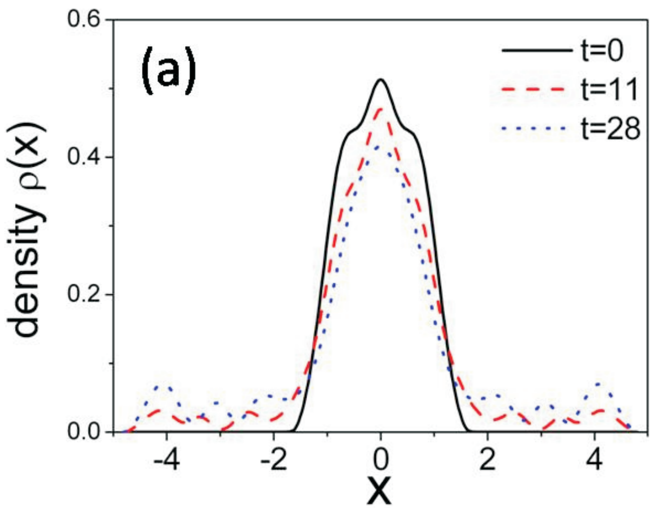
Interband Tunneling: Single boson tunneling

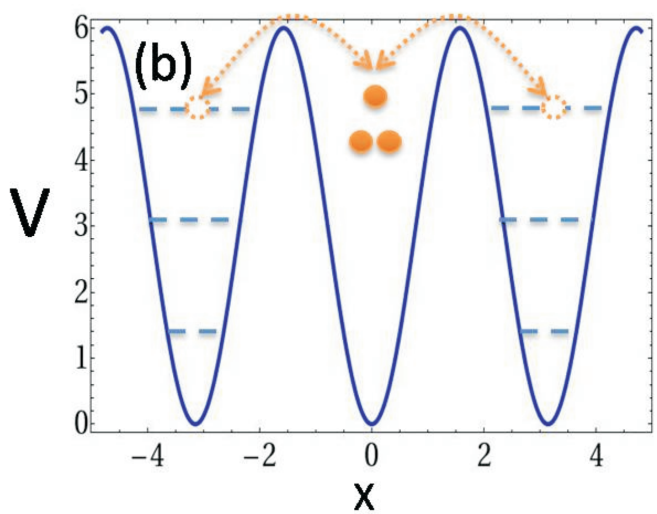
Three bosons initially in the middle well: $\Psi \approx |0,3,0\rangle_0$

(a) $g = 9.85$



Single boson tunneling to left and right well via $|0,3,0\rangle_0 \Leftrightarrow |1,2,0\rangle_3 \Leftrightarrow |0,2,1\rangle_3$ i.e. via second-excited states !

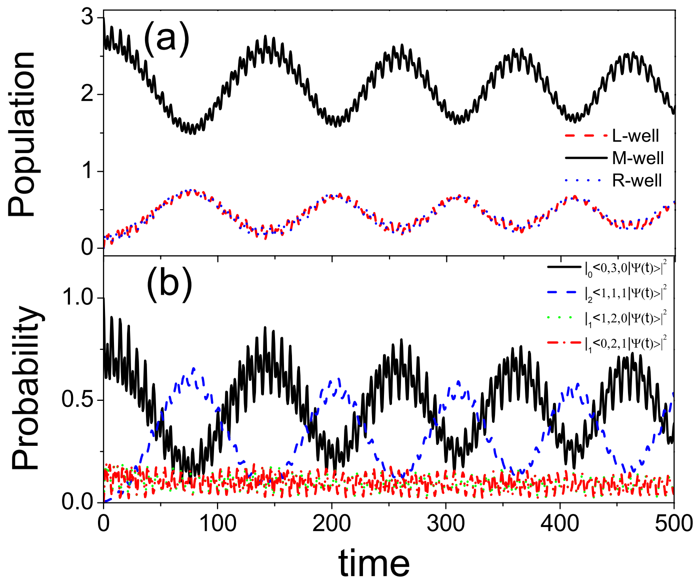




Interband Tunneling: Two boson tunneling

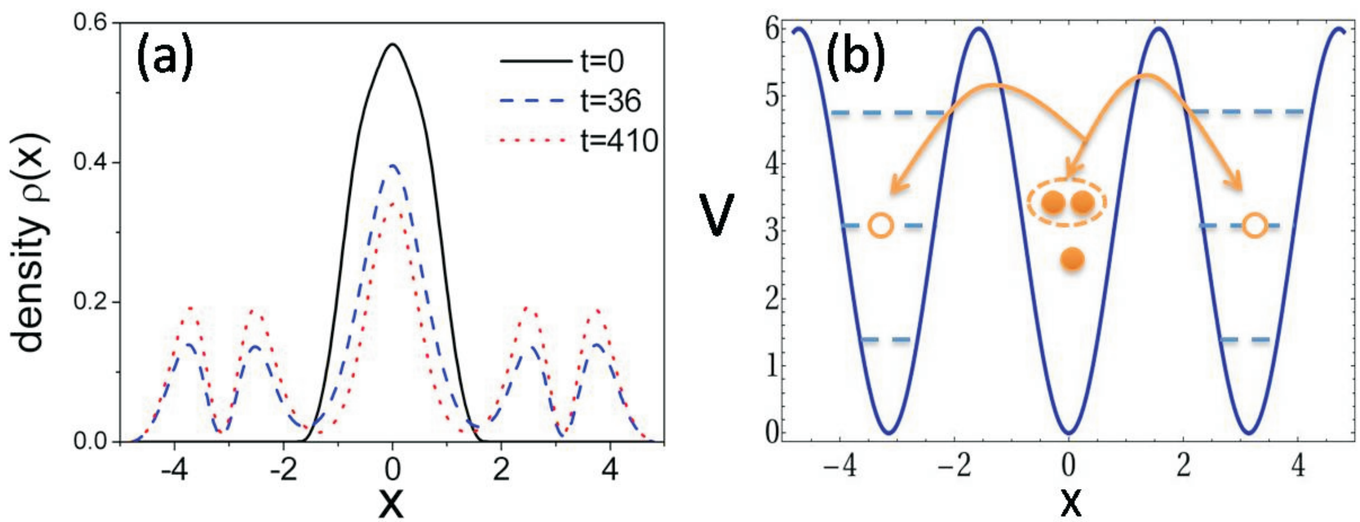
Three bosons initially in the middle well: $\Psi \approx |0,3,0\rangle_0$

(a) $g = 5.8$



Two boson tunneling to the left and right well via $|0,3,0\rangle_0 \Leftrightarrow |1,1,1\rangle_6$ i.e. two first-excited states !

Cao *et al*, NJP **13**, 033032 (2011)



4. Multi-mode quench dynamics in optical lattices

Main features

Focus: Correlated non-equilibrium dynamics of in one-dimensional finite lattices following a sudden interaction quench from weak (SF) to strong interactions!

Phenomenology: Emergence of density-wave tunneling, breathing and cradle-like processes.

Mechanisms: Interplay of intrawell and interwell dynamics involving higher excited bands.

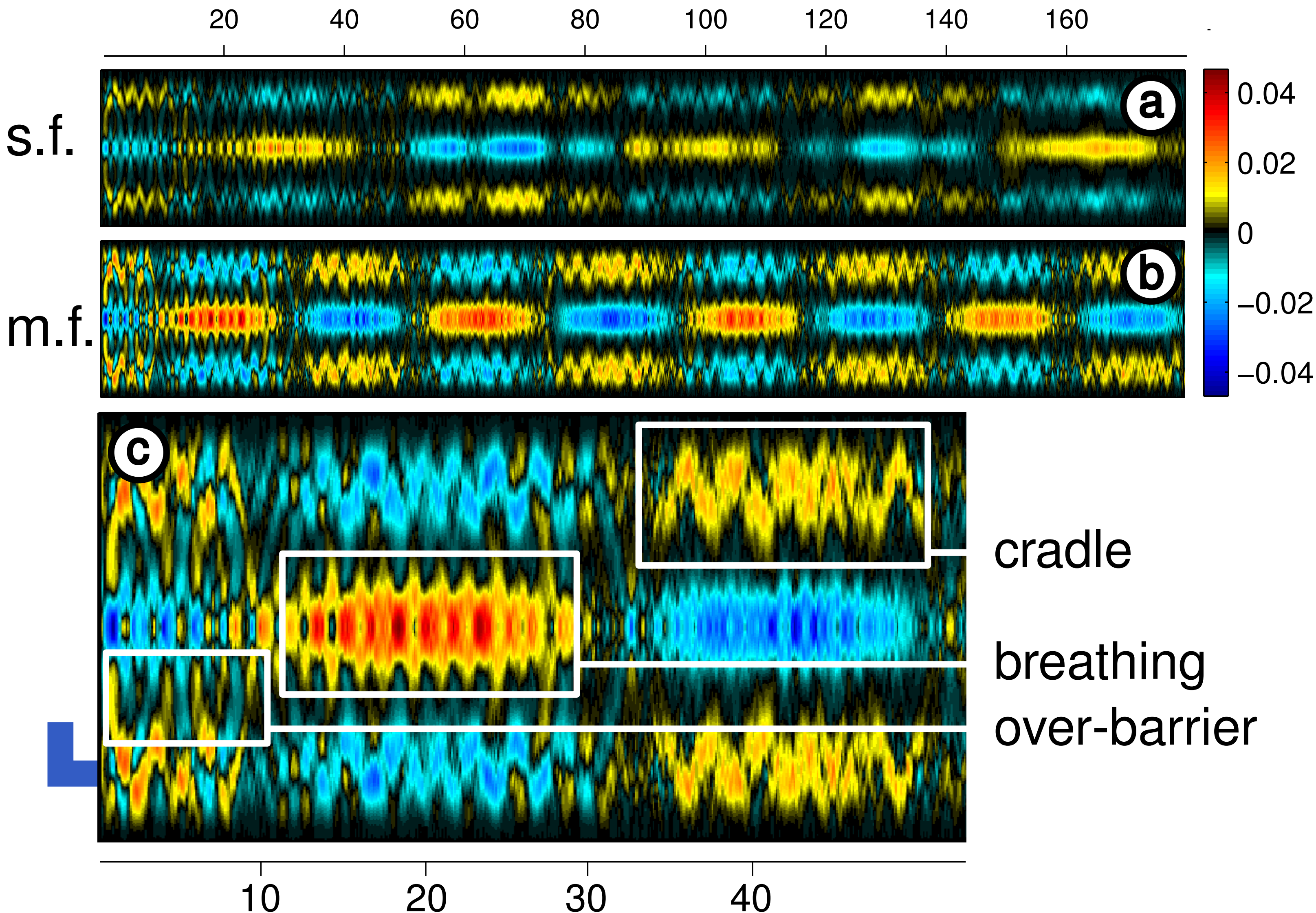
Resonance phenomena: Coupling of density-wave and cradle modes leads to a corresponding beating phenomenon !

$\Rightarrow$ Effective Hamiltonian description and tunability.

Incommensurate filling factor $\nu > 1 (\nu < 1)$

Post quench dynamics....

Fluctuations $\delta\rho(x,t)$ of the one-body density for weaker (a) and stronger (b) quench: Spatiotemporal oscillations.

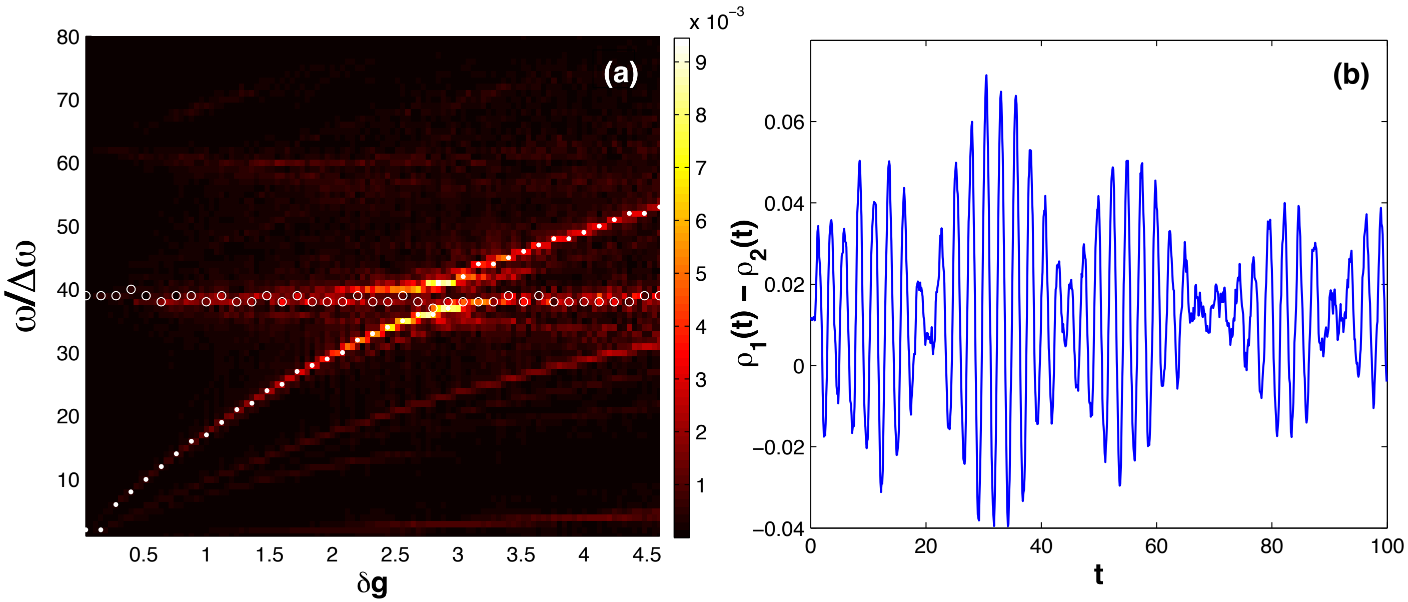


Density waves and their tunneling.

Mode analysis

- Density tunneling mode: Global ’envelope’ breathing
  - Identification of relevant tunneling branches (number state analysis)
  - Fidelity analysis shows 3 relevant frequencies: pair and triple mode processes
  - Transport of correlations and dynamical bunching antibunching transitions
- On-site breathing and craddle mode: Similar analysis possible involving now higher excitations

Craddle and tunneling mode interaction



Fourier spectrum of the intrawell-asymmetry $\Delta\rho_L(\omega)$:

Avoided crossing of tunneling and craddle mode !

$\Rightarrow$ Beating of the craddle mode - resonant enhancement.

S.I. Mistakidis, L. Cao and P. S., JPB 47, 225303 (2014), PRA 91, 033611 (2015)

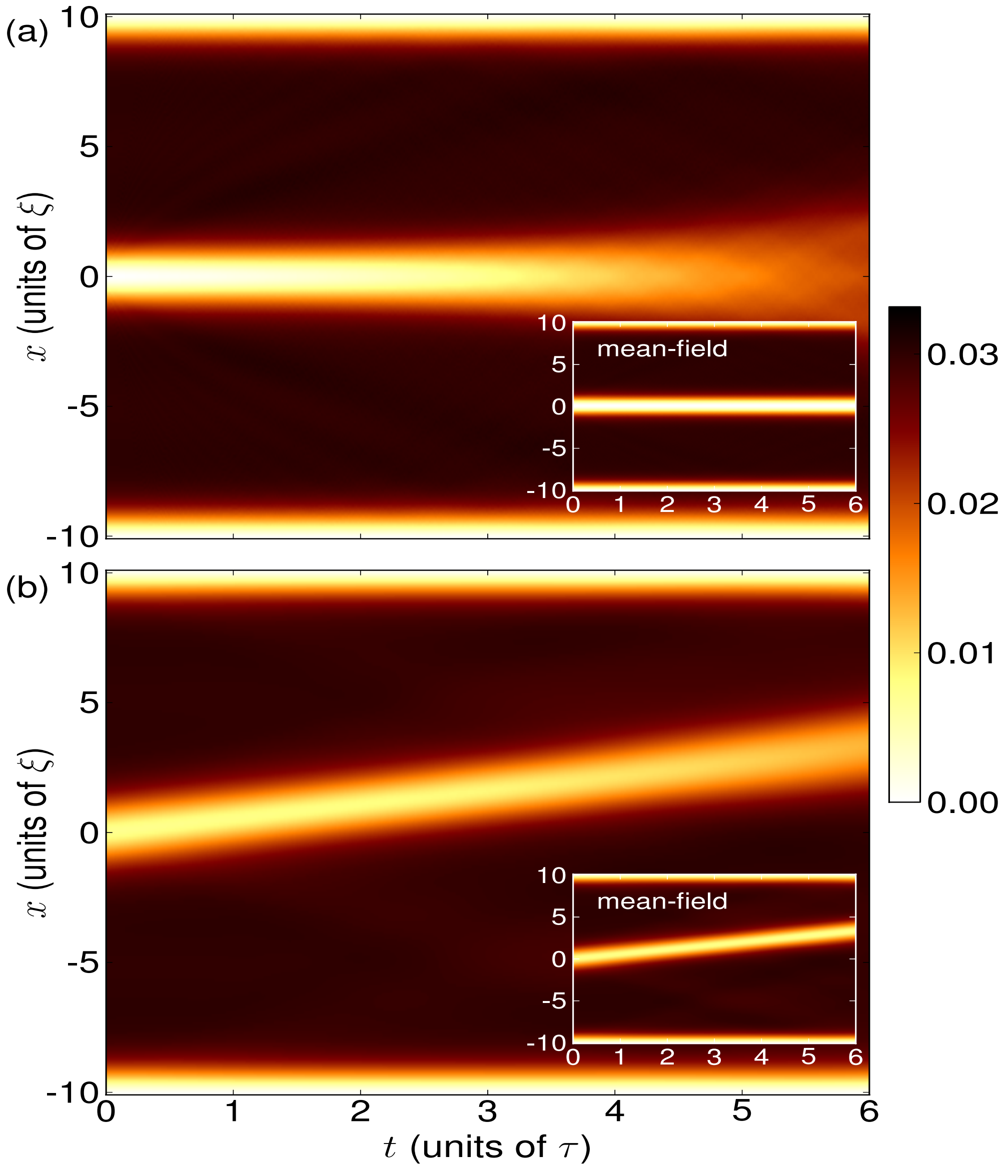
5. Many-body processes in black and grey matter-wave solitons

Setup and preparation

- N weakly interacting bosons in a one-dimensional box
- Initial many-body state: Little depletion, density and phase as close as possible to dark soliton in the dominant natural orbital
- Preparation: Robust phase and density engineering scheme.

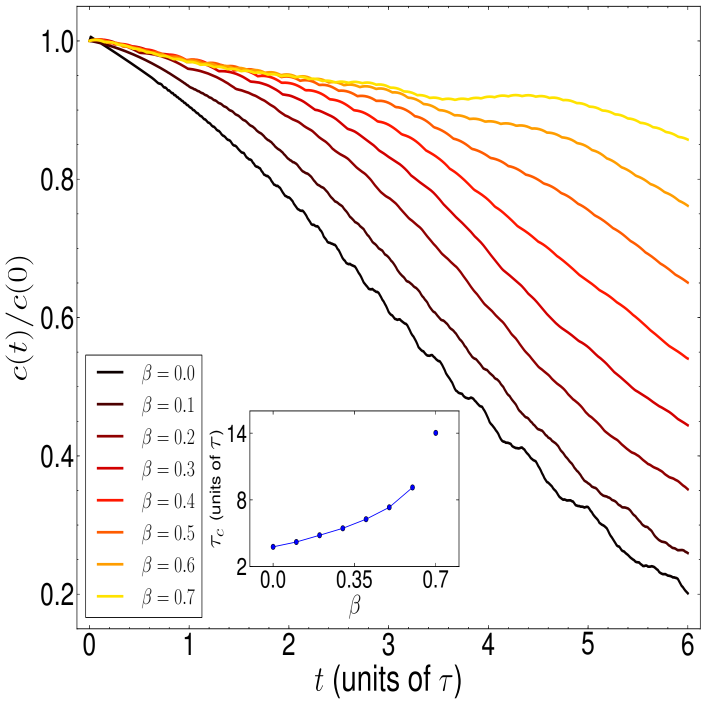
  CARR ET AL, PRL 103, 140403 (2009); PRA 80, 053612 (2009); PRA 63, 051601 (2001); RUOSTEKOSKI ET AL, PRL 104, 194192 (2010)

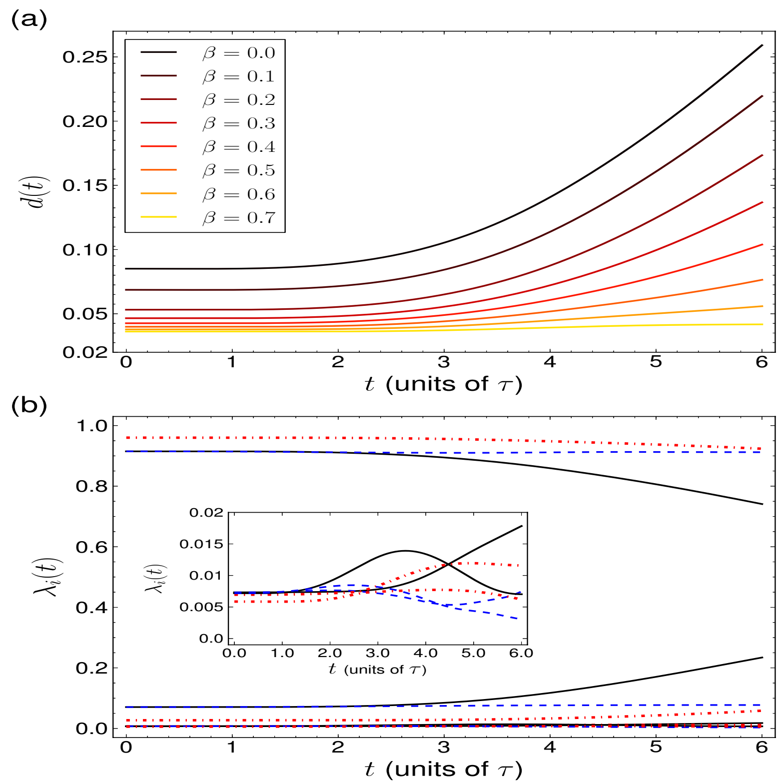
Density dynamics



- Reduced one-body density $\rho_1(x,t)$
- $N = 100$, $\gamma = 0.04$
- Black (top) and grey (bottom) soliton
- $M = 4$ optimized orbitals
- Inset: Mean-field theory (GPE)
- Slower filling process of density dip for moving soliton

Evolution of contrast and depletion

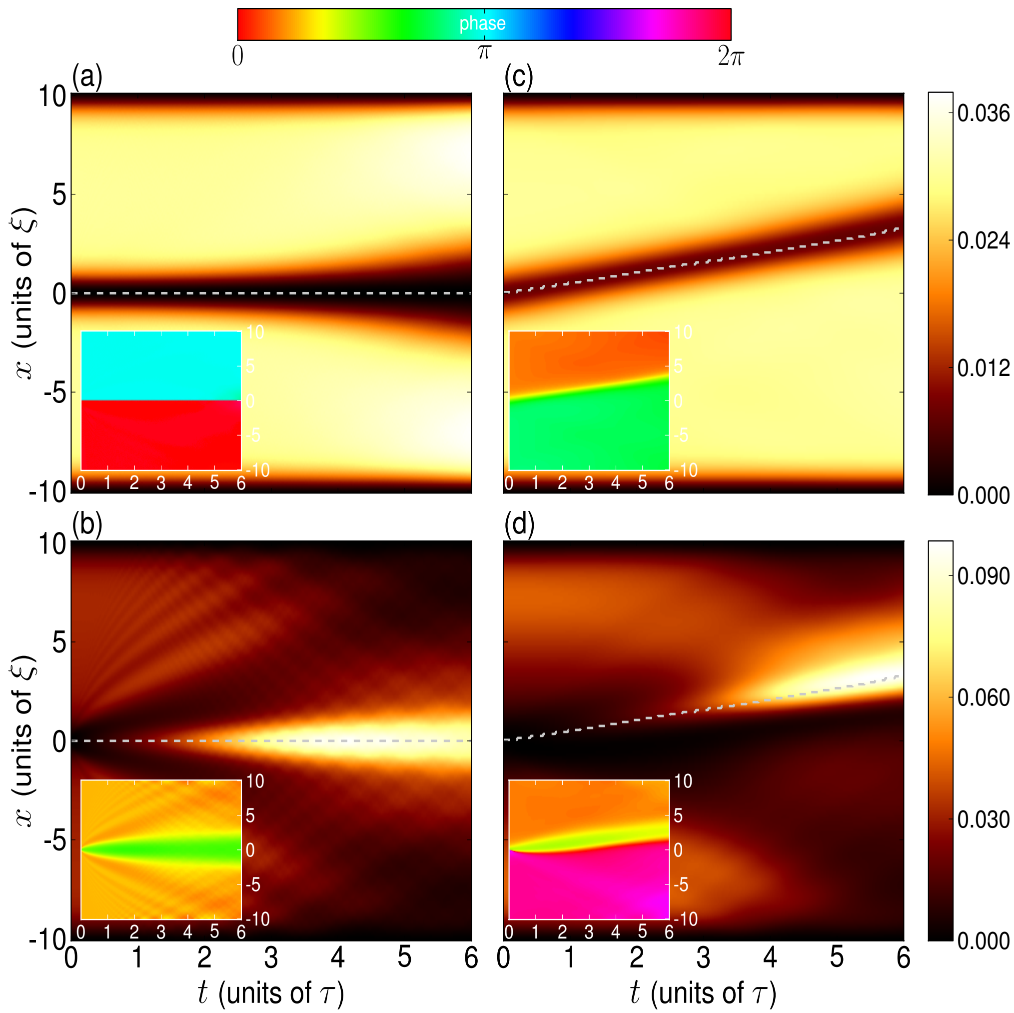




- Relative contrast $c(t)/c(0)$ of dark solitons for various $\beta = \frac{u}{s}$ ($c(t) = \frac{\max \rho_1(x,0) - \rho_1(x_t^s,t)}{\max \rho_1(x,0) + \rho_1(x_t^s,t)}$)

- Dynamics of quantum depletion $d(t) = 1 - \max_i \lambda_i(t) \in [0,1]$ and evolution of the natural populations $\lambda_i(t)$ for $\beta = 0.0$ (solid black lines) and $\beta = 0.5$ (dashed dotted red lines). $\hat{\rho}_1(t) = \sum_{i=1}^{M} \lambda_i(t) \, |\varphi_i(t)\rangle\langle\varphi_i(t)|$

Natural orbital dynamics

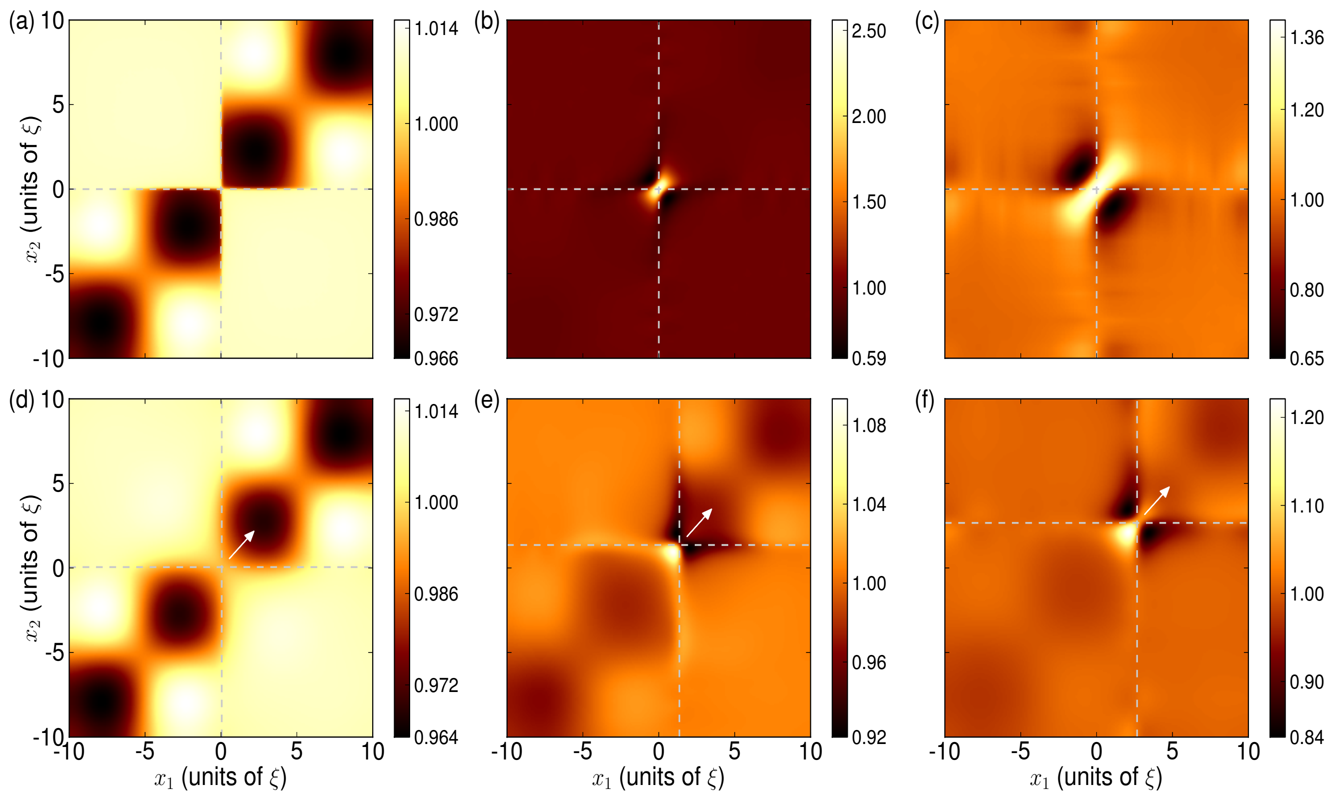


- Density and phase (inset) evolution of the dominant and second dominant natural orbital. (a,b) black soliton (c,d) grey soliton $\beta = 0.5$.

Localized two-body correlations

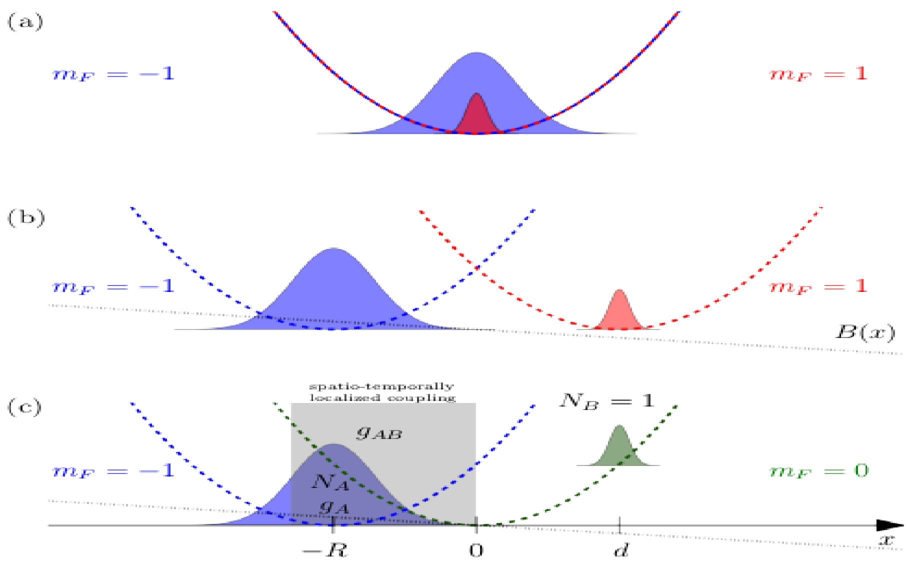
- Two-body correlation function $g_2(x_1, x_2; t)$ for a black soliton (first row) and a grey soliton $\beta = 0.5$ (second) at times $t = 0.0$ (first column), $t = 2.5\tau$ (second) and $t = 5\tau$ (third).

S. Krönke and P.S., PRA 91, 053614 (2015)



6. Correlated dynamics of a single atom coupling to an ensemble

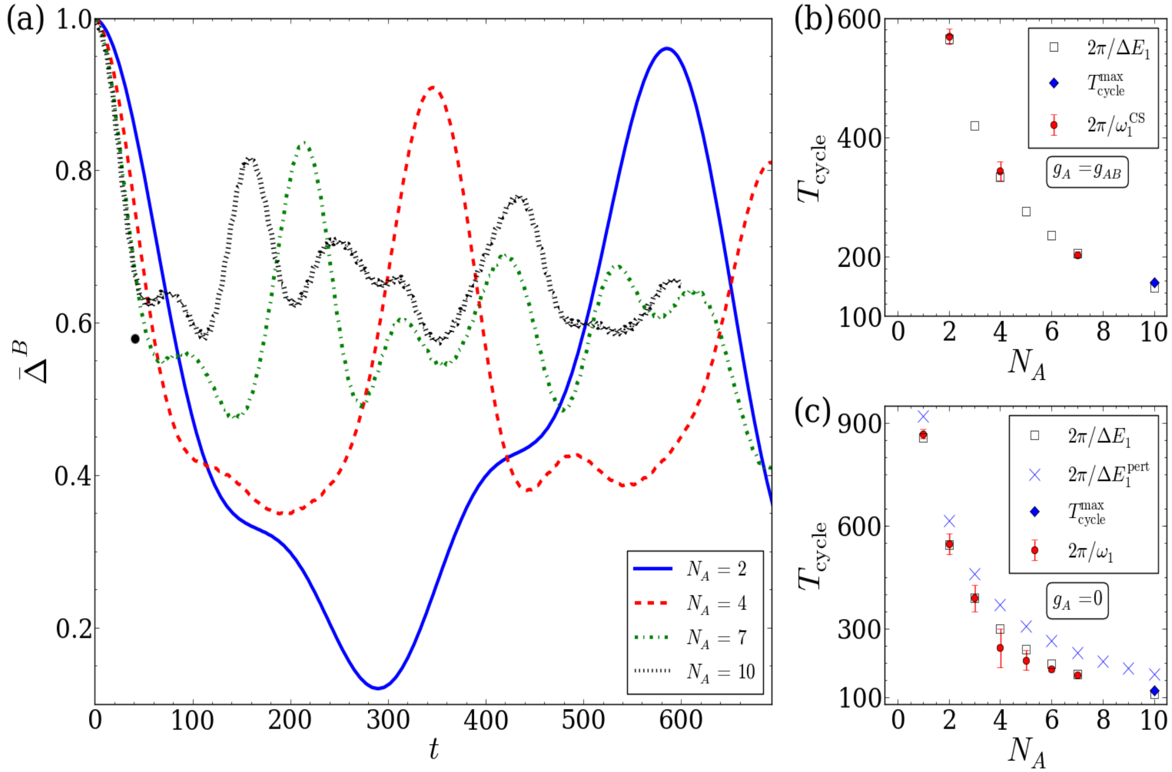
Setup and preparation



- Bipartite system: impurity atom plus ensemble of e.g. bosons of different $m_F = \pm 1$ trapped in optical dipole trap
- Application of external magnetic field gradient separates species
- Initialization in a displaced ground ie. coherent state via RF pulse to $m_F = 0$ for impurity atom.
- $\Rightarrow$ Single atom collisionally coupled to an atomic reservoir: Energy and correlation transfer - entanglement evolution.

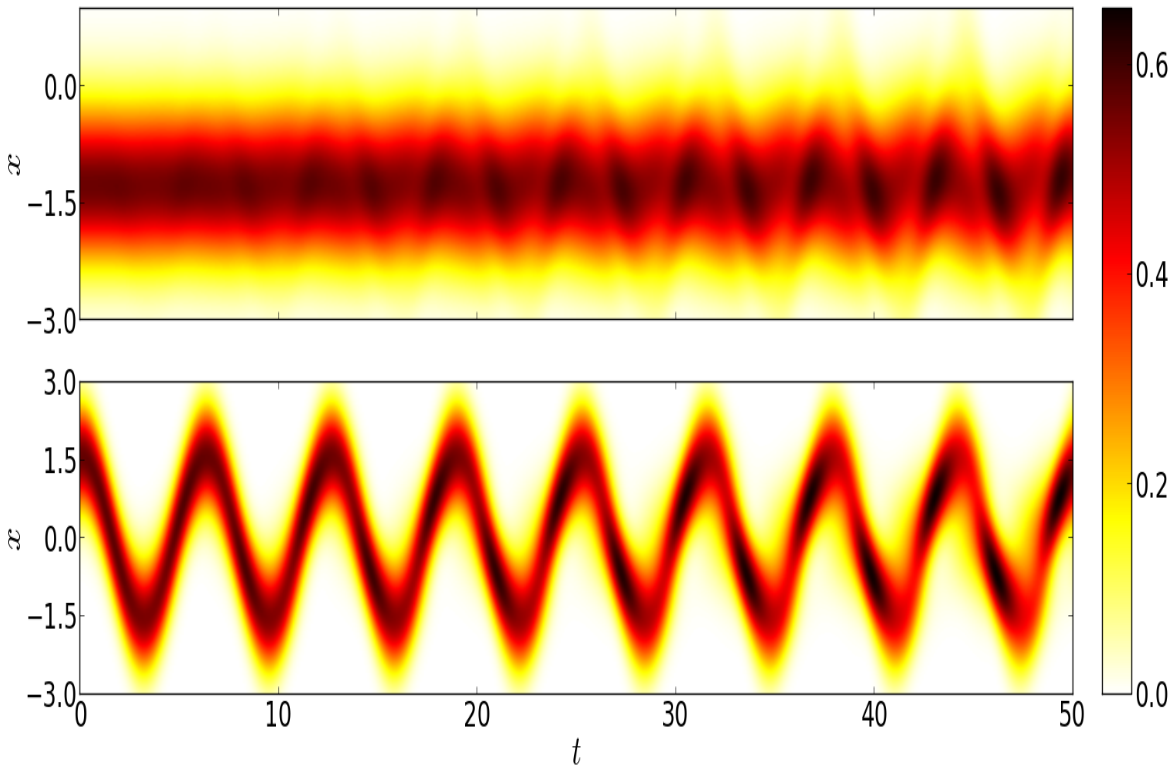
J. Knörzer, S. Krönke and P.S., NJP 17, 053001 (2015)

Energy transfer



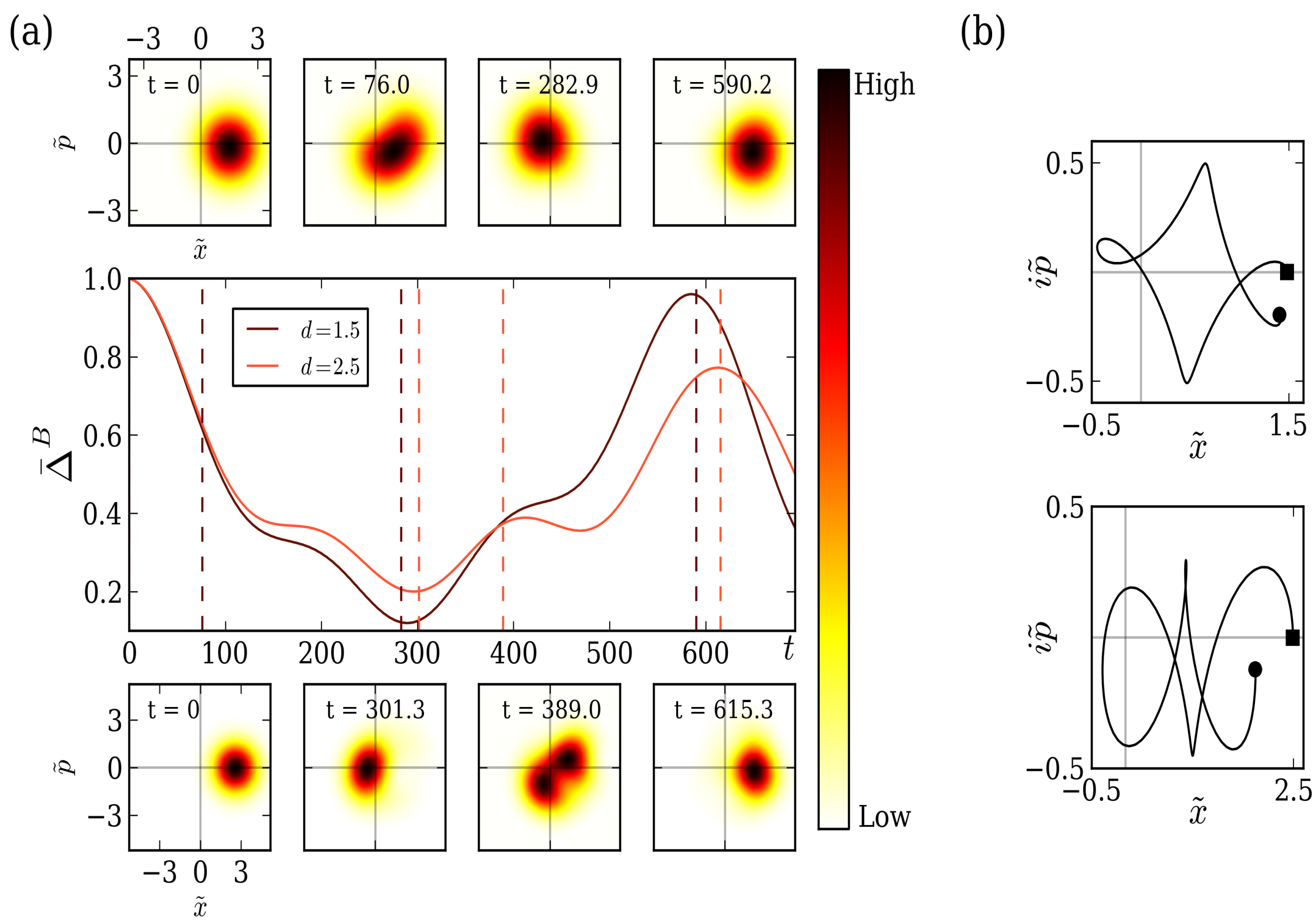
- Spatiotemporally localized inter-species coupling: Focus on long-time behaviour over many cycles.
- Energy transfer cycles with varying particle number of the ensemble

One-body densities



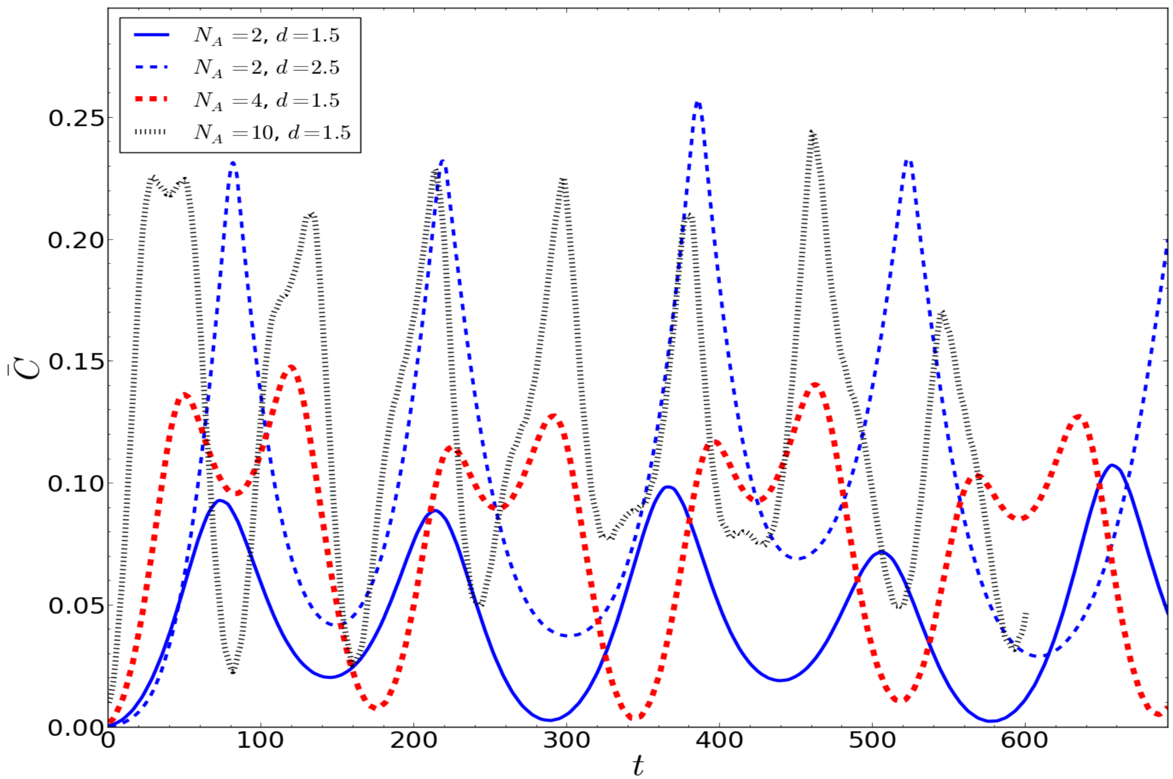
- Time-evolution of densities for the two species (ensemble-top, impurity-bottom) for first eight impurity oscillations.
- Impurity atom initiates oscillatory density modulations in ensemble atoms.
- Backaction on impurity atom.

Coherence analysis



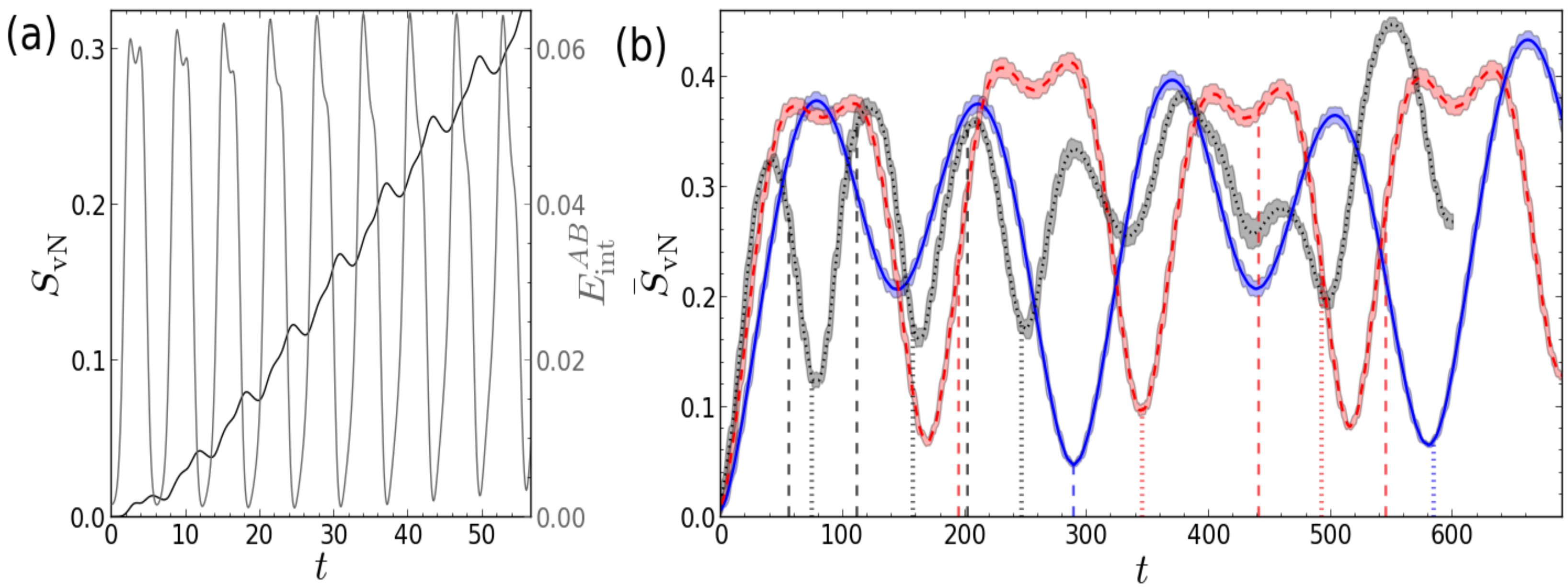
Time-evolution of normalized excess energy Δ_t^B with Husimi distribution $Q_t^B(z,z^*) = \frac{1}{\pi}\langle z|\hat{\rho}_t^B|z\rangle\,, \quad z \in \mathbb{C}$ of reduced density $\hat{\rho}_t^B$ at certain time instants.

Coherence measure



Distance (operator norm) to closest coherent state, as a function of time for different atom numbers in the ensemble.

Correlation analysis



- (a) Short-time evolution of the von Neumann entanglement entropy $S_{\rm vN}(t)$ and inter-species interaction energy $E_{\rm int}^{AB}(t) = \langle \hat{H}_{AB} \rangle_t$.
- (b) Long-time evolution of $\bar{S}_{\rm vN}(t)$. for $N_A = 2$ (blue solid line), $N_A = 4$ (red, dashed) and $N_A = 10$ (black, dotted).

J. KNÖRZER, S. KRÖNKE AND P.S., NJP 17, 053001 (2015)

Other projects...

- Correlation effects in the quench-induced phase separation dynamics of a two species ultracold quantum gas

  S.I. Mistakidis, G.C. Katsimiga, P.G. Kevrekidis and P. S., New J. Phys. 20, 043052 (2018)

- Correlation induced localization of lattice trapped bosons coupled to a Bose-Einstein condensate

  K. Keiler, S. Krönke and P. S., New J. Phys. 20, 033030 (2018)

- Spectral properties and breathing dynamics of a few-body Bose-Bose mixture in a 1D harmonic trap

  M. Pyzh, S. Krönke, C. Weitenberg and P.S., New J. Phys. 20, 015006 (2018)

- Dark-bright soliton dynamics beyond the mean-field approximation

  G. C. Katsimiga, G.M. Koutentakis, S.I. Mistakidis, P. G. Kevrekidis and P.S., New J. Phys. 19, 073004 (2017)

Other projects...

- Probing Ferromagnetic Order in Few-Fermion Correlated Spin-Flip Dynamics G. M. Koutentakis, S. I. Mistakidis, P. S., arxiv 1804.07199
- Repulsive Fermi Polarons and Their Induced Interactions S.I. Mistakidis, G.C. Katsimiga, G.M. Koutentakis and P.S., in preparation
- Quantum point spread function for imaging trapped few-body systems with a quantum gas microscope S. Krönke, M. Pyzh, C. Weitenberg, P.S., arxiv 1806.08982

7. Structure of mesoscopic molecular ions

Motivation

Focusing on the physics of ions in a gas of trapped ultracold atoms: Hybrid atom-ion systems.

- Controlled state-dependent atom-ion scattering
- Ultracold chemical reactions and charge transport
- Novel tunneling and state-dependent transport processes
- Spin-dependent interactions
- Emulate condensed matter systems on a finite scale, including dynamics: polarons, charge-phonon coupling, ... PRL 111, 080501 (2013)
- Mesoscopic molecular ions and ion-induced density bubbles - PRL 89, 093001 (2002); PRA 81, 041601 (2010)

Setup and Methodology

- Atom-ion interaction introduces an additional length scale $R^* = \sqrt{\frac{2C_4\mu}{\hbar^2}}$ which has to be resolved
- Modelling of ultracold atom-ion collisions
  - QD-theory links defect parameters to asymptotic scattering properties
  - Model potential: $V(z) = V_0 e^{-\gamma z^2} - \frac{1}{z^4 + \frac{1}{\omega}}$
- 'Molecular' bound states: Only the weakest bound states are of relevance. Maximum is at positions of order R^*.
- Methodology: Multi-Layer Multi-Configuration Time-Dependent Hartree for Bosons (Fermions)

S. Krönke, L. Cao, O. Vendrell, P.S., *New J. Phys.* **15**, 063018 (2013)

L. Cao, S. Krönke, O. Vendrell, P.S., *J. Chem. Phys.* **139**, 134103 (2013)

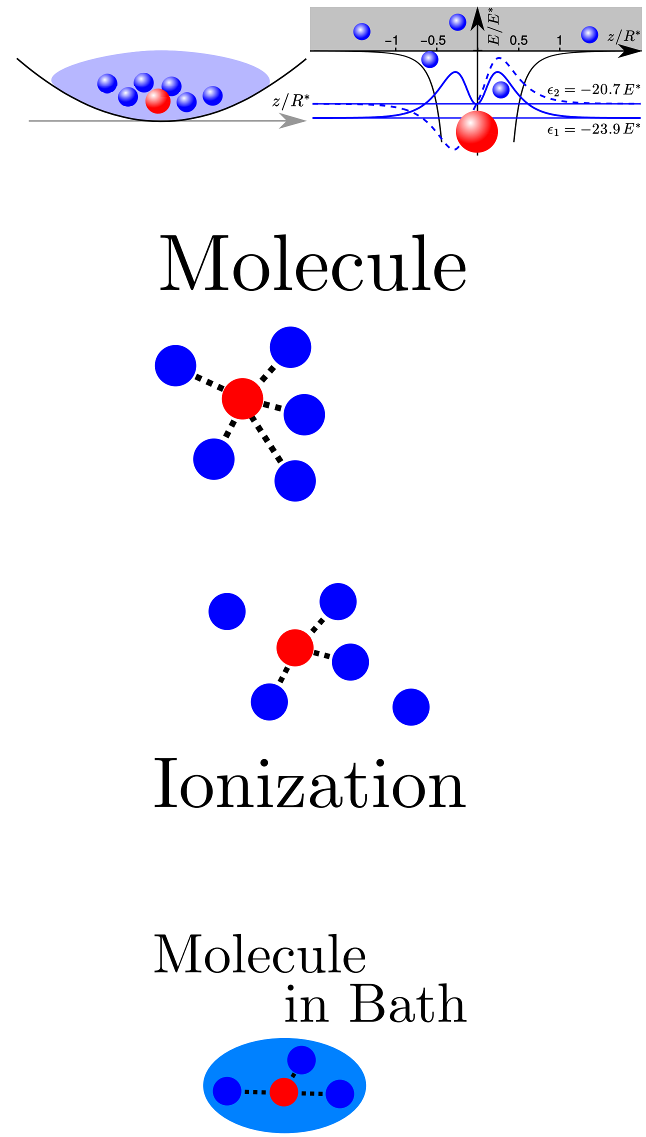
Overview of possible structures

Challenges:

- Include Motion of Ion
- Many-Body Bound States

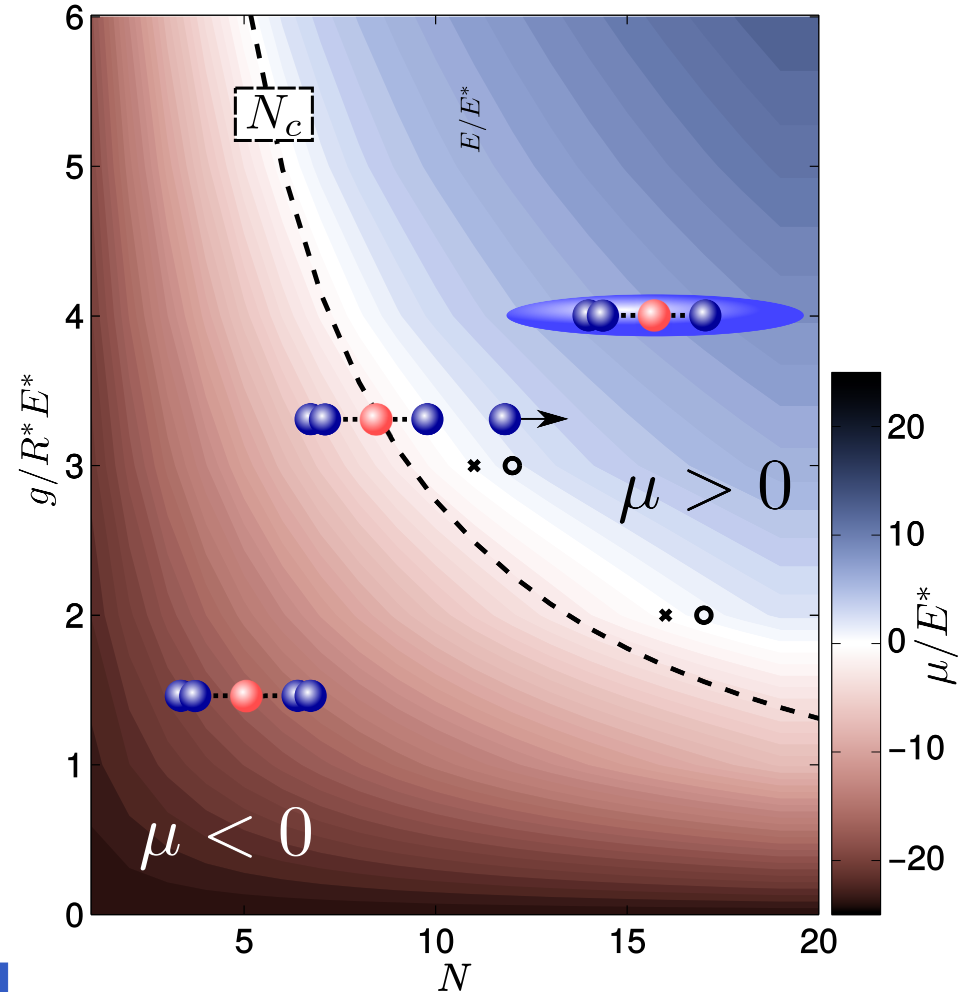
Main Observations:

- Formation of Ionic Molecule: Massive quantum object
- Phase diagram of compound system
- Stabilization by shell-structure formation
- Dynamical response
- Dissociation
- Strong self-localization of ion
- Formation of Thomas-Fermi bath



J. SCHURER, A. NEGRETTI AND P.S., PRL 119, 063001 (2017)

Phase diagram



- Two distinct phases:
  - $\mu < 0$: Mesoscopic charged molecule
  - $\mu > 0$: Unbound, but trapped, atomic fraction
  - Dissociation around $\mu = 0$ N_c for bound atoms
- Energetic considerations: $g_c \approx (\omega - \epsilon_1)/(N_c - 1)$
- Near linear decrease of $E(N)$

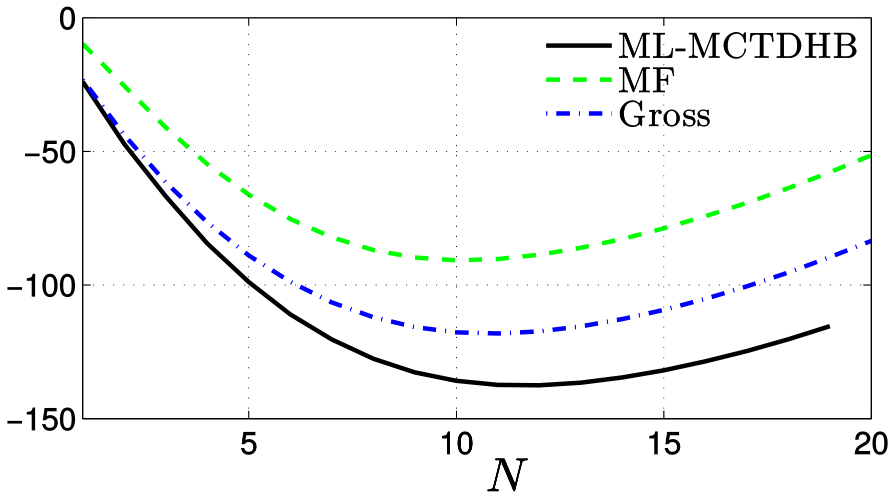
Nature of the many-body mesoscopic ion state

Possible Ansatzes

Mean-field: $\Psi_{\rm MF}(z_{\rm I}, z_1, \cdots, z_N) = \varphi(z_{\rm I}) \prod_{i=1}^{N} \chi(z_i)$

Product form in ion frame (Gross): $Z_{\rm I} = z_{\rm I}, Z_i = z_i - z_{\rm I}$
$\Psi_{\rm G}(Z_{\rm I}, Z_1, \cdots, Z_N) = \varphi(Z_{\rm I}) \prod_{i=1}^{N} \chi(Z_i)$

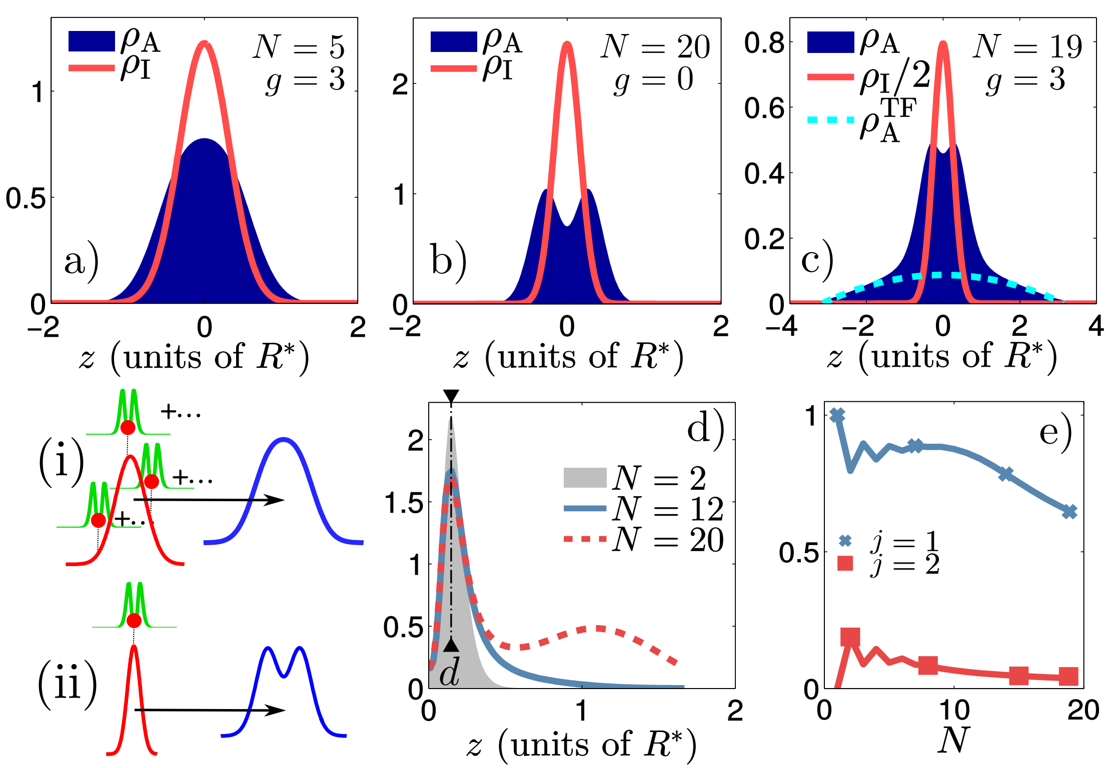
Fully correlated ML-MCTDHB approach: Imaginary time-propagation (relaxation).



$\frac{E}{E^*}$ as a function of N

Molecular structure: Densities and correlations

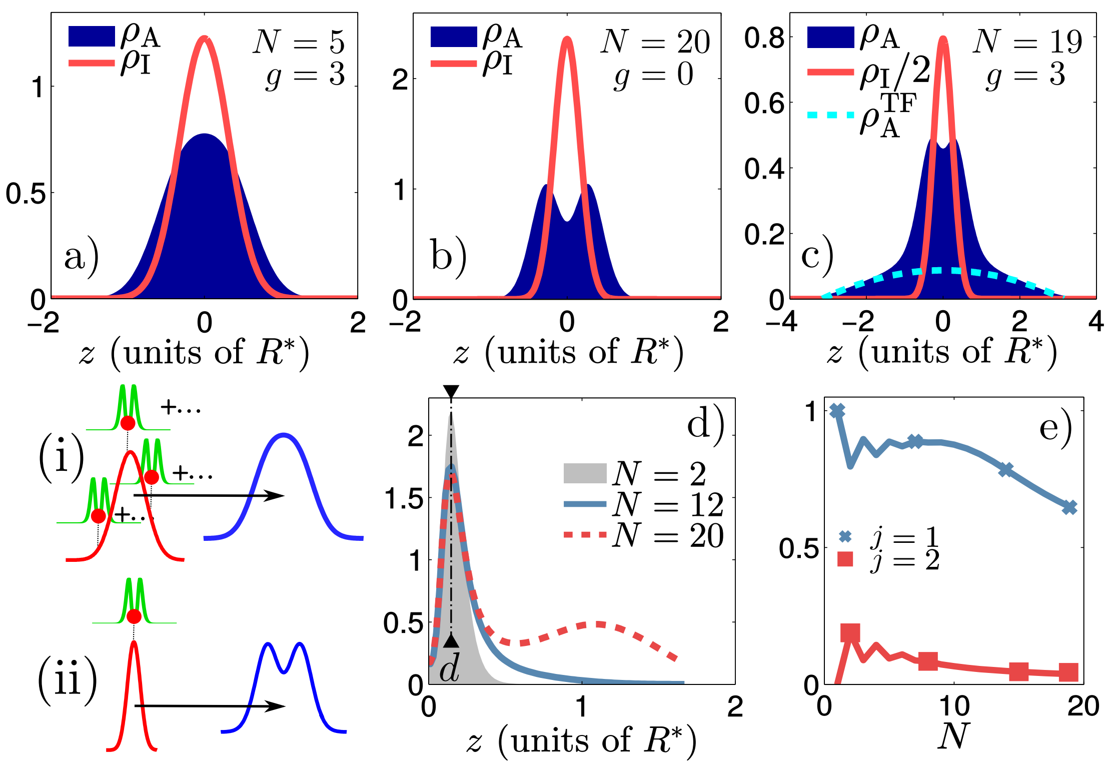
Inspect the atomic and ionic density profiles $\rho_{\mathrm{I(A)}}(z) = \langle \hat{\Psi}^\dagger_{\mathrm{I(A)}}(z) \hat{\Psi}_{\mathrm{I(A)}}(z) \rangle$



- Localization of ion for larger N
- Density wings of atoms around ion: Atom-ion induced density hole
- TF asymptotics masks strong correlations
- Atom-ion correlation function $g_2(z) = \frac{\langle \hat{\Psi}^\dagger_{\mathrm{I}}(z) \hat{\Psi}^\dagger_{\mathrm{A}}(-z) \hat{\Psi}_{\mathrm{A}}(-z) \hat{\Psi}_{\mathrm{I}}(z) \rangle}{N \rho_{\mathrm{I}}(z) \rho_{\mathrm{A}}(-z)}$
  - Bunching and binding distance d for $N < N_c$
  - MF yields no binding
  - Broadening with increasing $N < N_c$
  - Unbound fraction for $N > N_c$

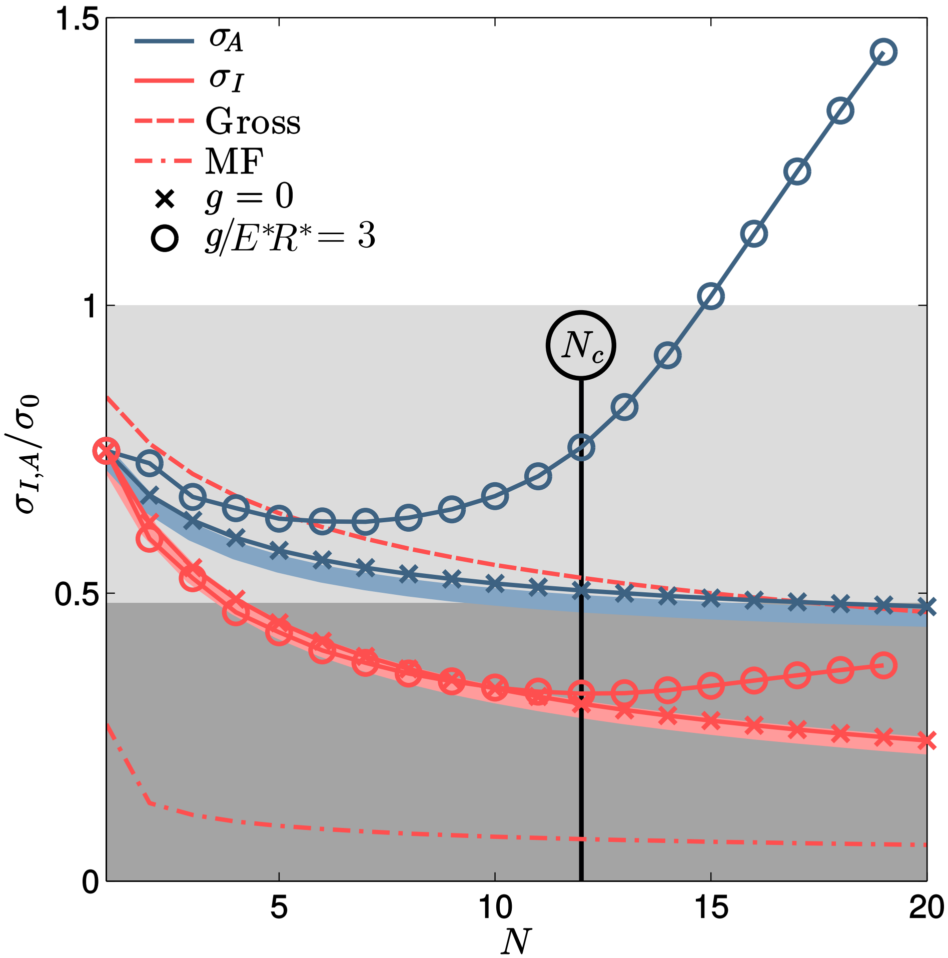
Molecular structure: Densities and correlations

Inspect the atomic and ionic density profiles $\rho_{\mathrm{I(A)}}(z) = \langle \hat{\Psi}^{\dagger}_{\mathrm{I(A)}}(z)\hat{\Psi}_{\mathrm{I(A)}}(z)\rangle$



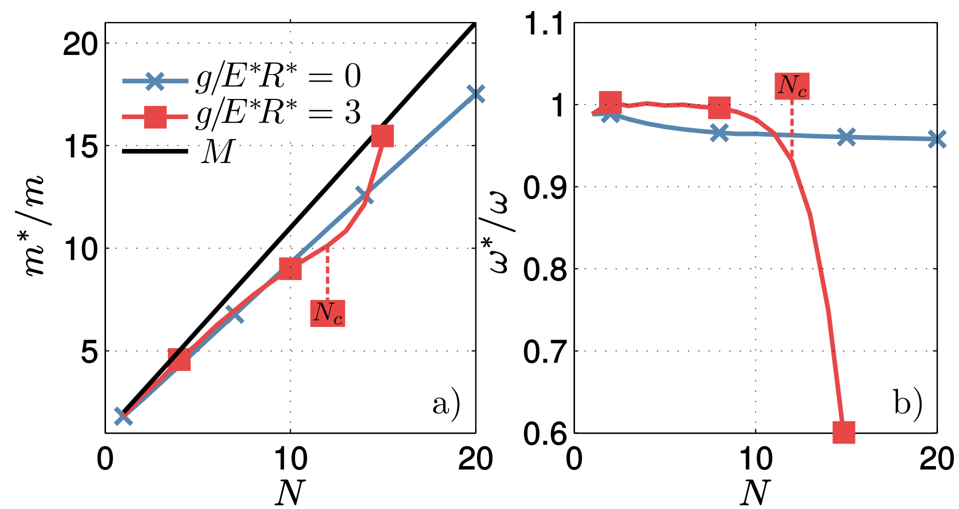
- Population of bound states $f_j = \langle \hat{a}_j^{\dagger}\hat{a}_j\rangle$
- Population of second bound state stabilizes molecule
- Increased N_c in correlated ML-MCTDHB approach ⇔ 1D analogue of shell structure formation

Self-localization



- Atomic and ionic variance $\sigma_{\mathrm{A}}^2 = \langle \frac{1}{N} \sum_{i=1}^{N} z_i^2 \rangle$, $\sigma_{\mathrm{I}}^2 = \langle z_{\mathrm{I}}^2 \rangle$
- $g = 0$: $N + 1$-body cluster: Self localization by increase of total mass and localization of CM
- Under- (MF) and overestimation (Gross) of variance
- $g > 0$: σ_{A} exhibits a minimum: increases already for $N < N_c$ due to spatial widening and population of second bound state
- Molecule under pressure: Bound state scale reaches trap length

Dynamical response of the strongly correlated molecular ion



- Effective single particle picture m^*, ω^*
- Gross ansatz: m and $\omega\sqrt{1+N}$
- Effective force via many-body wave function: Partial trace of $F_\mathrm{I} = -[\partial_{Z_\mathrm{I}}, H]$

- $N < N_c$: Effective mass increases linearly with N, ω^* varies little
- Approaching N_c: m^* becomes sublinear
- For $N > N_c$ m^* approaches M and ω^* decreases strongly: slow response
- $\Rightarrow$ Single particle picture breaks down

- Future:
  - Explore further properties of molecular ions: excited molecular states
  - Moving ions: Energy and correlation transfer
  - Multiple ions: Crystals in a sea of atoms
  - ....

8. Entanglement induced interactions in binary mixtures

Background and Motivation

Exchange of bosonic (quasi-)particles provided by one species leads to induced interactions in the other species:

Electrons in a solid acquire an attractive interaction by exchange of phonons $\rightarrow$ Fröhlich Hamiltonian (system-bath regime)

Ultracold atomic systems: ideal platform for the investigation of atomic mixtures

Beside the efforts on macroscopic ensembles: recent experiments focus on few-body physics

A. WENZ *et al*, SCIENCE **342**, 457 (2013); G. ZÜRN *et al*, PRL **111**, 175302 (2013); S. MURMANN *et al*, PRL **114**, 080402 (2015); F. SERWANE *et al*, SCIENCE **332**, 336 (2011); G. ZÜRN *et al*, PRL **108**, 075303 (2012).

including fermionic pairing via effective interactions.

Entanglement based framework

- Conceptual framework for identification and characterization of induced interactions in binary mixtures
- Reveal intricate relation of entanglement an induced interactions
- Deduce an effective single-species description based on weak entanglement
- Incorporates few-body character and trap (beyond bosonic bath-type approach)
- Applications to ultracold Bose-Fermi mixture: induced Bose-Bose and Fermi-Fermi interactions

J. CHEN, J. SCHURER AND P.S., PRL 121, 043401 (2018)

Theoretical approach....

Hamiltonian for binary mixture $\hat{H} = \hat{H}_A + \hat{H}_B + \hat{H}_{AB}$

Employing Schmidt decomposition of exact eigenstate of the mixture

$$|\Psi\rangle = \sum_{i=1}^{\infty} \sqrt{\lambda_i}\, |\psi_i^A\rangle|\psi_i^B\rangle,$$

- λ_i real positive Schmidt numbers $\lambda_1 > \lambda_2 > \cdots \leftrightarrow$ strength of the interspecies entanglement
- $\lambda_1 = 1$ and $\lambda_{i\neq 1} = 0$ mixture is non-entangled
- Species mean-field (SMF) approximation: product form $|\Psi\rangle = |\psi^A_{\text{SMF}}\rangle|\psi^B_{\text{SMF}}\rangle \rightarrow$ mutual impact of the species is merely an additional potential

Note: Large intraspecies correlations can still be present.

Theoretical approach....

Projecting onto the q-th Schmidt state $\langle\psi_q^{\bar\sigma}|$

$$\sum_{i=1}^{\infty}\sqrt{\lambda_q}\sqrt{\lambda_i}\langle\psi_q^{\bar\sigma}|\hat H|\psi_i^{\bar\sigma}\rangle|\psi_i^{\sigma}\rangle=\mu_q|\psi_q^{\sigma}\rangle,$$

with $\mu_q=\lambda_q E$, E: eigenenergy of $|\Psi\rangle$.

Some algebra yields:

$$\lambda_1 \boldsymbol{H}_{11}^{\bar\sigma}|\psi_1^{\sigma}\rangle+\sum_{i\neq 1}\sum_{j\neq i}\sqrt{\lambda_1}\lambda_i\sqrt{\lambda_j}\boldsymbol{H}_{1i}^{\bar\sigma}M_i\boldsymbol{H}_{ij}^{\bar\sigma}|\psi_j^{\sigma}\rangle=\mu_1|\psi_1^{\sigma}\rangle$$

with $\boldsymbol{H}_{ij}^{\bar\sigma}=\langle\psi_i^{\bar\sigma}|\hat H|\psi_j^{\bar\sigma}\rangle$ $M_q=\left[\mu_q-\lambda_q\boldsymbol{H}_{qq}^{\bar\sigma}\right]^{-1}$

So far general. Now: species are weakly entangled

$$\sqrt{\lambda_1}\approx 1 \quad \text{and} \quad \sqrt{\lambda_{i\neq 1}}\ll 1,$$

$\Rightarrow$ First Schmidt state carries the dominant weight.

Theoretical approach....

Side remarks:

- Validity of the weak-entanglement regime extends far beyond the perturbative regime
- It is also permissible to mitigate the interspecies entanglement by using a unitary transformation of the Hamiltonian, such as the Fröhlich-Nakajima transformation or the Lee-Low-Pines transformation for polarons

Next: Taylor expansion: $\sqrt{\lambda_{i\neq 1}}$ are of order $\delta \ll 1$

Effective Hamiltonian for species σ

$$\hat{H}^{\sigma}_{\text{eff}} = H^{\bar{\sigma}}_{11} + \sum_{i\neq 1} \frac{\sqrt{\lambda_i} H^{\bar{\sigma}}_{1i} H^{\bar{\sigma}}_{i1}}{t_{1i}} \qquad t_{qj} = \langle \psi^{\sigma}_q | \langle \psi^{\bar{\sigma}}_q | \hat{H} | \psi^{\bar{\sigma}}_j \rangle | \psi^{\sigma}_j \rangle$$

with the associated effective Schrödinger equation

$$\hat{H}^{\sigma}_{\text{eff}} | \psi^{\sigma}_{\text{eff}} \rangle = E^{\sigma}_{\text{eff}} | \psi^{\sigma}_{\text{eff}} \rangle$$

Discussion of effective Hamiltonian

$$\hat{H}^{\sigma}_{\text{eff}} = H^{\bar{\sigma}}_{11} + \sum_{i \neq 1} \frac{\sqrt{\lambda_i} H^{\bar{\sigma}}_{1i} H^{\bar{\sigma}}_{i1}}{t_{1i}} \qquad \hat{H}^{\sigma}_{\text{eff}} |\psi^{\sigma}_{\text{eff}}\rangle = E^{\sigma}_{\text{eff}} |\psi^{\sigma}_{\text{eff}}\rangle$$

- Effective state $|\psi^{\sigma}_{\text{eff}}\rangle$ is eigenstate of $\hat{H}^{\sigma}_{\text{eff}}$ whose eigenvalue is closest to $E^{\sigma}_{1} = \langle \psi^{\sigma}_{1} | \hat{H}^{\sigma}_{\text{eff}} | \psi^{\sigma}_{1} \rangle$ Approximation to $|\psi^{\sigma}_{1}\rangle$ which contains the dominant physics.
- Effective Hamiltonian $\hat{H}^{\sigma}_{\text{eff}}$ depends on the many-body state of the mixture
- Applicable for ground and excited states of the mixture.
- Excellent starting-point for: Gaining deep insights and extract relevant mechanisms in coupled binary mixtures
- Analytical and interpretational power

Discussion of effective Hamiltonian

$$\hat{H}^{\sigma}_{\text{eff}} = H^{\bar{\sigma}}_{11} + \sum_{i\neq 1} \frac{\sqrt{\lambda_i} H^{\bar{\sigma}}_{1i} H^{\bar{\sigma}}_{i1}}{t_{1i}} \qquad \hat{H}^{\sigma}_{\text{eff}}|\psi^{\sigma}_{\text{eff}}\rangle = E^{\sigma}_{\text{eff}}|\psi^{\sigma}_{\text{eff}}\rangle$$

- Mixture nonentangled: SMF case. Effective Hamiltonian becomes $\hat{H}^{\sigma}_{\text{eff}} = \hat{H}_{\sigma} + \hat{V}^{\sigma}_{\text{SMF}}$ with $\hat{V}^{\sigma}_{\text{SMF}}$ being an additional SMF induced potential: Partial trace with respect to the species $\bar{\sigma}$ over the interspecies interaction $\hat{H}_{AB}$.
- Weak-entanglement regime i.e. beyond SMF approximation: $\sqrt{\lambda_i} \ll 1; i > 1$ $H^{\bar{\sigma}}_{11}$ is dominant; Second term $\sum_{i\neq 1} \frac{\sqrt{\lambda_i} H^{\bar{\sigma}}_{1i} H^{\bar{\sigma}}_{i1}}{t_{1i}}$ solely originates from interspecies entanglement: contains additional potential term and **induced interaction** $[\propto (H^{\bar{\sigma}}_{1i})^2]$.

Discussion of effective Hamiltonian

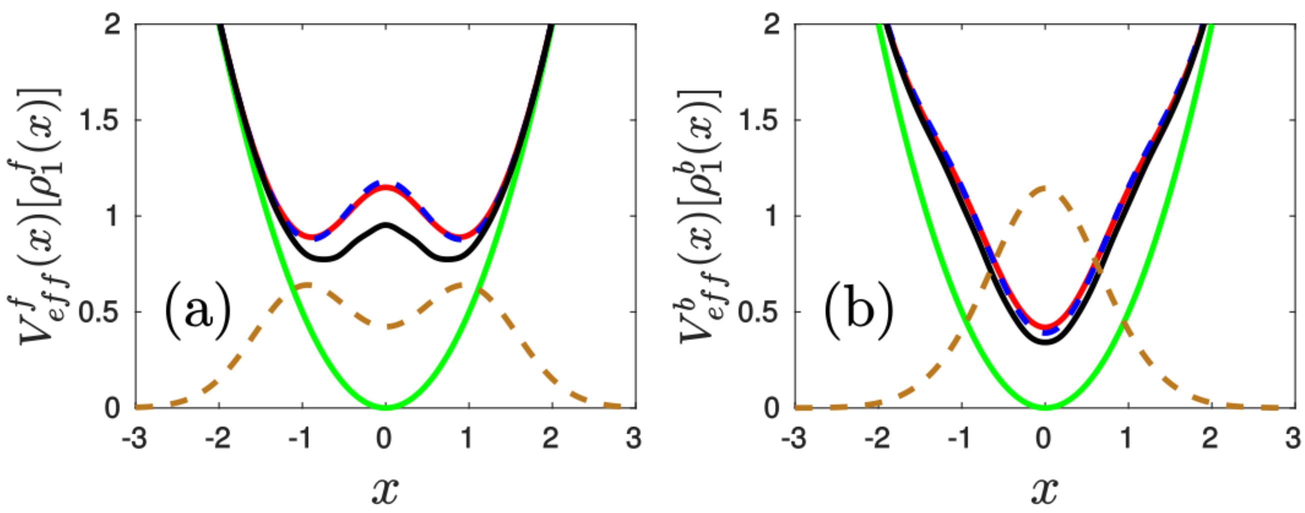
$$\hat{H}^{\sigma}_{\text{eff}} = H^{\bar{\sigma}}_{11} + \sum_{i \neq 1} \frac{\sqrt{\lambda_i} H^{\bar{\sigma}}_{1i} H^{\bar{\sigma}}_{i1}}{t_{1i}} \qquad \hat{H}^{\sigma}_{\text{eff}} |\psi^{\sigma}_{\text{eff}}\rangle = E^{\sigma}_{\text{eff}} |\psi^{\sigma}_{\text{eff}}\rangle$$

- Series with monotonously decreasing pre-factors $\sqrt{\lambda_i}$
- $N_\sigma \gg N_{\bar{\sigma}}$, system-bath regime, the induced interaction in the bath-species σ becomes negligible. Induced interaction in the $\bar{\sigma}$ species becomes increasingly important.

Application: Bose-Fermi mixture

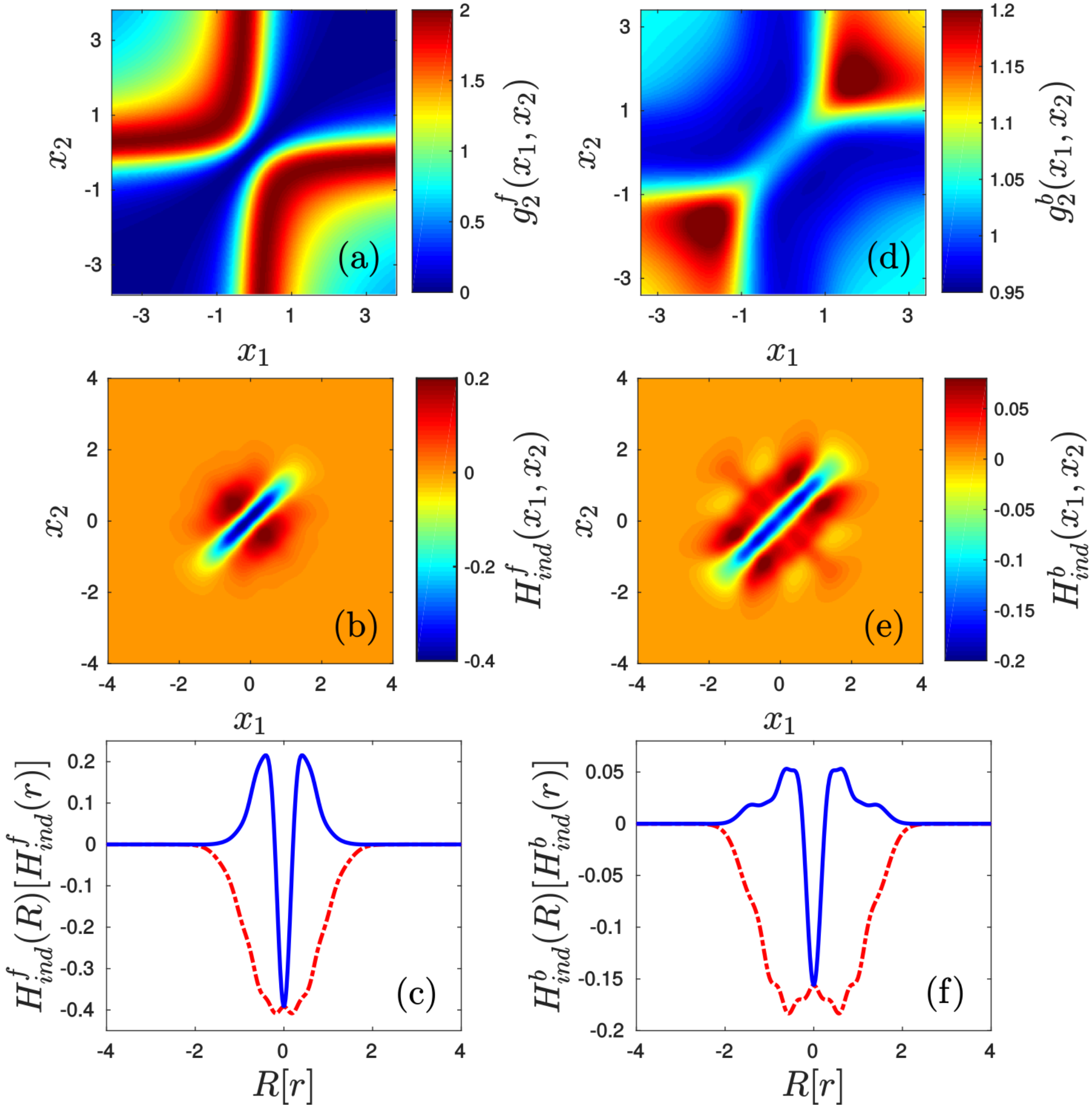
Induced interactions and induced potentials for a few-body ensemble of 1D ultracold Bose-Fermi mixture ($g_{bf} = 1, N_f = N_b = 2$).

Obtained from ML-MCTDHX simulations (Cao et al, JCP 147, 044106 (2017)).



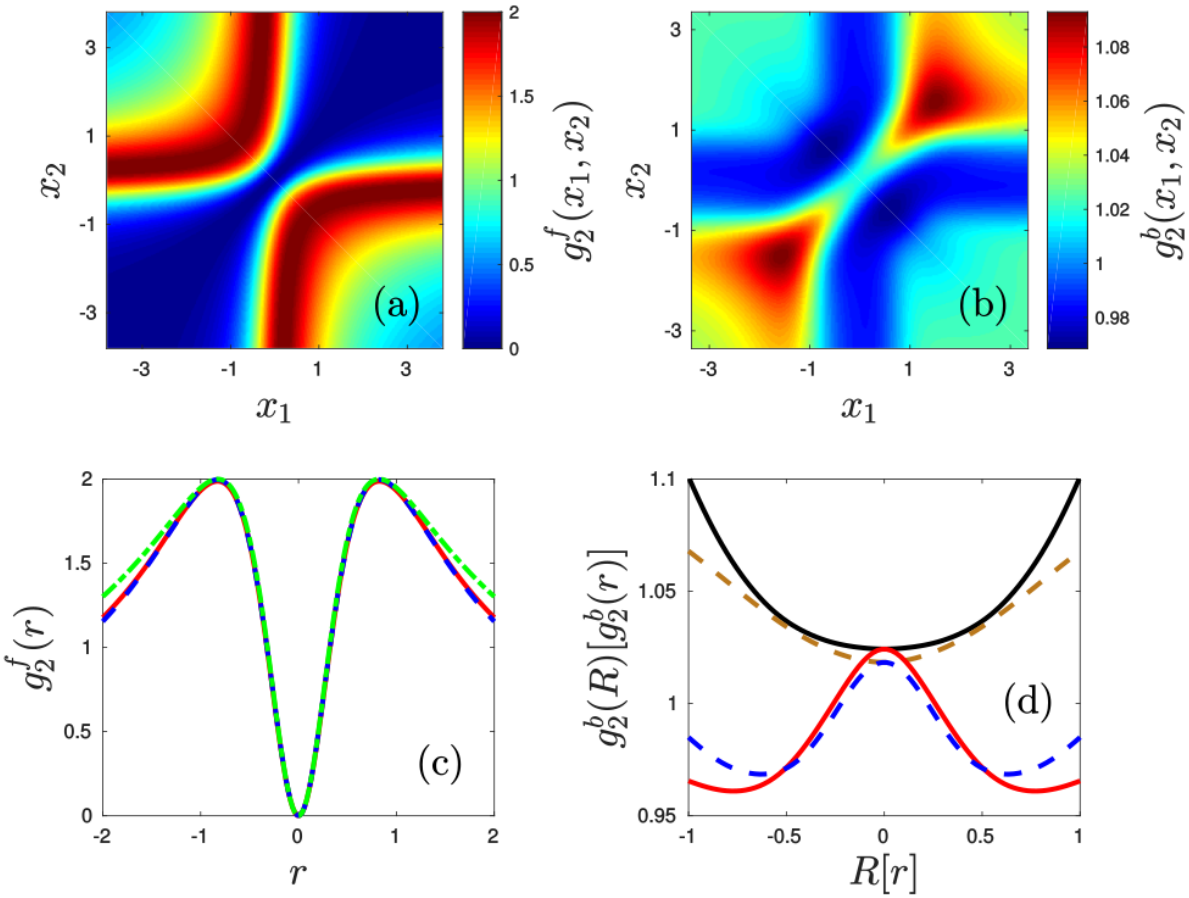
Effective potentials and reduced one-body density. Fermionic (a) and bosonic (b) species. NI (green solid), SMF (blue dashed), $V_1^\sigma(x)]$ (red solid), beyond SMF (black solid). Reduced one-body densities fermionic (a) and bosonic (b) species (brown dashed).

Application: Bose-Fermi mixture



Induced interactions and pair-correlation functions. Upper panels: pair-correlation functions $g_2^\sigma(x_1, x_2)$ for fermionic (a) and bosonic (d) species. Middle and lower panels: induced interactions among fermions (b,c) and bosons (e,f) together with its diagonals [red dashed lines, $x_1 = x_2$ and $R = (x_1 + x_2)/2$] and off-diagonals (blue solid lines, $x_1 = -x_2$ and $r = x_1 - x_2$).

Application: Bose-Fermi mixture



Comparisons of pair-correlation functions. $g_2^\sigma(x_1, x_2)$ via effective Hamiltonian for fermionic (a,c) and bosonic (b,d) species. Off-diagonals (blue dashed) and diagonals (brown dashed). Off-diagonal of g_2^f for SMF (green dash-dot) and ML-MCTDHX results (solid).

- Effective entanglement based theory accounts for
  - induced potentials
  - induced interactions
  - interpretative power and gain of insights
  - manipulation of induced interactions: pairing, etc.
  - ....

9. Concluding remarks

Conclusions

- ML-MCTDHB is a versatile efficient tool for the nonequilibrium dynamics of ultracold bosons.
- Few- to many-body systems can be covered: Shown here for the emergence of collective behaviour.
- Tunneling mechanisms
- Many-mode correlation dynamics: From quench to driving.
- Beyond mean-field effects in nonlinear excitations.
- Open systems dynamics, impurity and polaron dynamics, etc.
- Mixtures !

Thank you for your attention !