One-dimensional Yb gases with strong two-body losses

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Université Paris-Saclay, LPTMS

Mini-workshop “Open systems in quantym many-body physics”
Collège de France – April 14, 2023

université PARIS-SACLAY
LPTMS Laboratoire de Physique Théorique et Modèles Statistiques
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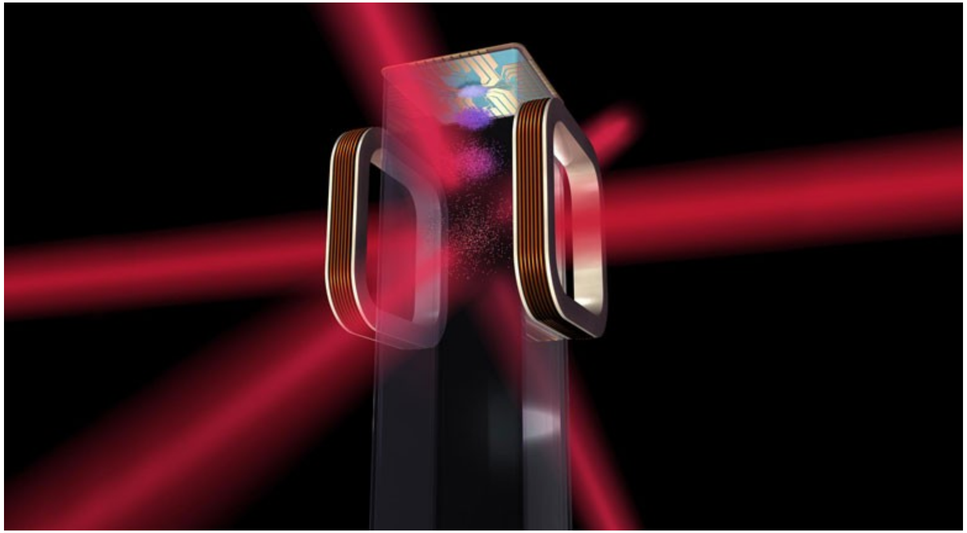
Coherence and decoherence in quantum gases



Gases of bosons or fermions cooled to quantum degeneracy

- No disorder
- Isolated from environments
- Controlled unitary dynamics

Dalibard, Bloch, Zwerger RMP (2008) – Zurek, RMP (2003)

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Yet, particle losses have always been a problem (and still are!)

In reality, the quantum gas is coupled to an environment

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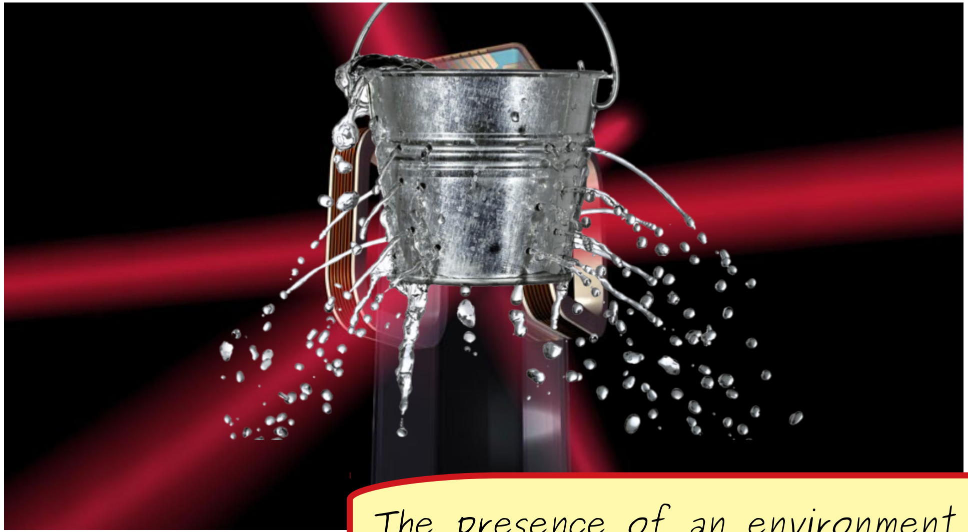

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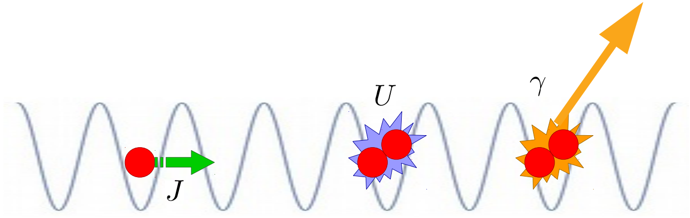
Today's talk:

can we change this viewpoint and find situations where losses produce interesting physics?

Dalibard, Bloch, Zwerger RMP (2008) – Zurek, RMP (2003)

Losses and engineered correlations



The problem: a one-dimensional bosonic gas with strong two-body losses

First experiment: Rempe 2009 (MPQ-Munich)
1D optical lattice with Rb-Rb Feshbach molecules (bosons)
Gas prepared with 1 molecule per site. The optical lattice is lowered, what happens?

Syassen et al. Science (2009)

Losses and engineered correlations

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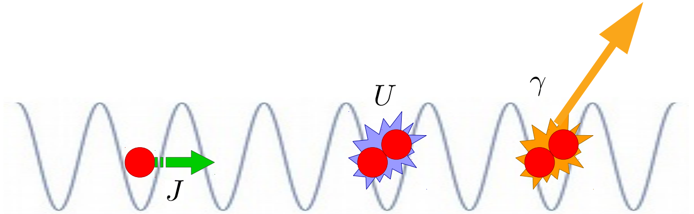

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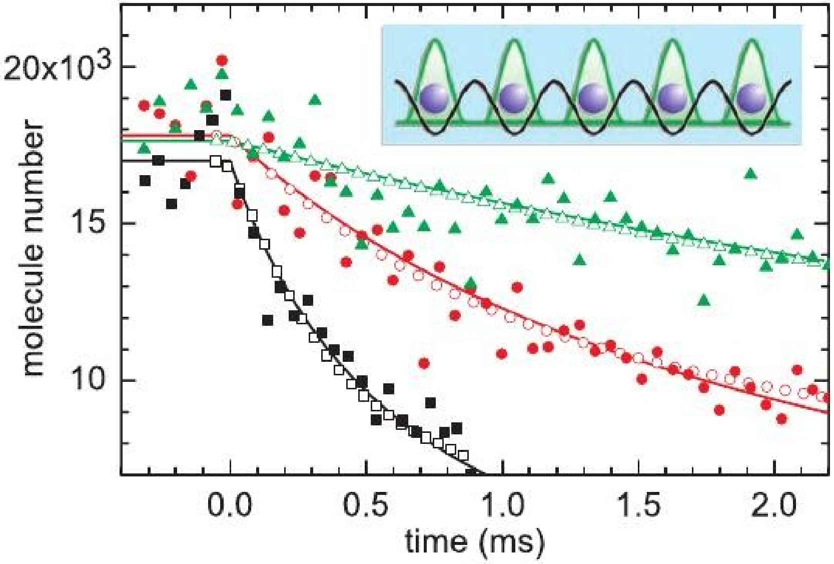

By increasing the loss rate beyond a certain threshold, the gas depopulates more slowly. Emergence of a novel decay time.

Theory: *quantum Zeno effect (works by Garcia-Ripoll and Cirac, 2009)*

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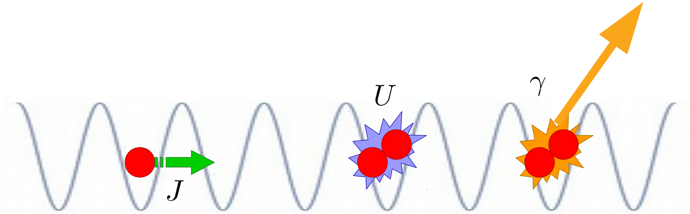
Losses and engineered correlations



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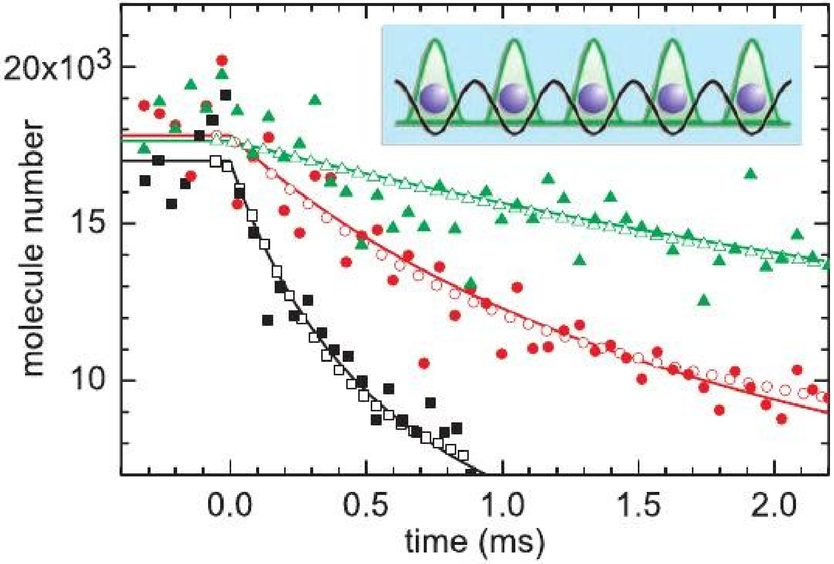

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The open problem: *to characterise completely the dynamics of a gas subject to two-body losses and in particular the interplay between losses and quantum dynamics*

A theoretical activity ignited by discussions @CdF with Fabrice Gerbier and Jérôme Beugnon before the pandemics :)

Syassen et al. Science (2009)

Interesting or not interesting?

My focus: two-body losses

Mean-field / phenomenological analysis

$$\frac{dn(\tau)}{d\tau} = -\kappa n^2(\tau)$$

⇒

The trap empties completely

$$n(\tau) = \frac{n(0)}{1 + \frac{\kappa\tau}{n(0)}} \sim \frac{1}{\tau}$$

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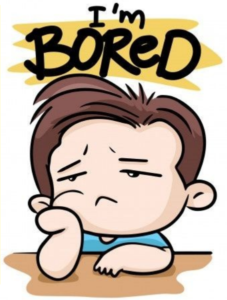

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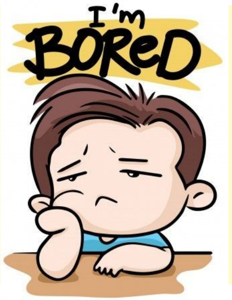
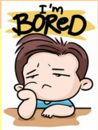


Our results for one-dimensional lattice models:	Bosons	Fermions
Weak dissipation	We don't expect anything fancy here  (but great results in the continuum! Bouchoule, Dubail…)	**Dissipative preparation of entangled Dicke states**
Strong dissipation (Zeno)	**Anomalous transient dynamics and creation of quantum correlations**	**Dissipative spin cooling and creation of quantum correlations**

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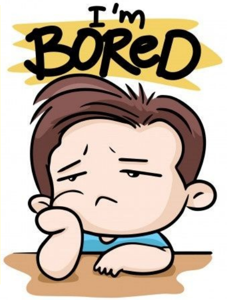

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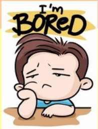
Weak dissipation	We don't expect anything fancy here (but great results in the continuum! Bouchoule, Dubail...) 	**Dissipative preparation of entangled Dicke states**
Strong dissipation (Zeno)	**Anomalous transient dynamics and creation of quantum correlations**	**Dissipative spin cooling and creation of quantum correlations**

The stationary states are trivial but they are reached in a non-trivial way

The stationary states are not trivial

Outline

- **Part 1:** Two-body losses in correlated bosonic gases
- **Part 2:** Two-body losses in correlated fermionic gases
- **Conclusions**

A master equation for strong two-body losses

The 1D Bose-Hubbard Hamiltonian with parameters J and U

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho(t) = -\frac{i}{\hbar}[H, \rho(t)] + \gamma \sum_j b_j^2 \rho(t) b_j^{\dagger 2} - \frac{1}{2}\left(b_j^{\dagger 2} b_j^2 \rho(t) + \rho(t) b_j^{\dagger 2} b_j^2\right)$$

Syassen et al. Science (2008) – Garcia-Ripoll et al. NJP (2009)

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Time-scales of the problem

$\frac{1}{\gamma}$ Decay time of double occupancies or more

$\frac{\hbar}{J}$ Typical time of the hopping dynamics

Idea: *use this separation of timescales to develop an effective perturbative approach*

Perturbative parameter: $J/(\hbar\gamma)$

1) For J=0 all hard-core bosons states are stable (no decay)
2) A small value of J gives to the hardcore bosons a little decay width

$$\Gamma \propto \frac{J^2}{\gamma}$$

Syassen et al. Science (2008) – Garcia-Ripoll et al. NJP (2009)

A master equation for hard-core bosons

- Derivation of an effective master equation restricted to the steady space (no double occupancies or more)
- Introduce spin operators

$$H_1 = -J \sum_j \sigma_j^+ \sigma_{j+1}^- + \sigma_{j+1}^+ \sigma_j^-$$

$$C_j = \sqrt{\Gamma_{\text{eff}}} \sigma_j^- \left(\sigma_{j+1}^- + \sigma_{j-1}^- \right)$$

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New emergent time scale

$$\Gamma_{\text{eff}} = \frac{J^2}{\hbar\gamma} \frac{2}{1 + \left(\frac{U}{\hbar\gamma}\right)^2}$$

Time-scales of the problem

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$\frac{1}{\Gamma_{\text{eff}}}$ Effective decay time for hard-core bosons

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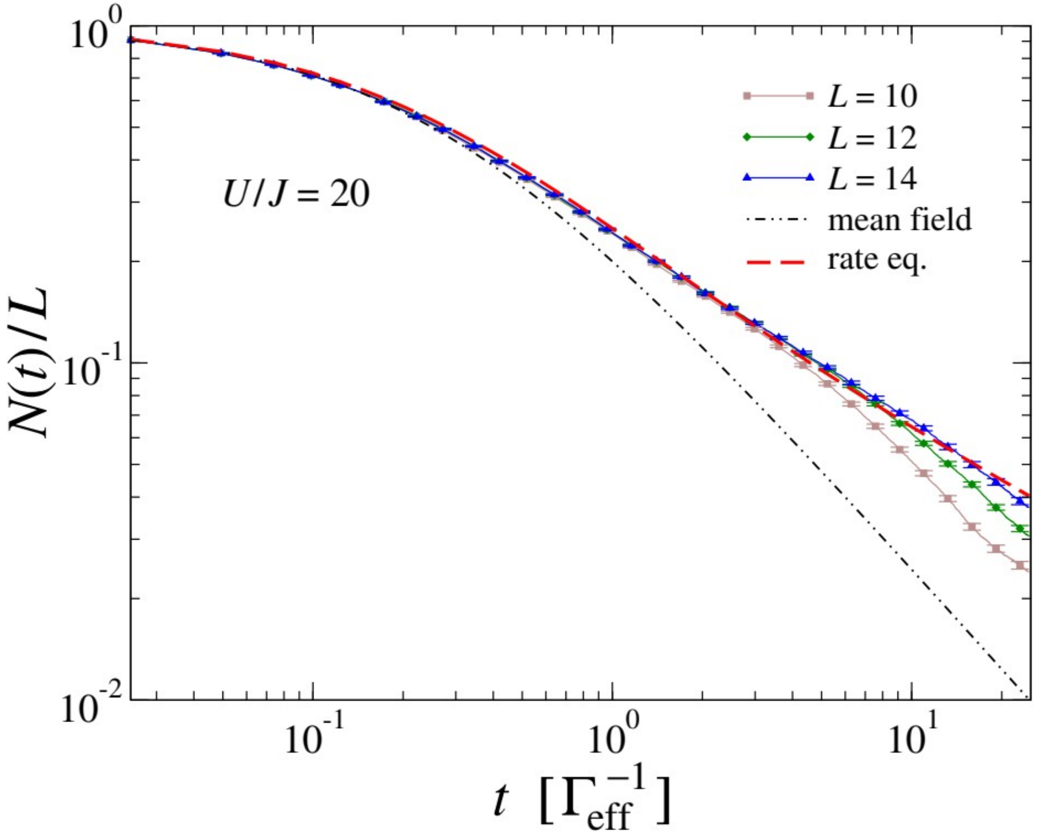
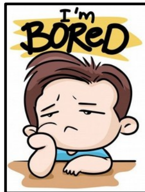
An anomalous transient dynamics

Initial state:
one particle per site

Exact simulations:
Quantum-trajectory stocastic unraveling of the many-body master equation



We developed a simple analytical theory that describes the dynamics accurately
Here we plot its numerical solution.



$$n(t) = \frac{1}{1 + \Gamma_{\rm eff} t}$$

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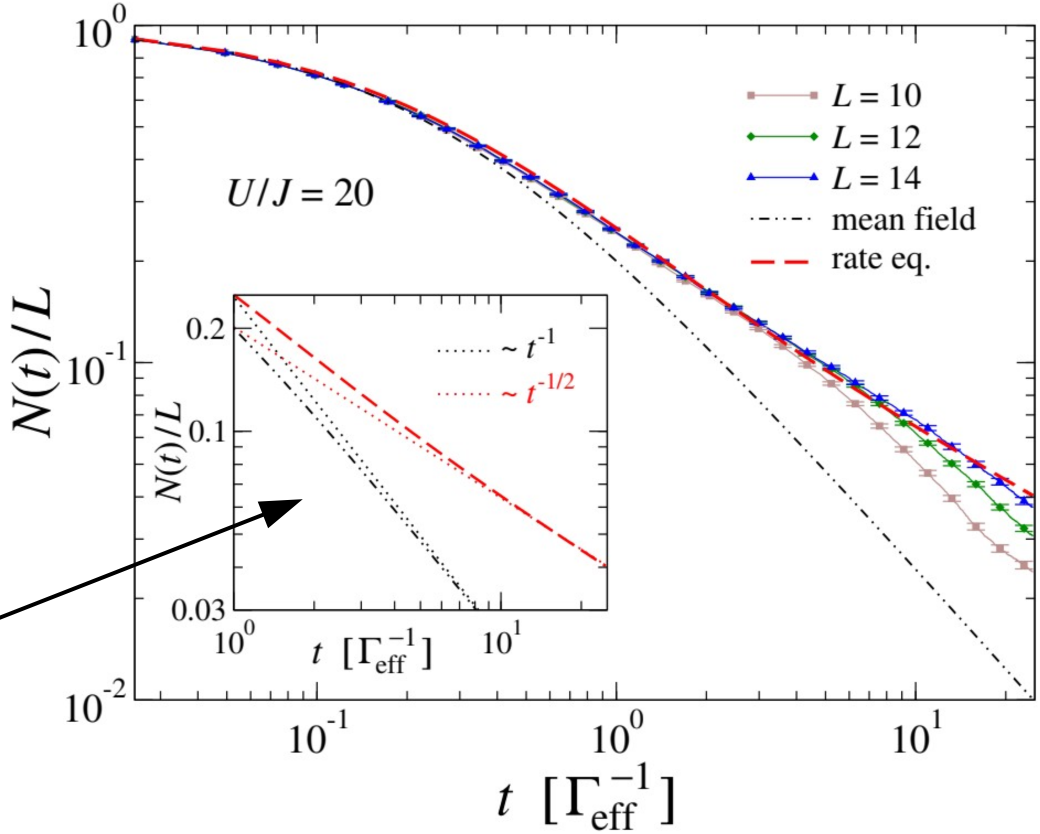
Quantum and classical fluctuations: a qualitatively different transient dynamics!



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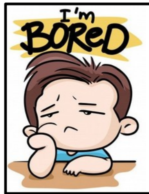

$$n(t) = \frac{1}{1+\Gamma_{\text{eff}}t}$$

D. Rossini, A. Ghermaoui, M. Bosch Aguilera, R. Vatré, R. Bouganne, J. Beugnon, F. Gerbier, LM, PRA 103 L060201 (2021)

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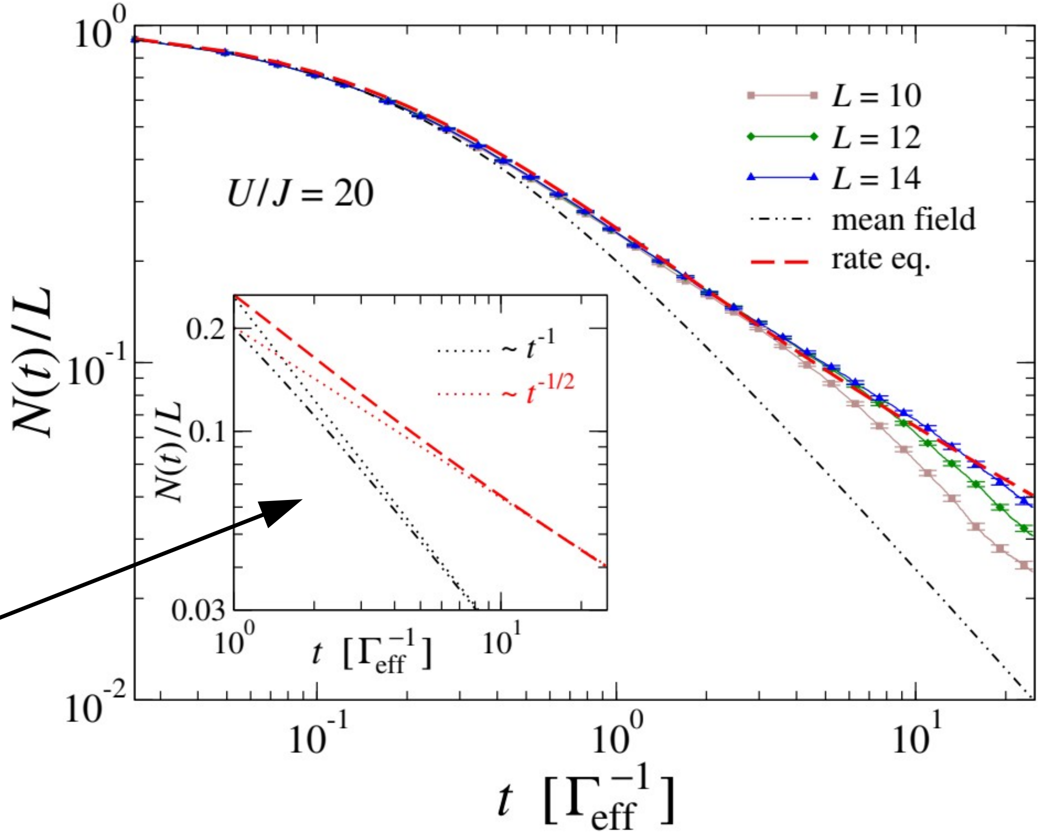

We also have an approximate analytical formula

$$n(t) = \frac{\sqrt{1 + \frac{\Gamma_{\rm eff} t}{2\pi}}}{1 + \Gamma_{\rm eff} t}$$

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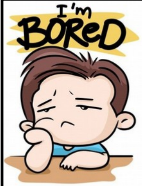

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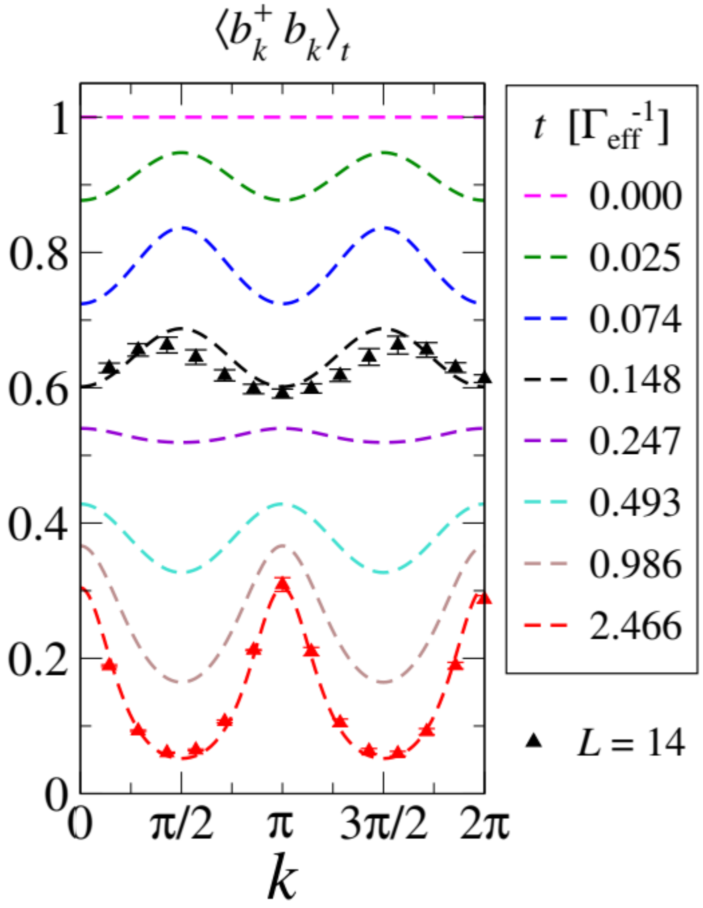
Momentum distribution function

Bosonic momentum distribution function

- Clear peaks develop at different momenta at different times
- Observable in time-of-flight experiment
- No relation with an equilibrium distribution



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Zero-range correlation function

The time-evolution of the population gives direct access to the correlation function of the gas

$$\frac{dn(t)}{dt} = -\Gamma_{\text{eff}} \langle \hat{n}(\hat{n}-1)\rangle_t = -\Gamma_{\text{eff}}\, g_t^{(2)}\, n^2(t) \qquad g_t^{(2)} = \frac{\langle b^\dagger b^\dagger b b\rangle_t}{\langle \hat{n}\rangle_t^2}$$

From the previous slide, we know that:

$$n(t) \sim \frac{1}{\sqrt{8\pi\Gamma_{\text{eff}} t}}$$

Our result: In the *long-time limit* we have an effective **three-body** interaction

$$\frac{dn(t)}{dt} = -4\pi\Gamma_{\text{eff}} n^3(t) \qquad g_t^{(2)} \sim 4\pi n(t)$$

How do we get these results?

Time-scales of the problem

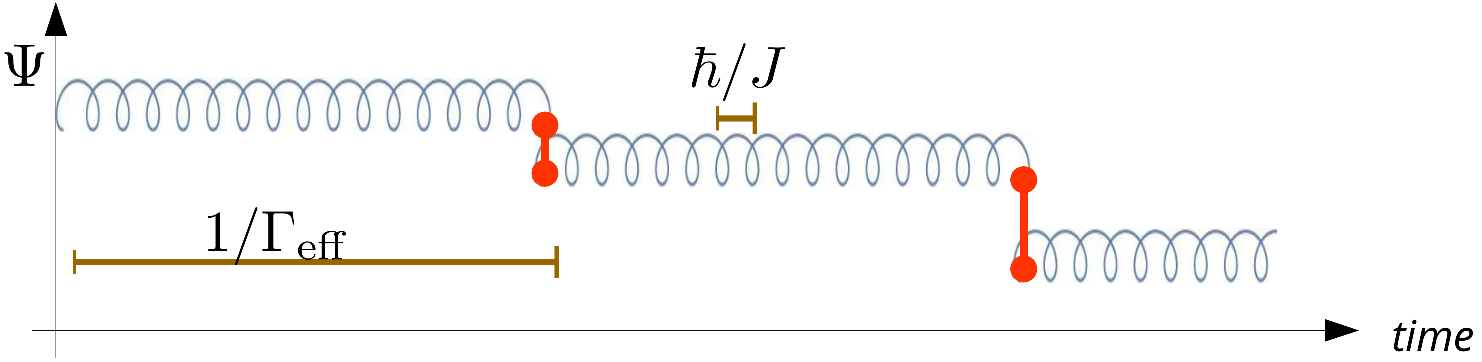
$\frac{1}{\gamma}$ Decay time of double occupancies or more

$\frac{\hbar}{J}$ Typical time of the hopping dynamics

$\frac{1}{\Gamma_{\text{eff}}}$ Decay time of single occupied sites

$$\dot{\rho} = -\frac{i}{\hbar}[H_1, \rho] + \Gamma_{\text{eff}} \sum_j \left[C_j \rho C_j^\dagger - \frac{1}{2} \left(C_j^\dagger C_j \rho + \rho C_j^\dagger C_j \right) \right]$$

Intuitive picture: loss events are rare. Between two lossy events the system has a lot of time to evolve unitarily



Generalised thermalisation

How to characterize the state $|\Psi(t)\rangle = e^{-\frac{i}{\hbar}\hat{H}_1 t}|\Psi(0)\rangle$ at long times?

$$H_1 = -J\sum_j \sigma_j^+\sigma_{j+1}^- + \sigma_{j+1}^+\sigma_j^-$$

Jordan-Wigner transformation

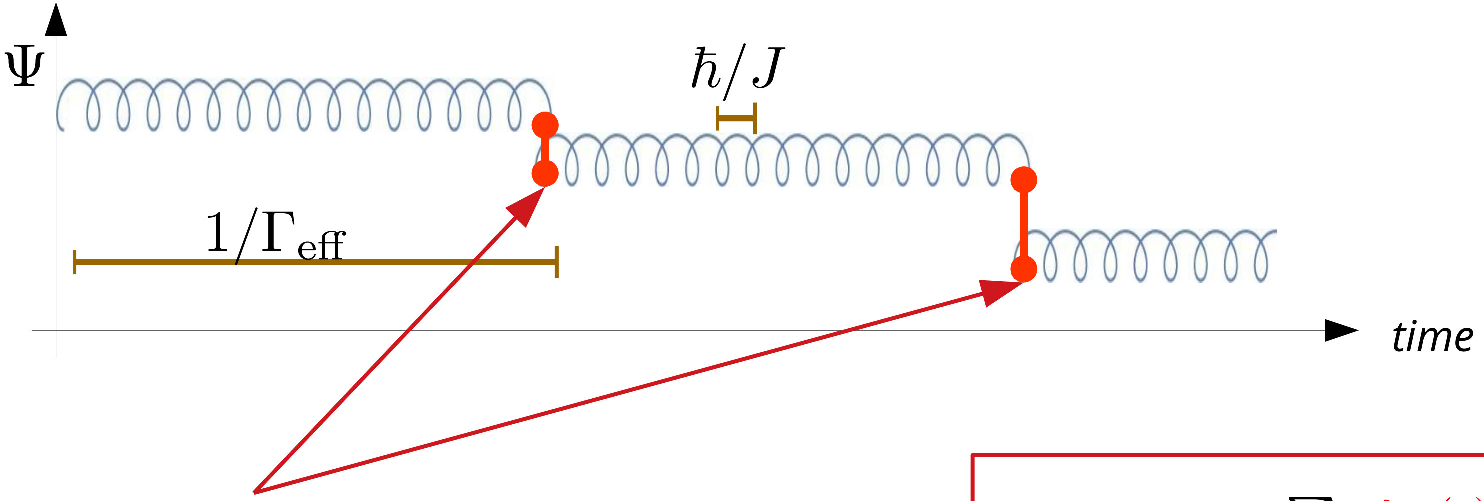
$$H_1 = -2J\sum_k \cos(k) c_k^\dagger c_k$$

Thermalization in closed quantum systems:
At long times the quantum state is indistinguishable from a generalised Gibbs state

$$\lim_{t\to\infty}\langle\Psi(t)|\hat{A}_j|\Psi(t)\rangle = \mathrm{tr}\left[\frac{e^{-\sum_k \lambda_k c_k^\dagger c_k}}{Z}\hat{A}_j\right]$$

Rigol, Dunjko, Yurovsky, Olshanii, PRL 98, 050405 (2007)

Time-dependent generalised thermalisation



At the moment of the loss event I only need to know the values of the appropriate Lagrange multipliers!

$$\rho(t) = \frac{e^{-\sum_k \lambda_k(t) c_k^\dagger c_k}}{Z}$$

Time-dependent generalised Gibbs ensemble

Lange, Lenarcic, Rosch PRB 2018

Write the equations satisfied by the generalised Lagrange multipliers

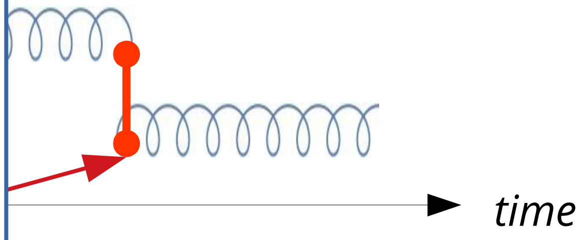
Time-dependent generalised thermalisation

In practice:

- The time-dependent generalised Gibbs ensemble is a fermionic Gaussian state
- Compute the time-evolution of the occupation of each mode k with the master equation

$$\frac{d}{dt} n_k(t) = -\frac{4\Gamma_{\mathrm{eff}}}{L} \sum_q n_q(t) n_k(t) [\sin(k) - \sin(q)]^2$$

Simple set of coupled first-order differential equations.
Polynomial effort in the system size L.



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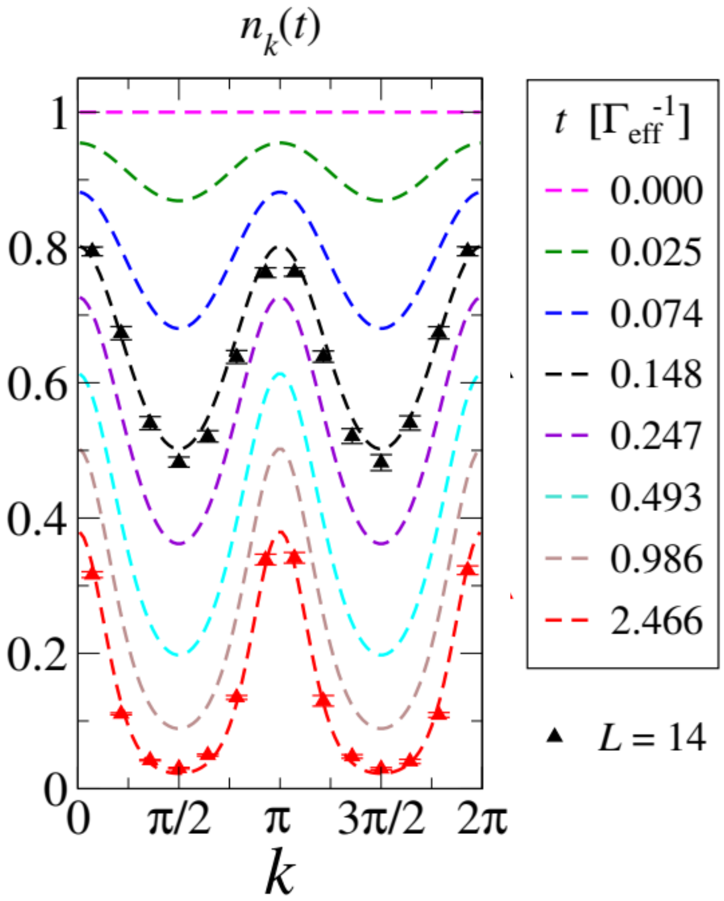
Fermionic rapidities

- Observable with an expansion in the 1D tube (stable modes of the 1D dynamics)
- Clear peaks at well-defined quasimomenta

$$n_k(t) \sim f(t) e^{-g(t)\sin^2 k}$$



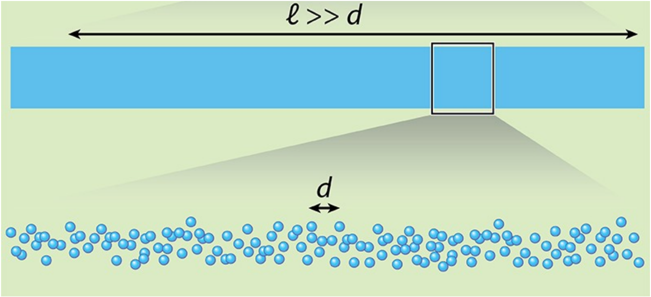
Gangardt and Shlyapnikov , NJP 2006
D. Rossini, A. Ghermaoui, M. Bosch Aguilera, R. Vatré, R. Bouganne, J. Beugnon, F. Gerbier, LM, PRA 103 L060201 (2021)

A hydrodynamic theory in the trap

The rate equations are amenable to a treatment of the problem within the framework of the local density approximation.

- Two-body losses with a harmonic confinement.

$$n_k(t) \qquad \to \qquad n_k(x,t)$$



A Boltzmann-like equation

$$\frac{\partial n_k(x,t)}{\partial t} + \frac{\hbar k}{m}\frac{\partial n_k(x,t)}{\partial x} + F(x)\frac{\partial f_k(x,t)}{\partial k} = -\Gamma_{\mathrm{eff}}\int (k-q)^2 f_k(x,t) f_q(x,t)\mathrm{d}q$$

Harmonic confinement

$$F(x) = -\kappa x$$

Rosso, Biella, LM, SciPost Phys. 12, 044 (2022)

A hydrodynamic theory in the trap

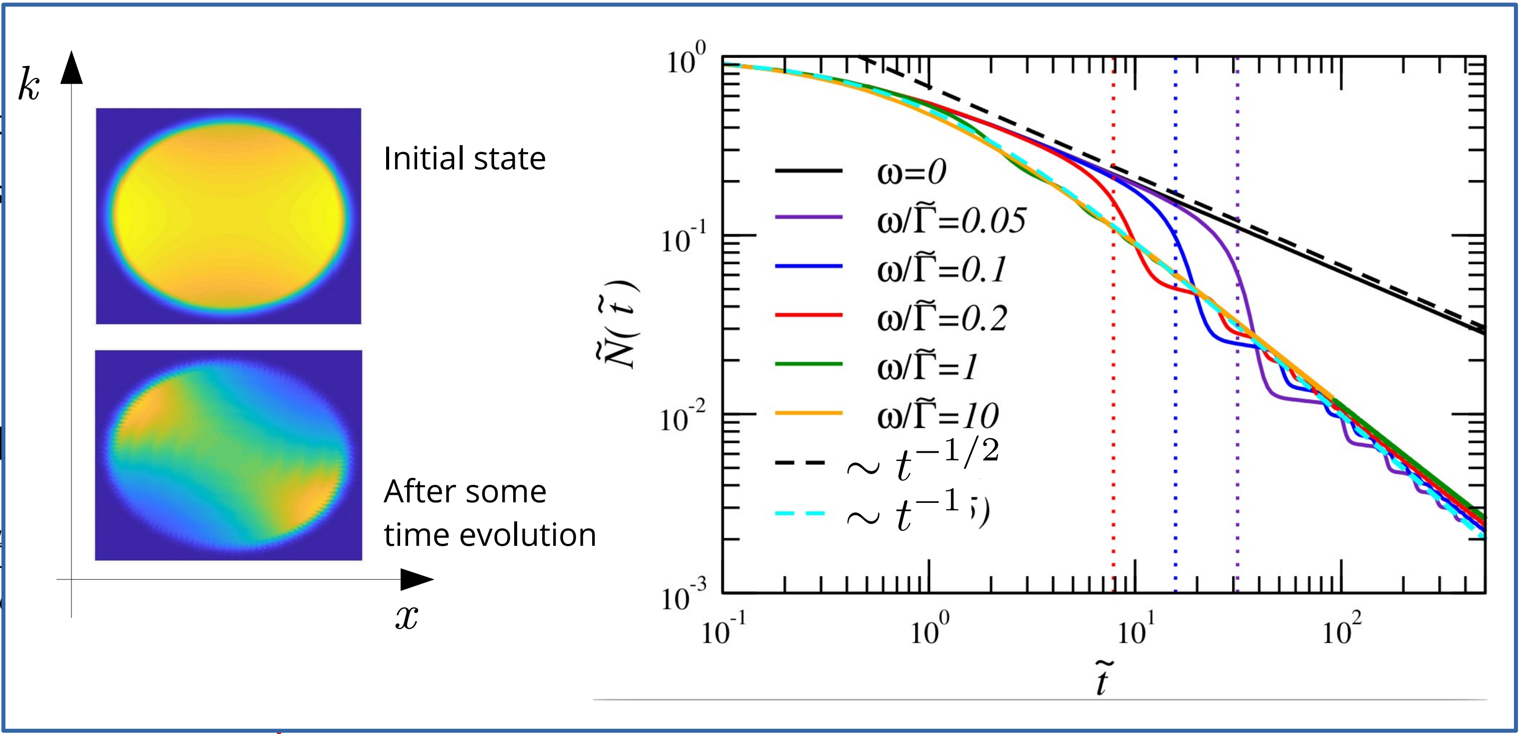
The rate equations
the problem within
density approximat

- Two-body losses

$n_k(t)$

A Boltzmann-like eq

$\frac{\partial n_k(x,t)}{\partial t} + \frac{\hbar k}{m} \frac{\partial n_k}{}$



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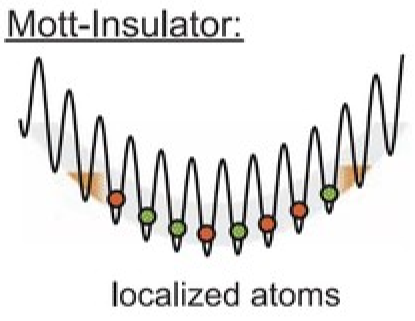
Two-body losses in 1D spin ½ fermi gases

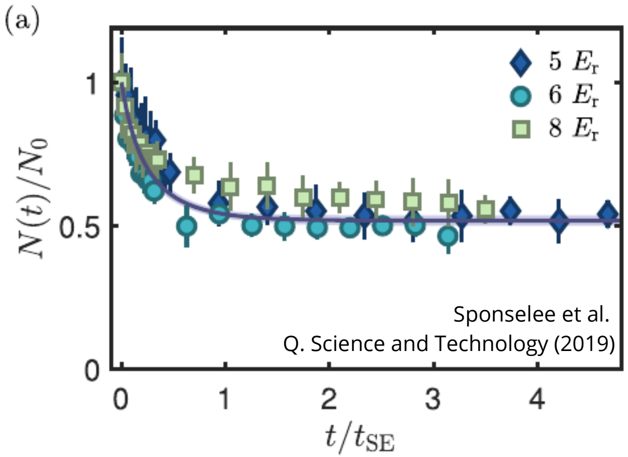
Initial state:



Note the presence of spin-1/2!

Quantum quench:

- Lower the optical lattice
- Atoms delocalise
- Two-body losses take place



Experiments: molecules (JILA) and ytterbium (Hamburg and Kyoto)

- The gas does not depopulate even if it is spin balanced.
- There is a finite population in the stationary state.

Main previous theory works:

Foss-Feig, Thomson, Daley, Rey, PRL 109, 230501 (2012)

Nakagawa, Tsuji, Kawakami, Ueda, PRL 124, 147203 (2020)

Nakagawa, Kawakami, Ueda, PRL 126, 110404 (2021)

A master equation for 2-body losses

$$\dot{\rho} = -\frac{i}{\hbar}\left[-J\sum_{j,\sigma}\left(c^{\dagger}_{j,\sigma}c_{j+1,\sigma} + H.c.\right) + U\sum_{j} n_{j,\uparrow}n_{j,\downarrow}, \rho\right] + \gamma\sum_{j} L_j \rho L_j^{\dagger} - \frac{1}{2}\{L_j^{\dagger}L_j, \rho\}$$

The jump operator takes out one spin singlet
→ The dynamics conserves spin
→ The gas cannot depopulate completely

$$L_j = c_{j,\uparrow}c_{j,\downarrow}$$

Foss-Feig, Thomson, Daley, Rey, PRL 109, 230501 (2012) – Nakagawa, Tsuji, Kawakami, Ueda, PRL 124, 147203 (2020)

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Example for 2 fermions. Consider the spin part of the wavefunction:

$|\uparrow\uparrow\rangle$ → *No particle losses*

$|\downarrow\downarrow\rangle$ → *No particle losses*

$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$ → *No particle losses*

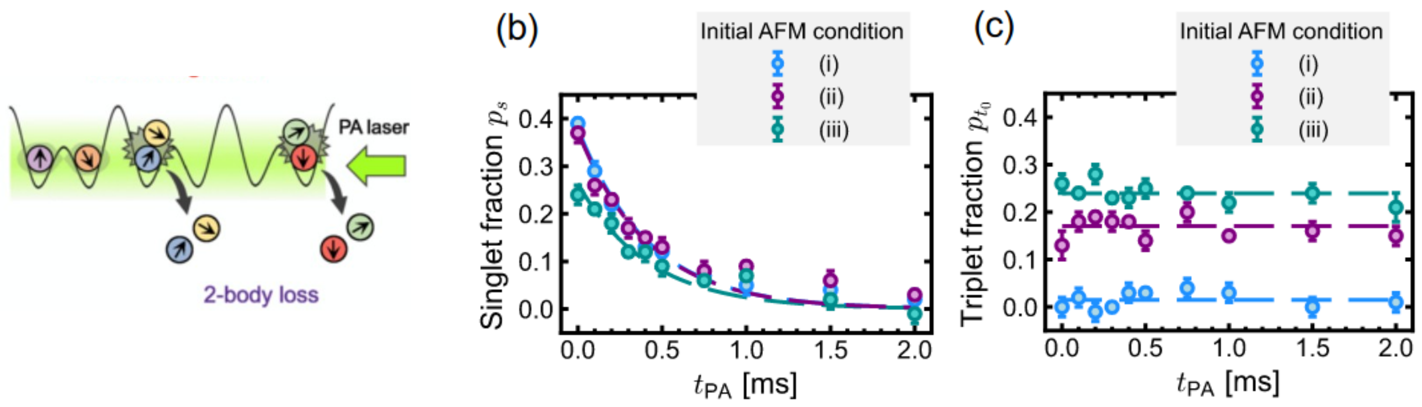
$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$ → *Particle losses are possible*

Foss-Feig, Thomson, Daley, Rey, PRL 109, 230501 (2012) – Nakagawa, Tsuji, Kawakami, Ueda, PRL 124, 147203 (2020)

A master equation for 2-body losses

$$\dot{\rho} = -\frac{i}{\hbar}\Big[-J\sum_{j,\sigma}\big(\quad \dots \quad \rho\}$$

Recent experimental observation in an SU(6) Yb gas – Takahashi group: PRL **130** 063001 (2023)



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$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$ → *No particle losses*

$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$ → *Particle losses are possible*

Foss-Feig, Thomson, Daley, Rey, PRL 109, 230501 (2012) – Nakagawa, Tsuji, Kawakami, Ueda, PRL 124, 147203 (2020)

Dynamical theories for fermionic gases

Weakly interacting and weakly dissipative regime

Our result: A correction to the mean-field equation that takes into account the spin conservation in the thermodynamic limit

$$\dot{n}(t) = -\kappa \left(n(t)^2 - \frac{4}{\hbar^2} \frac{\langle \hat{S}^2 \rangle}{L^2} \right) \xrightarrow{\text{stationary state}} \langle S^2 \rangle \approx \hbar^2 \left(\frac{N}{2} \right)^2 \approx \hbar^2 \frac{N}{2} \left(\frac{N}{2} - 1 \right)$$

In the thermodynamic limit, the stationary state has maximal spin

A Dicke state! **Entanglement through dissipation!**

Rosso, Biella, Rossini, LM PRA **104**, 053305 (2021)

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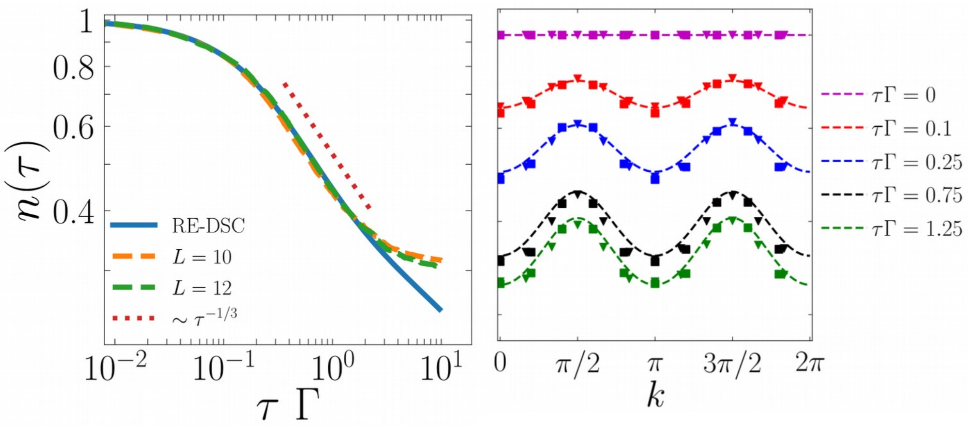
Rosso, Biella, Rossini, LM PRA **104**, 053305 (2021)

Strongly interacting or strongly dissipative regime

Our result: Study of the quantum Zeno regime. A modified theory for fermionised fermions.



Rosso, Biella, De Nardis, LM PRA **107** 013303 (2023)

Conclusions

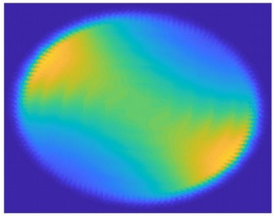
The lossy dynamics of one-dimensional quantum gases results from the interplay of unitary and dissipative dynamics:

Entangled stationary states & non-equilibrium dynamics

Our contribution: we have developed a theory for the dynamics of 1D lattcie gases in the weakly- and strongly-dissipative regimes, focusing on two-body losses

Bosonic gas

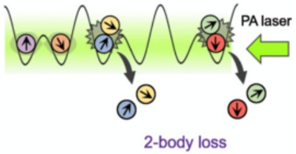
- Rate equations for the dynamics of the rapidities
- Hydrodynamical theory of the trap



D. Rossini, … J. Beugnon, F. Gerbier, LM, PRA **103** L060201 (2021)
Rosso, Biella, LM, SciPost Phys. **12**, 044 (2022)

Fermionic gas

- Spin conservation and entangled steady states
- 2-body losses in SU(N) gases
- Quantum Zeno effect and dissipative spin cooling



Rosso, Biella, Rossini, LM PRA **104**, 053305 (2021)
Rosso, Biella, LM PRA **105**, L051302 (2022)
Rosso, Biella, De Nardis, LM PRA **107** 013303 (2023)

Perspectives - experiments

A generation of **old-style experiments**

- performed when theory was not sufficiently developed
- Average over many 1D tubes hides interesting non-equilibrium scalings

Main result: No probe of emerging correlations, just the emergence of a new lifetime

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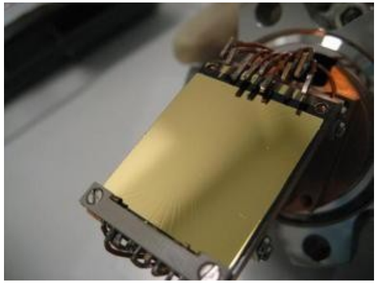
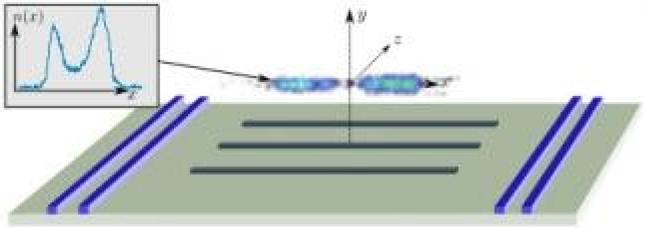
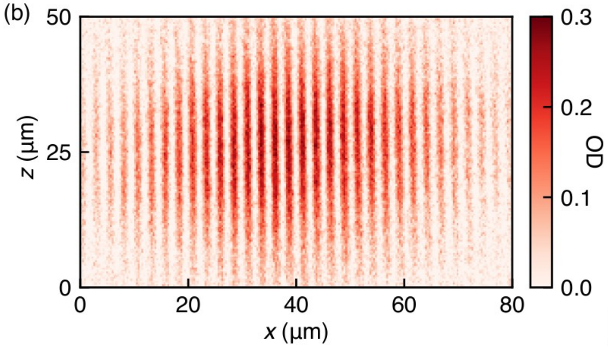
New activities

- Takahashi: small two-sites double-wells. First clean data on the generation of entanglement.
  - Can we scale it up?
- One-dimensional resolved experiments (quantum gas microscope, atom chip experiments...)







Images taken from labs of I. Bouchoule and LKB

Acknowledgememts

Guillaume Roux

Lorenzo Gotta
LPTMS → Geneva

Lorenzo Rosso

Alberto Nardin
Trento → LPTMS

The group on
1D quantum
matter @ LPTMS

Our recent
collaborators
on these
projects

Jacopo De Nardis

Alberto Biella
LPTMS → Trento

Thank you

The new LPTMS building:
"We are looking forward to your visit!"