TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

VCQ Vienna Center for Quantum Science and Technology

ATOMINSTITUT

Non-equilibrium dynamics of a one-dimensional Bose gas

2nd Quantum Thermodynamics Conference – Mallorca, Spain – 2015-02-25

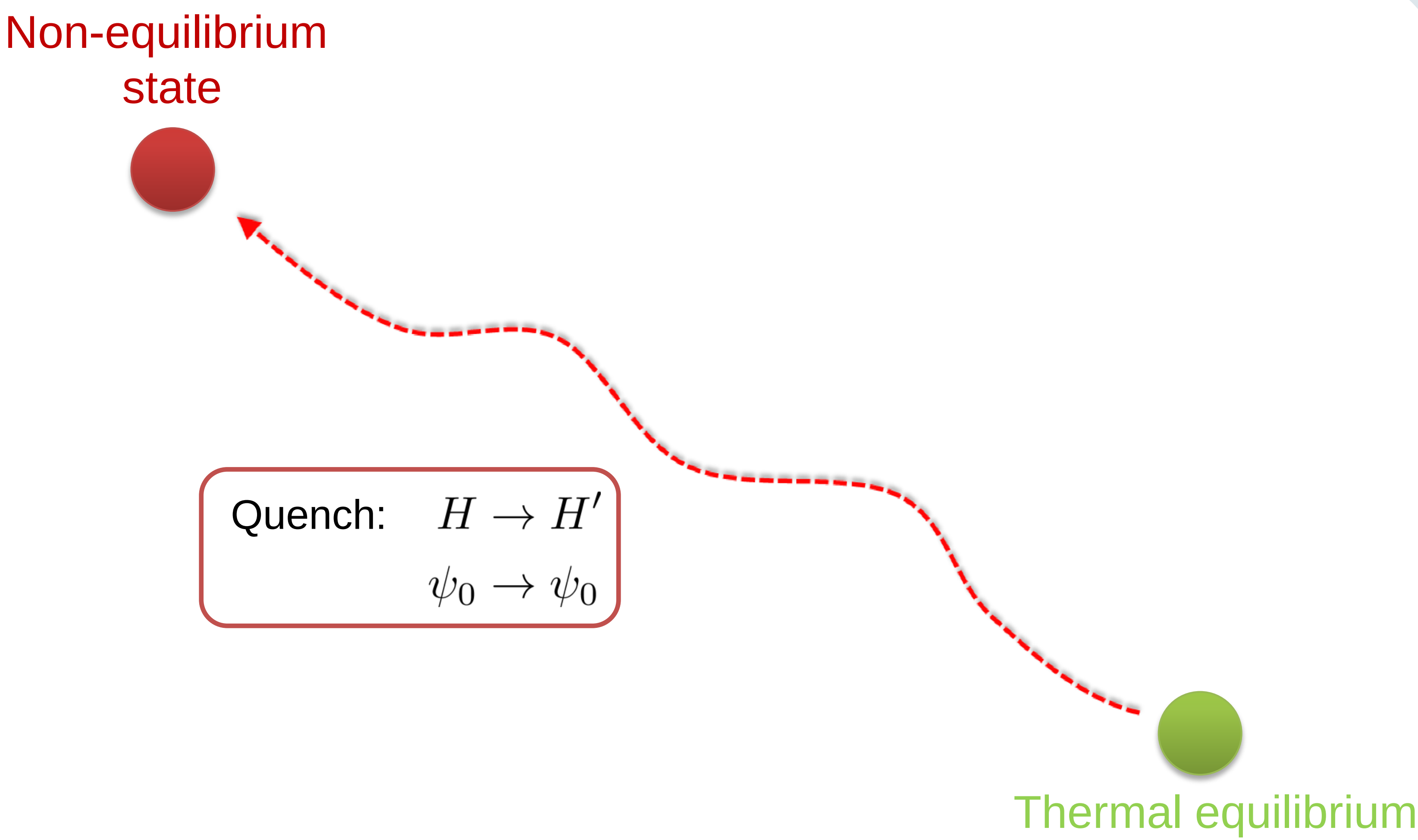
Bernhard Rauer
Schmiedmayer Group, Atominstitut, TU Vienna
Vienna Center for Quantum Science and Technology

Motivation

Start from an isolated quantum system in thermal equilibrium

Thermal equilibrium

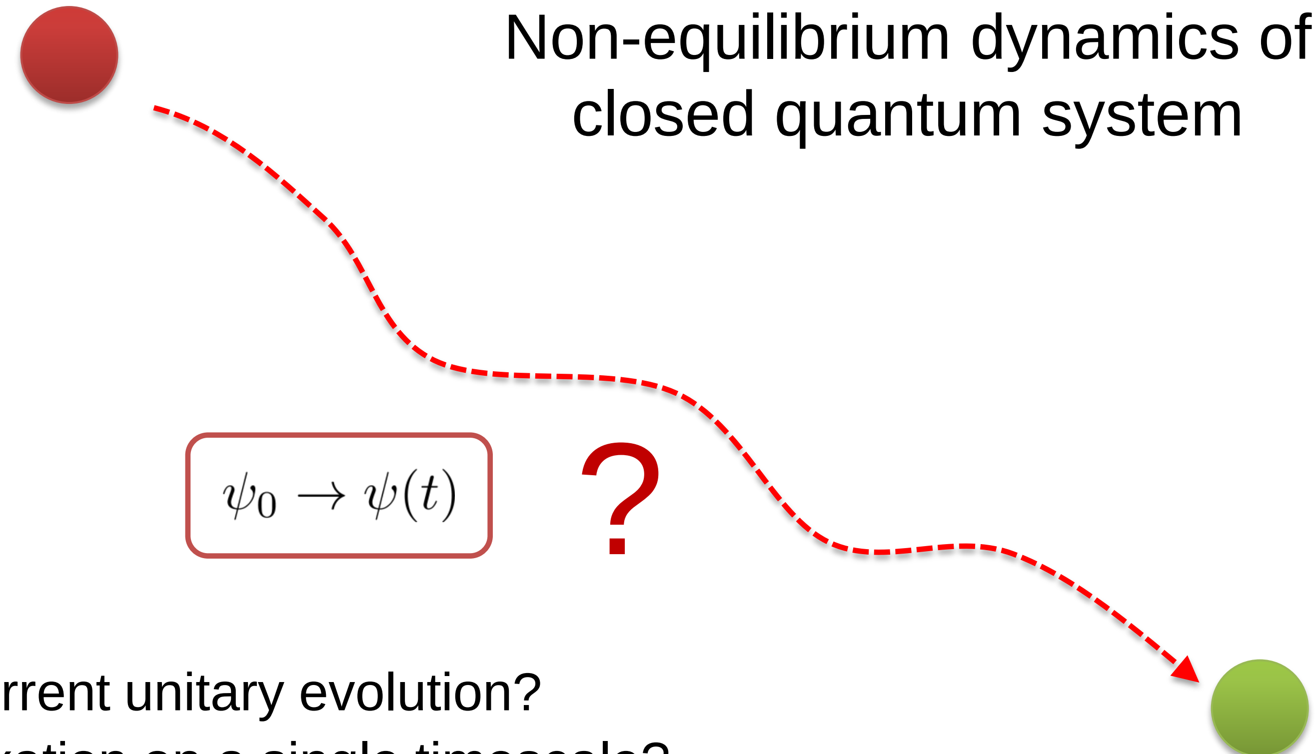
Motivation


Non-equilibrium state
Quench: $H \to H'$
$\psi_0 \to \psi_0$
Thermal equilibrium

Motivation

Non-equilibrium
state

Non-equilibrium dynamics of
closed quantum system



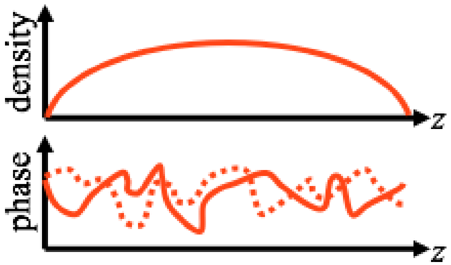
Thermal equilibrium
(total loss of memory)

Recurrent unitary evolution?
Relaxation on a single timescale?
Multiple timescales?
Thermalization?

Experimental system: 1D Bose gas

1D Bose gas on an atom chip:

- Precise control over system parameters
- Near perfect isolation from the environment
- Direct probes through absorption imaging

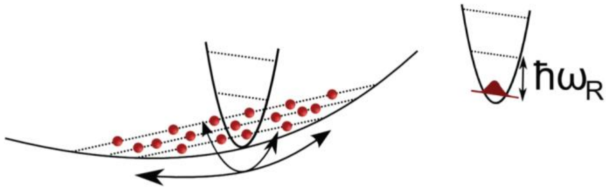


Experimental parameters:

- Weakly interacting regime
- 2000 – 10 000 atoms of ^{87}Rb
- Temperature of 20 – 100 nK
- Trap frequencies

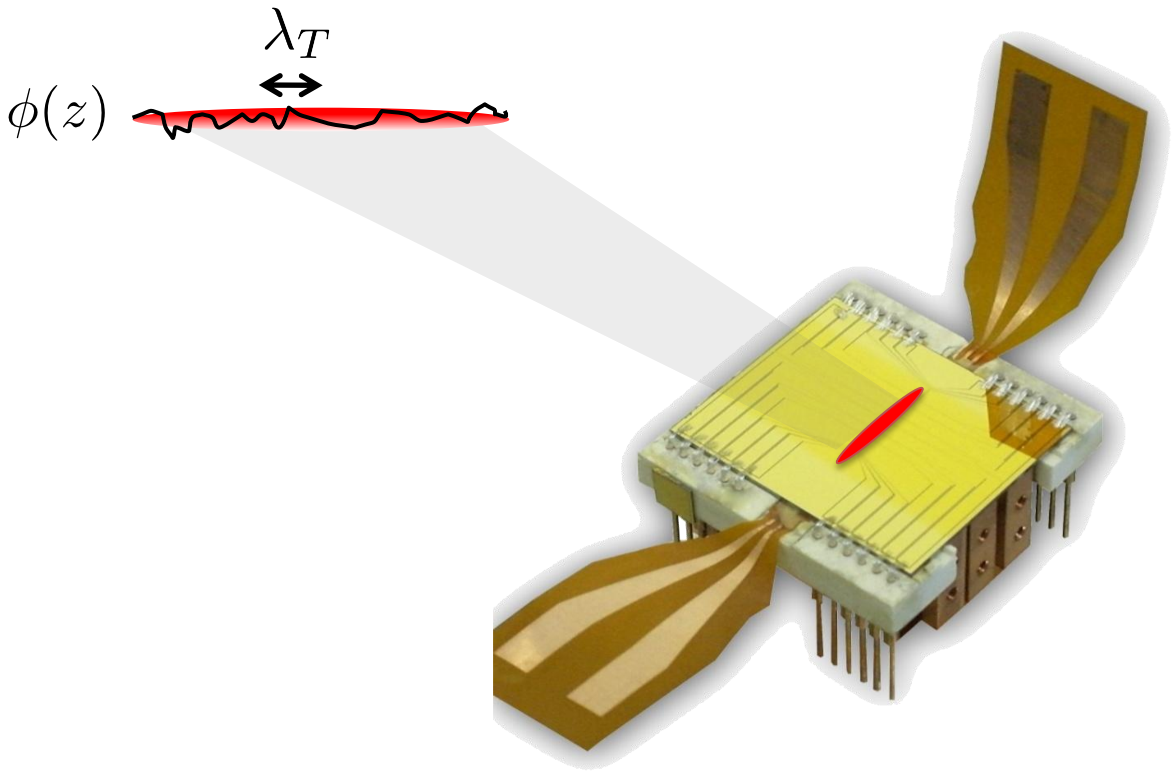
$$\omega_\perp = 2\pi \cdot 2\,kHz$$

$$\omega_\parallel = 2\pi \cdot 10\,Hz$$



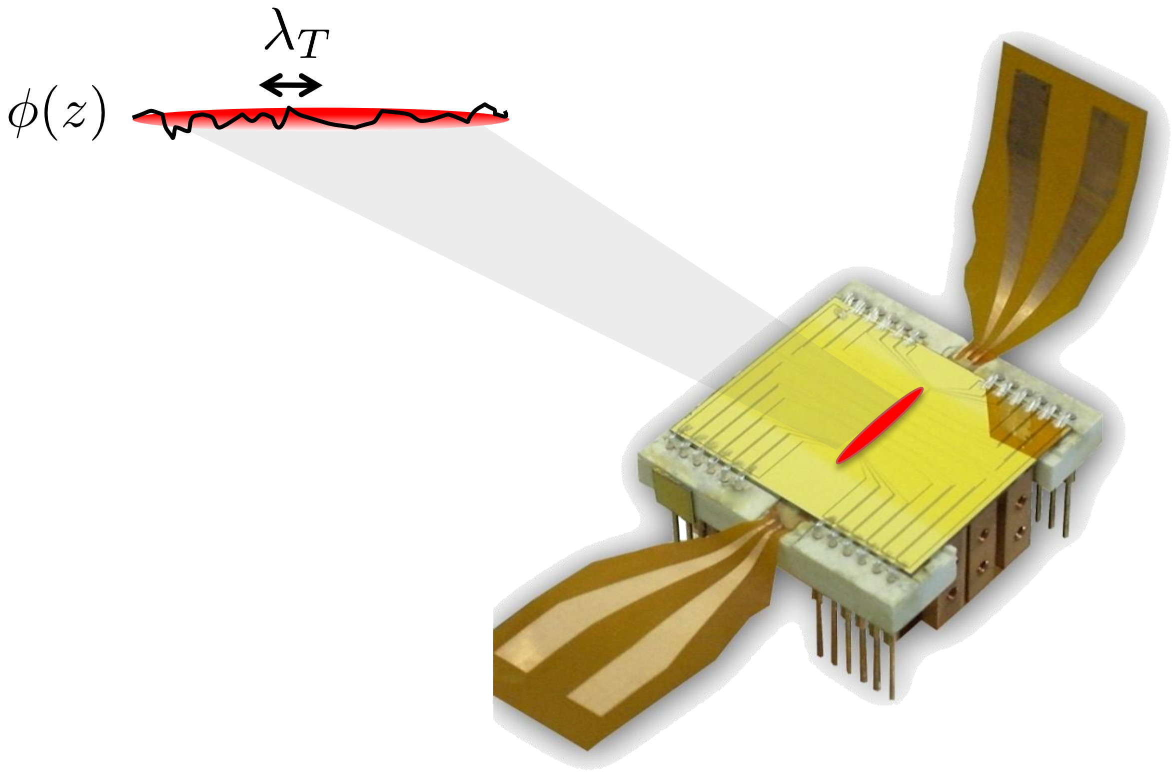
$$\mu,\ k_B T < \hbar\omega_\perp$$

Experimental scheme



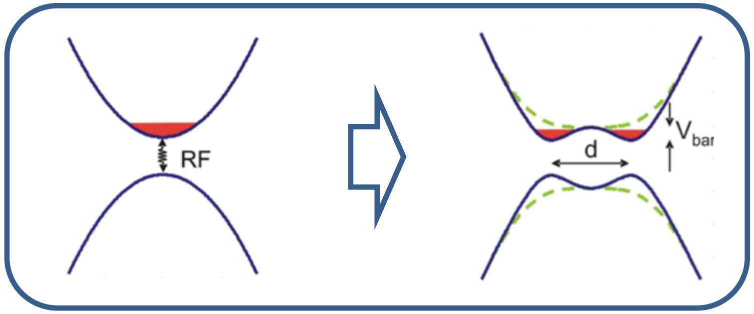
Start with a single, phase fluctuating
1D quasi-condensate

Experimental scheme

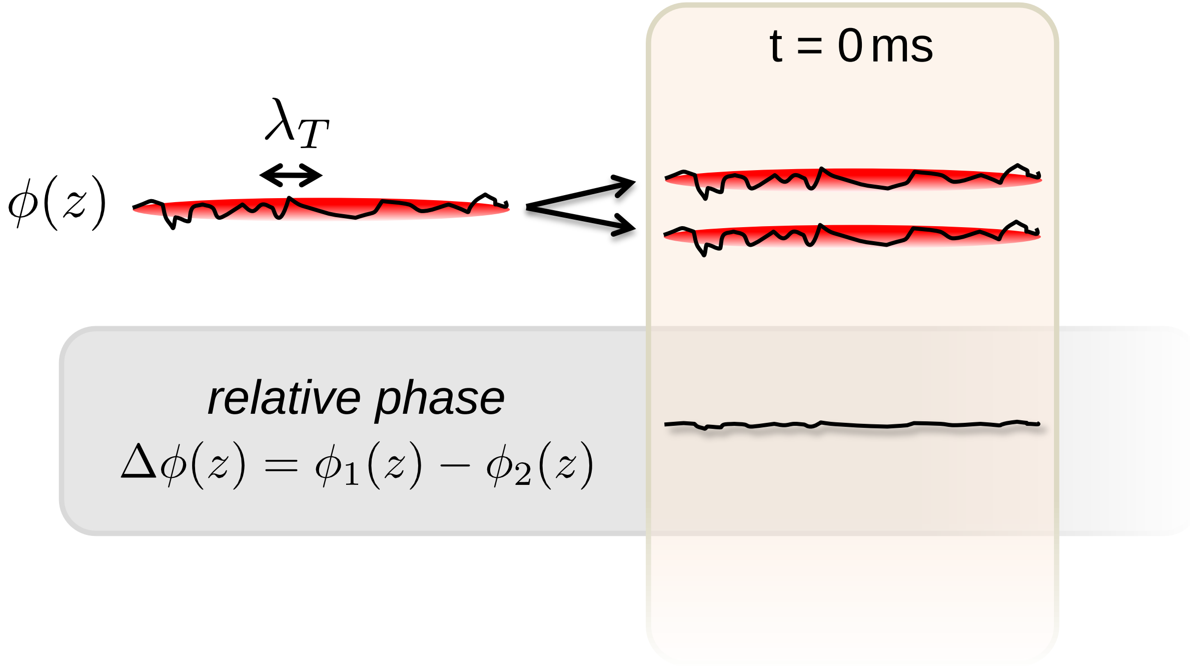


Start with a single, phase fluctuating 1D quasi-condensate

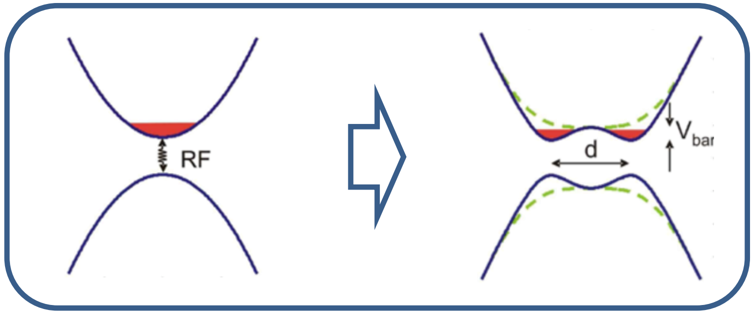
split it via RF dressed state potentials



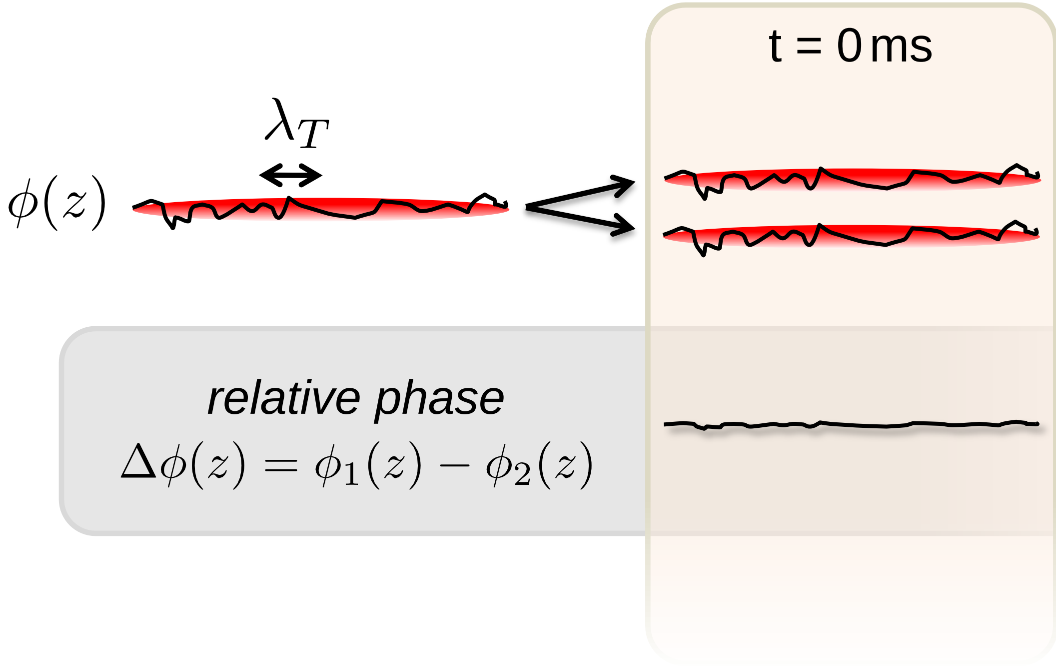
Experimental scheme



Quench by coherent splitting



Experimental scheme

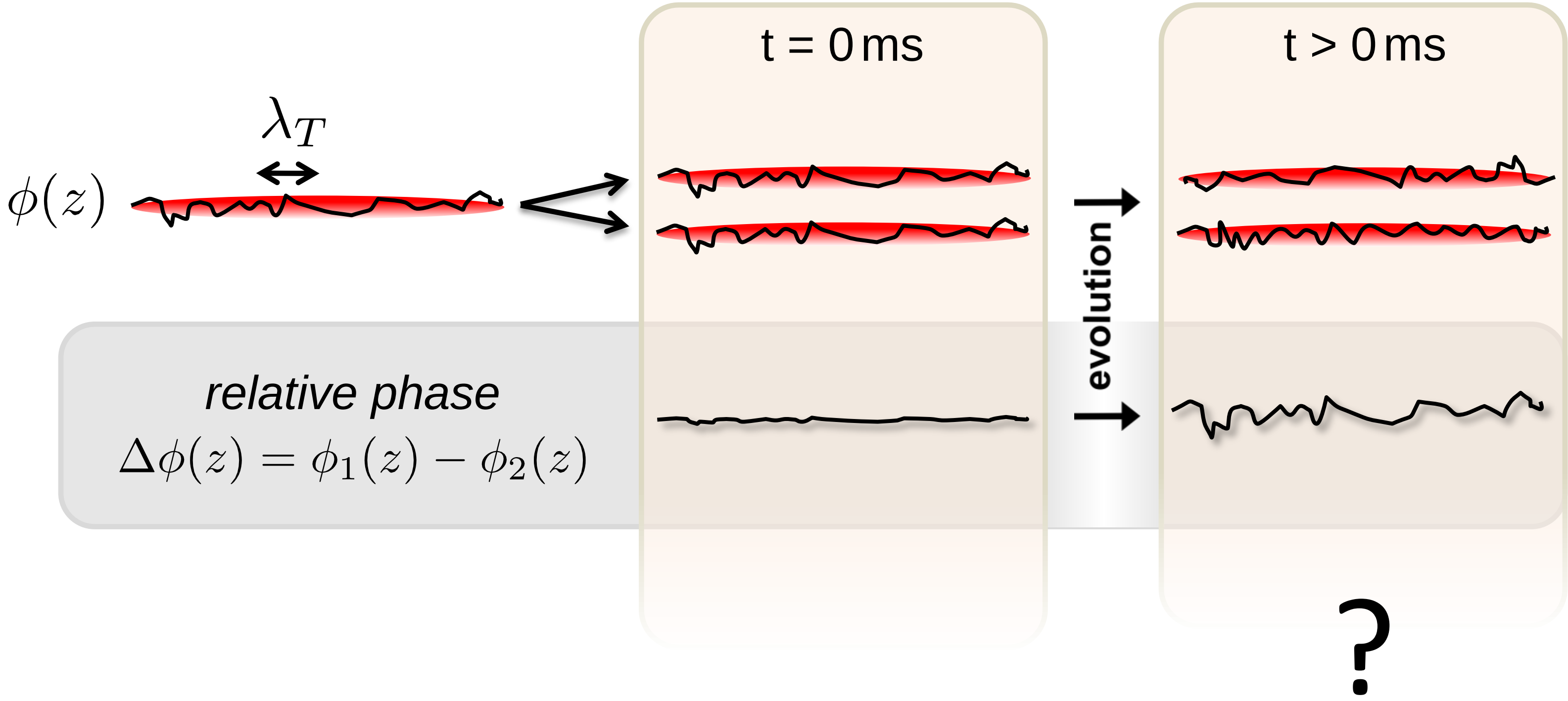


common modes:
high energy (thermal noise)

relative phase
$\Delta\phi(z) = \phi_1(z) - \phi_2(z)$

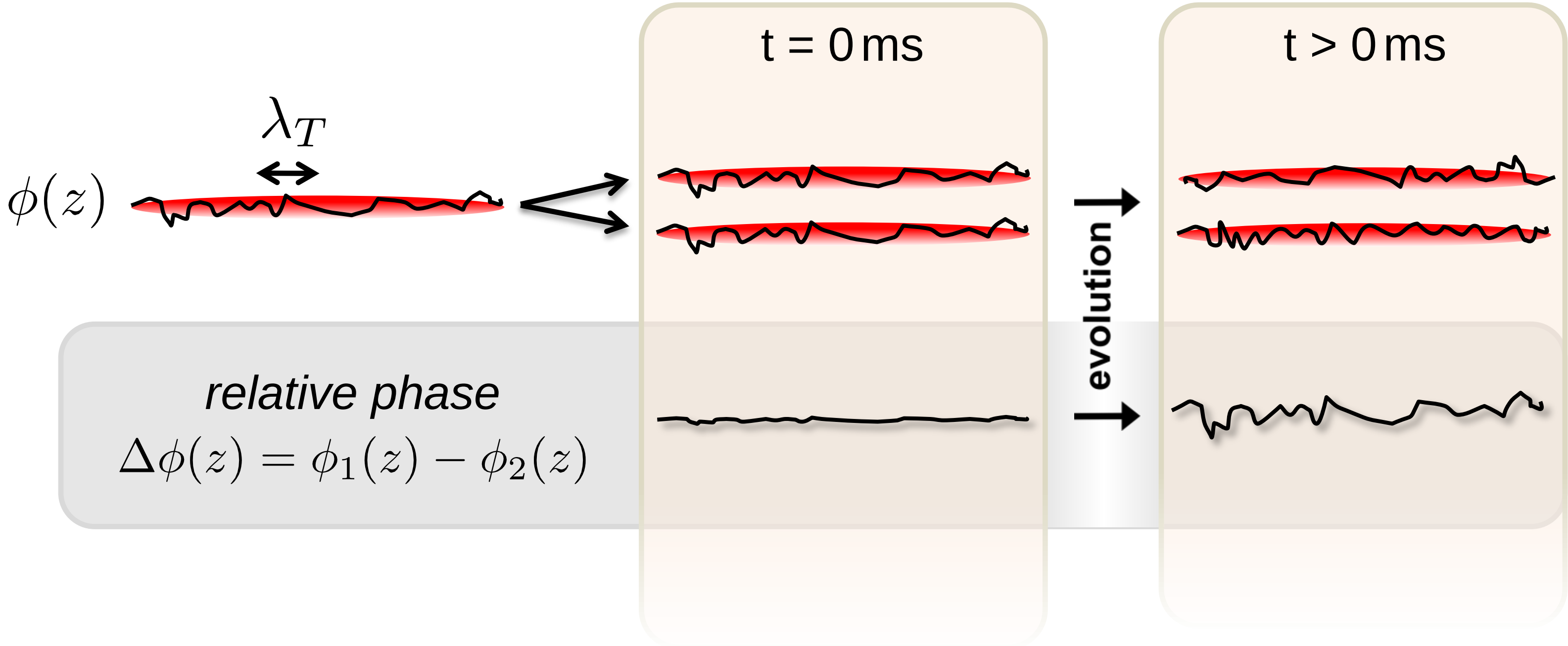
relative modes:
low energy (quantum noise)

Experimental scheme

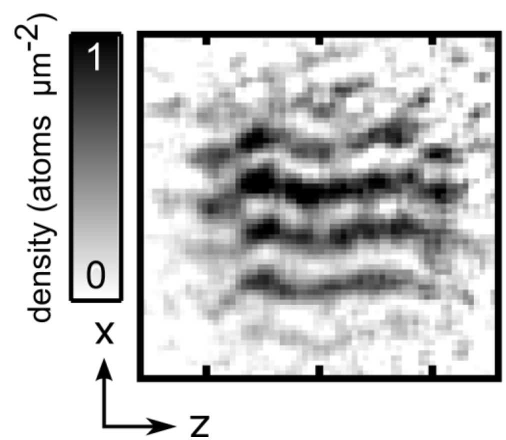


How does this state evolve in time?

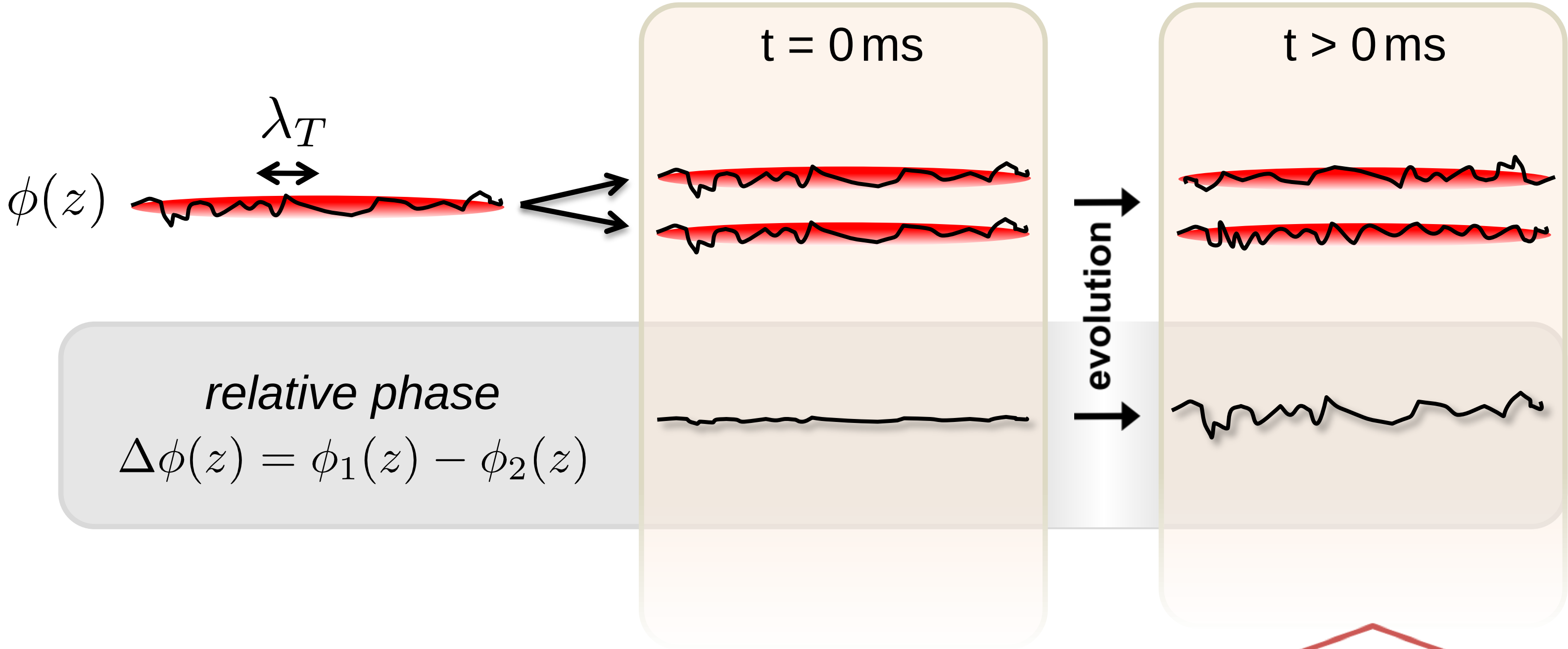
Experimental scheme



Probe the system using matter-wave interference:

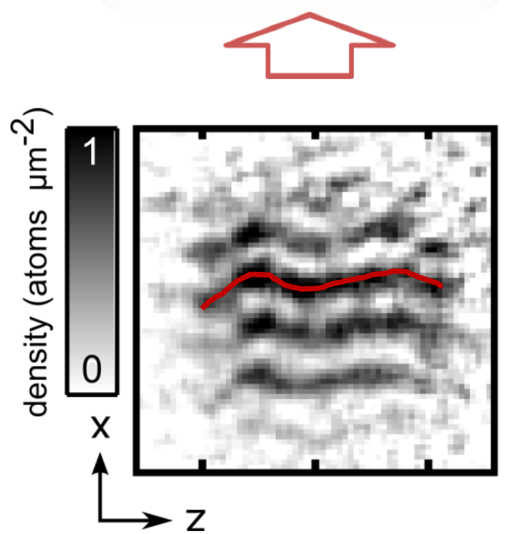


Experimental scheme



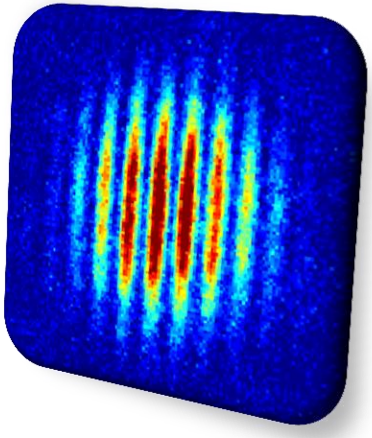
Probe the system using matter-wave interference:

direct access to the relative phase field!



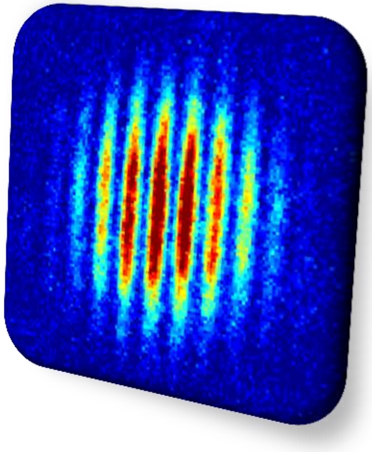
Outline

- Local relaxation dynamics
- Characterization of the relaxed state
- Dissipative cooling of a 1D Bose gas

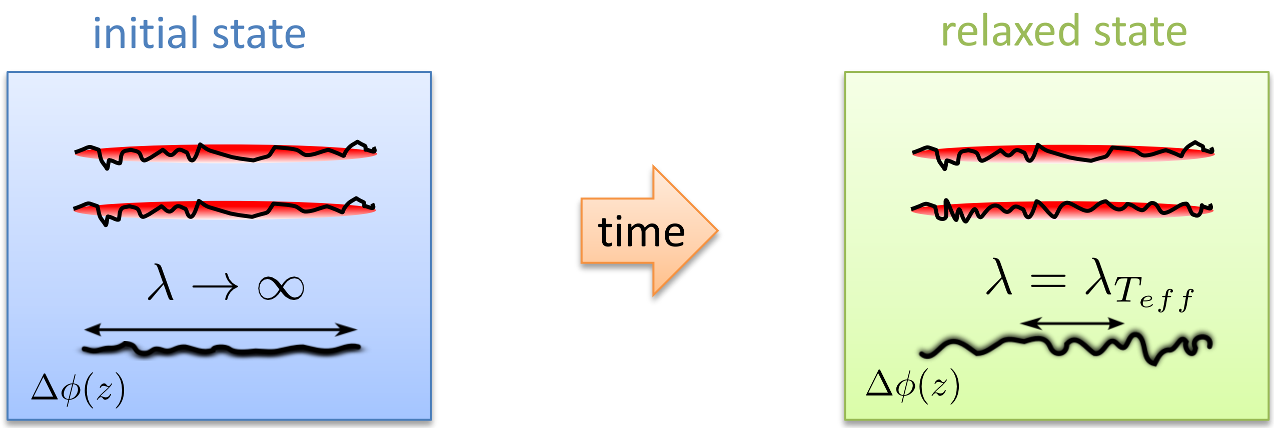


Outline

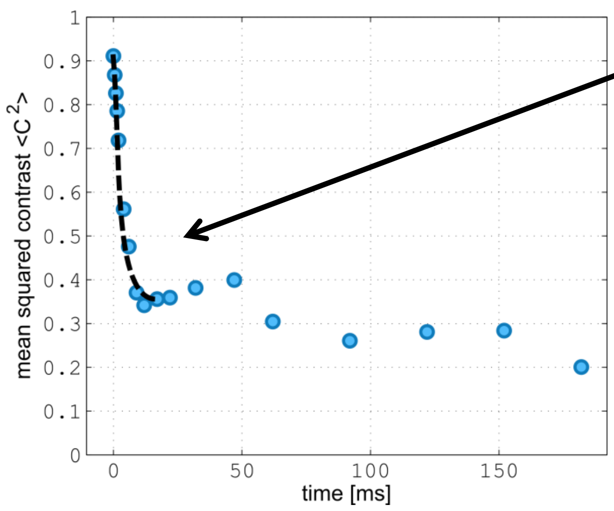
- Local relaxation dynamics
- Characterization of the relaxed state
- Dissipative cooling of a 1D Bose gas



Local relaxation dynamics

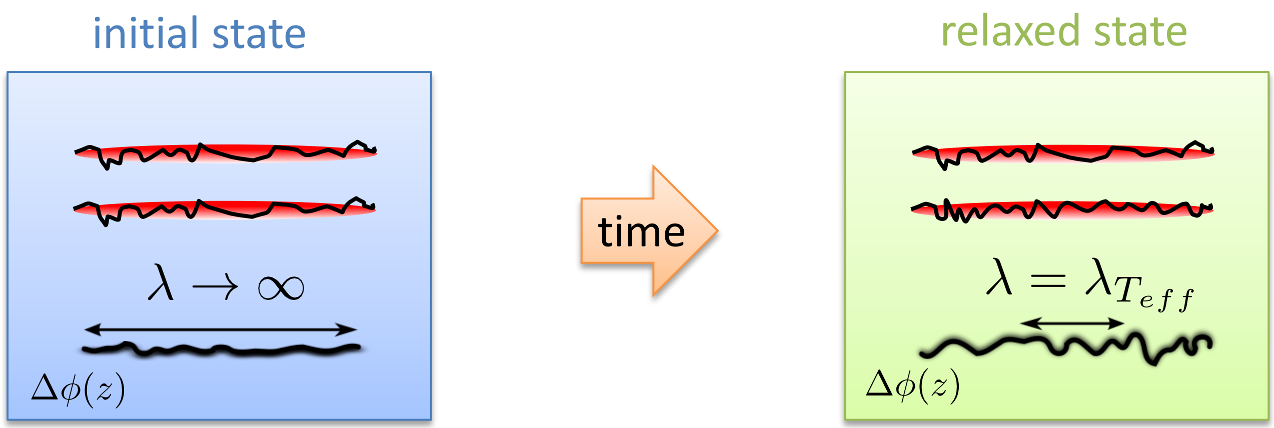


integrated contrast evolution:

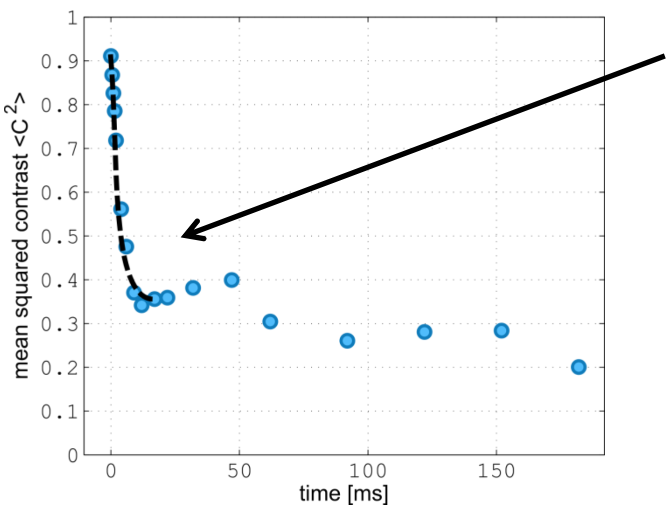


Raprid establishment of a steady state exhibiting thermal correlations!

Local relaxation dynamics



integrated contrast evolution:

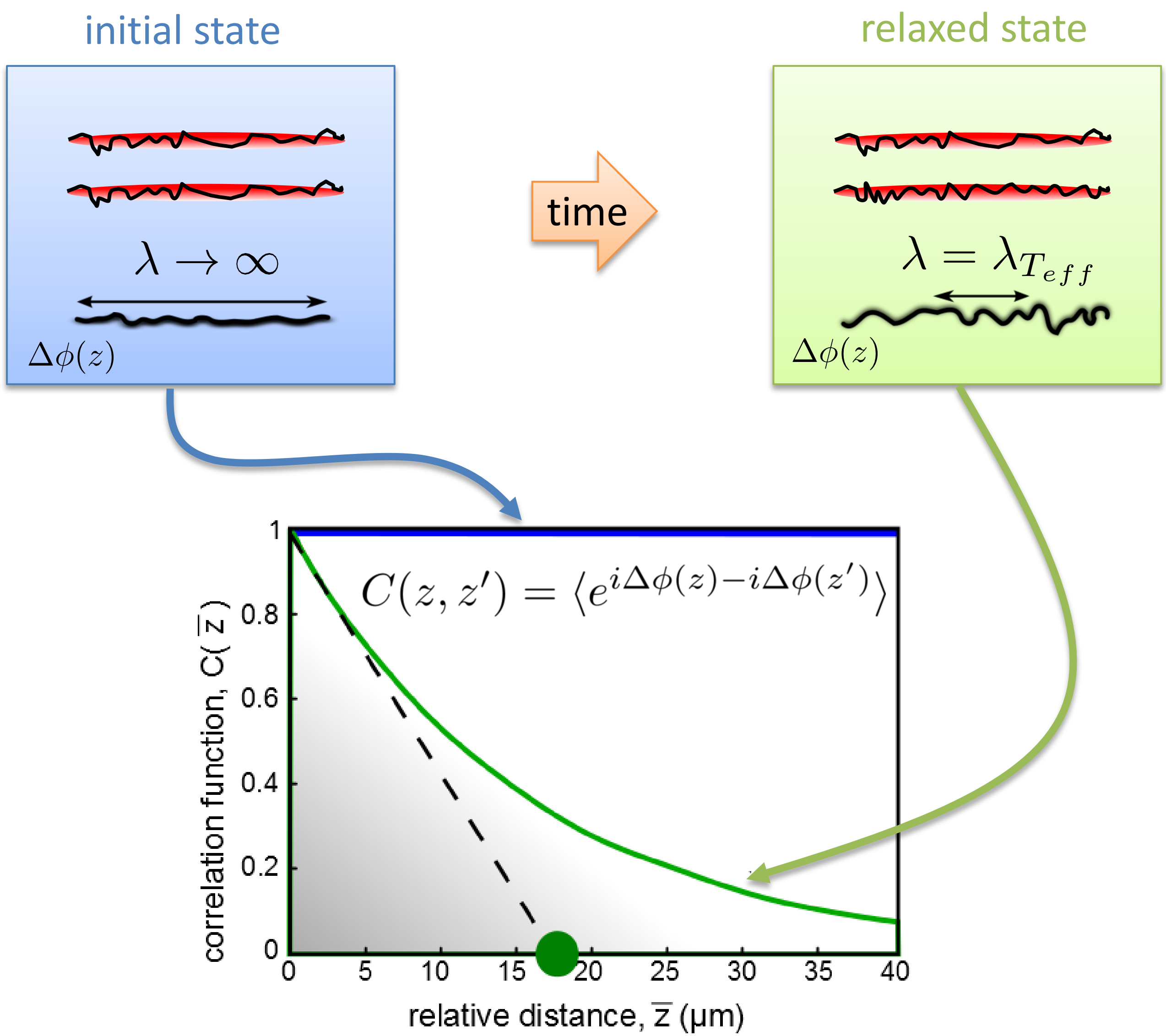


Raprid establishment of a steady state exhibiting thermal correlations!

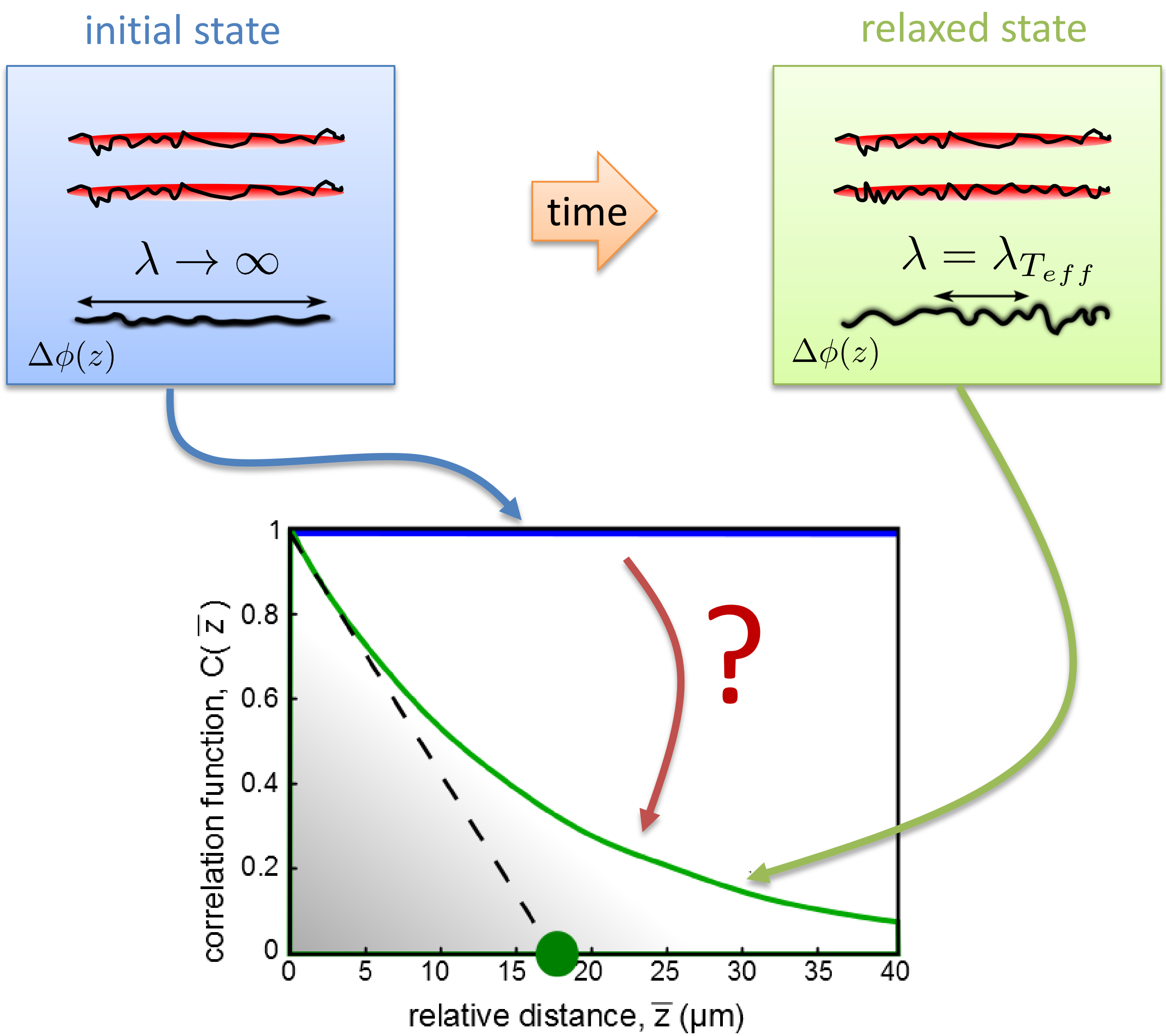
Analysing this locally through two-point correlation function of the relative phase

$$C(z, z') = \langle e^{i\Delta\phi(z) - i\Delta\phi(z')} \rangle$$

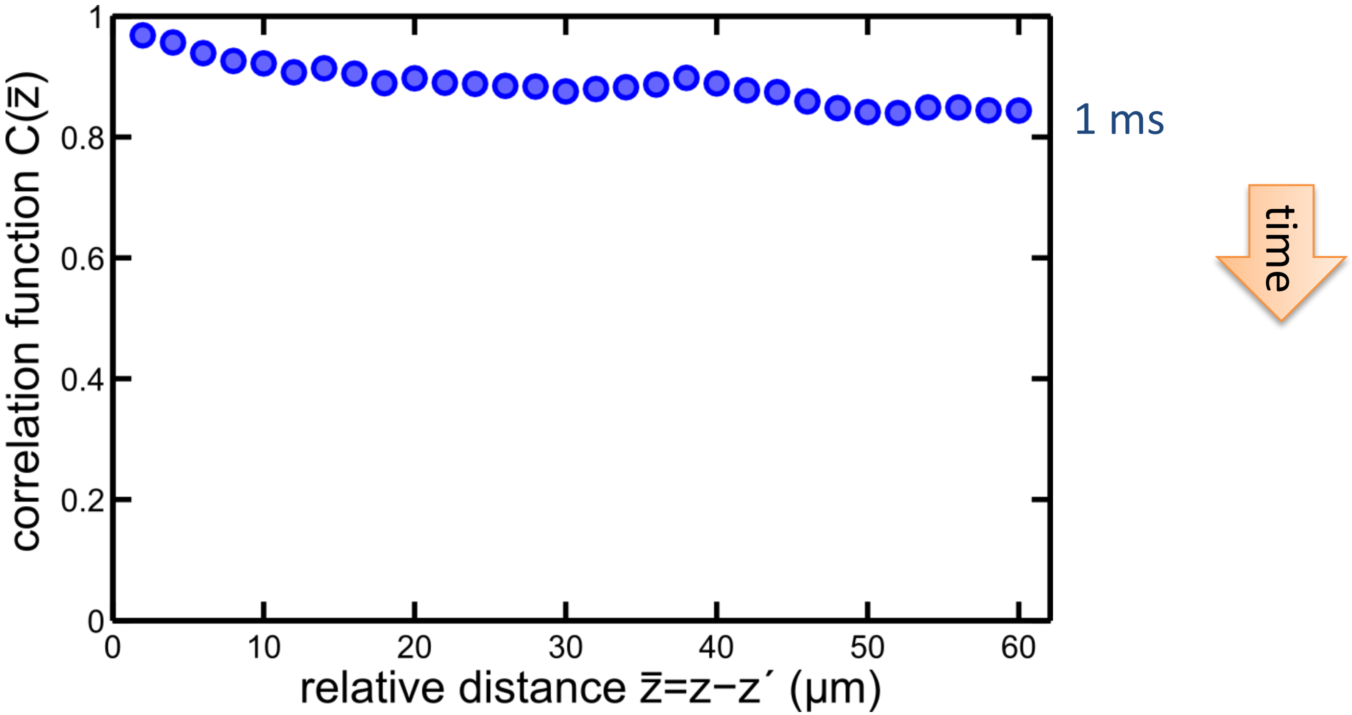
Local relaxation dynamics



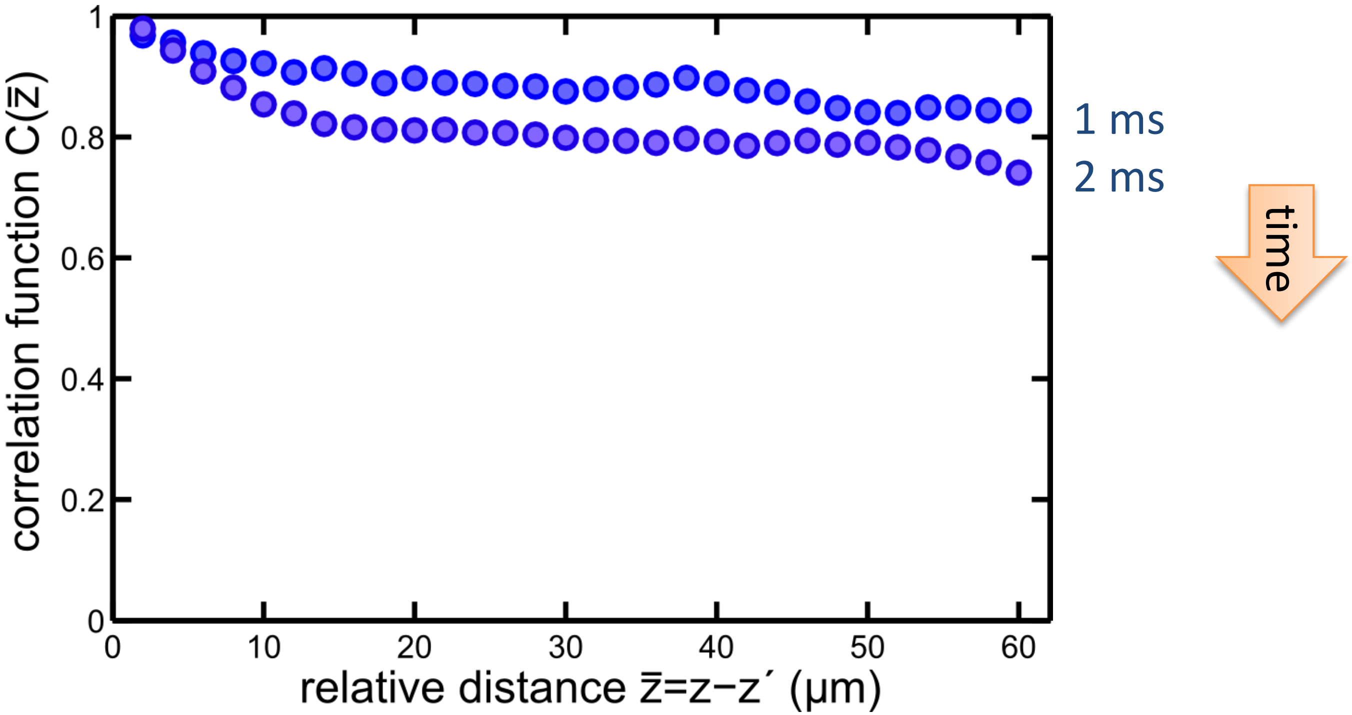
Local relaxation dynamics



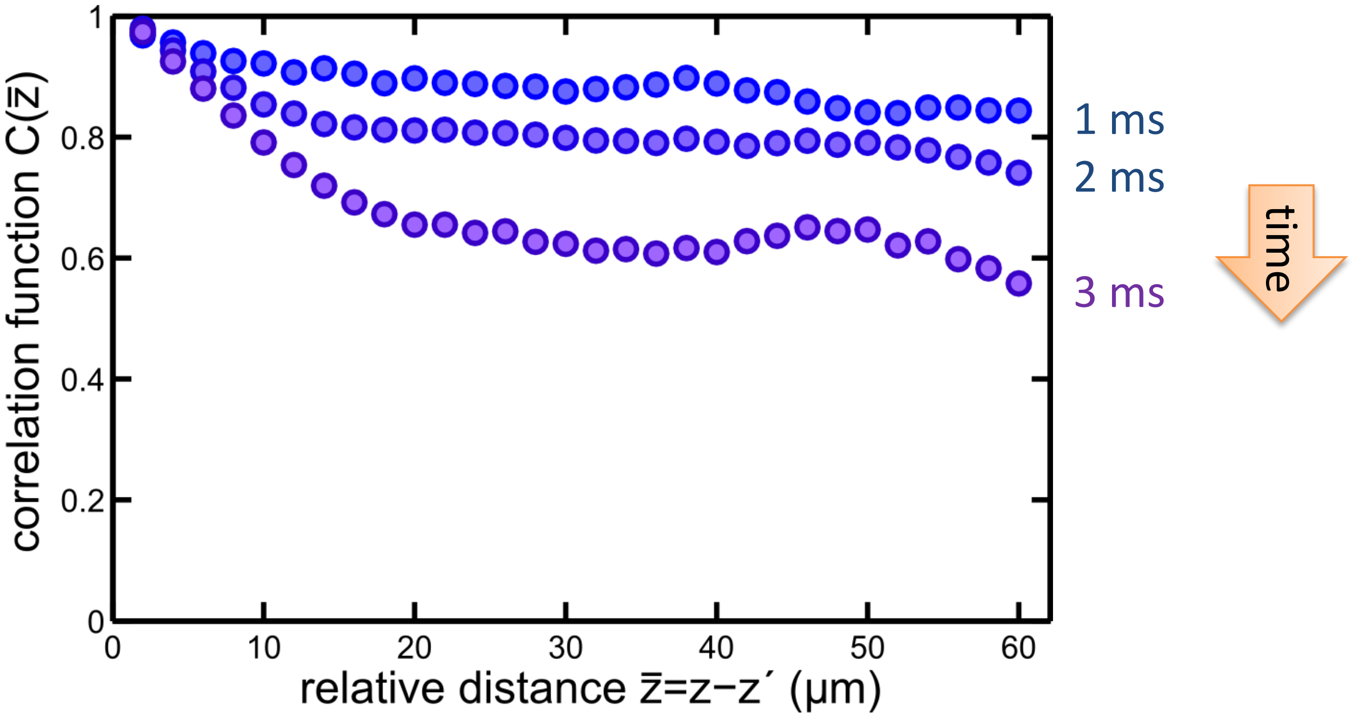
Local relaxation dynamics



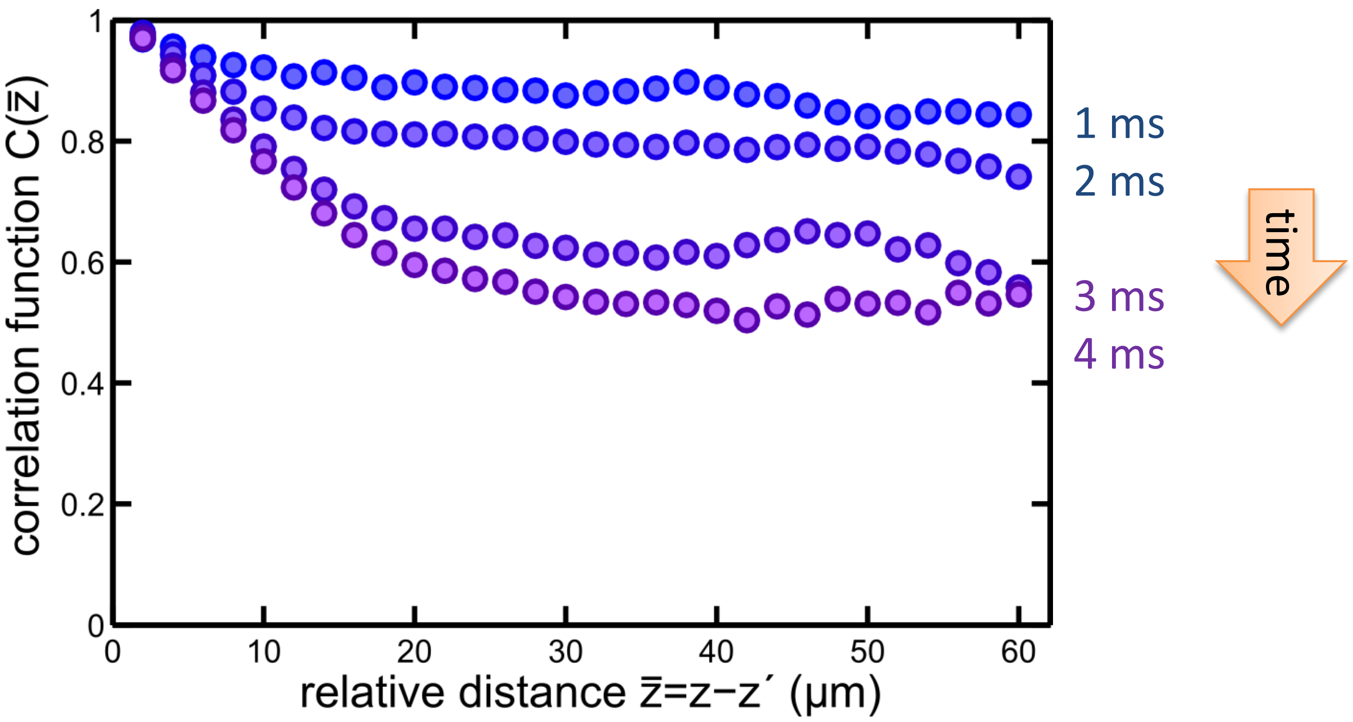
Local relaxation dynamics



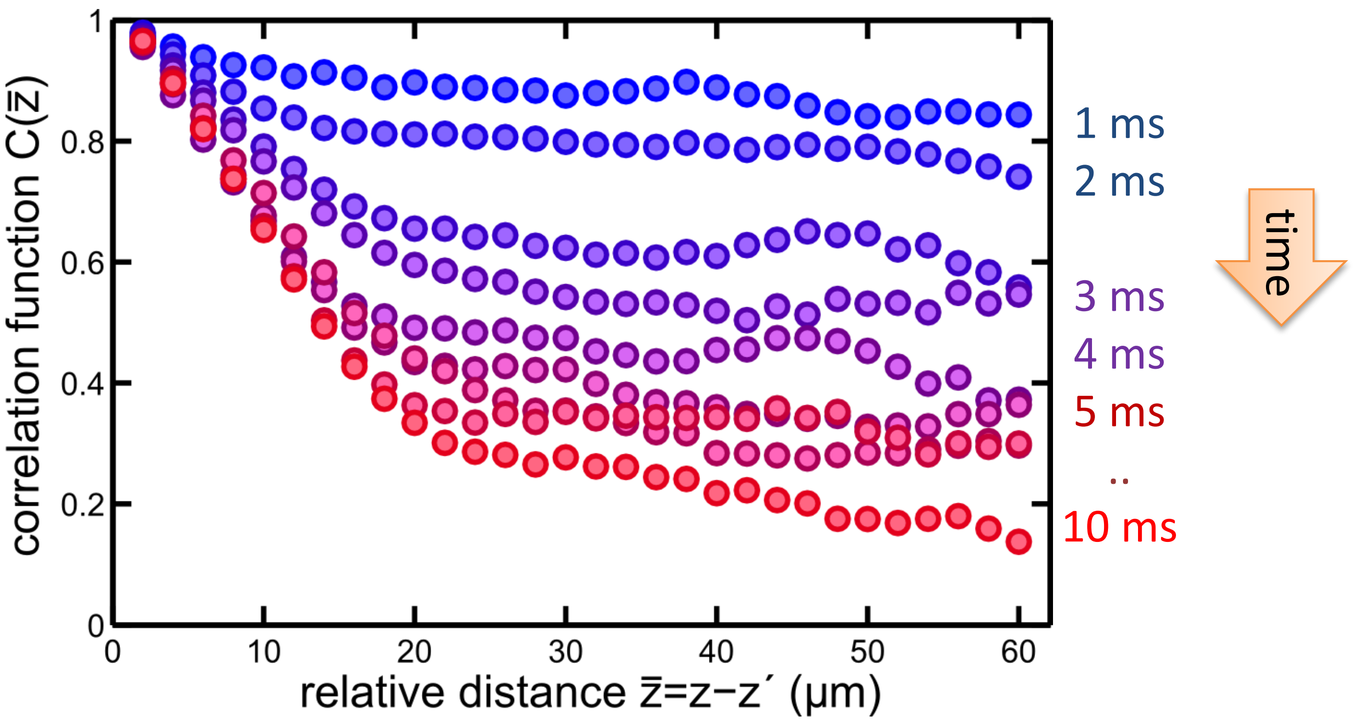
Local relaxation dynamics



Local relaxation dynamics

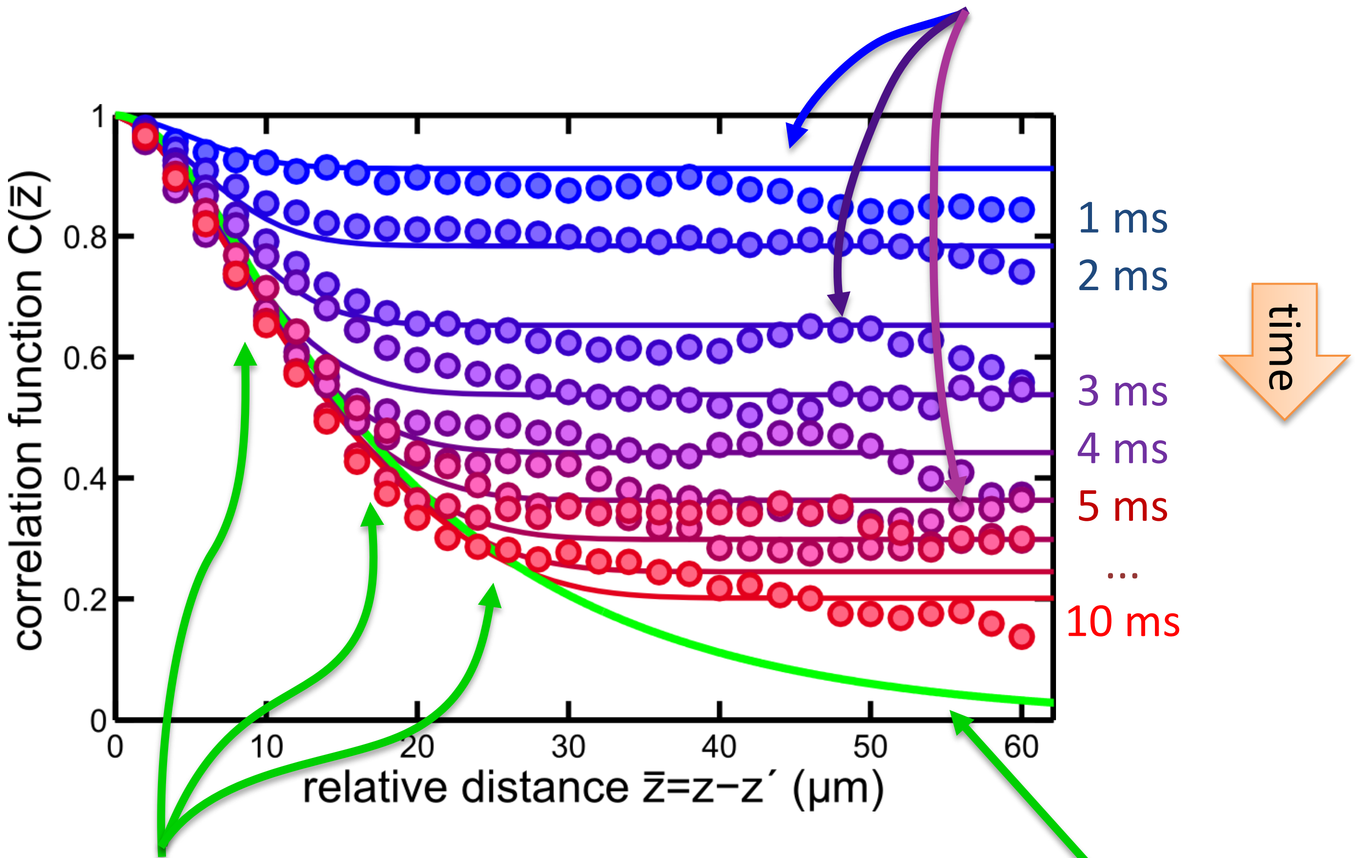


Local relaxation dynamics



Local relaxation dynamics

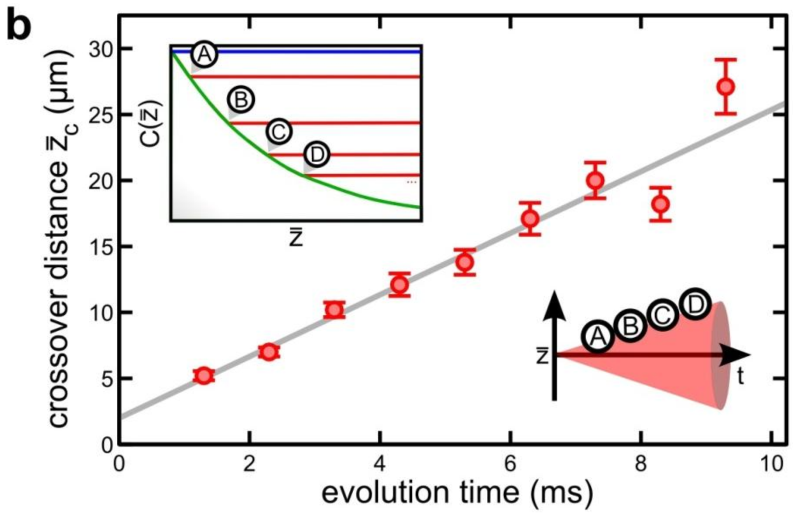
beyond z_c , long-range order remains



thermal decay up to a characteristic distance z_c

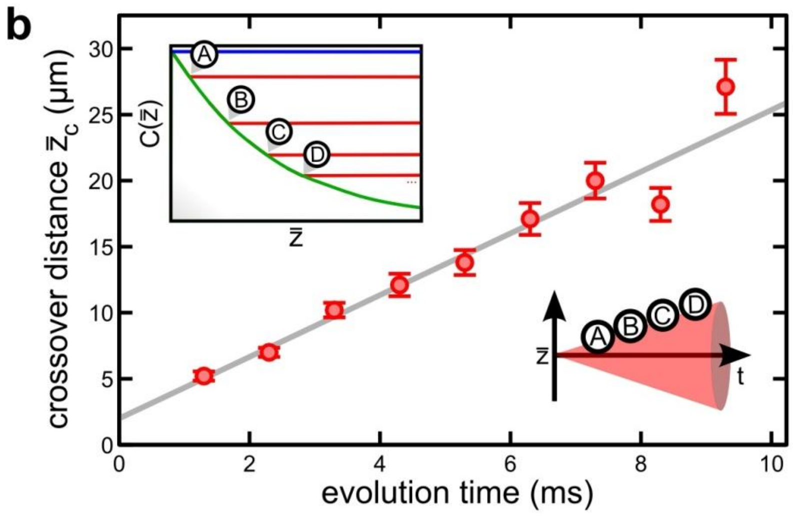
prethermalized state

Local relaxation dynamics



Thermal correlations emerge locally and spread in a light-cone like evolution!

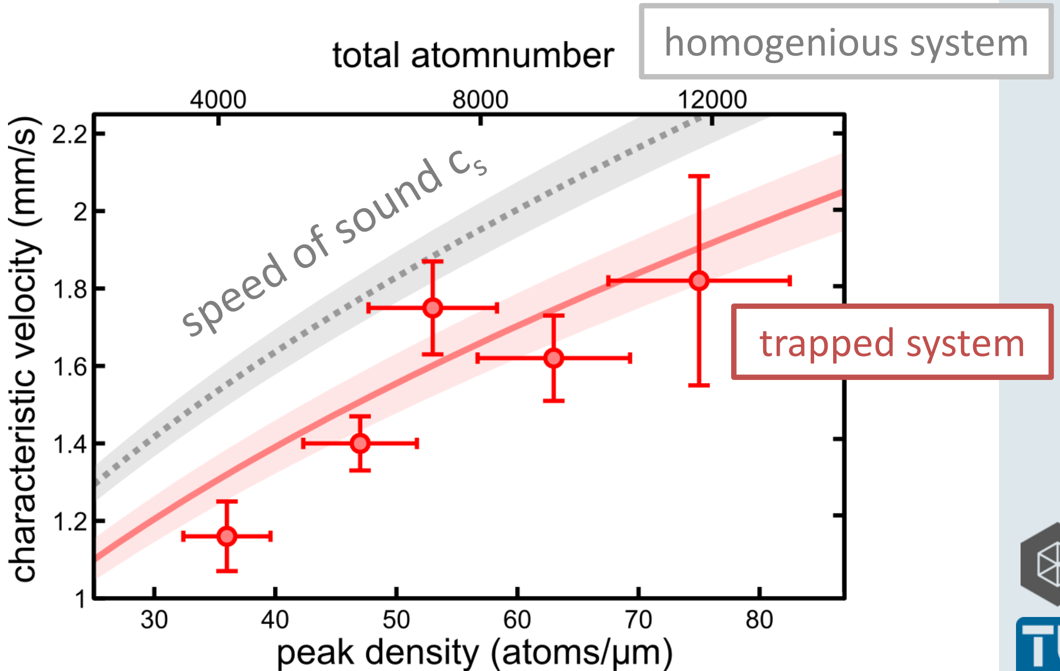
Local relaxation dynamics



Thermal correlations emerge locally and spread in a light-cone like evolution!

characteristic velocity of the correlation front:

$$z_c = 2c\,t$$

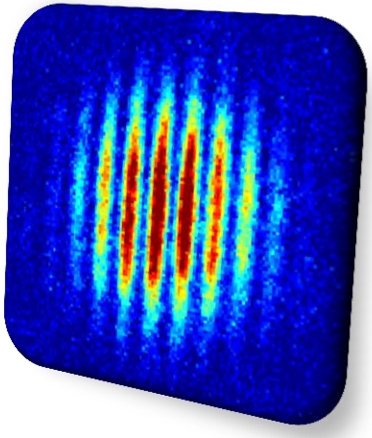


quasi-particles pairs propagate information in opposite directions

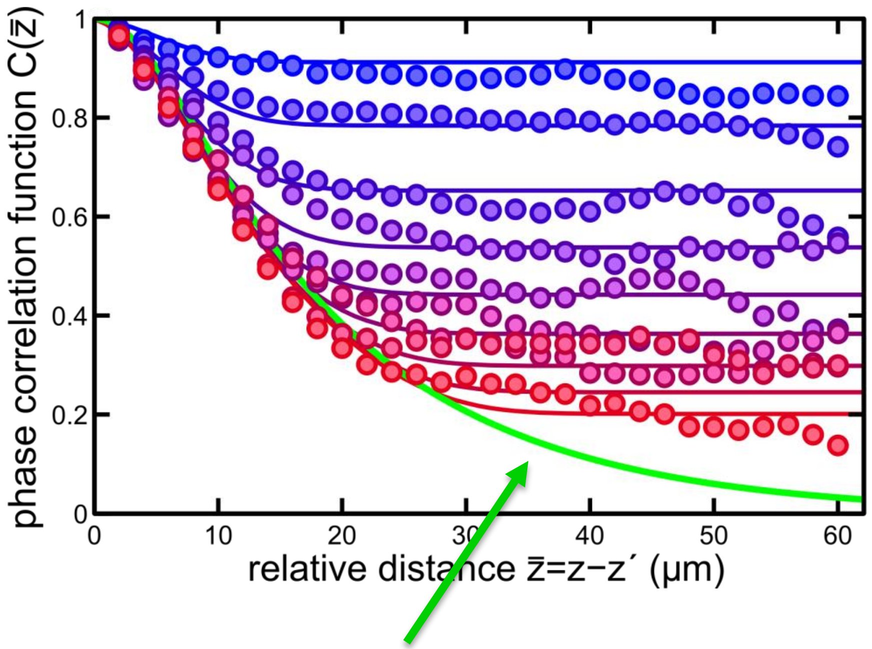
Langen et al. Nat. Phys. **9**, 640-643 (2013)

Outline

- Local relaxation dynamics
- Characterization of the relaxed state
- Dissipative cooling of a 1D Bose gas



Characterization of the relaxed state



relaxed prethermalized state
with a temperature

$$k_B T_{eff} = \frac{\mu_{init}}{4}$$

set by the initial binomial fluctuations which put the same energy into each mode

The 1D Bose gas with contact interactions is an integrable system

Dynamics is driven by dephasing of the phonon modes populated during the quench

The fact that the relaxed state shows thermal correlations is only a result of the initial state

What happens if we start form a different initial state?

Gring et al. Science **337**, 1318 (2012)

Generalized Gibbs ensemble

1D Bose gas with contact interactions is an integrable system with many conserved quantities

→ inhibited thermalization

Integrable systems are conjectured to relax to a maximum entropy state described by a generalized Gibbs ensemble (GGE):

$$\hat{\rho} = \frac{1}{Z} \exp\left(- \sum_m \lambda_m \mathcal{I}_m \right)$$

Lagrange multipliers:

$$\lambda_m = \beta_m = 1/k_B T_m$$

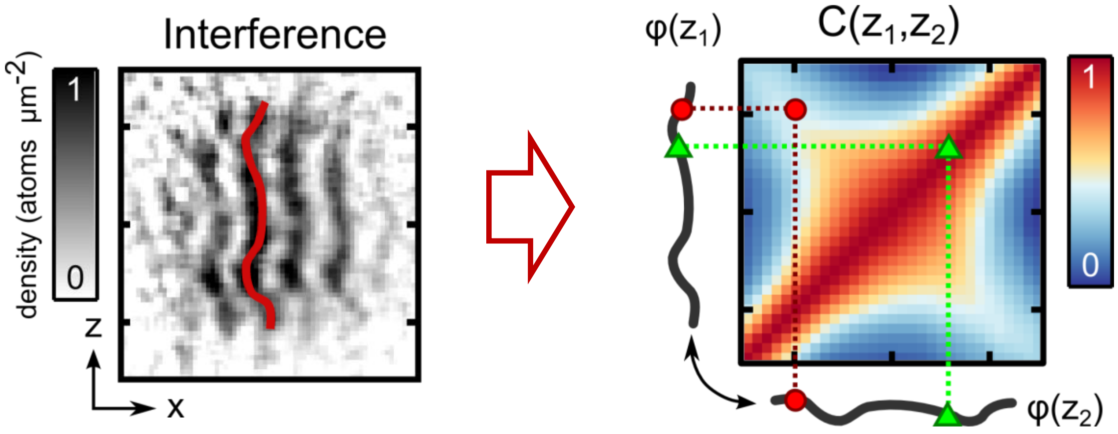
generalized temperatures

conserved quantity integral of motion

Many parameters needed to describe the thermal state!

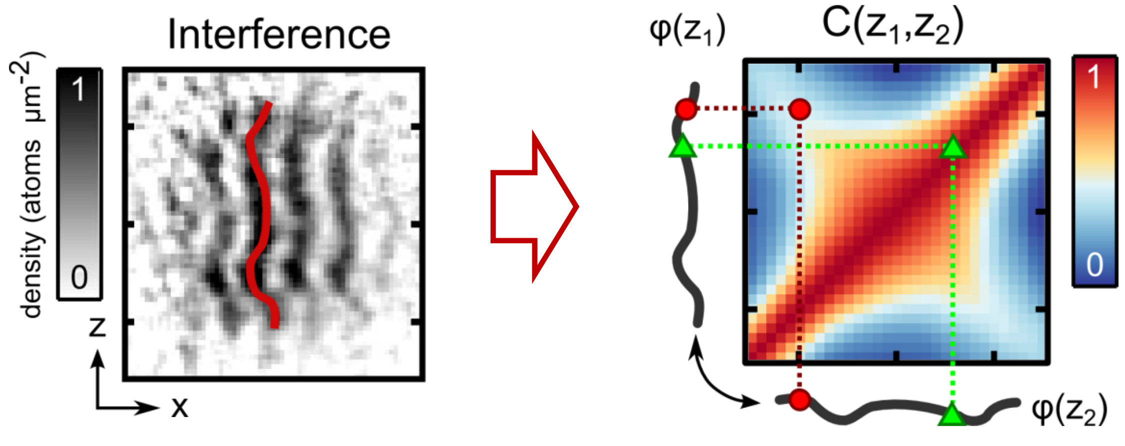
Full 2-point correlations

Non-translation-invariant phase correlation function:

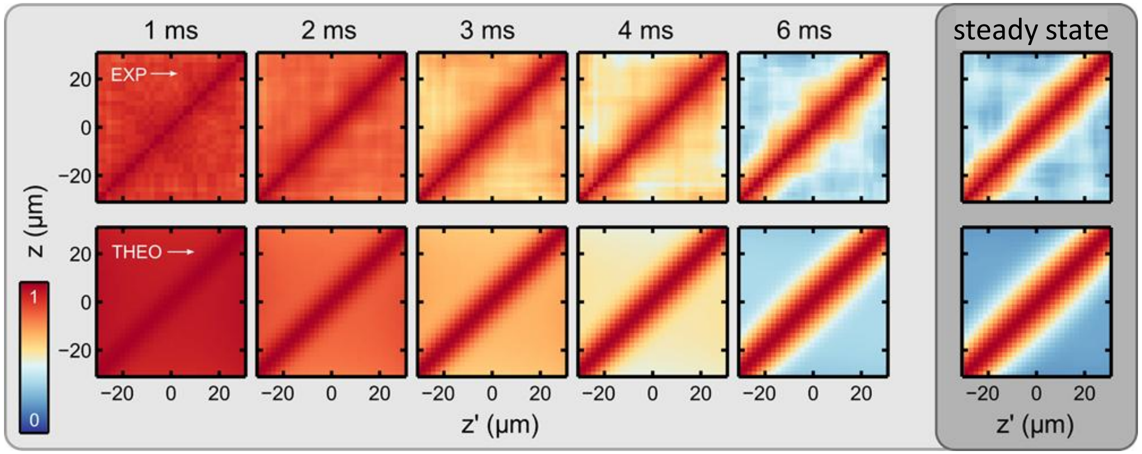


Full 2-point correlations

Non-translation-invariant phase correlation function:

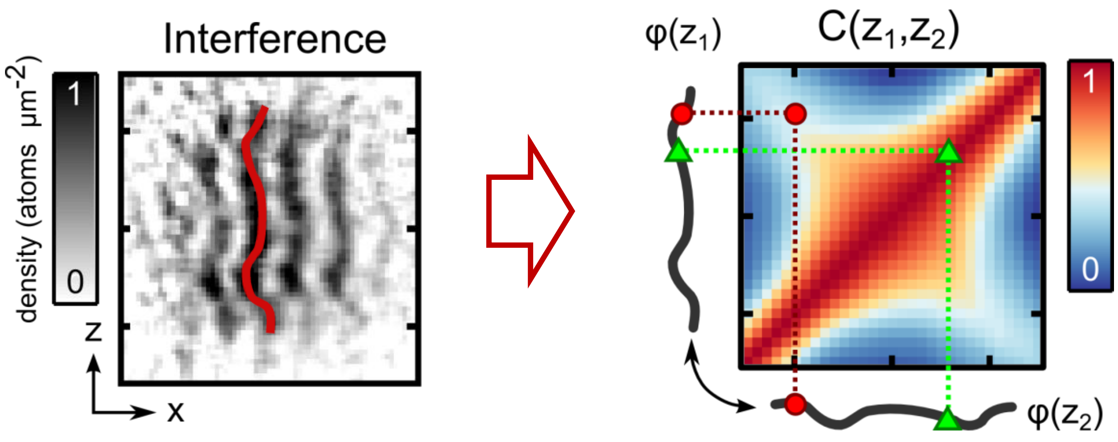


Light-cone dynamics:

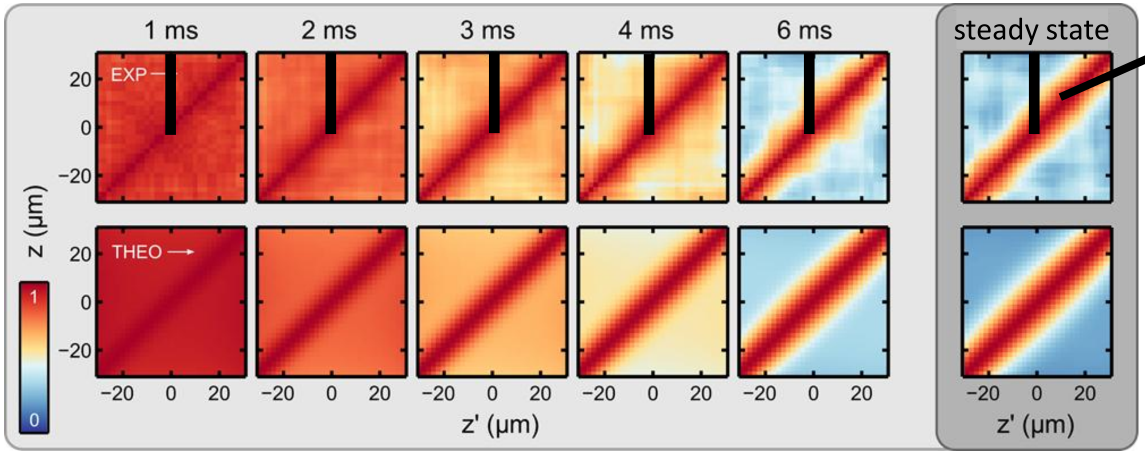


Full 2-point correlations

Non-translation-invariant phase correlation function:



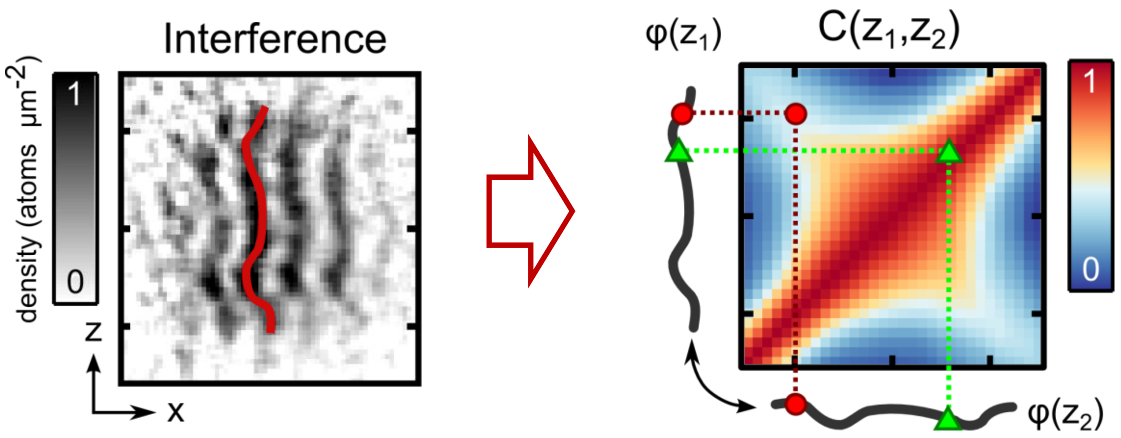
Light-cone dynamics:



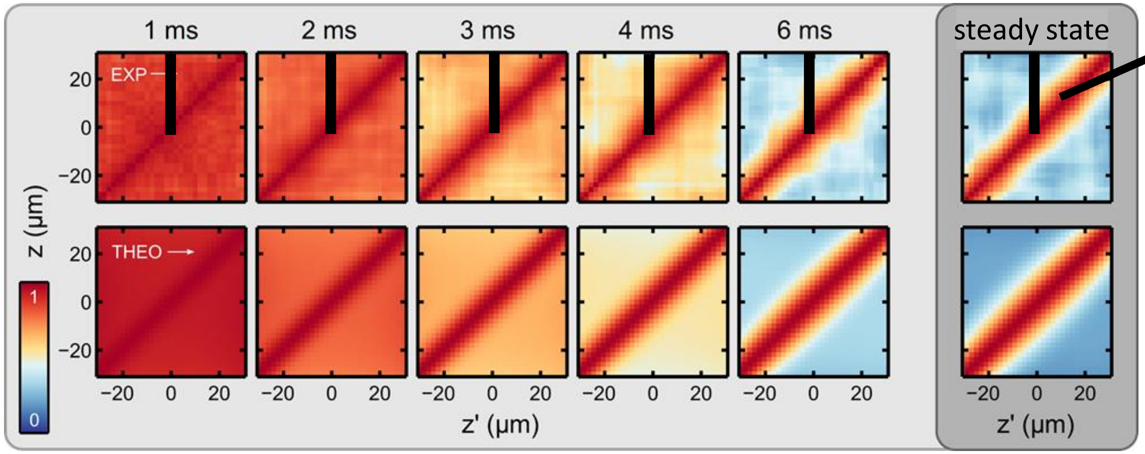
Previous correlation functions were cuts through this full two-point function

Full 2-point correlations

Non-translation-invariant phase correlation function:



Light-cone dynamics:



Previous correlation functions were cuts through this full two-point function

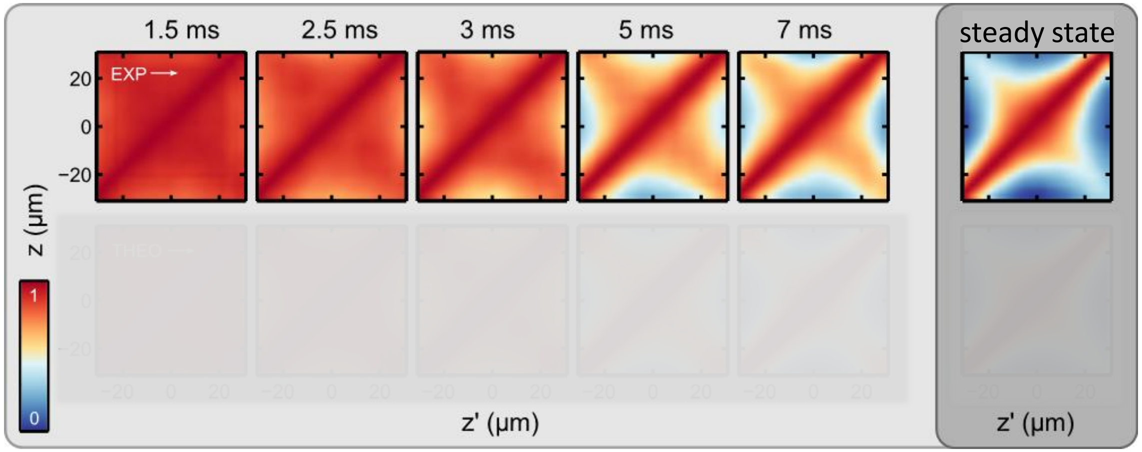
Unity correlations on the diagonal and exponential decay away from $z_1 = z_2$

Result of the initial state created in the splitting process

Dynamics and steady state can be described by one temperature!

Observation of a GGE

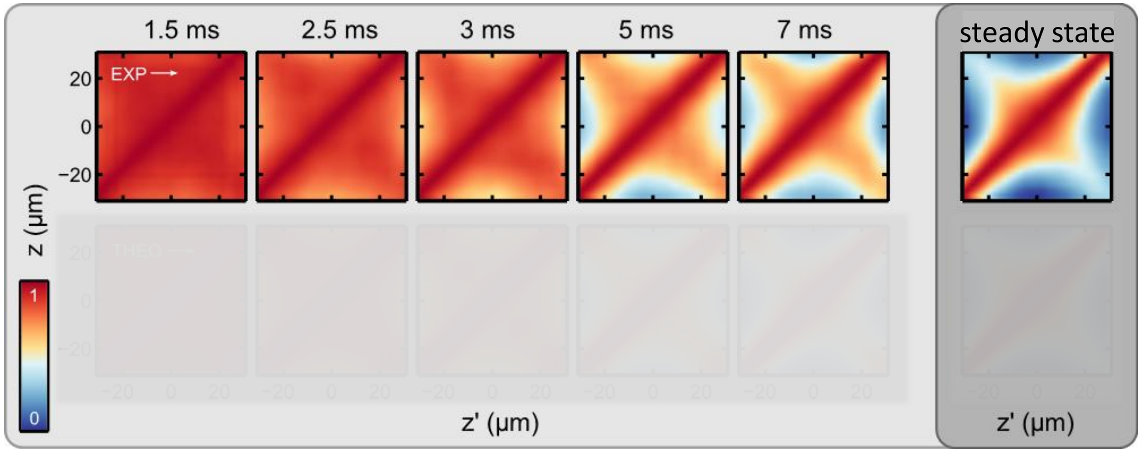
Different initial state by modified splitting process:



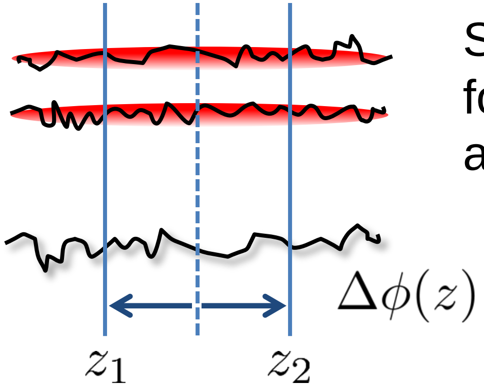
clearly visible cross-structure in the correlation function

Observation of a GGE

Different initial state by modified splitting process:



clearly visible cross-structure in the correlation function

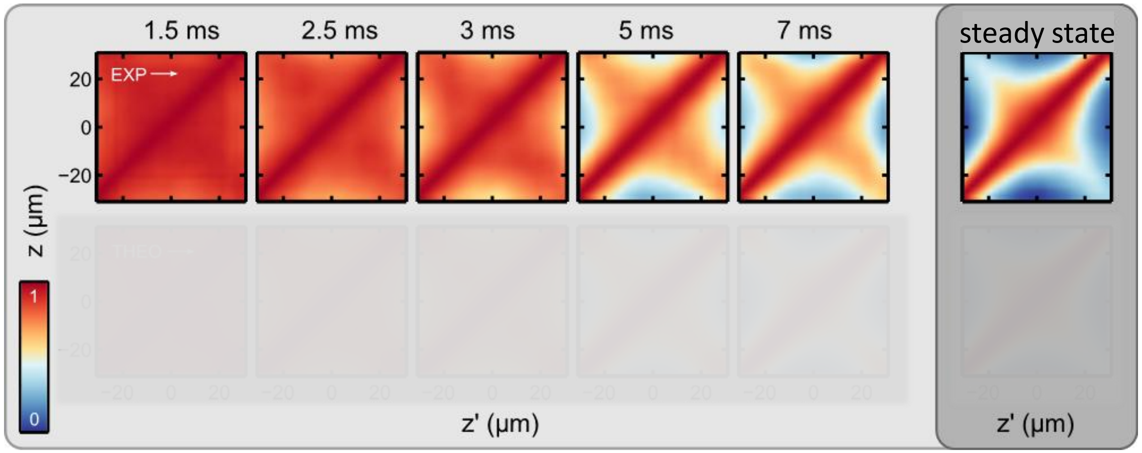


Stronger correlations for points equally far away from the center

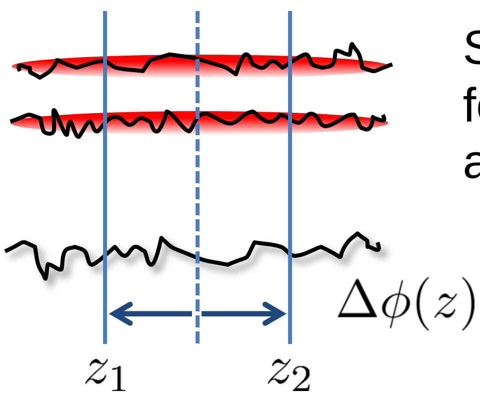
$$z_1 = -z_2$$

Observation of a GGE

Different initial state by modified splitting process:



clearly visible cross-structure in the correlation function



Stronger correlations for points equally far away from the center

$$z_1 = -z_2$$

Can be explained by an imbalanced population of even and odd modes

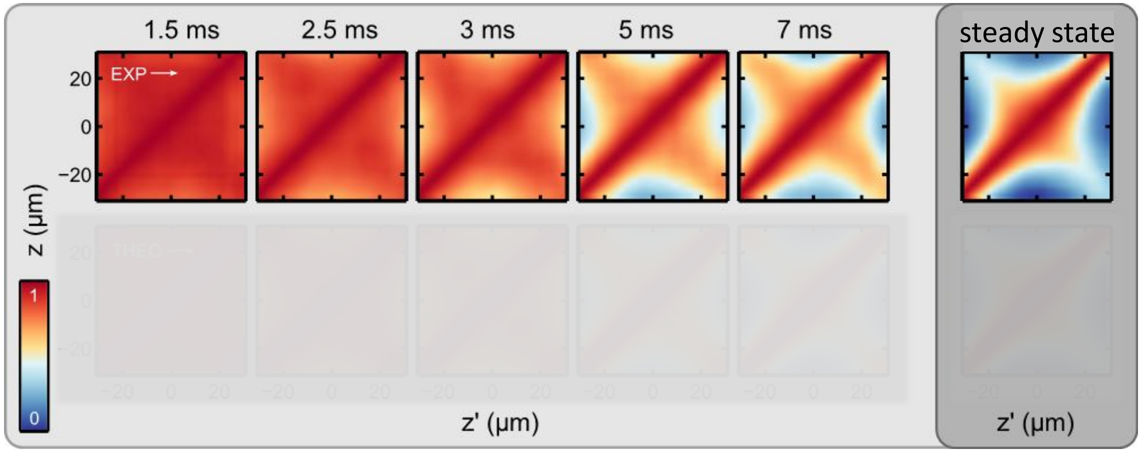
⇨ At least 2 temperatures needed to describe this

Direct observation of a GGE!

$$\hat{\rho} = \frac{1}{Z} e^{-\sum_m \lambda_m \mathcal{I}_m}$$

Observation of a GGE

Different initial state by modified splitting process:



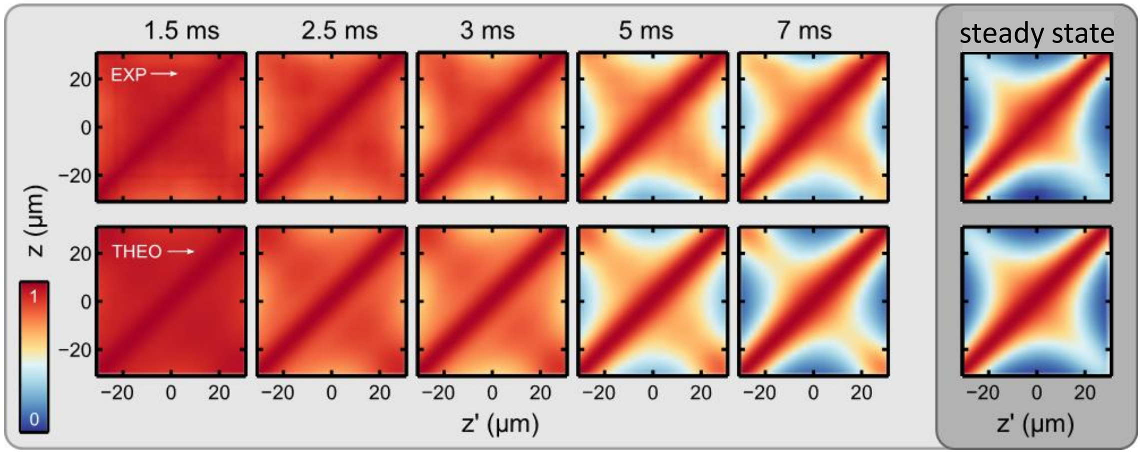
generalized Gibbs Ensemble:

$$\hat{\rho} = \frac{1}{Z} e^{-\sum_m \lambda_m \mathcal{I}_m}$$

χ^2 Analysis shows that the steady state is not compatible with a single temperature

Observation of a GGE

Different initial state by modified splitting process:

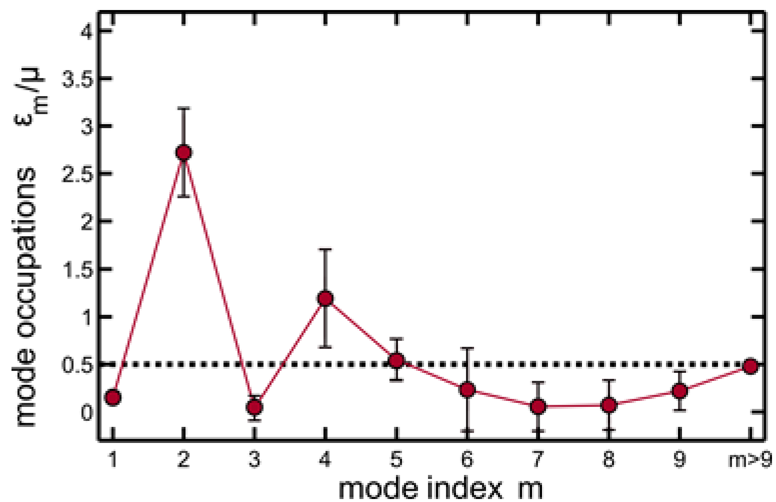


generalized Gibbs Ensemble:

$$\hat{\rho} = \frac{1}{Z}\, e^{-\sum_m \lambda_m \mathcal{I}_m}$$

χ^2 Analysis shows that the steady state is not compatible with a single temperature

Fitting the stead state reveals the individual mode occupations



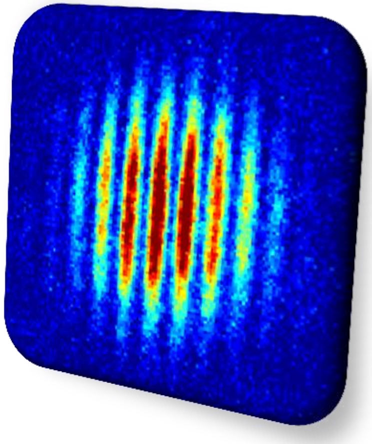
With 10 fitted temperatures we can describe the steady state and the dynamics!

(number corresponds to what we expect from resolution and decreasing contribution of higher modes)

Langen et al. Science **348**, 207 (2015)

Outline

- Local relaxation dynamics
- Characterization of the relaxed state
- Dissipative cooling of a 1D Bose gas

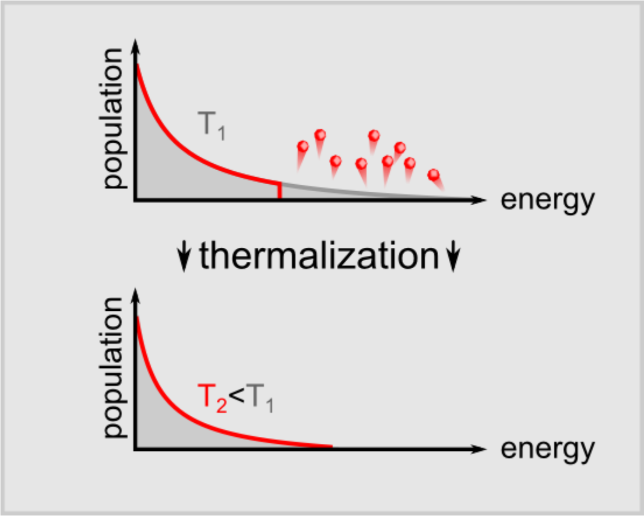


Motivation

<u>Conventional evaporative cooling:</u>

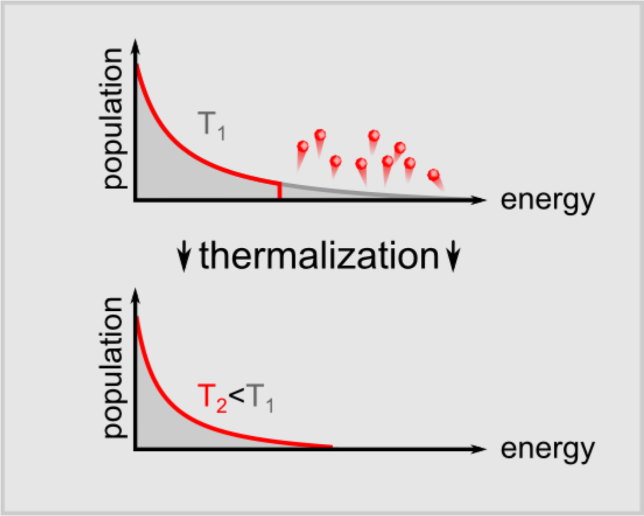
key ingredients:

- energy selective out-coupling of particles
- consecutive thermalization



Motivation

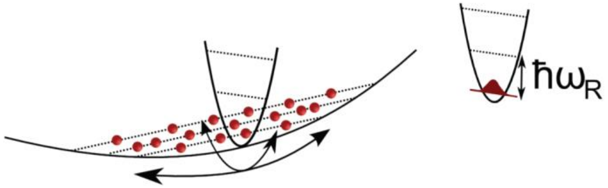
Conventional evaporative cooling:



key ingredients:

- energy selective out-coupling of particles
- consecutive thermalization

1D Bose gas:



Energy selective removal of particles is in principle possible but thermalization is inhibited

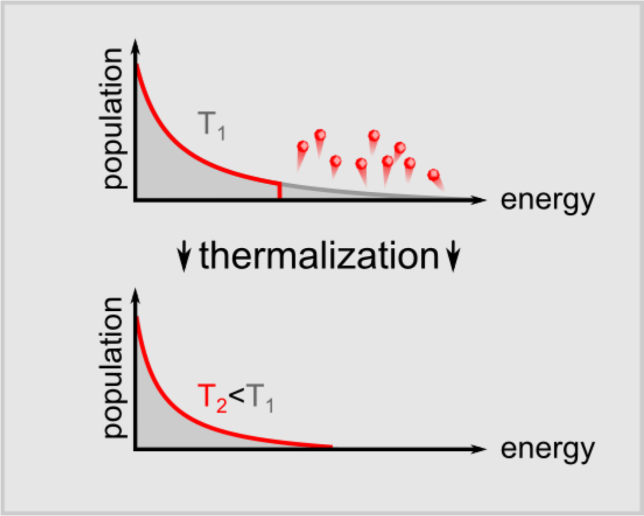
→ should render cooling ineffective

Motivation

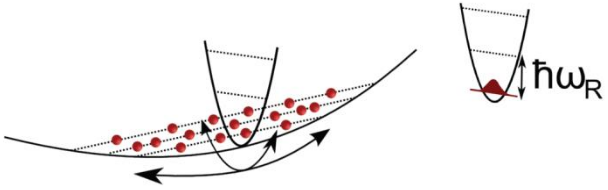
Conventional evaporative cooling:

key ingredients:

- energy selective out-coupling of particles
- consecutive thermalization



1D Bose gas:



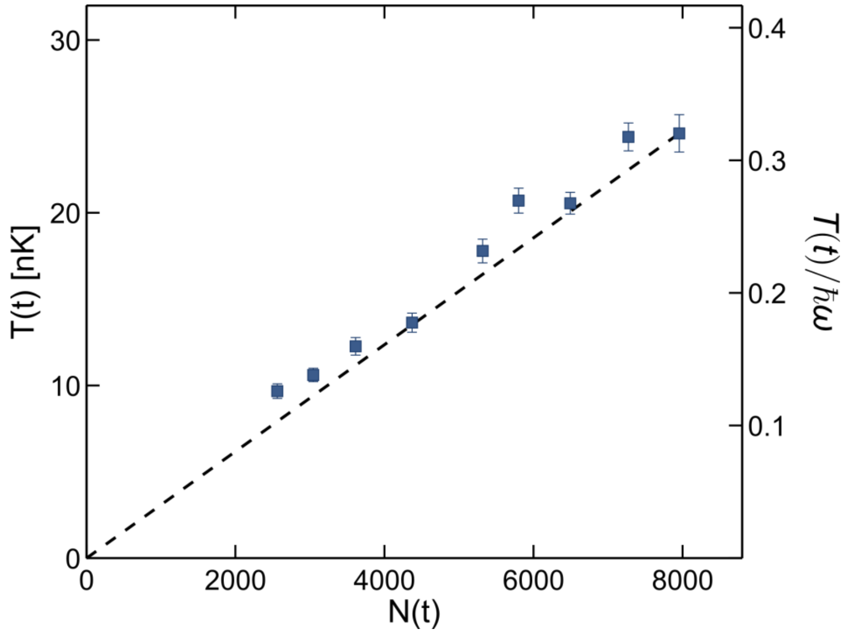
Energy selective removal of particles is in principle possible but thermalization is inhibited

→ should render cooling ineffective

Nevertheless cooling is observed in experiment. Why?

Measurement

Measurement of the temperature evolution under continuous dissipation of atoms:



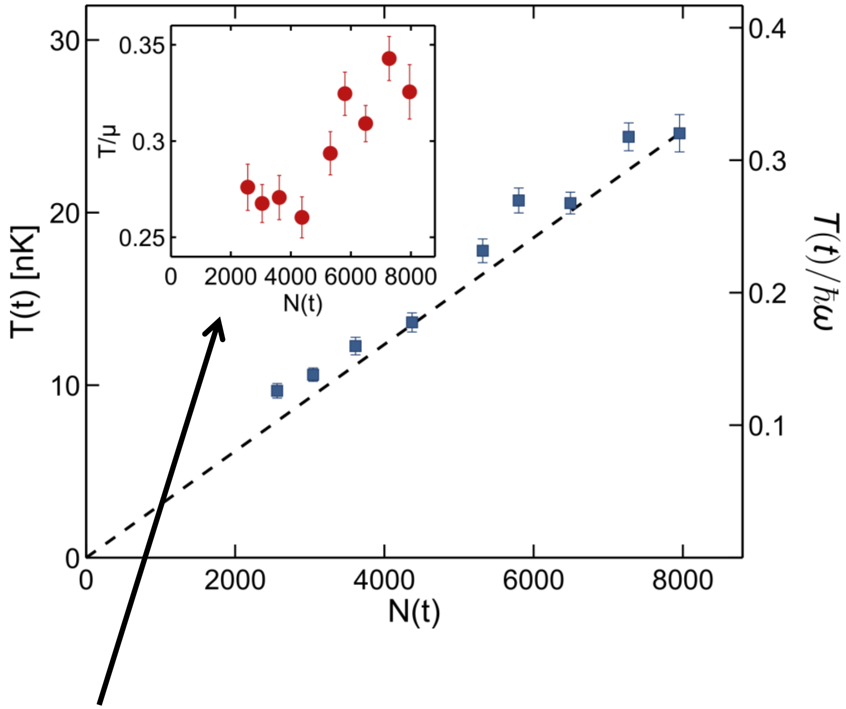
Clear signature of cooling

Observe a linear scaling of Temperature with particle number N

$$T \propto N$$

Measurement

Measurement of the temperature evolution under continuous dissipation of atoms:



Clear signature of cooling

Observe a linear scaling of Temperature with particle number N

$$T \propto N$$

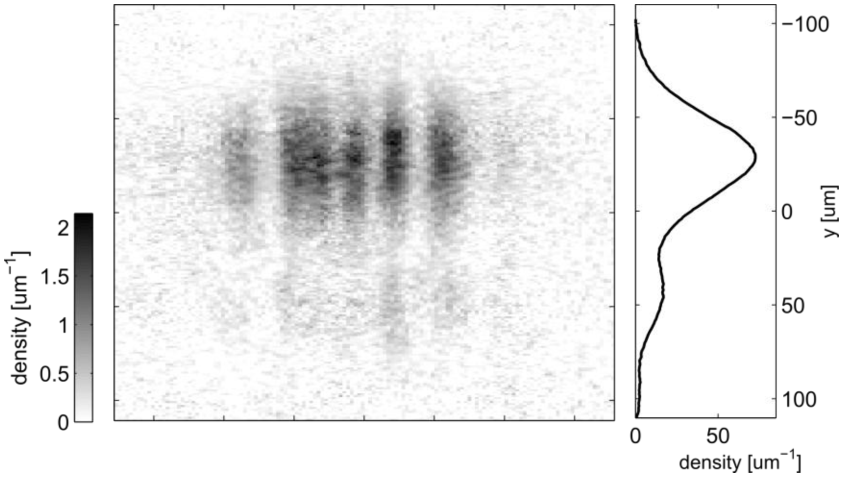
System gets more coherent

Thermal coherence length goes up

Out-coupling process

Atoms are extracted from the trap by RF-transitions to untrapped states.

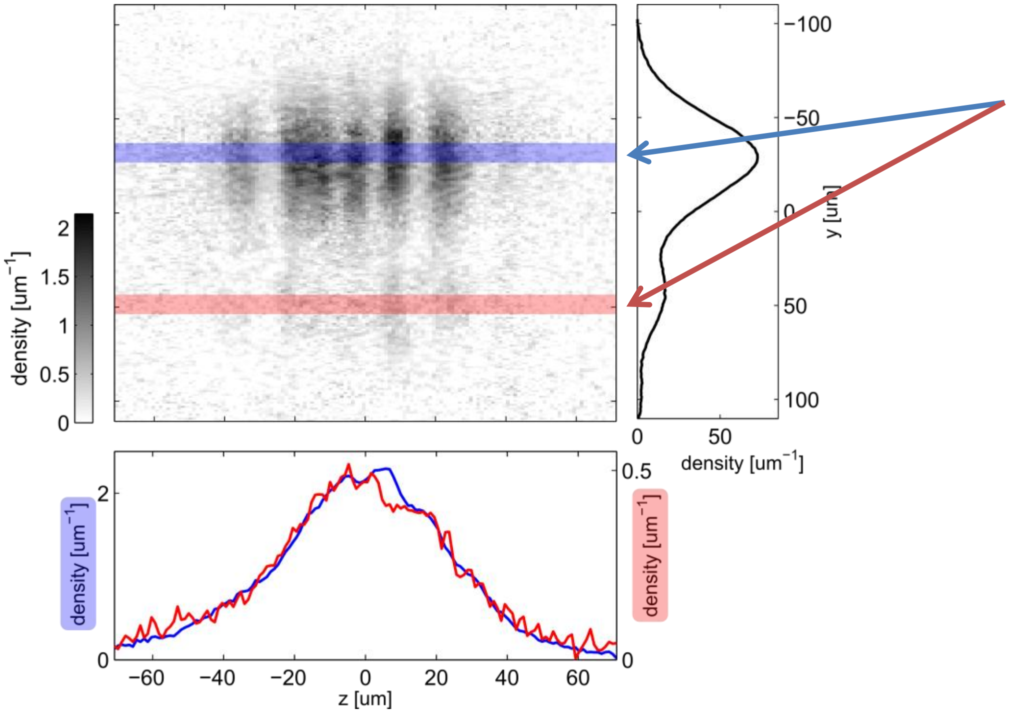
Example of pulse that out-couples a small fraction:



Out-coupling process

Atoms are extracted from the trap by RF-transitions to untrapped states.

Example of pulse that out-couples a small fraction:

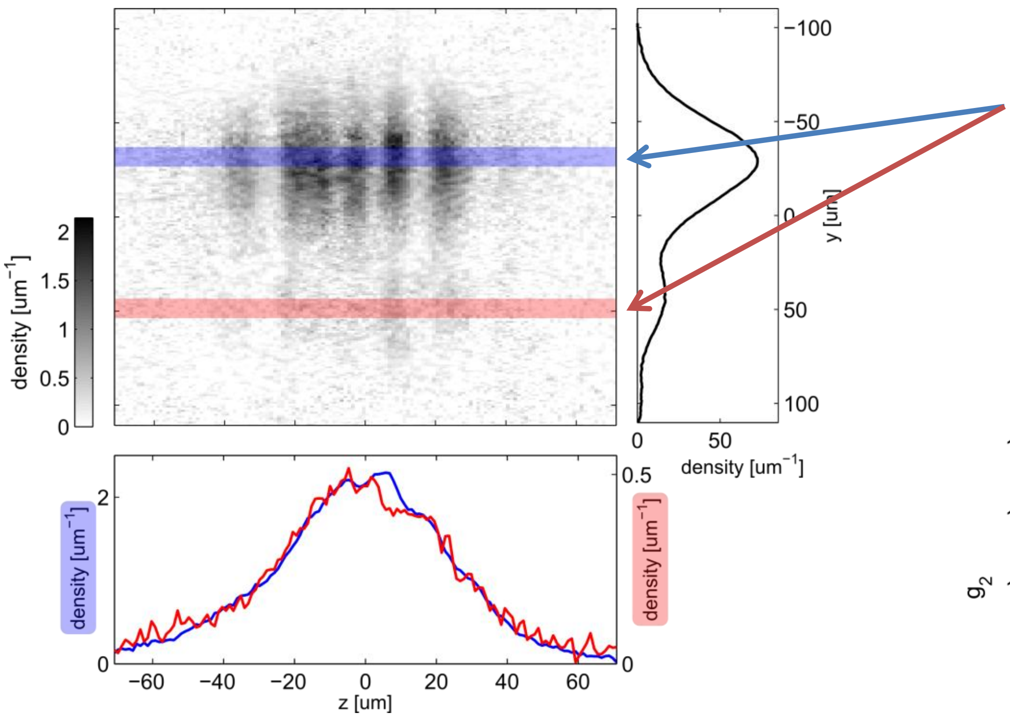


Cuts through the source cloud and the out-coupled cloud show the same profile

Out-coupling process

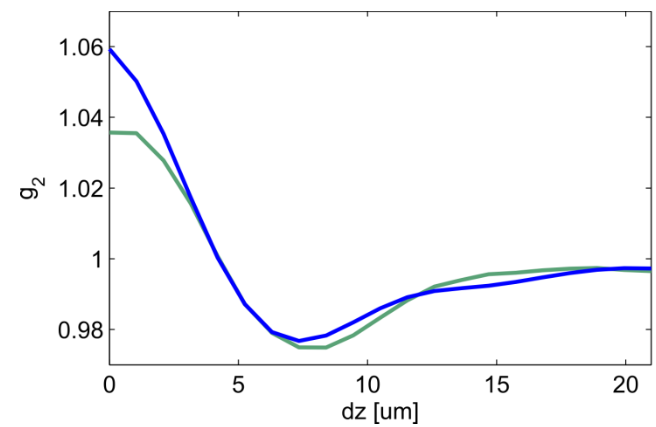
Atoms are extracted from the trap by RF-transitions to untrapped states.

Example of pulse that out-couples a small fraction:



Cuts through the source cloud and the out-coupled cloud show the same profile

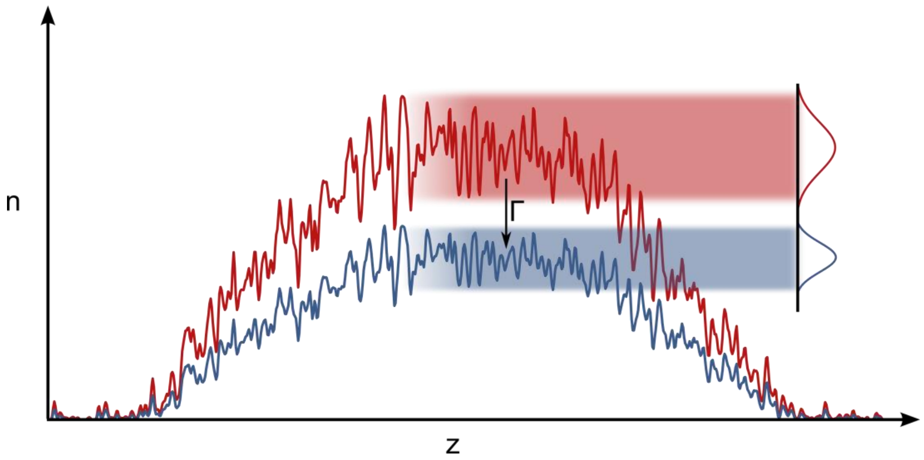
Also the density species are show the same correlations:



Out-coupling is homogeneous along the 1D axis

Mechanism

Homogeneous out-coupling of atoms scales down not only the average density but also the density fluctuations:



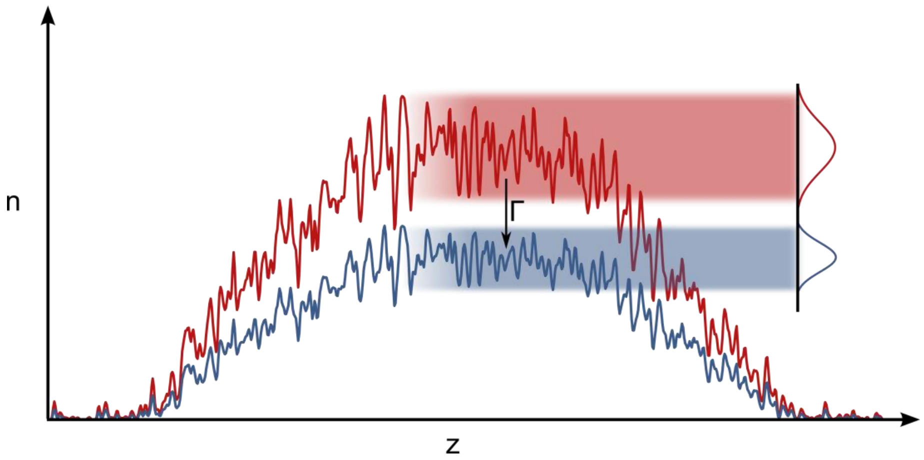
$$\langle |n_k|^2 \rangle \rightarrow \Gamma^2 \langle |n_k|^2 \rangle$$

$$\langle |\phi_k|^2 \rangle \rightarrow \langle |\phi_k|^2 \rangle$$

takes out energy from density quadrature creating a non-equilibrium state that dephases

Mechanism

Homogeneous out-coupling of atoms scales down not only the average density but also the density fluctuations:



$$\langle |n_k|^2 \rangle \;\rightarrow\; \Gamma^2 \langle |n_k|^2 \rangle$$

$$\langle |\phi_k|^2 \rangle \;\rightarrow\; \langle |\phi_k|^2 \rangle$$

takes out energy from density quadrature creating a non-equilibrium state that dephases

In the limit of slow evaporation this results in a linear scaling of temperature and atom number

$$T(t) = \left(\frac{n_0(t)}{n_0(0)}\right)^{3/2} T(0) = \frac{N(t)}{N(0)}\, T(0)$$

Conclusion and Summery

- Local relaxation dynamics
  - local emergence of thermal correlations
- Characterization of the relaxed state
  - observation of a generalized Gibbs ensemble
- Dissipative cooling of a 1D Bose gas
  - down-scaling of density fluctuations through dissipation

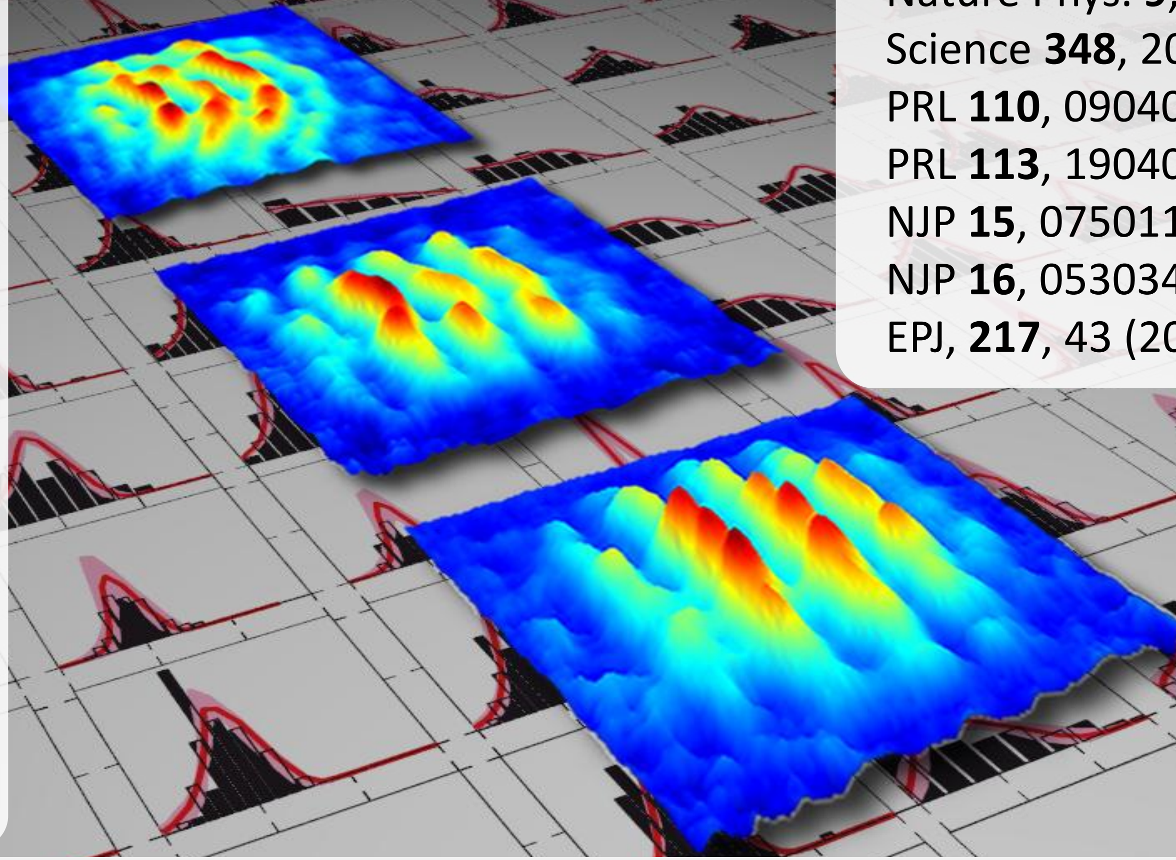
Thank you!

www.atomchip.org

Bernhard Rauer
Tim Langen
Thomas Schweigler
Maximilian Kuhnert
Michael Gring
Remi Geiger
David Adu Smith
Jörg Schmeidmayer

Theory:

Igor Mazets
Pjotrs Grisins
Sebastian Erne
Thomas Gasenzer
Takuya Kitagawa
Eugene Demler

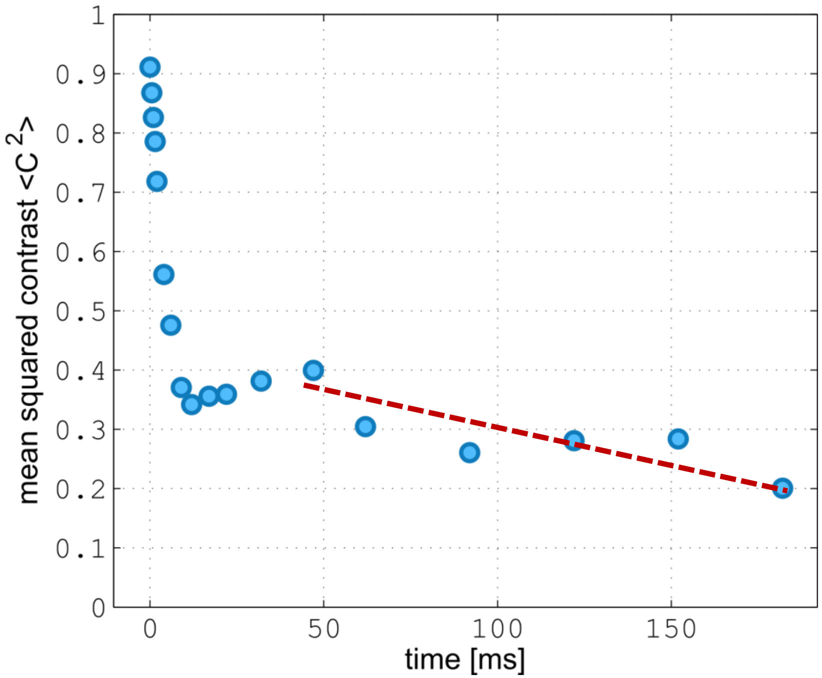


Science **337**, 1318 (2012)
Nature Phys. **9**, 640 (2013)
Science **348**, 207 (2015)
PRL **110**, 090405 (2013)
PRL **113**, 190401 (2014)
NJP **15**, 075011 (2013)
NJP **16**, 053034 (2014)
EPJ, **217**, 43 (2013)

FWF Der Wissenschaftsfonds.
CoQuS ComplexQuantumSystems
aqute
WIEN KULTUR
CHIMONO Nano-Optics for Molecules on Chips
SFB FoQuS
MARIE CURIE ACTIONS
SEVENTH FRAMEWORK PROGRAMME
Siemens AG Österreich
EUROPEAN SCIENCE FOUNDATION
SETTING SCIENCE AGENDAS FOR EUROPE
TU WIEN

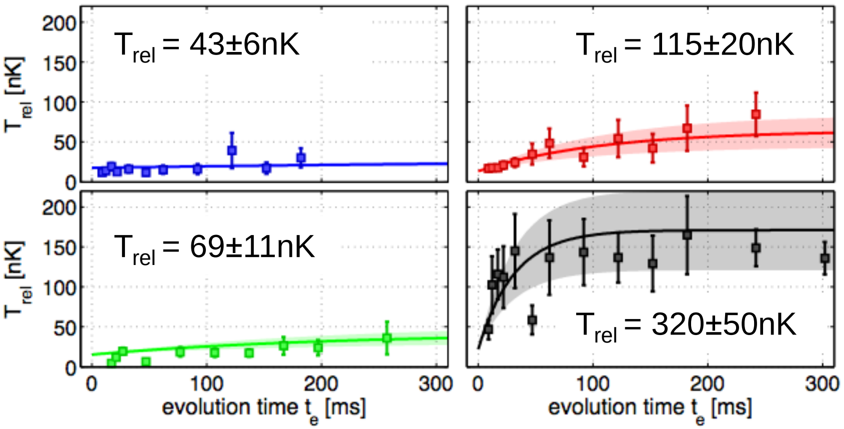
Long-term dynamics

Contrast evolution:



We clearly see a second much slower decay and the emergence of a further steady state!

relative temperature:



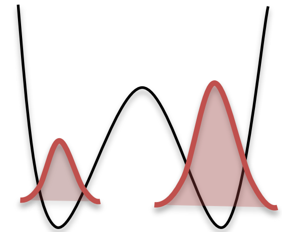
We think this can be attributed to a non-linear relaxation of the phonon modes.

Integrability does not have to be broken for this!

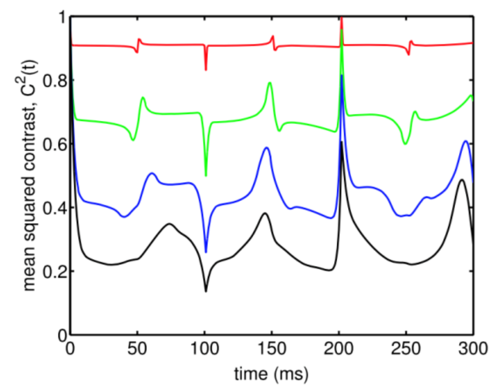
Stimming et al. PRA **83**, 023618 (2011)

Long-term dynamics

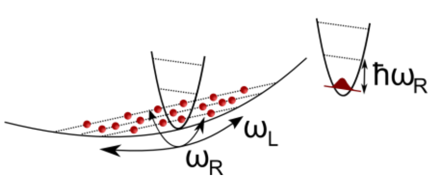
Proper quantitative analysis of the long-term evolution is challenging due to several reasons:



- Imbalanced splitting couples relative and common degrees of freedom
- Recurrent behavior of the system
- Excitations from the splitting process
- Atom loss



NJP 16, 053034 (2014)



Furthermore, the trapped system is only nearly integrable!

How does this integrability braking influence the dynamics?

(extension of the KAM theorem to quantum mechanics?)