TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

VCQ
Vienna Center for Quantum Science and Technology

ATOMINSTITUT

Pre-thermalisation and Relaxation in a 1d System

David Adu Smith

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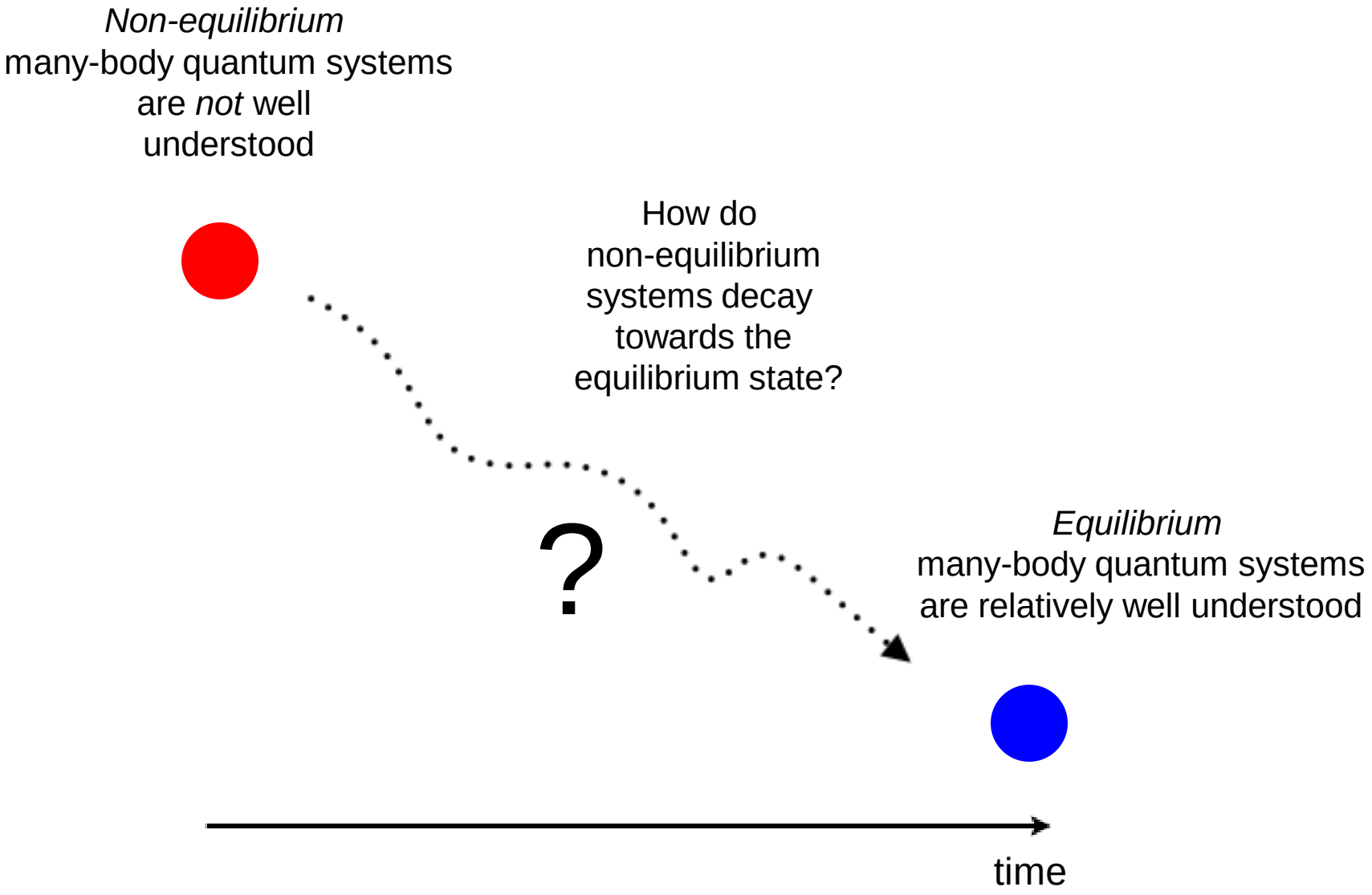
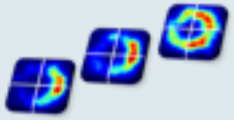
Non-Equilibrium Systems



Our Non-Equilibrium System



In an ultracold atom system:

A phase-coherently split 1d Bose gas

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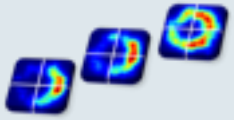

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1. Prepare an equilibrium 1d Bose gas

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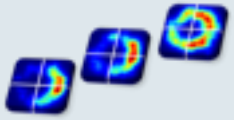

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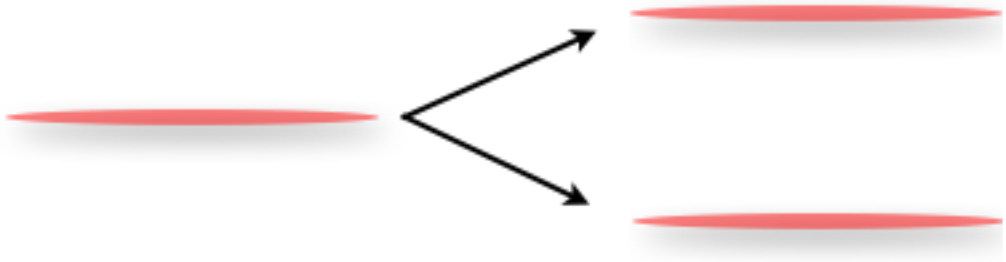

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Our Non-Equilibrium System

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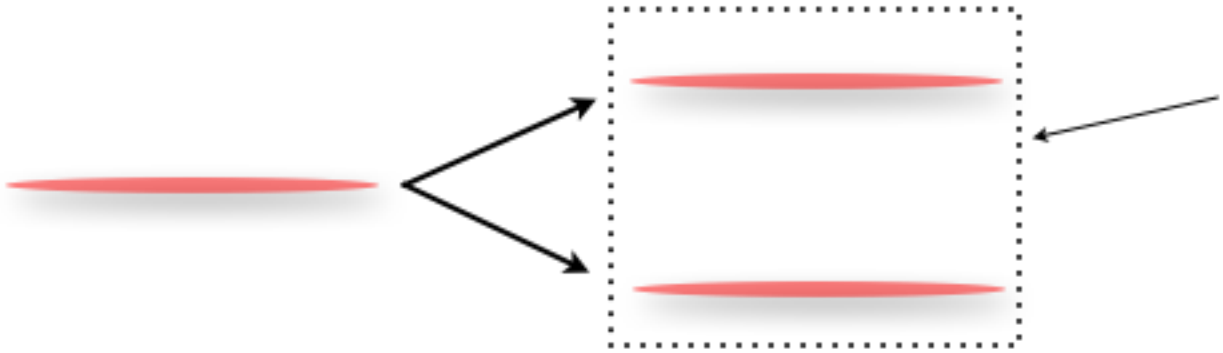

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1d Bose Gases

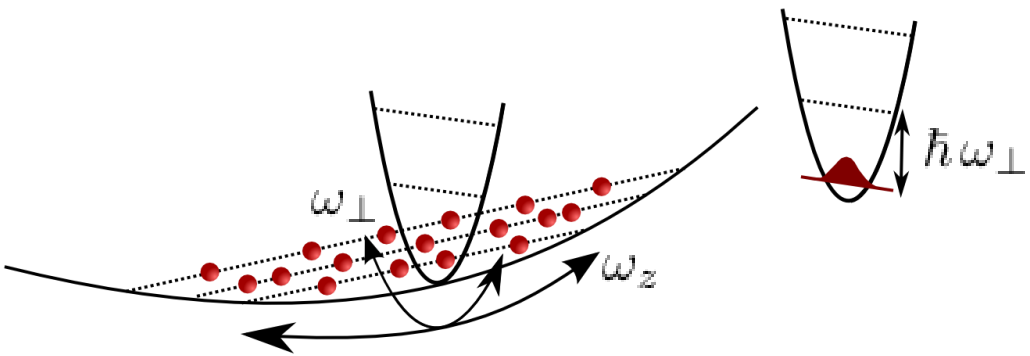
- For an effectively 1d Bose Gas (in a trap)

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

$$\omega_\perp \gg \omega_z$$

- Macroscopic occupation of radial ground state

- Longitudinal states populated



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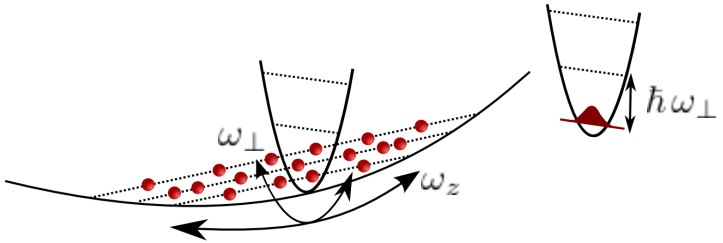

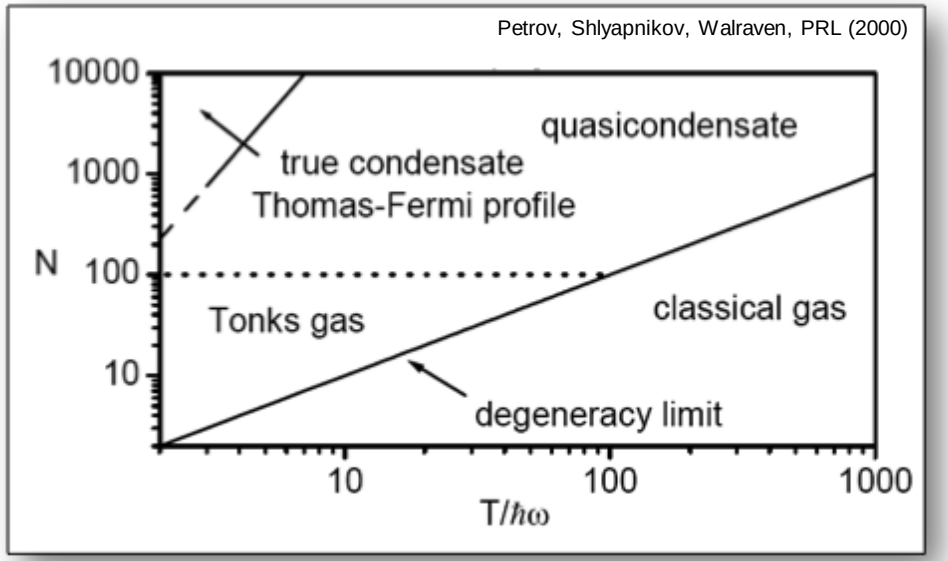

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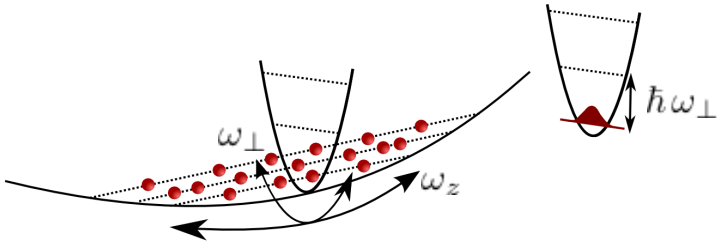
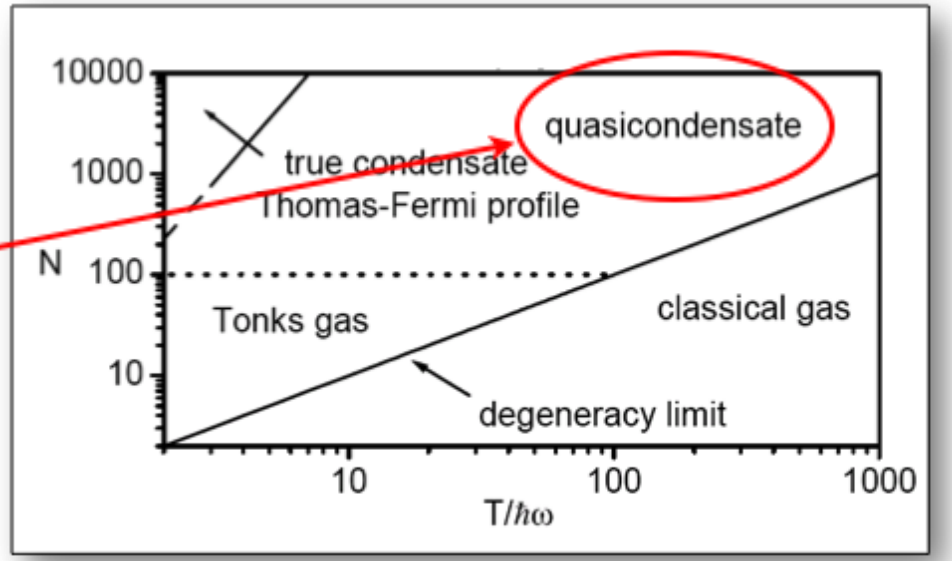
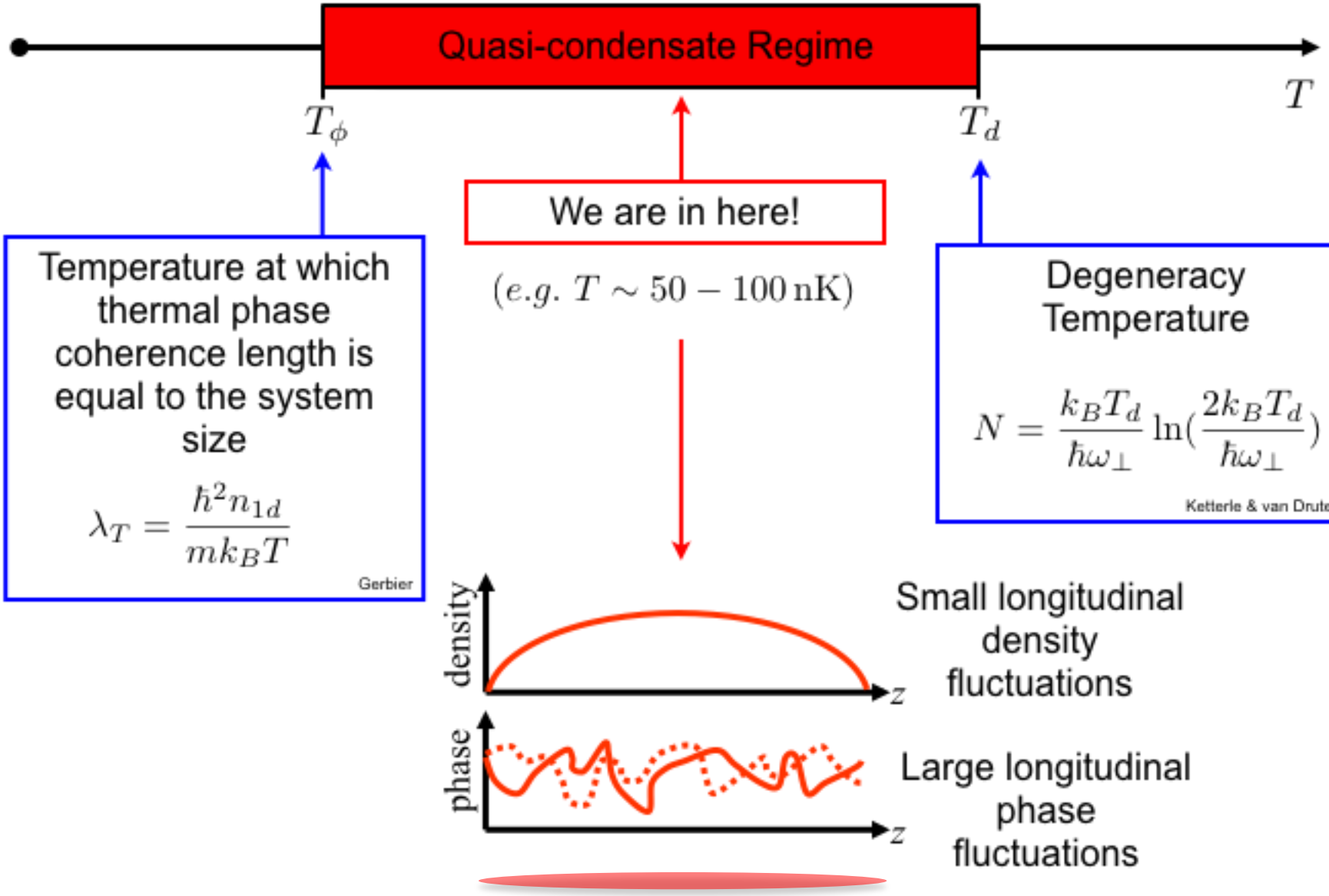


Weakly Interacting Regime

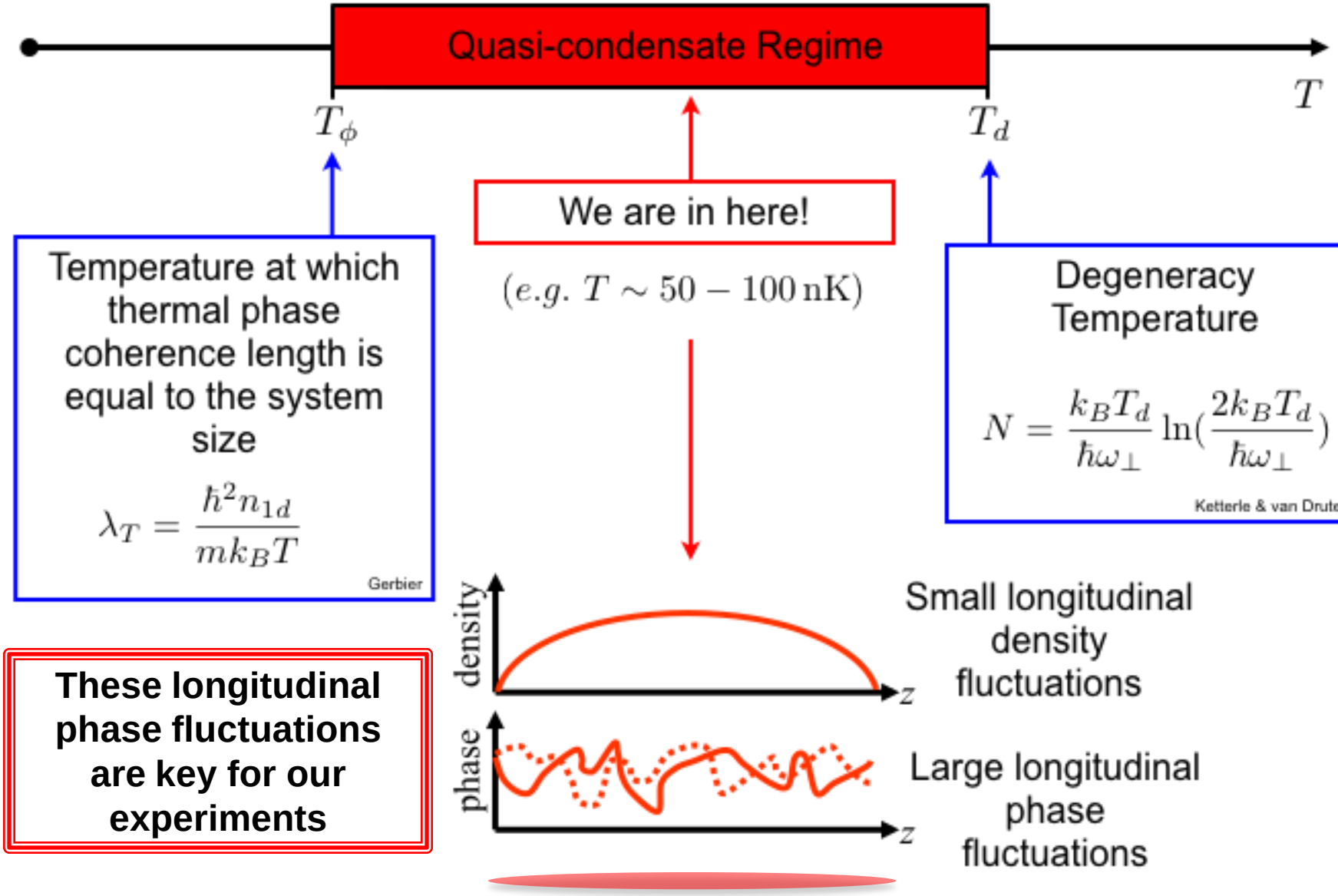
$$(e.g.\ \ \gamma = \frac{mg}{\hbar^2 n} \sim 10^{-2})$$



1d Bose Gases



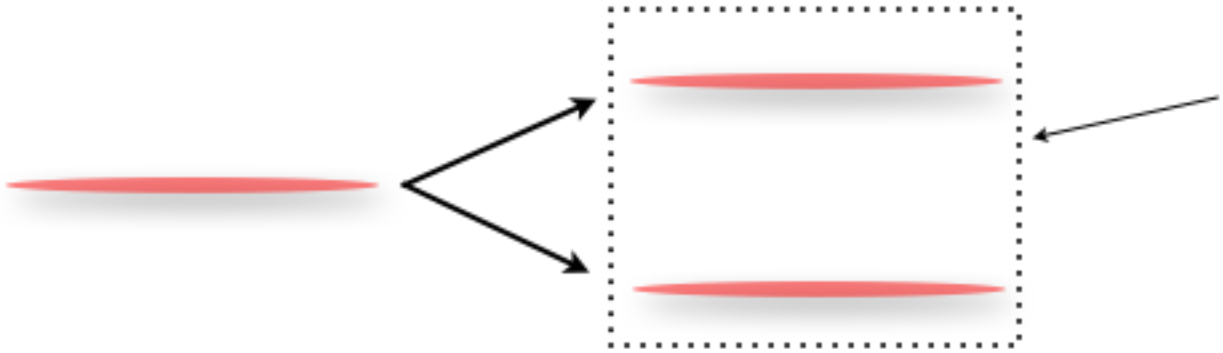
1d Bose Gases



Non-Equilibrium Systems: Examples

In an ultracold atom system:

A phase-coherently split 1d Bose gas



2. Phase-coherently split the gas into two (uncoupled) 1d gases

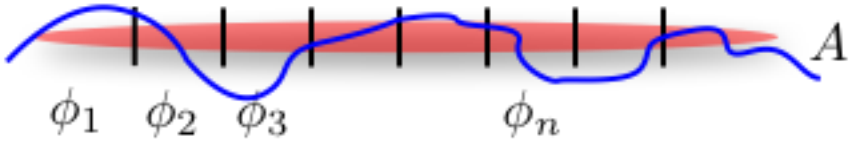
1. Prepare an equilibrium 1d Bose gas

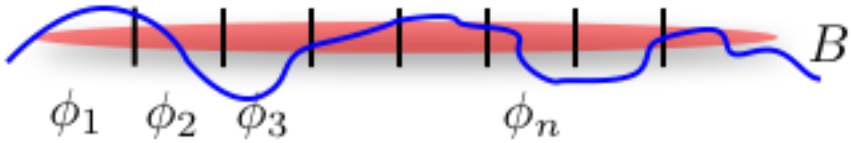
1d Bose Gases

Why is this a non-equilibrium system?

1d Bose gas in equilibrium

Phase-coherently split into two 1d gases





phase profiles are correlated

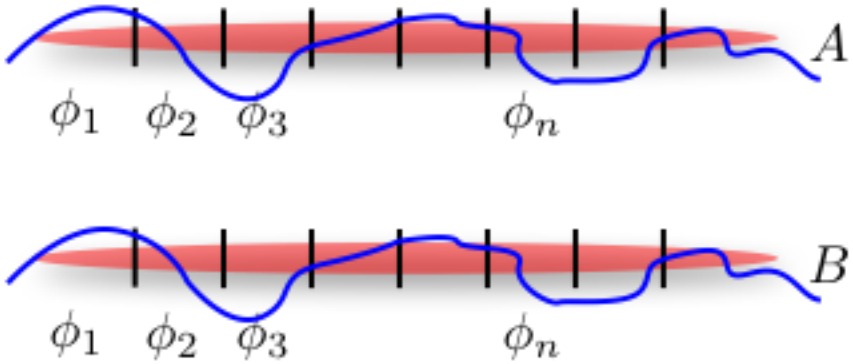
difference is only due to quantum shot noise of splitting process

This is our non-equilibrium system!

$$\text{At time } t_h = 0, \quad \phi_{nA} \cong \phi_{nB}$$

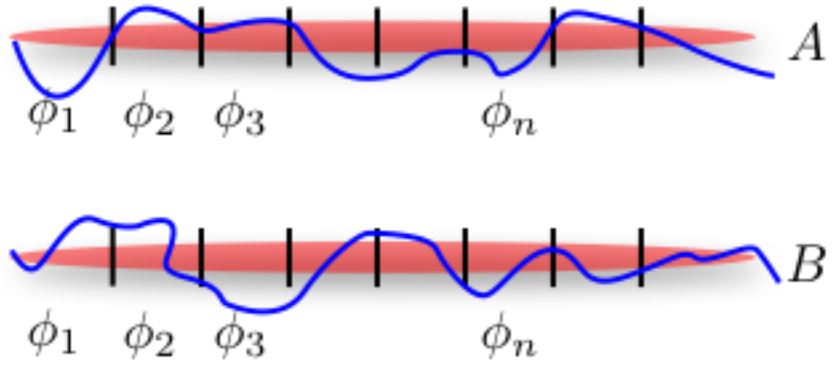
1d Bose Gases

correlated state



At time $t_h = 0$, $\phi_{nA} = \phi_{nB}$

uncorrelated state



At time $t_h = t$, $\phi_{nA} \neq \phi_{nB}$

Non-equilibrium

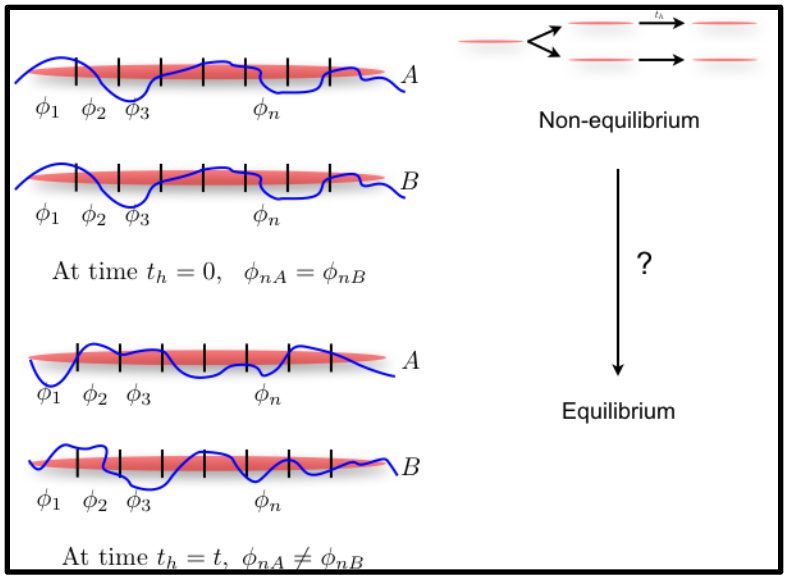
?

Equilibrium

(two independent gases
with random relative phase)

Non-Equilibrium Systems

Non-equilibrium
many-body quantum systems
are *not* well
understood



How do
non-equilibrium
systems decay
towards the
equilibrium state?

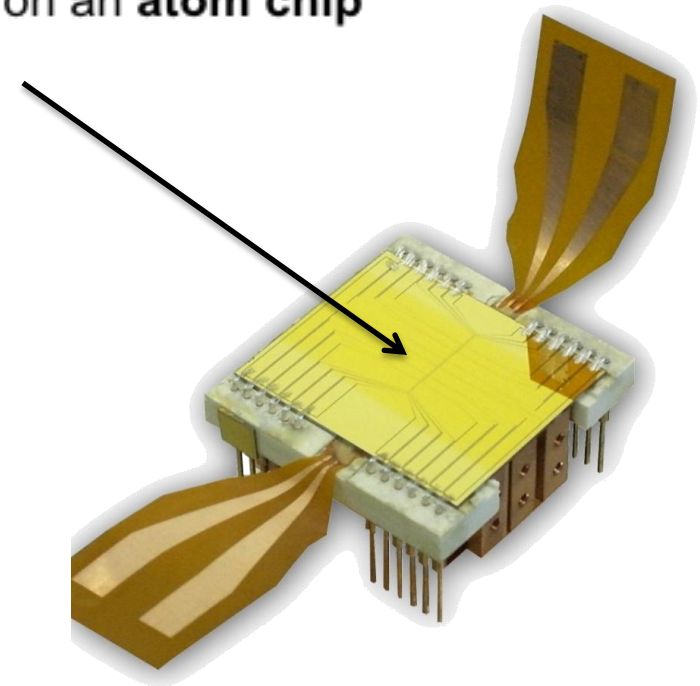
?

Equilibrium
many-body quantum systems
are well understood

time

Non-Equilibrium Dynamics

- Load ultracold atoms on an **atom chip**

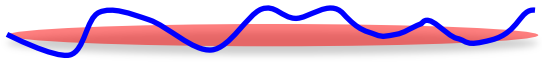


- Can make **long cigar-shaped traps** (high aspect ratio)
- Can attain **high radial trapping frequencies** (several kHz)
- and **low axial frequencies** (< 5 Hz)

Great for making **a single 1d gas** !

Non-Equilibrium Dynamics

- Load ultracold atoms on an **atom chip**
- Make an (equilibrium) **1d Bose gas**



$$T = 120 \pm 30 \text{ nK}$$

$$\text{Atom Number} \sim 5000$$

$$\lambda_T \sim 3 \ \mu\text{m} \longleftarrow \lambda_T \propto \frac{\rho}{T}$$

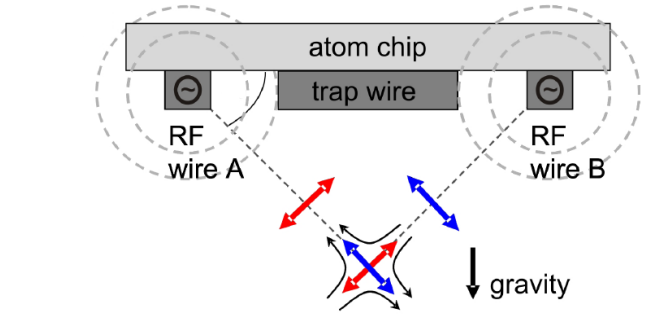
$$\omega_\perp = 2\pi \times (2.1 \pm 0.1) \text{ kHz}$$

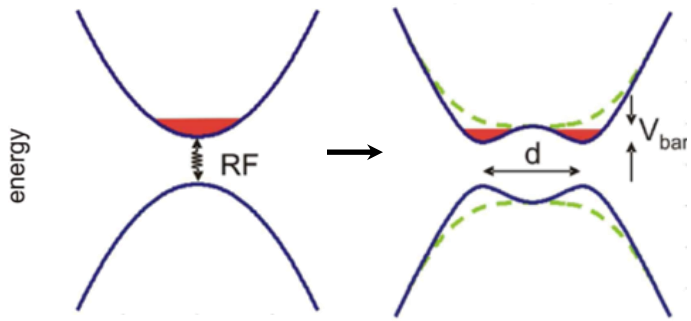
$$\omega_{||} = 2\pi \times (11 \pm 1) \text{ Hz}$$

Non-Equilibrium Dynamics

- Load ultracold atoms on an **atom chip**
- Make an (equilibrium) **1d Bose gas**
- Coherently **split the 1d gas** into two (*uncoupled!*) 1d gases

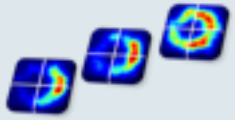
Radio-frequency (RF) dressing
is used to smoothly form a
double-well potential





Schumm et al., Nature Phys. 1, 57 (2005)

Non-Equilibrium Dynamics



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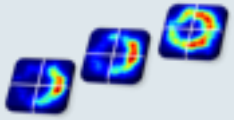

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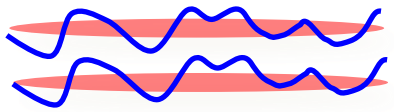

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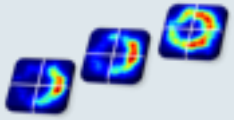

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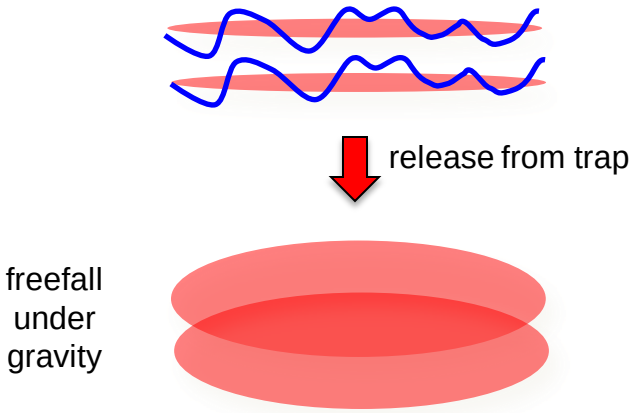

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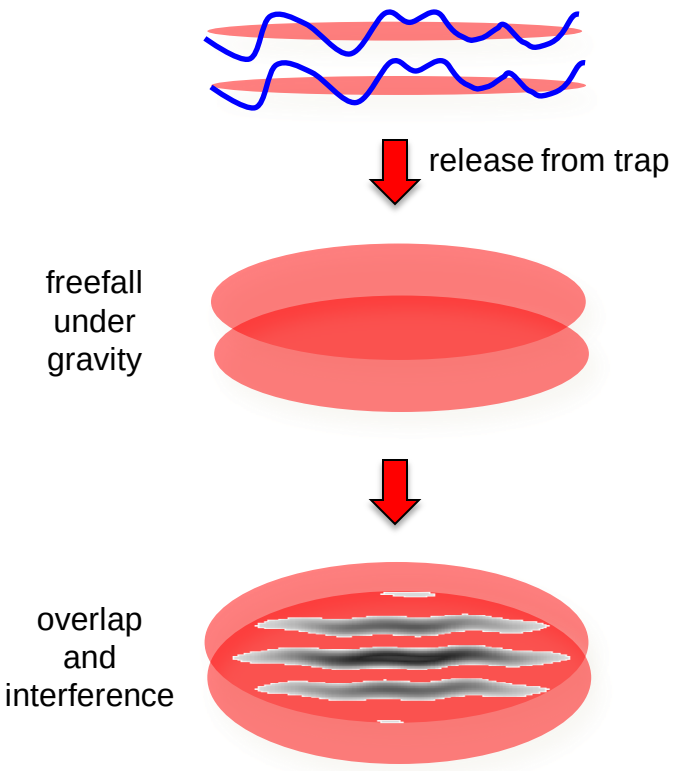

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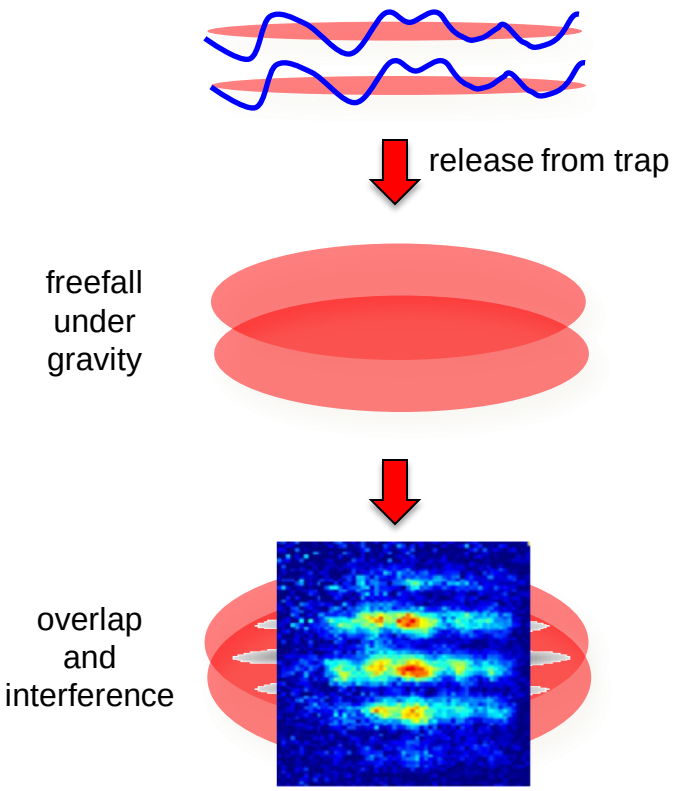

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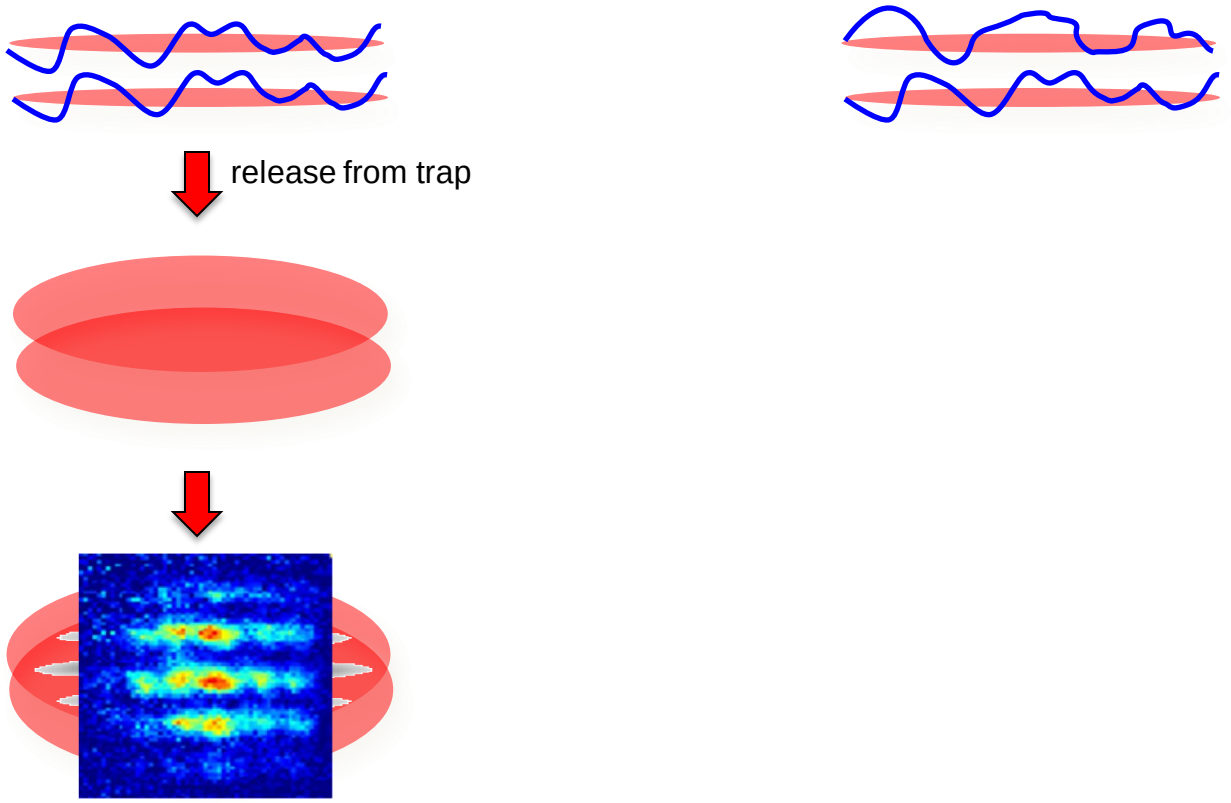

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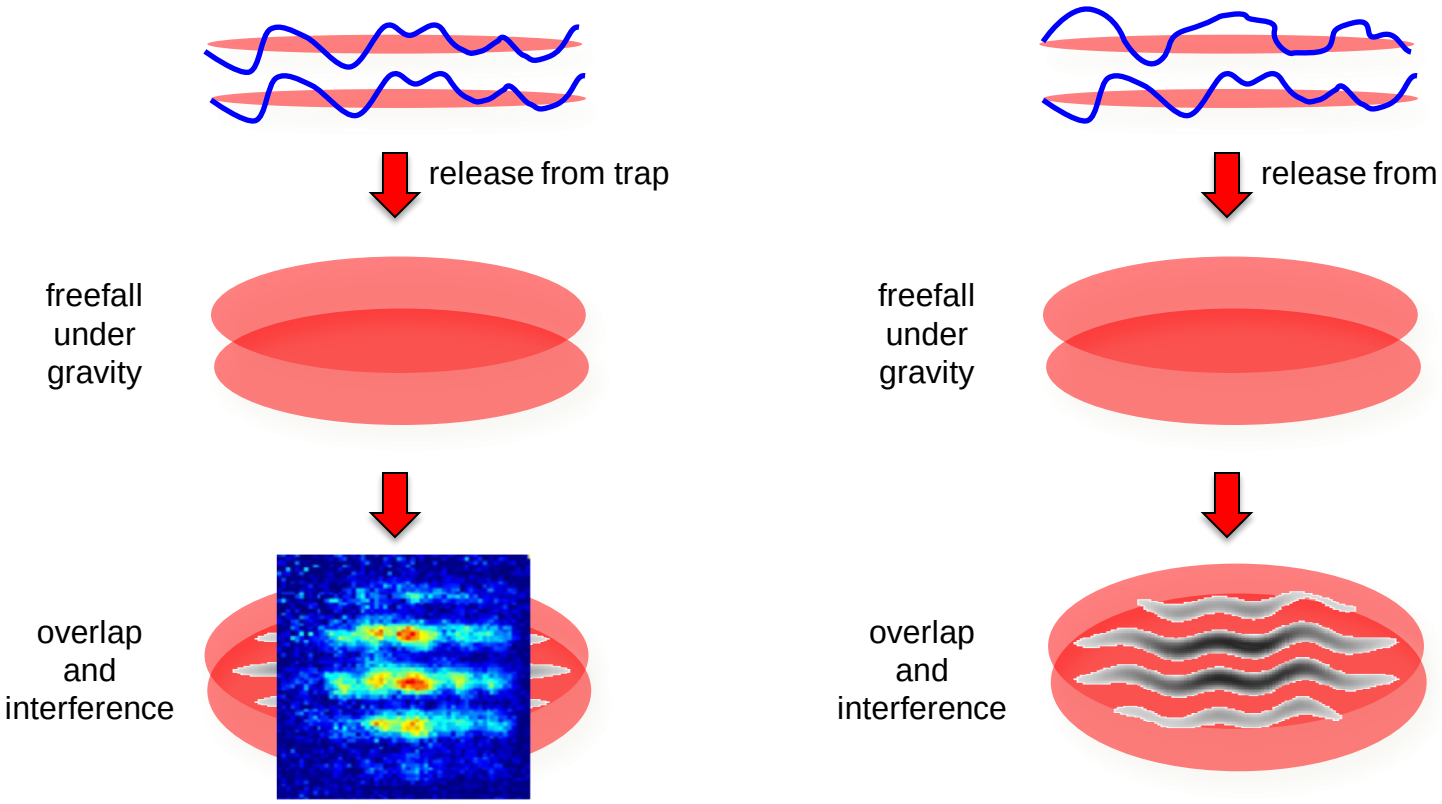

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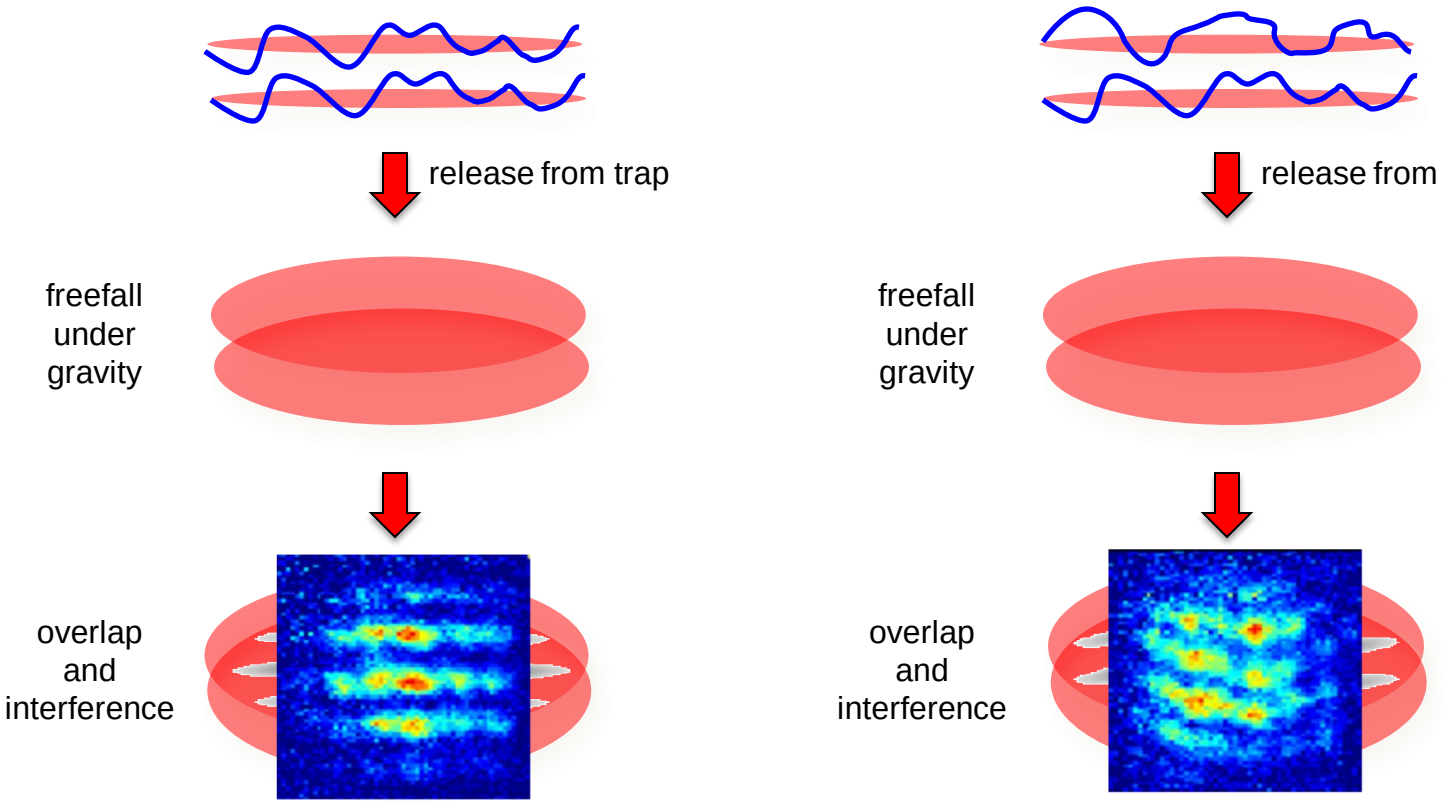

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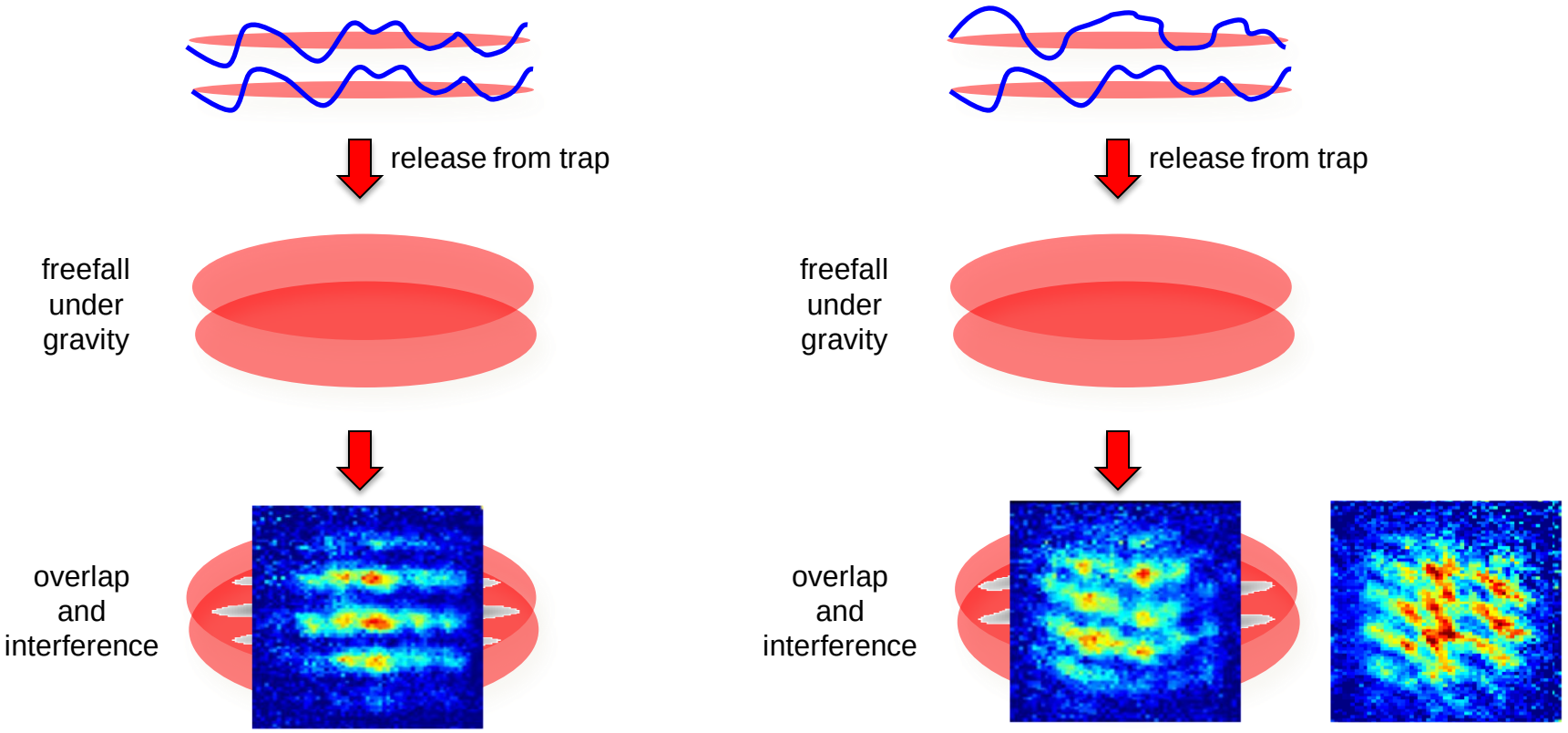
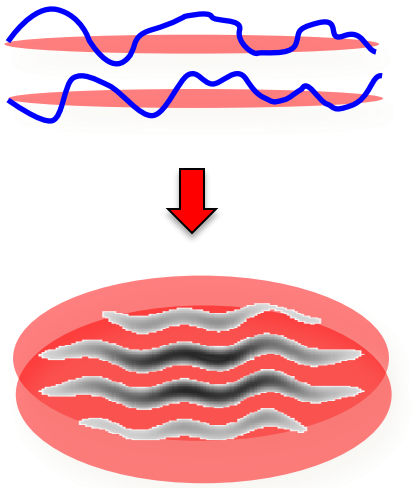


Extracting Information from Interference Patterns



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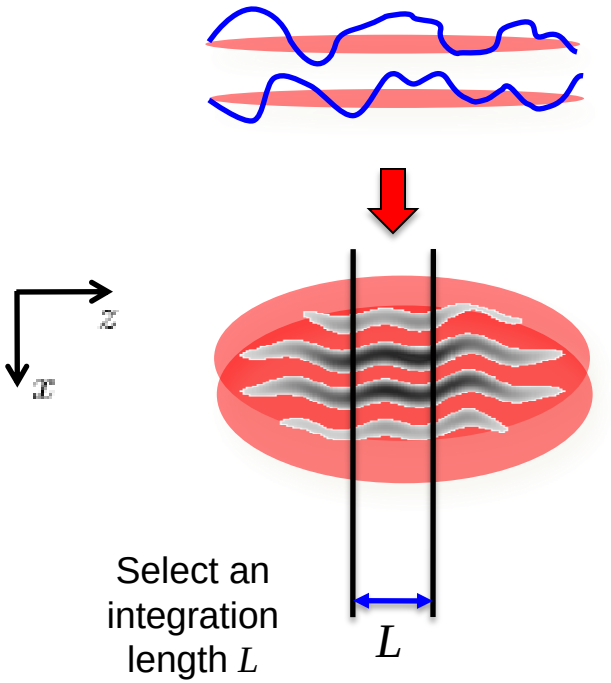
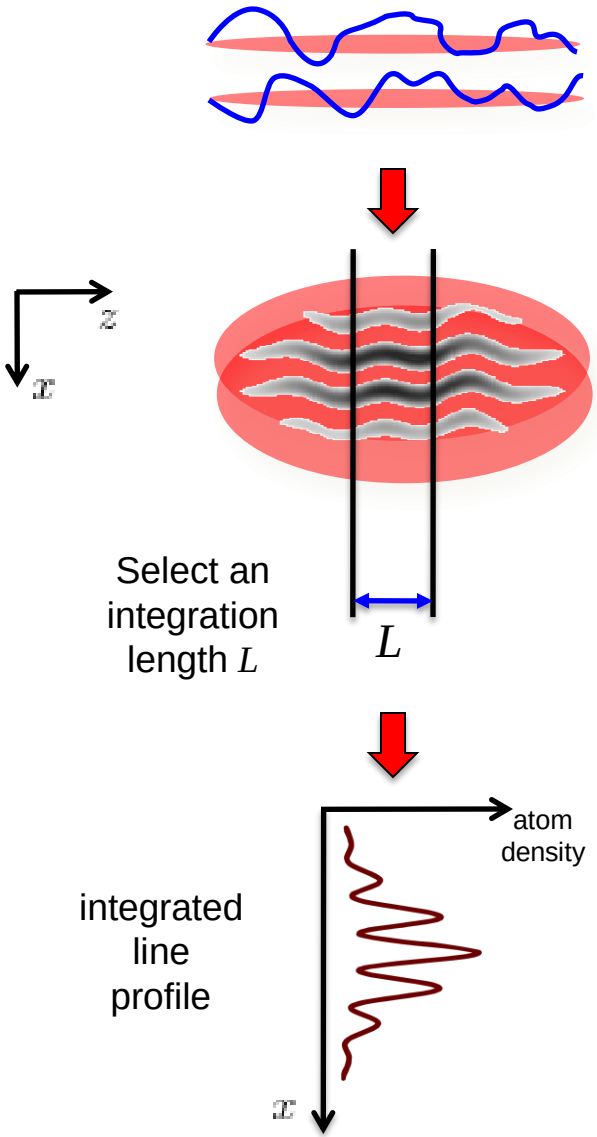


Select an integration length L

Extracting Information from Interference Patterns



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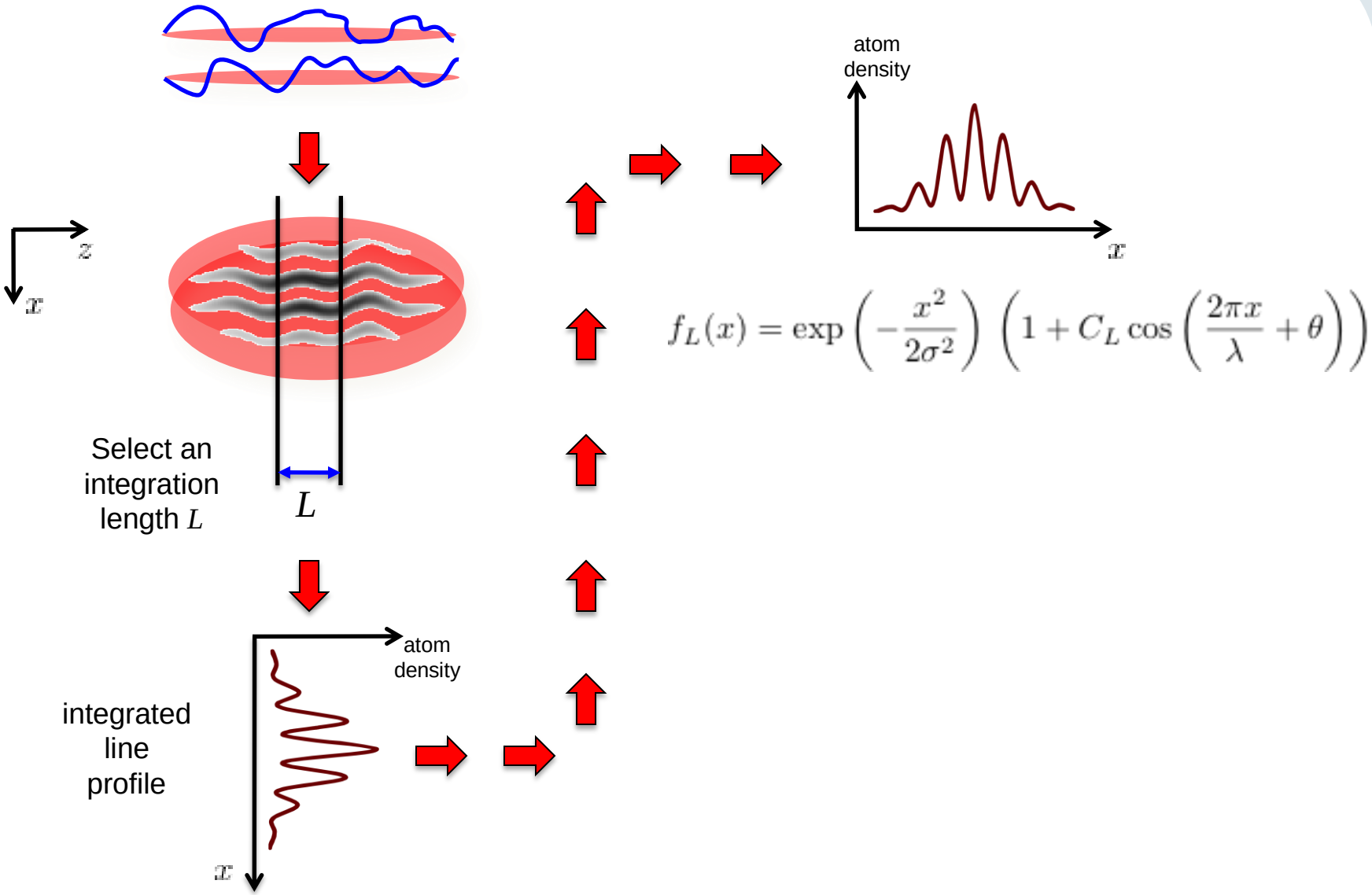

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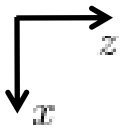

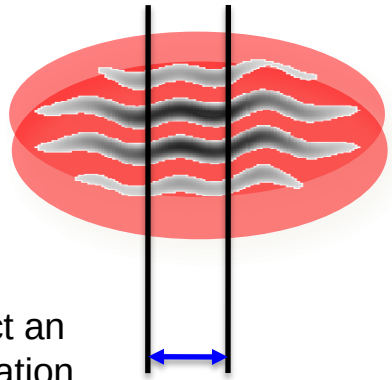

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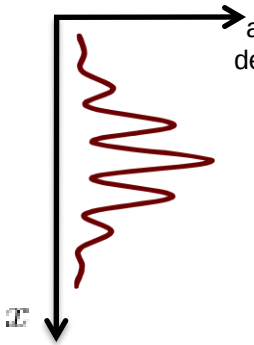
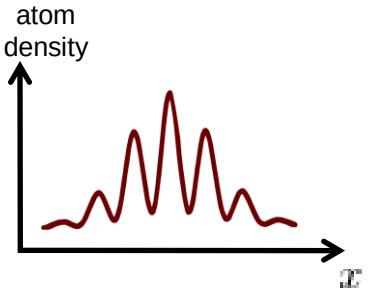


integrated line profile



$$f_L(x) = \exp\left(-\frac{x^2}{2\sigma^2}\right)\left(1 + C_L \cos\left(\frac{2\pi x}{\lambda} + \theta\right)\right)$$

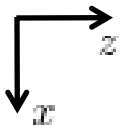
Contrast C_L

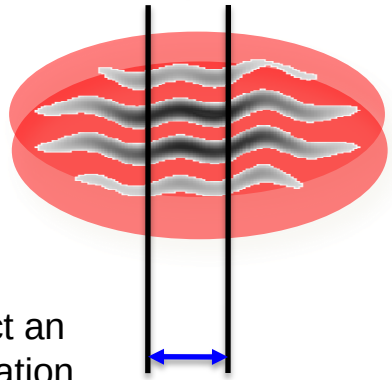
(over integration length L)

Phase θ

(phase of interference pattern with respect to gaussian background)

Extracting Information from Interference Patterns





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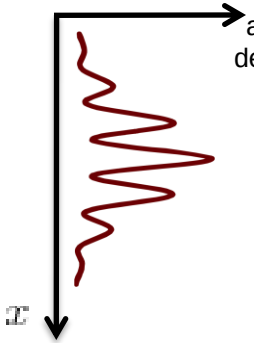

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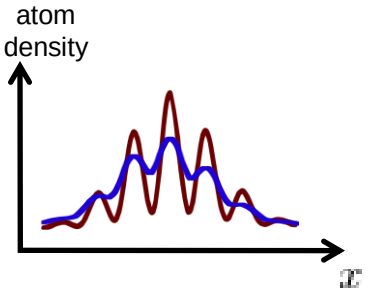

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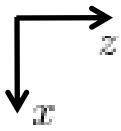
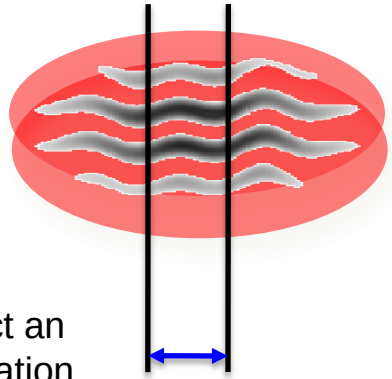
(phase of interference pattern with respect to gaussian background)

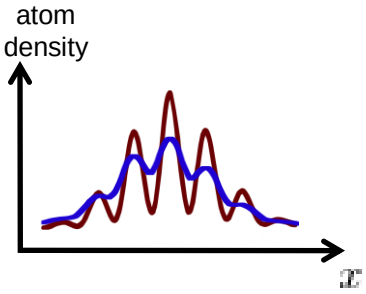
Extracting Information from Interference Patterns





Select an integration length L

L



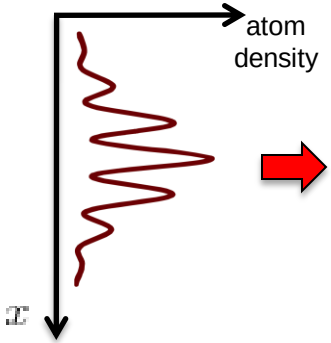
$$f_L(x) = \exp\left(-\frac{x^2}{2\sigma^2}\right)\left(1 + C_L \cos\left(\frac{2\pi x}{\lambda} + \theta\right)\right)$$

Contrast C_L

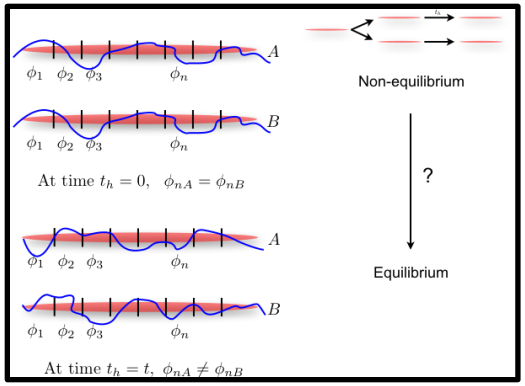
(over integration length L)

Phase θ

(phase of interference pattern with respect to gaussian background)



integrated line profile



A Previous Experiment

nature Vol 449|20 September 2007|doi:10.1038/nature06149

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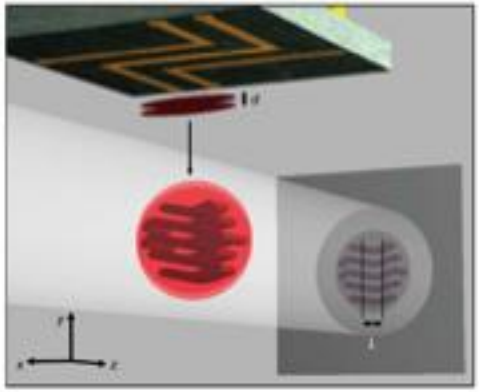

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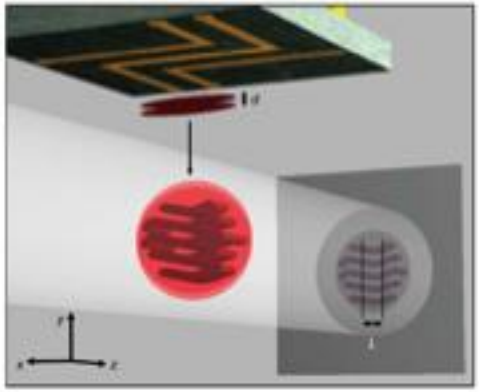

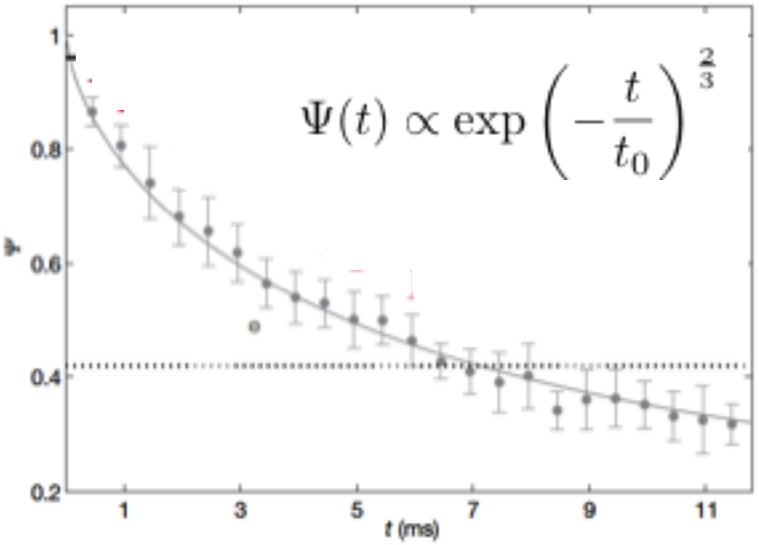

thermalisation?

- Measurement of a mean coherence factor Ψ
- Application of a theory of thermalisation

$$\Psi(t) \propto \exp\left(-\frac{t}{t_0}\right)^{\frac{2}{3}}$$

Burkov et al. Phys. Rev. Lett. **98** 200404 (2007)

A Previous Experiment

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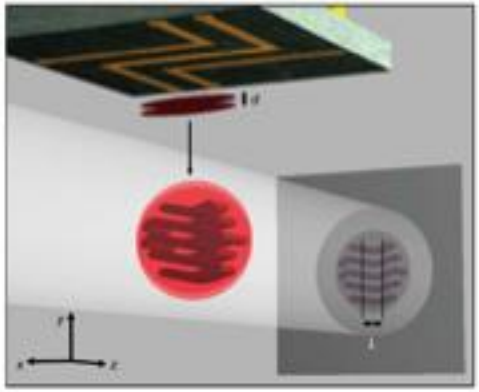

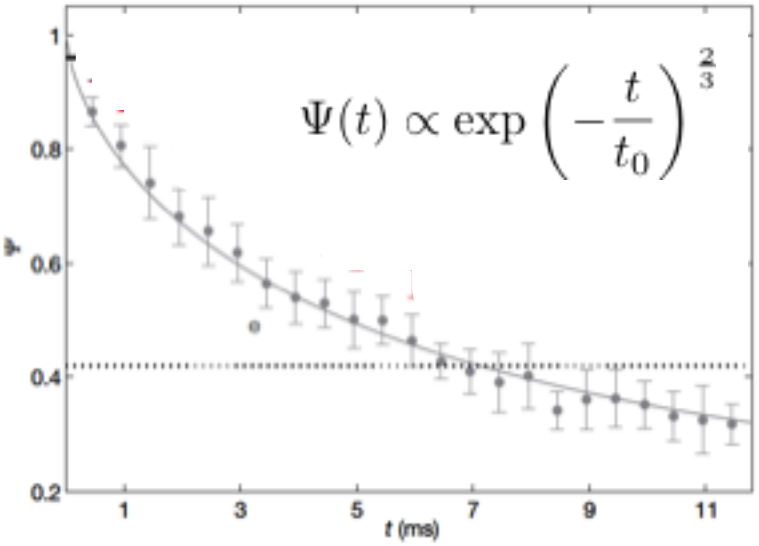

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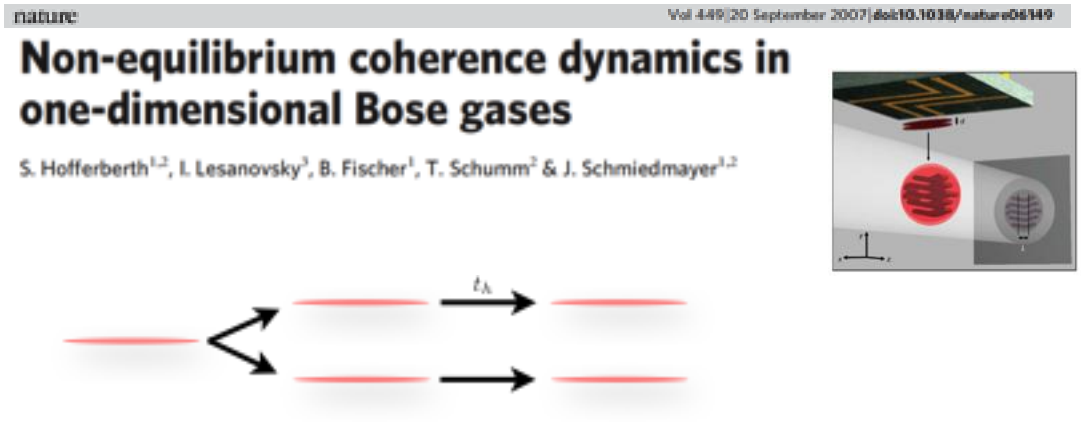
This attribution of thermalisation to the data was probably incorrect. Why?

A Previous Experiment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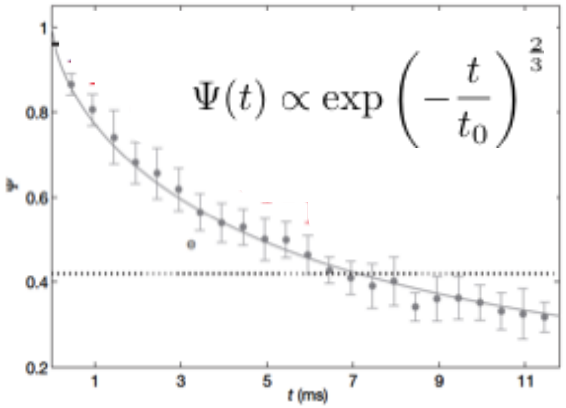
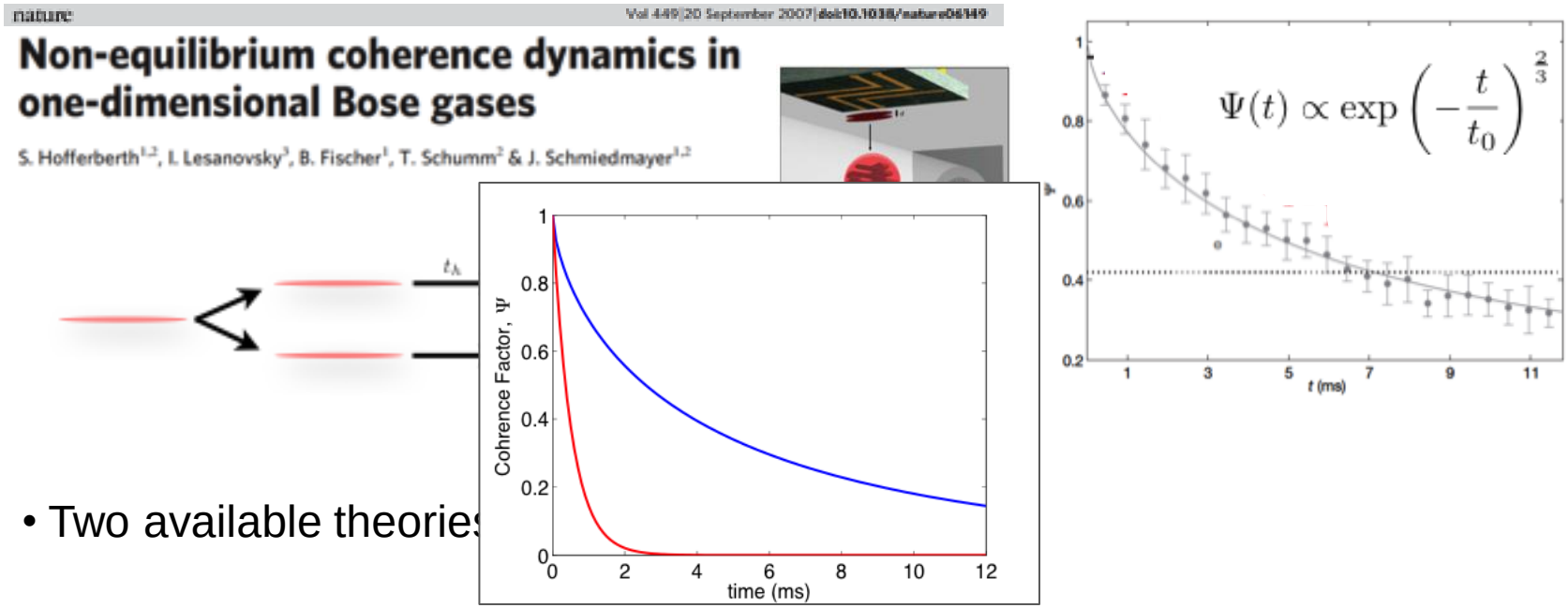


- Two available theories at the time (2007)

thermalisation	dephasing
$\Psi(t) \propto \exp\left(-\frac{t}{t_0}\right)^{\frac{2}{3}}$	$\Psi(t) \propto \exp\left(-\frac{t}{\tau}\right)$
Burkov et al. Phys. Rev. Lett. **98** 200404 (2007)	Bistritzer & Altman, PNAS **104** 24, 9955 (2007)

A Previous Experiment



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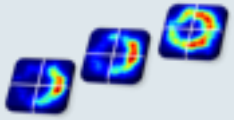
A New Experiment in Vienna



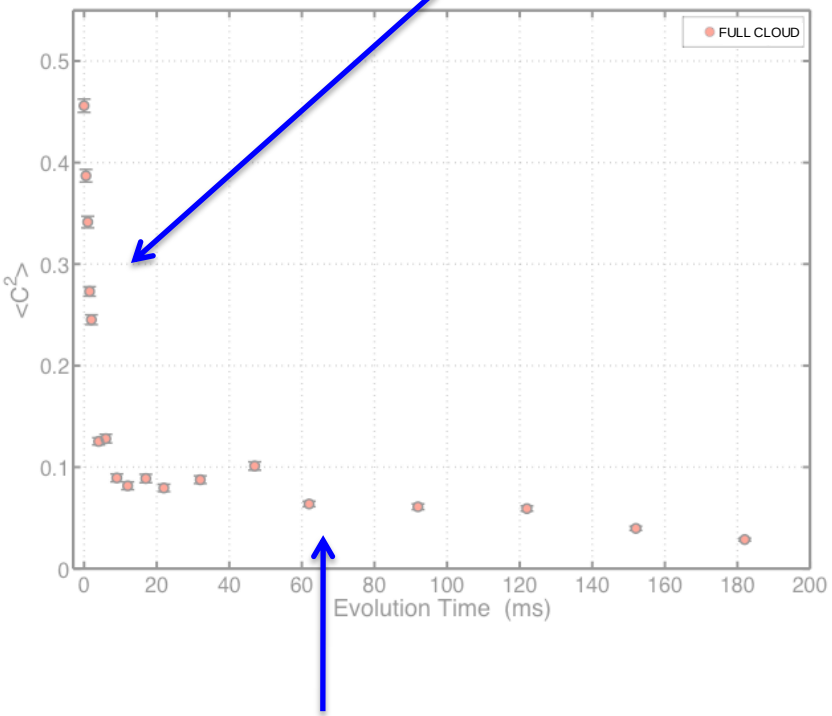
- More controlled splitting process
- Ability to measure for longer evolution times

A New Experiment in Vienna

- More controlled splitting process
- Ability to measure for longer evolution times

Our New Measurements

Rapid early-time decay



Long slow decay
(consistent with the heating rate in our atom trap)

A New Experiment in Vienna

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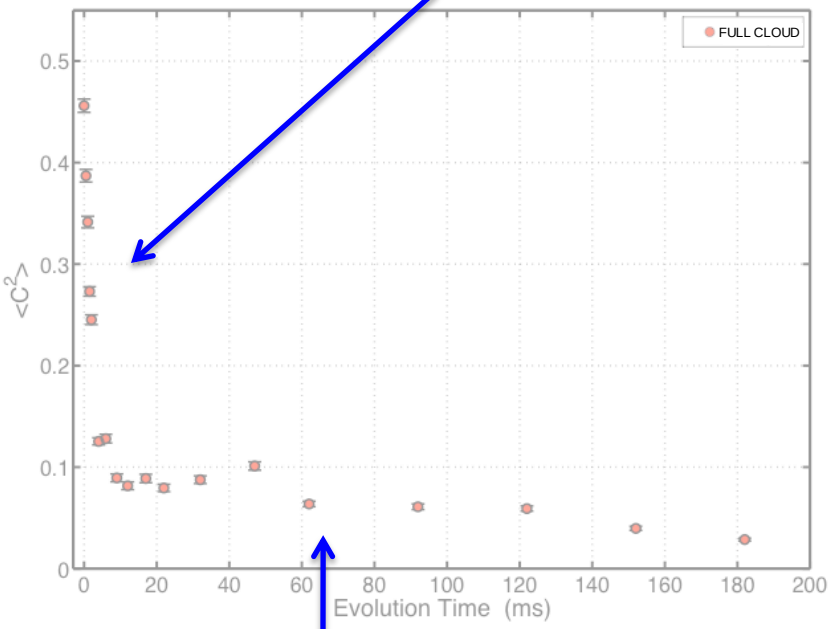

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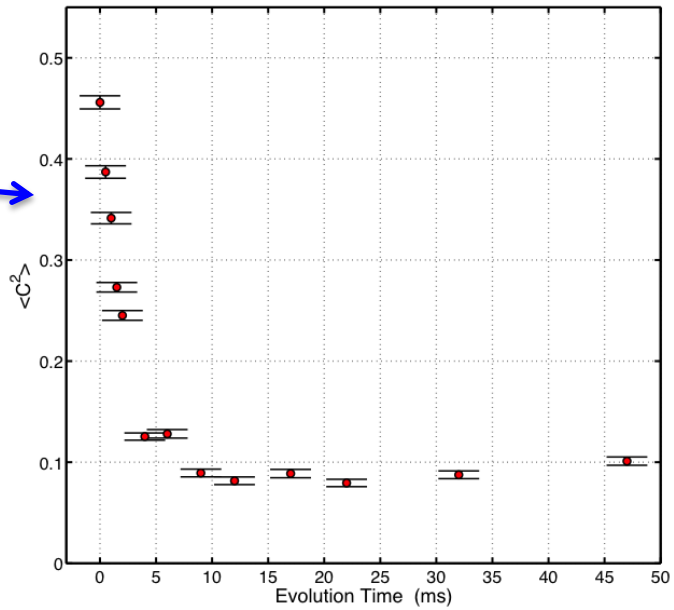

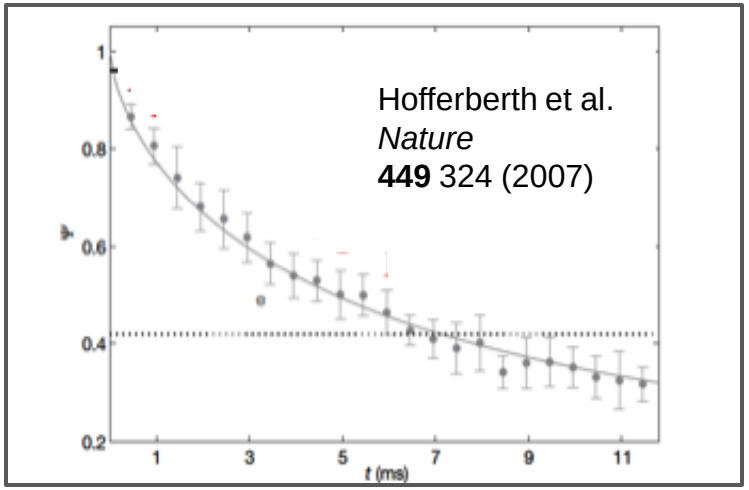

Hofferberth et al.
Nature
449 324 (2007)

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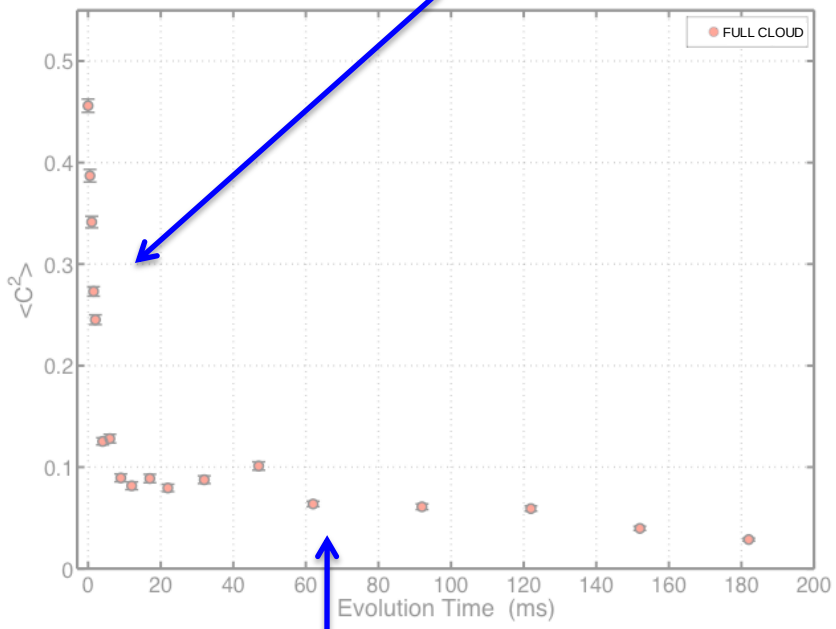

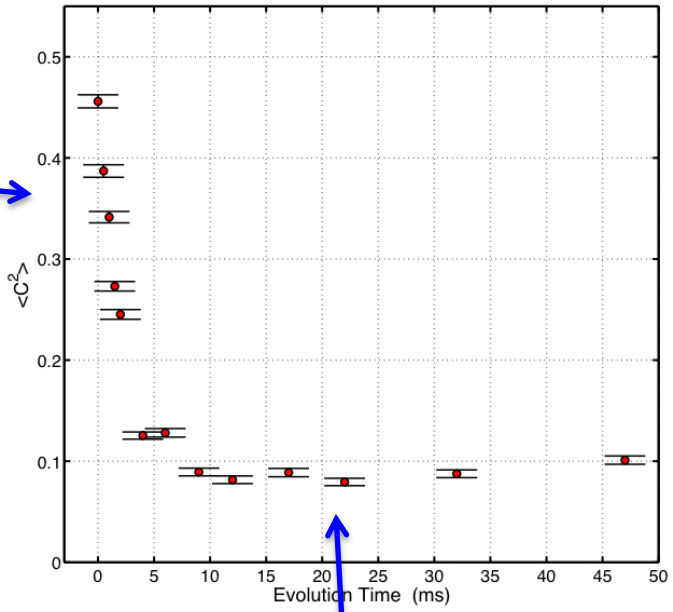

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Thermal Equilibrium ?

Beyond the Mean: Full Distribution Functions

For Equilibrium Systems:

nature physics | VOL 2 | OCTOBER 2006 | www.nature.com/naturephysics

ARTICLES

Full quantum distribution of contrast in interference experiments between interacting one-dimensional Bose liquids

VLADIMIR GRITSEV[1]*, EHUD ALTMAN[2], EUGENE DEMLER[1] AND ANATOLI POLKOVNIKOV[3]

Theoretical Proposal

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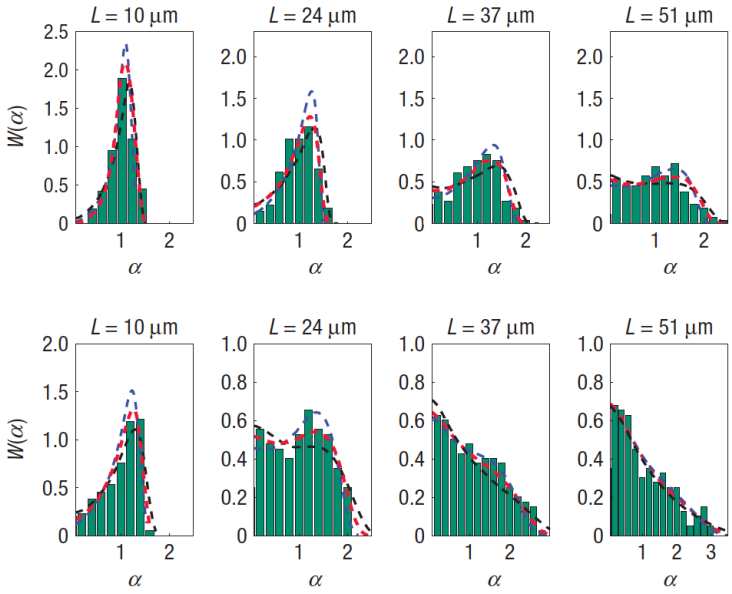
Probing quantum and thermal noise in an interacting many-body system

S. HOFFERBERTH[1,2,3], I. LESANOVSKY[2,4], T. SCHUMM[1], A. IMAMBEKOV[3,5], V. GRITSEV[3], E. DEMLER[3] AND J. SCHMIEDMAYER[1,2]*

Experimental Realisation

Disributions of Interference Contrast C_L



See also:
- Stimming et al. PRL 105, 015301 (2010) [theory]
- Betz et al. PRL 106, 020407 (2011) [experiment]

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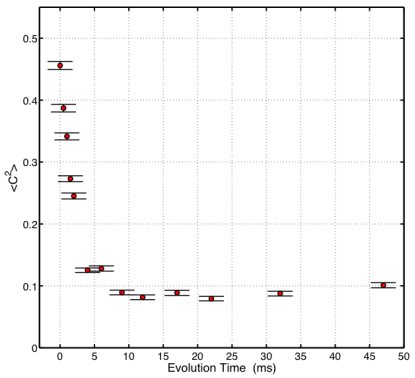
Experimental Realisation

We can use this equilibrium theory to investigate our "*equilibrium?*" state



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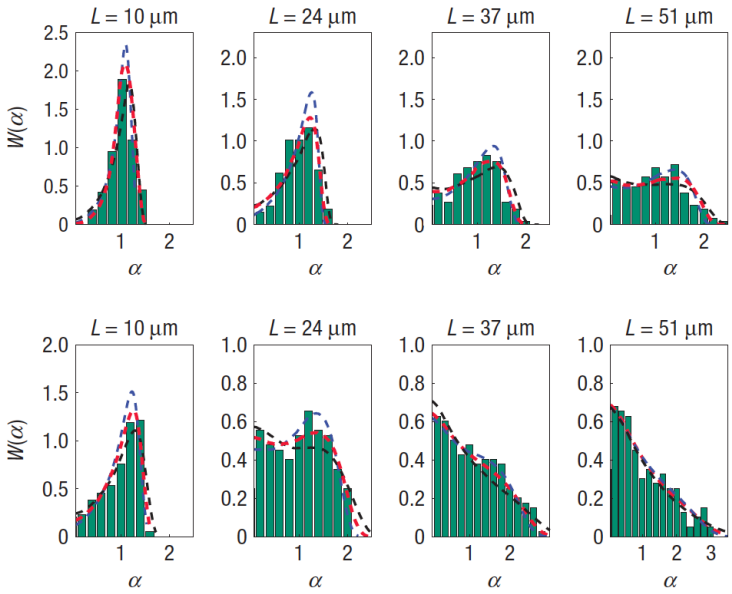


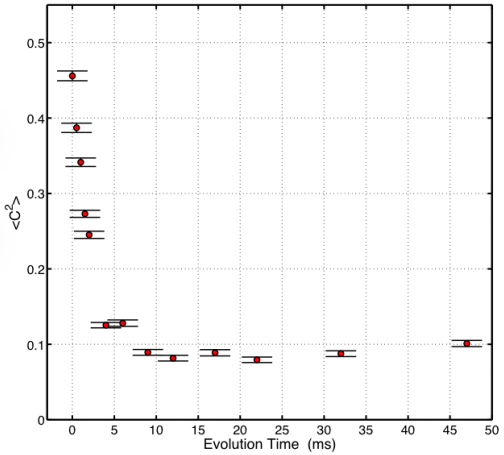
Applying Equilibrium Theory

Initial single gas

$T = 120 \pm 30$ nK

$\lambda_T \sim 3\ \mu$m

Atom Number ~ 5000



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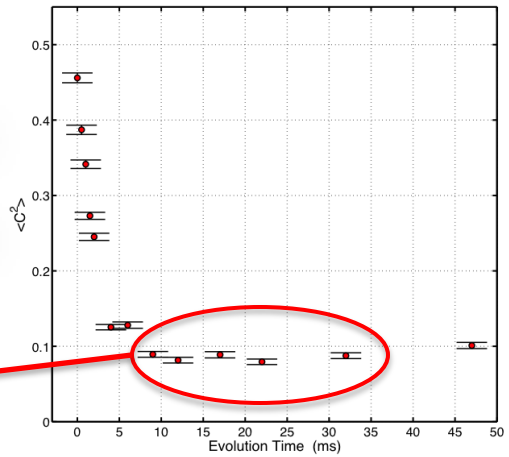
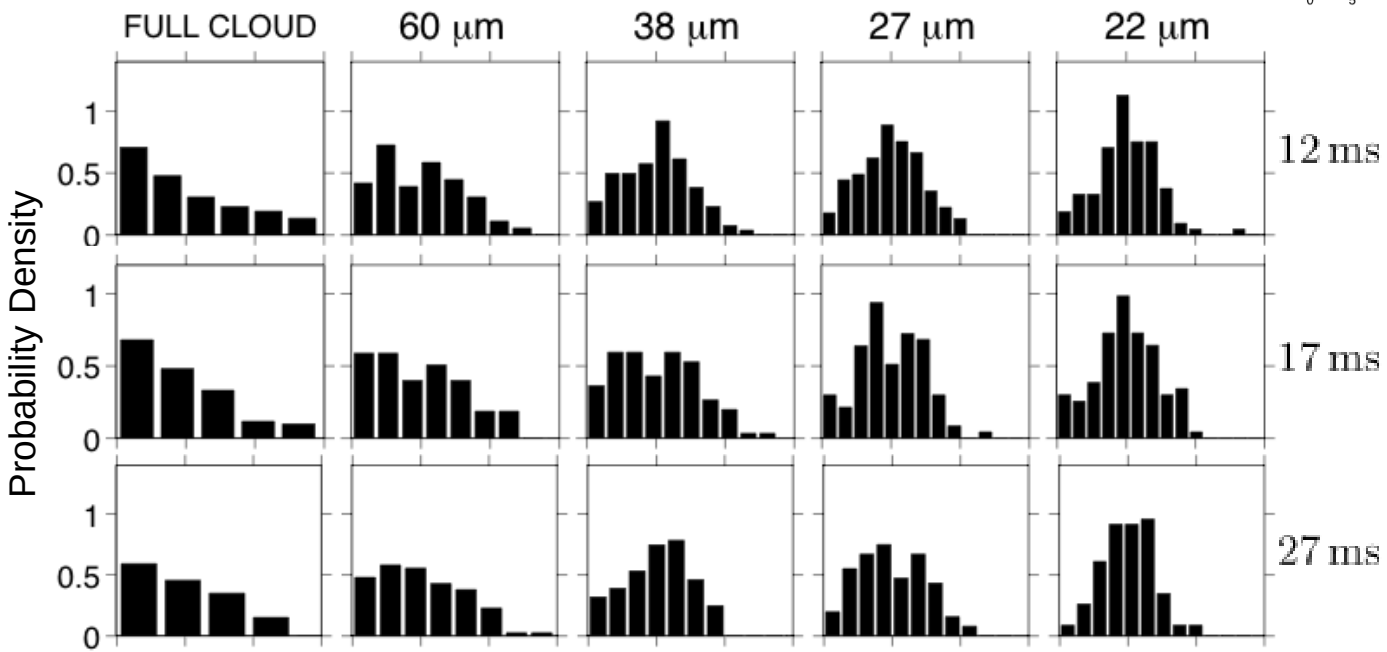


Interference Contrast C_L Distributions



Normalised Squared Contrast, $C^2/\langle C^2 \rangle$

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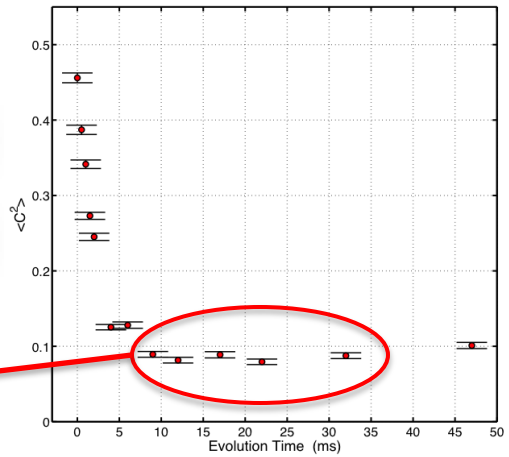

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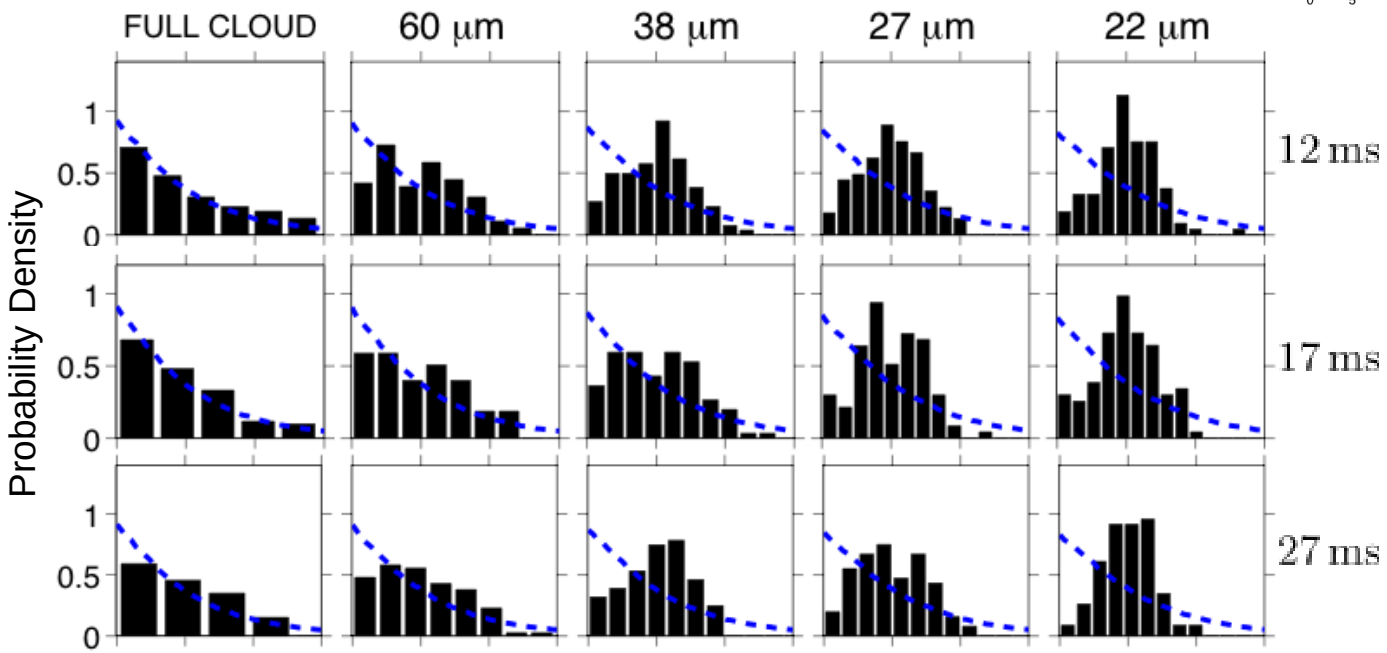

Normalised Squared Contrast, $C^2/\langle C^2 \rangle$

Compare
Equilibrium Theory
with
Non-Equilibrium
Experiment

T = 120 nK

Applying Equilibrium Theory

Initial single gas

$T = 120 \pm 30$ nK

$\lambda_T \sim 3\ \mu$m

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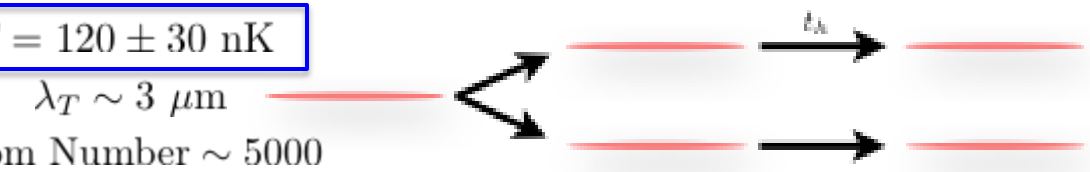

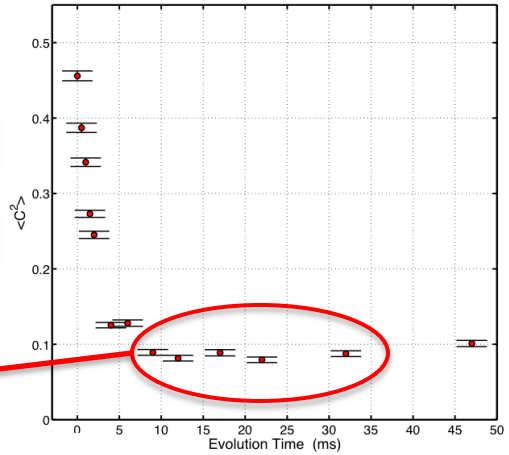

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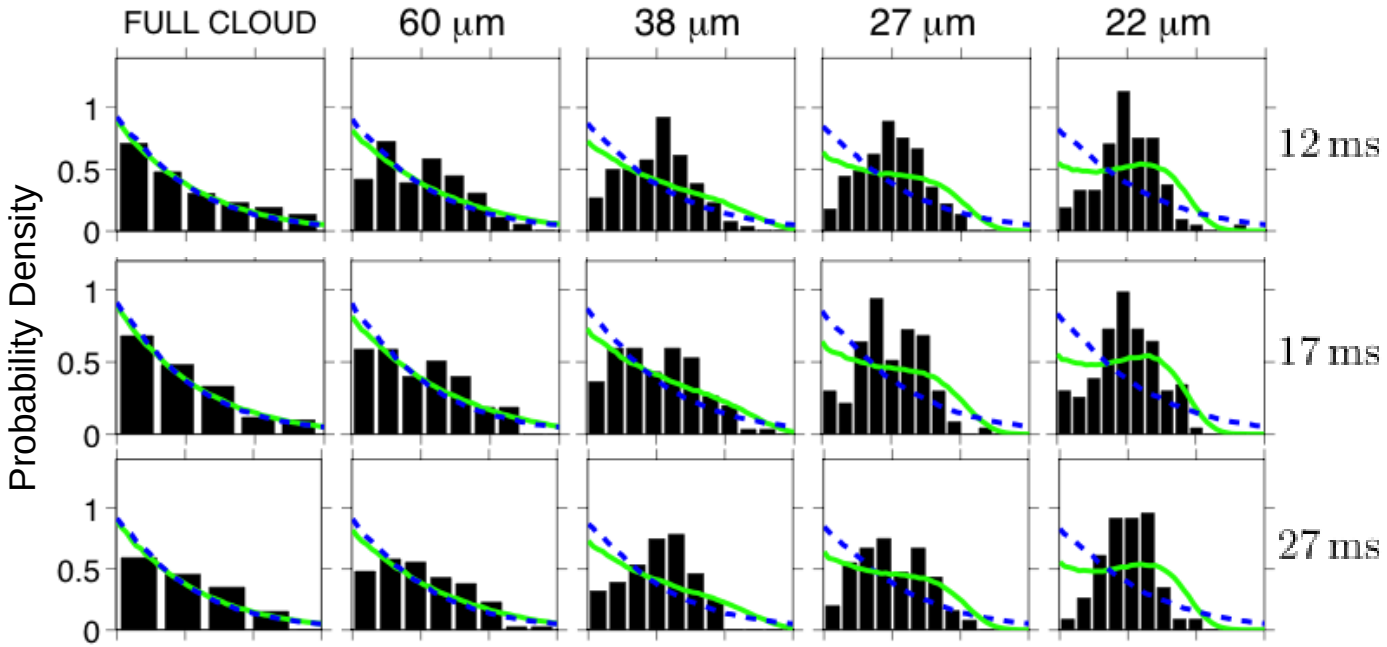

Compare
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T = 120 nK

T = 30 nK

Applying Equilibrium Theory

Initial single gas

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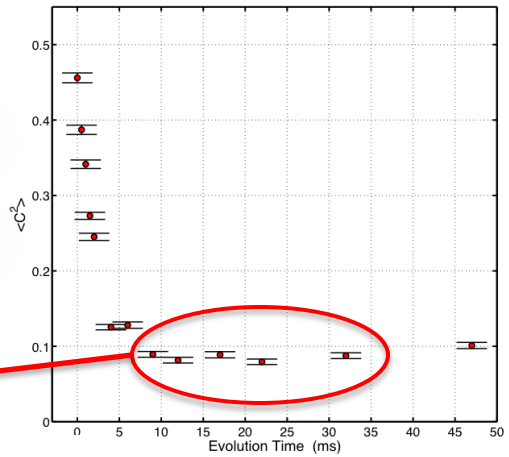

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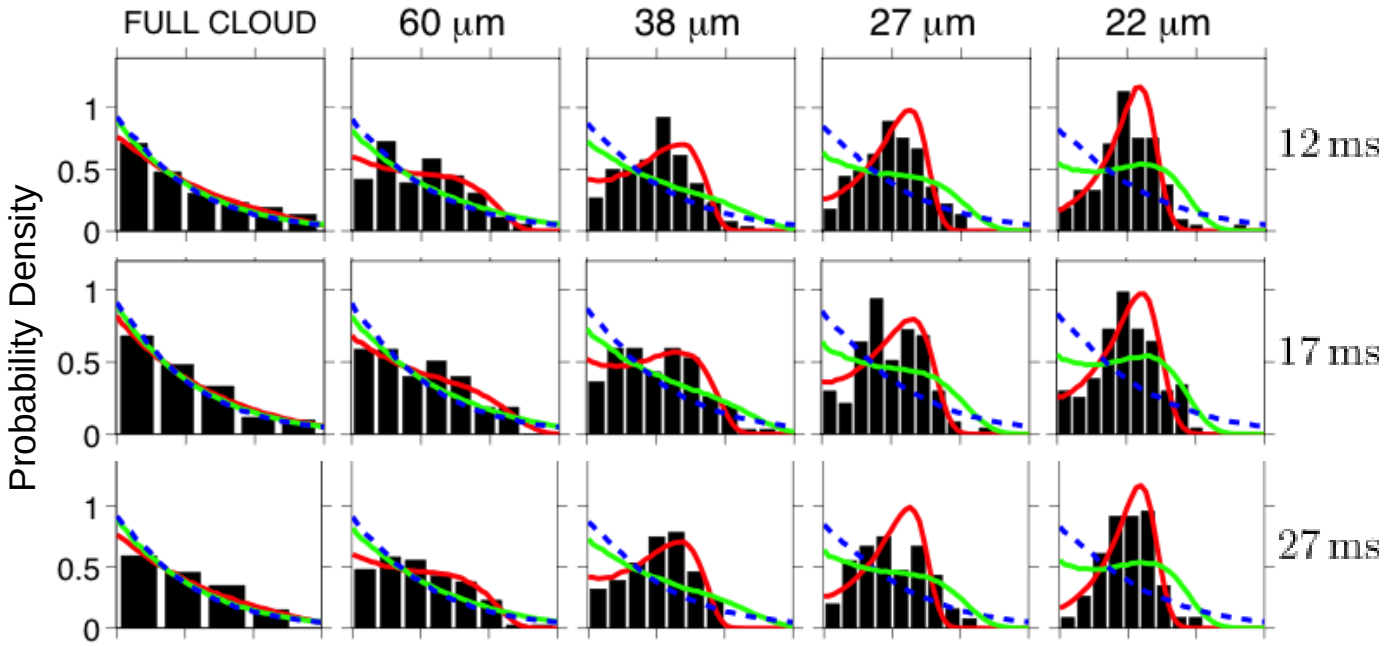

Compare
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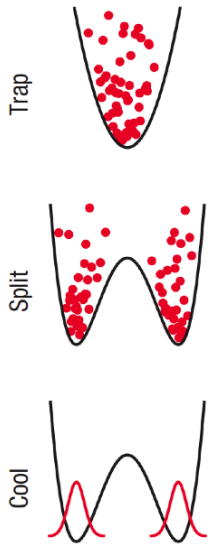
Experiment

T = 120 nK

T = 30 nK

T_{fit} = 15 ± 4 nK

Measuring Equilibrium Systems



We now want to
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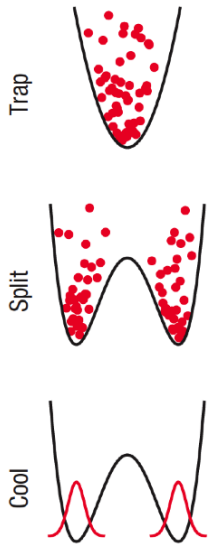
Measuring Equilibrium Systems



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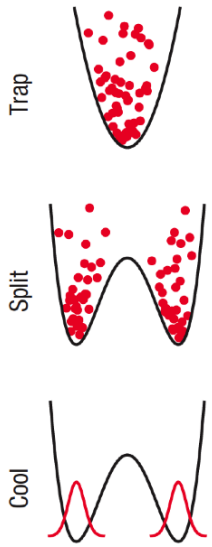
create
two independent
quasi-condensates

Measuring Equilibrium Systems



We now want to
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to
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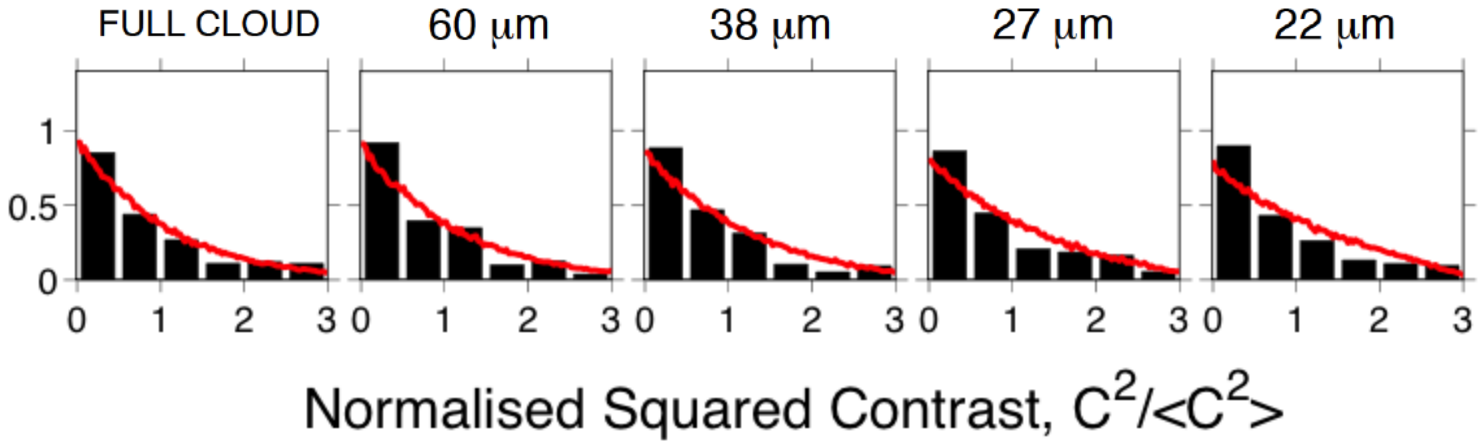
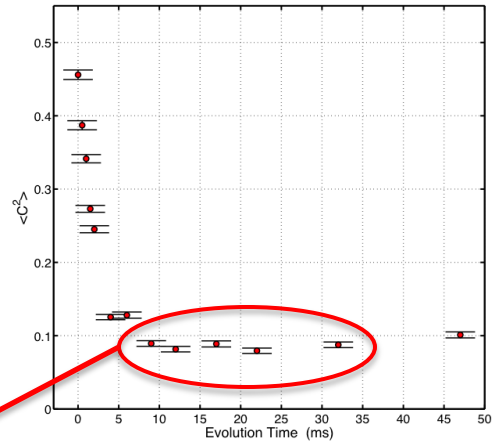
Equilibrium experiments agree with equilibrium theory

an example at 60 nK



Equilibrium vs Non-Equilibrium

non-equilibrium distributions
and
equilibrium distributions



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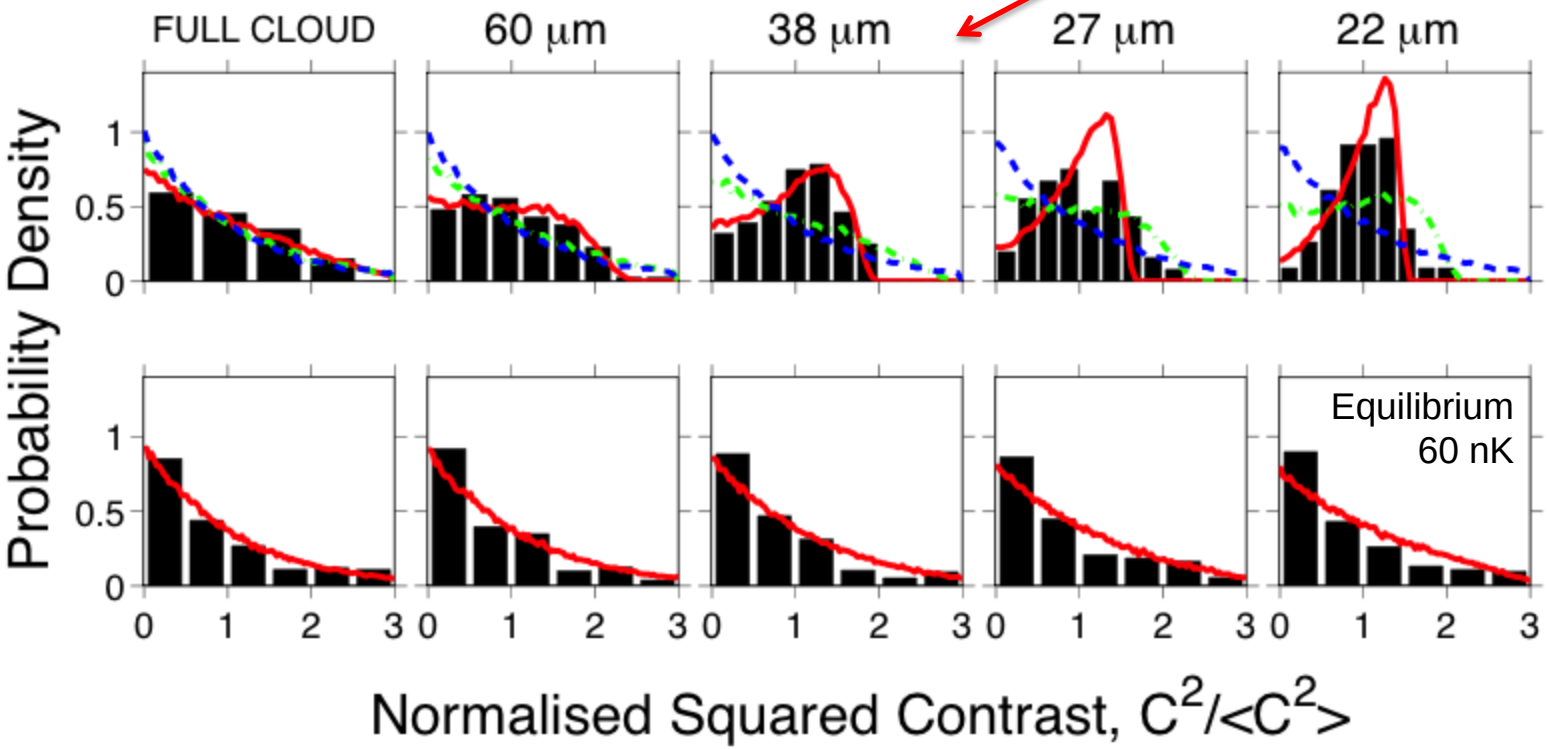


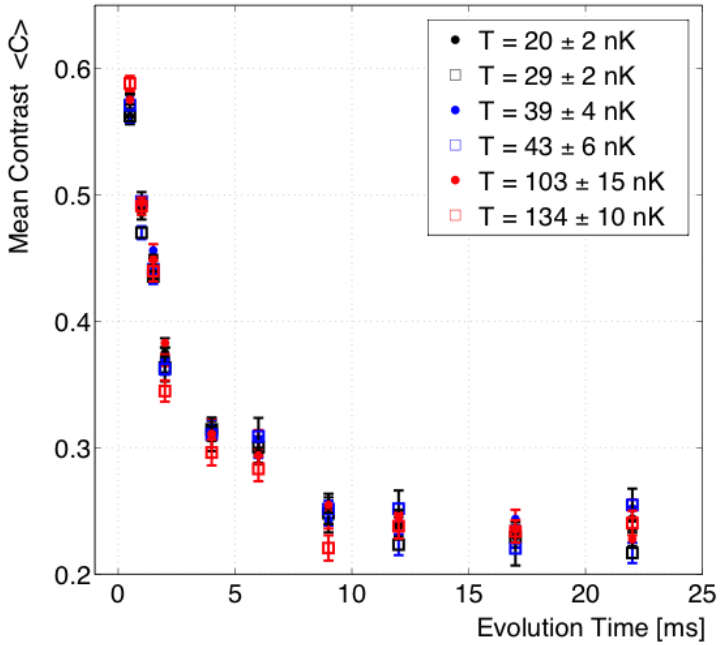
Non-Equilibrium Evolution

What happens when we change the initial temperature T of the unsplit system?

Non-Equilibrium Evolution

What happens when we change the initial temperature T of the unsplit system?

EXACTLY the same behaviour



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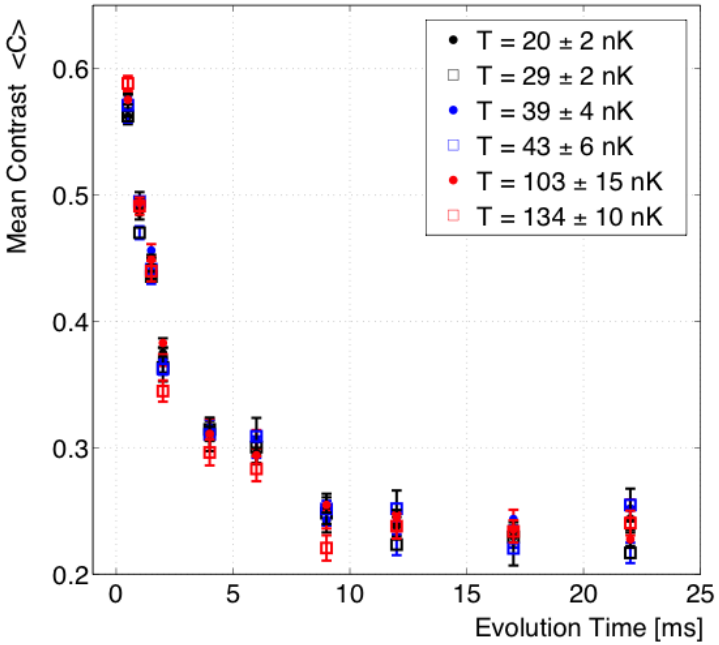
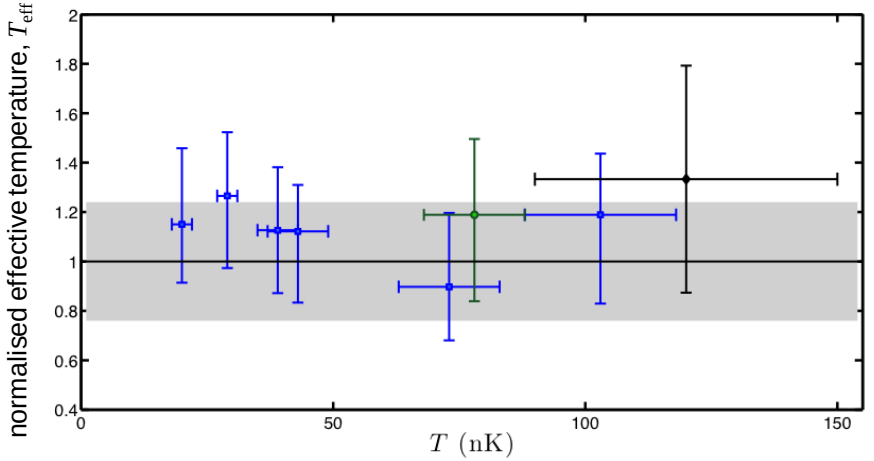
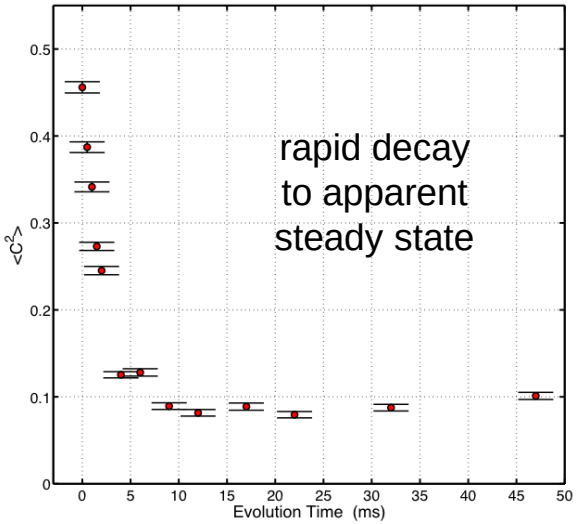




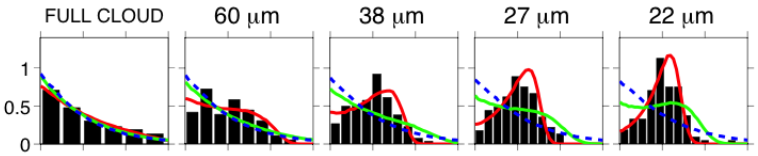
Recap

track evolution of non-equilibrium state
(using matter-wave interference)

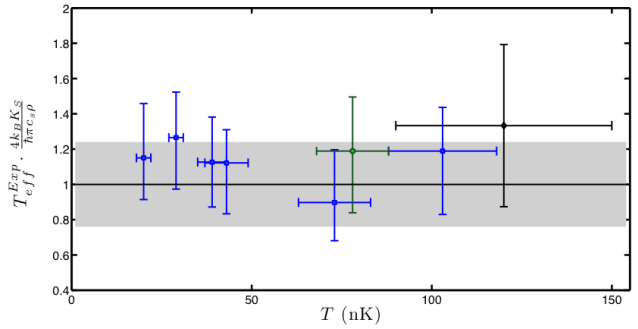


BUT
this is not a
thermal equilibrium state

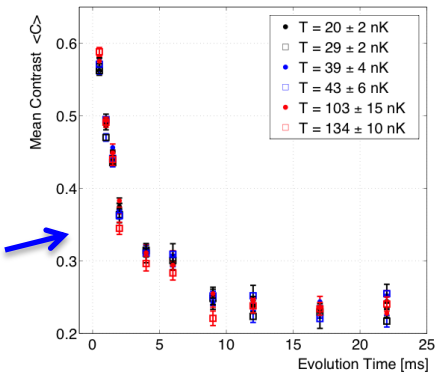
HOWEVER,
it is thermal-like in form



its effective temperature T_{eff}
does not change with
initial temperature T



AND
the initial rapid decay
is also independent of the
initial temperature T



This state represents a fixed point
in the evolution of the system!

Theoretical Description of Non-Equilibrium Dynamics

Kitagawa et al. *PRL* **104** 255302 (2010)

PRL **104,** 255302 (2010) PHYSICAL REVIEW LETTERS week ending 25 JUNE 2010

Ramsey Interference in One-Dimensional Systems: The Full Distribution Function of Fringe Contrast as a Probe of Many-Body Dynamics

Takuya Kitagawa,[1] Susanne Pielawa,[1] Adilet Imambekov,[2] Jörg Schmiedmayer,[3] Vladimir Gritsev,[4] and Eugene Demler[1]

+ Kitagawa et al. *New J. Phys.* **13** 073018 (2011)

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Kitagawa et al. *PRL* **104** 255302 (2010)
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- Integrable Luttinger-liquid-based theory

$$H_s = \int \left[\frac{\rho}{8m} (\partial_z \hat{\phi}_s)^2 + g \hat{n}_s^2 \right] dz$$

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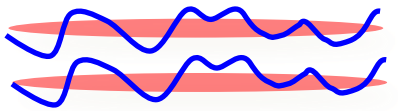

Just after splitting

thermally populated

$$\hat{\phi}_c(z) = \hat{\phi}_A(z) + \hat{\phi}_B(z)$$

$$\hat{\phi}_s(z) = \hat{\phi}_A(z) - \hat{\phi}_B(z)$$

populated only by
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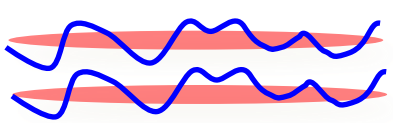

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This theoretical model describes the dynamics of the non-equilibrium system through the dephasing of the momentum modes (k-modes) of the system
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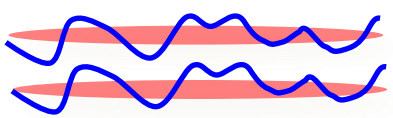

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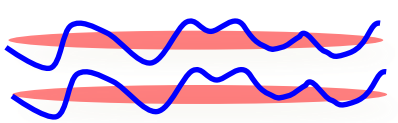

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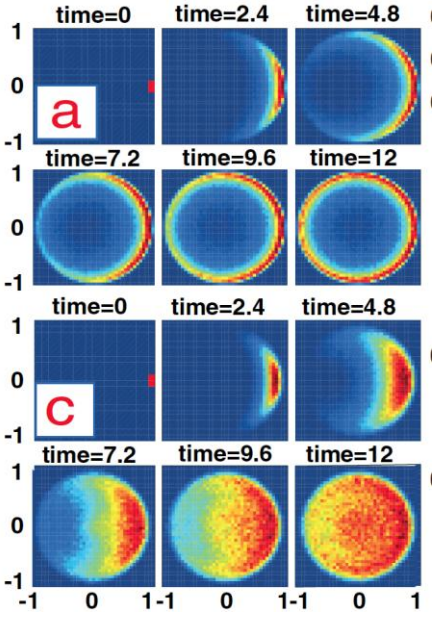
Two-observable FDFs



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Kitagawa et al. *PRL* **104** 255302 (2010)

- dephasing of the momentum modes (k-modes)
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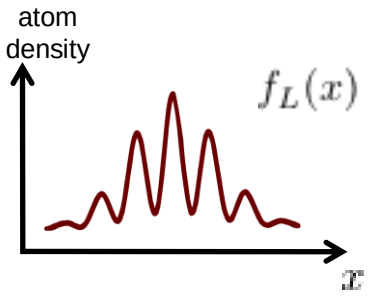


$$f_L(x) = \exp\left(-\frac{x^2}{2\sigma^2}\right)\left(1 + C_L \cos\left(\frac{2\pi x}{\lambda} + \theta\right)\right)$$

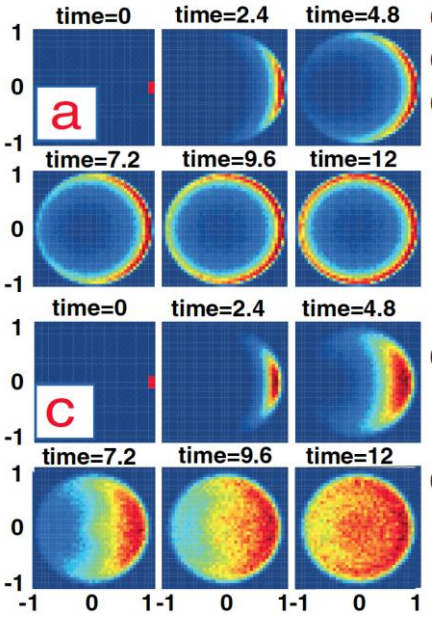
Contrast
C_L

(over integration length L)

Phase
θ

(phase of interference pattern with respect to gaussian background)

Two-observable FDFs



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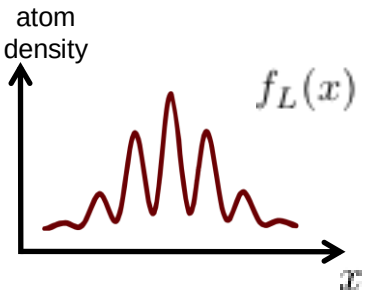

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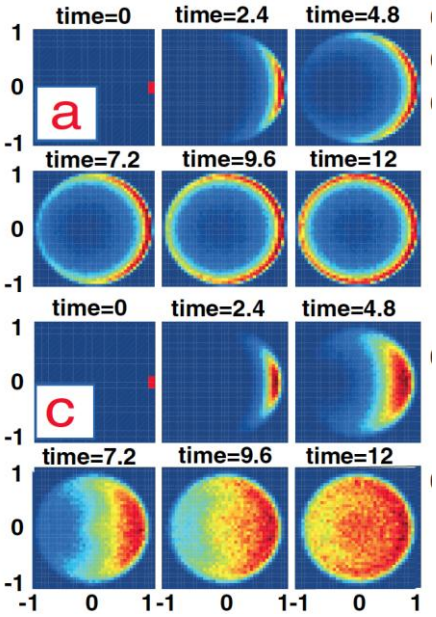
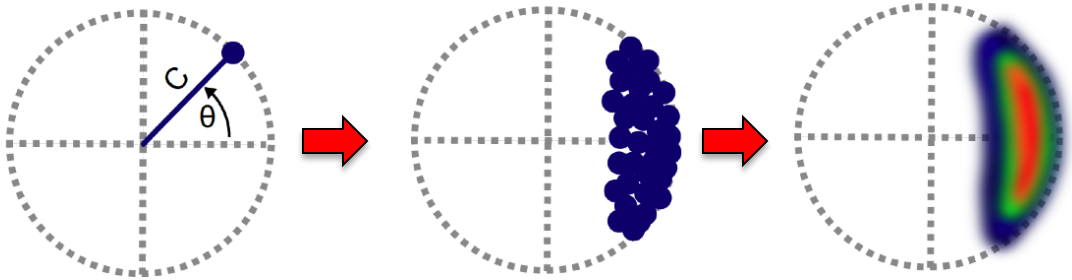


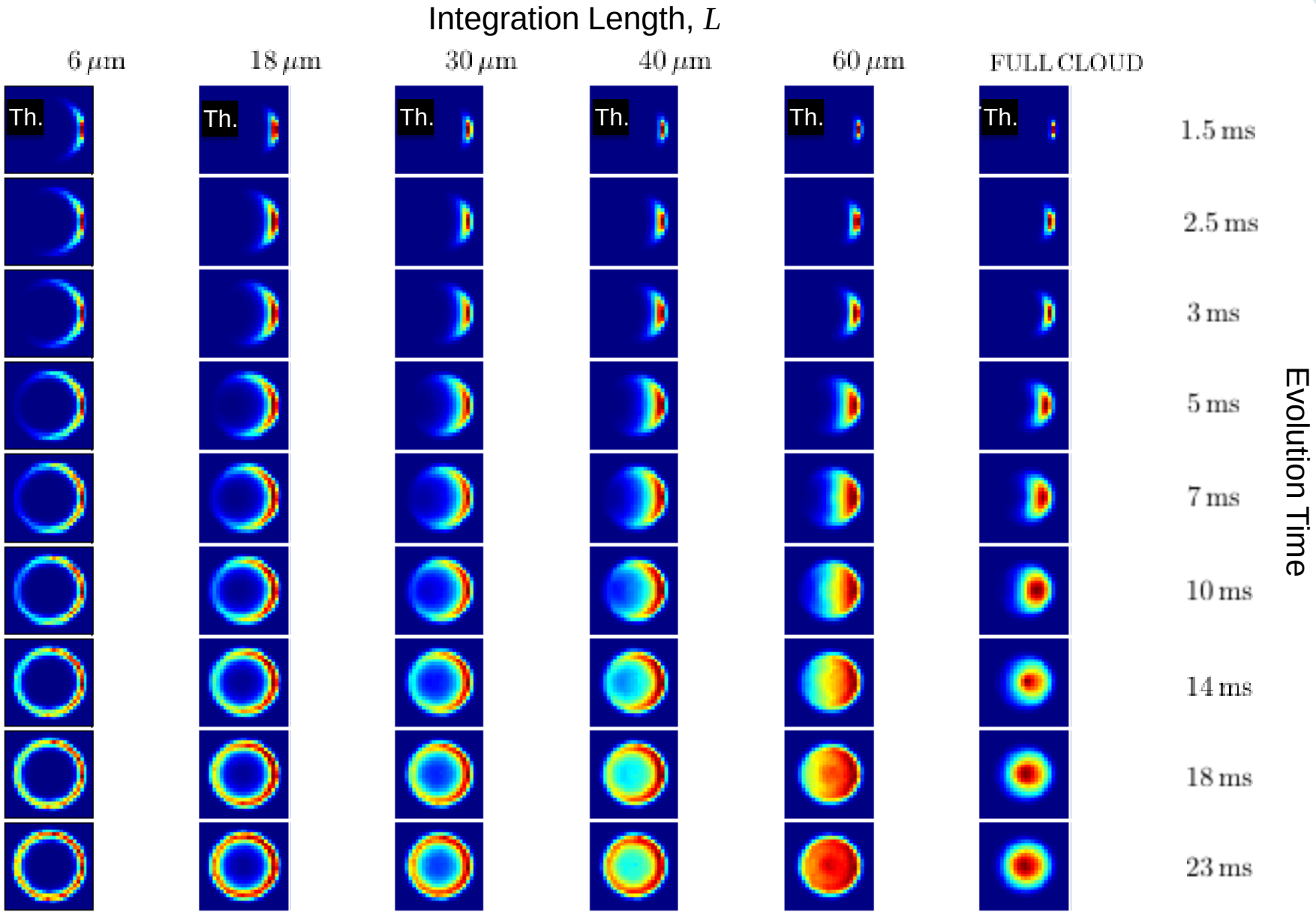


single measurement

many measurements

density plot

Theoretical Description of Non-Equilibrium Dynamics



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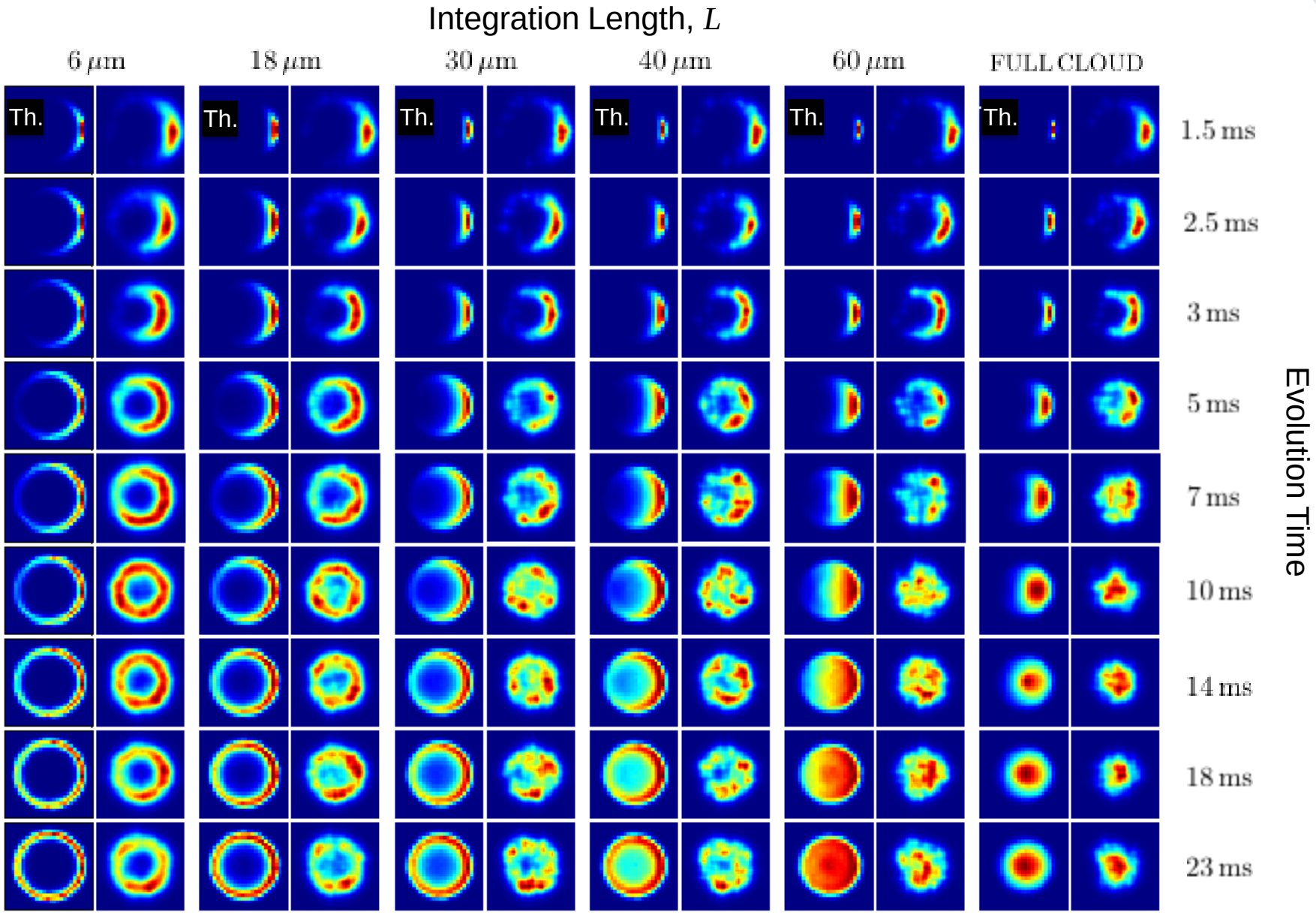
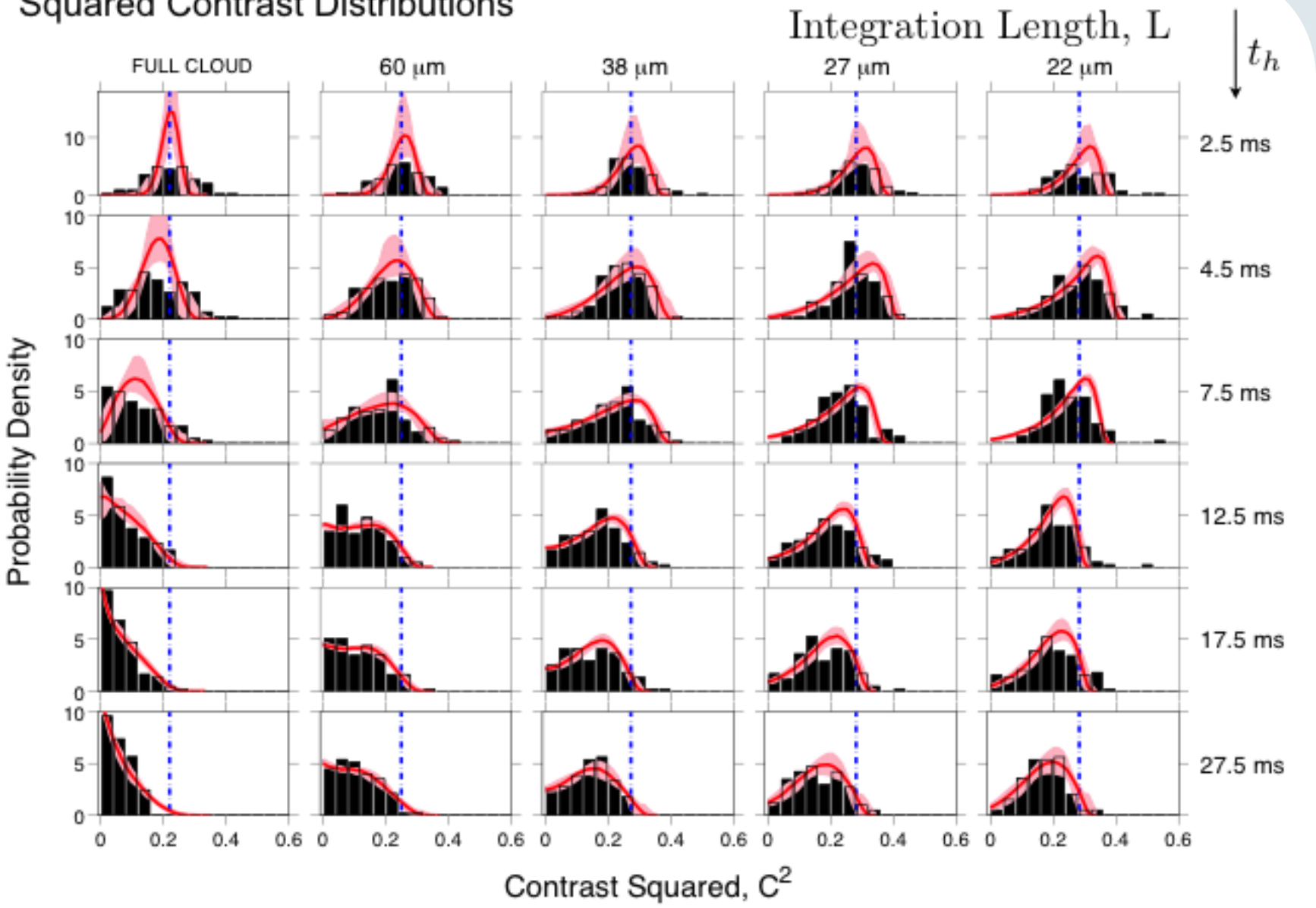


Theoretical Description of Non-Equilibrium Dynamics

- Squared Contrast Distributions



Theoretical Description of Non-Equilibrium Dynamics

Prediction for the effective temperature T_{eff} [Kitagawa et al. *New J. Phys.* **13** 073018 (2011)]

$$T_{\mathrm{eff}} = \frac{g\rho}{2k_B}$$

$g = 2\hbar\omega_\perp a_s$

$\rho = \mathrm{density}$

$\omega_\perp$ – radial trapping frequency

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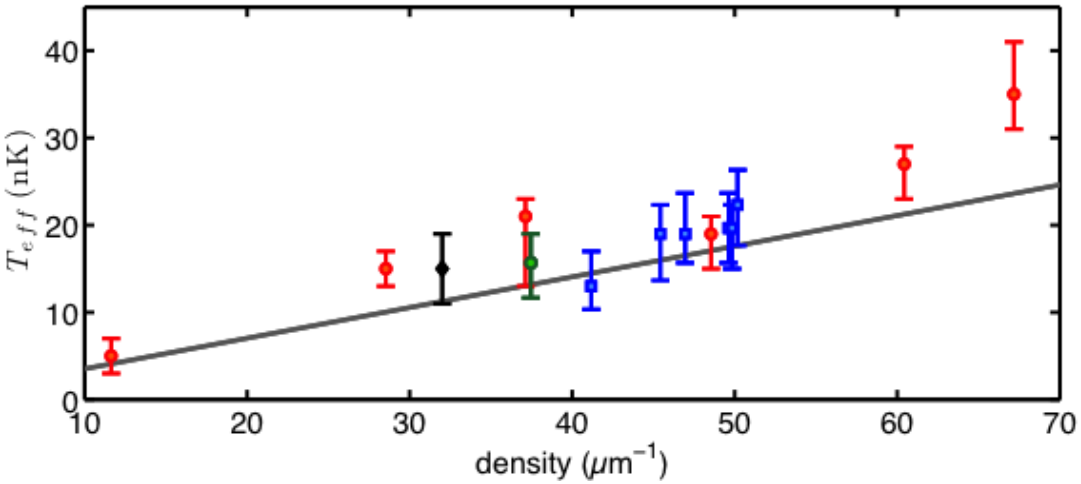

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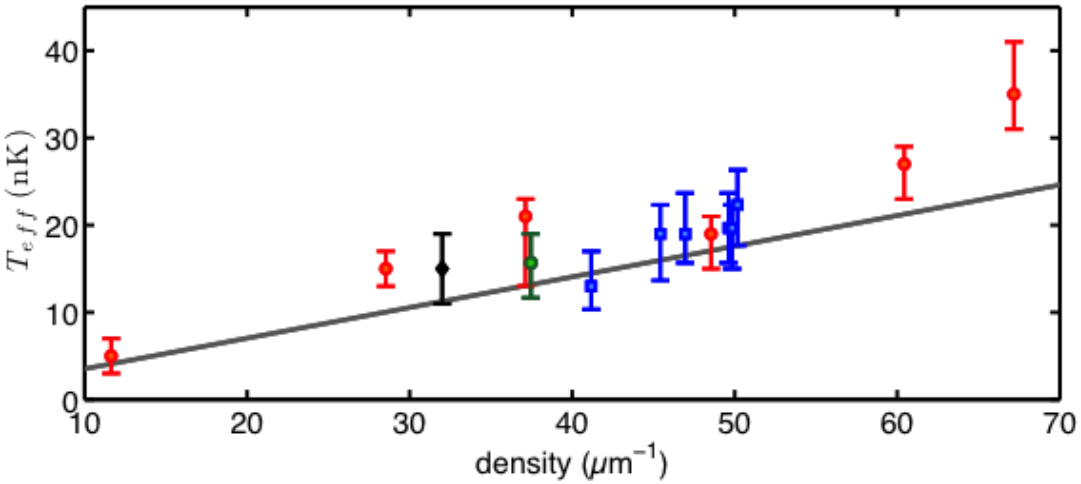
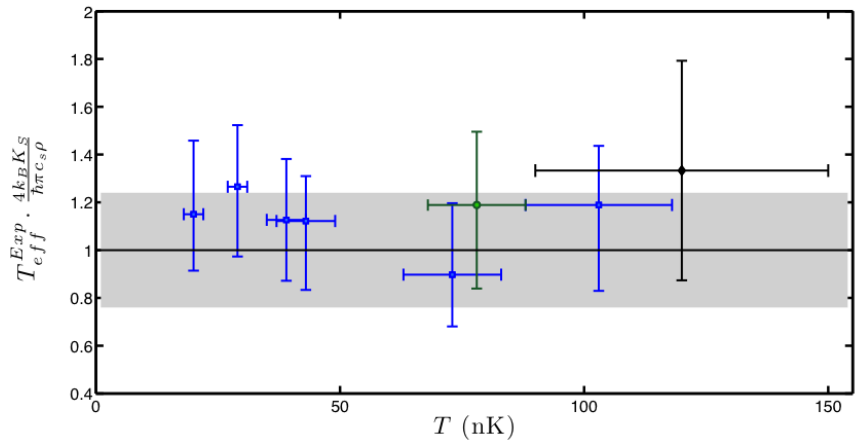
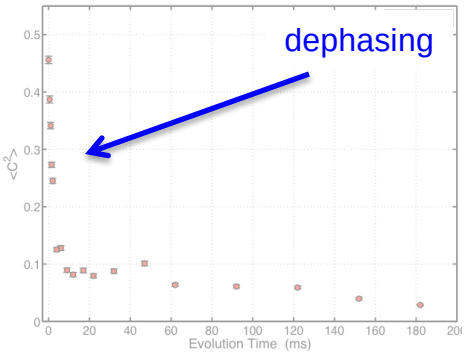
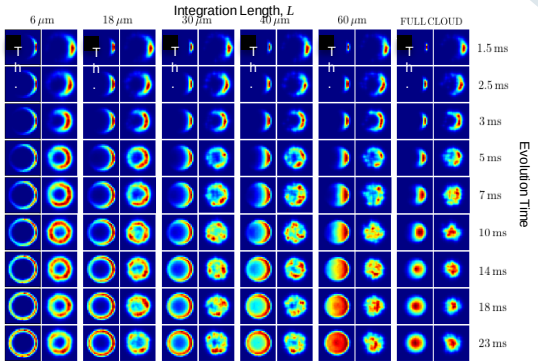




Pre-thermalisation

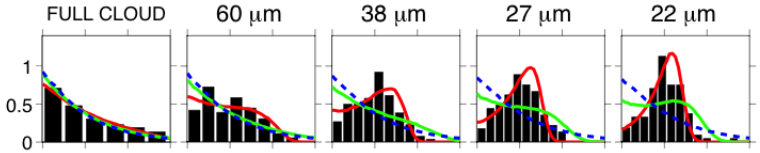
Our system decays to a quasi-stationary state that is not a thermal equilibrium state of the system



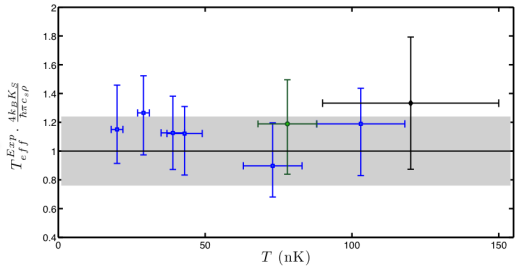


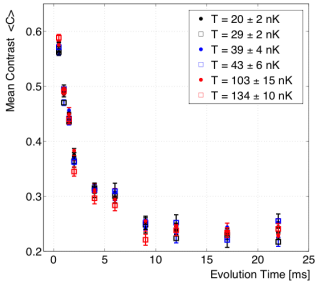
The decay is well described by dephasing

to a state that is thermal-like in form (observing the interference contrast C_L)



that displays an effective temperature T_{eff} and rapid initial decay that do not change with initial temperature T and hence is a fixed point in the evolution

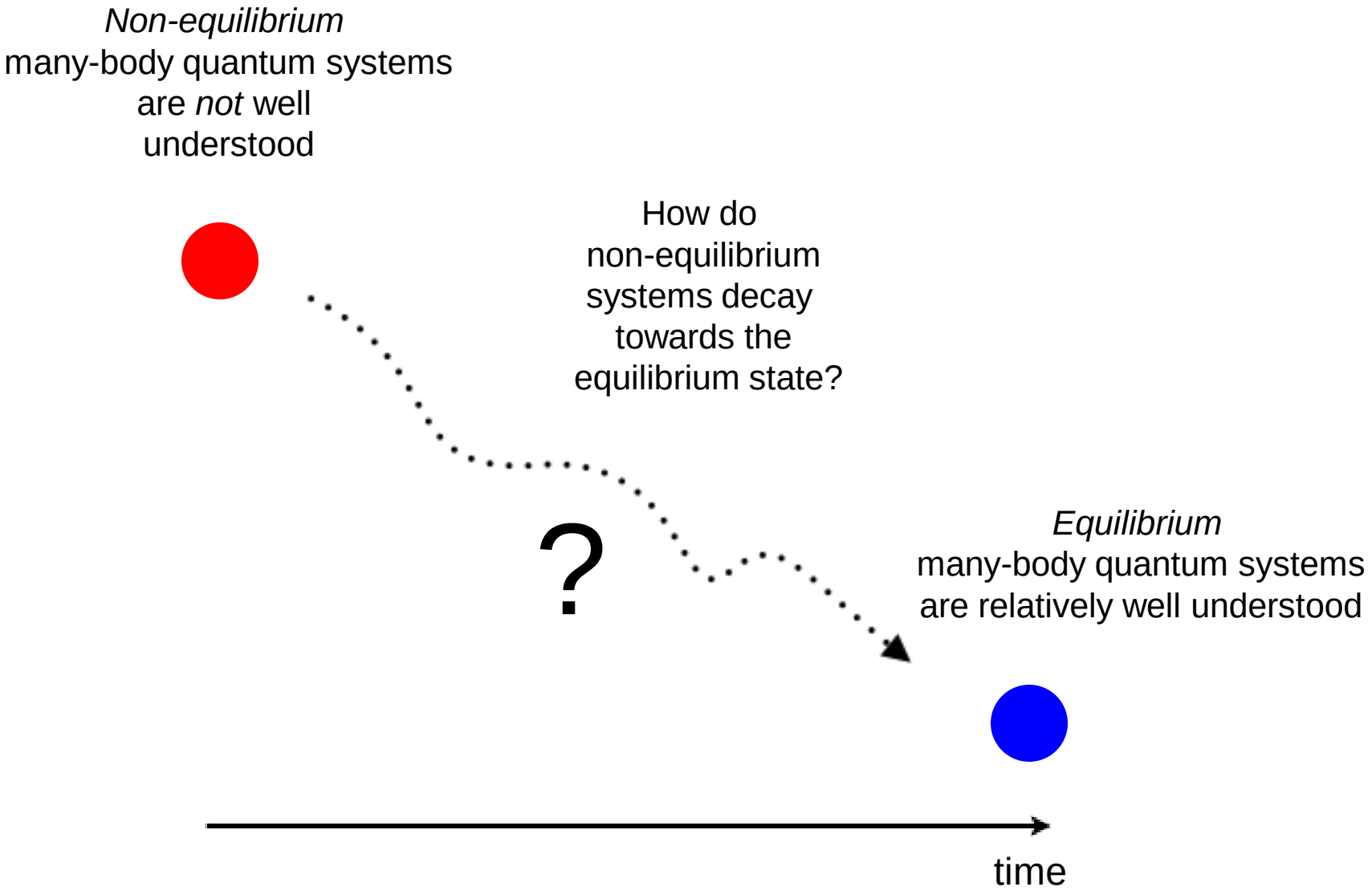




Pre-thermalisation: Berges, Borsányi, Wetterich, *Prethermalization*, PRL **93** 142002 (2004)

e.g. Moeckel and Kehrein, New J. Phys. 12, 055016 (2010).
Mathey and Polkovnikov, Phys. Rev. A 81, 033605 (2010).
Barnett, Polkovnikov, and Vengalattore, Phys. Rev. A 84, 023606 (2011).
Kitagawa et al. New J. Phys. 13 073018 (2011)
Kollar, Wolf, Eckstein, Phys. Rev. B 84, 054304 (2011).

Non-Equilibrium Systems



Thank you.

VCQ
Vienna Center for Quantum Science and Technology

ATOMINSTITUT

FWF Der Wissenschaftsfonds. SFB FoQuS CoQuS Complex Quantum Systems MARIE CURIE ACTIONS aqute EUROPEAN SCIENCE FOUNDATION Siemens AG Österreich WIENKULTUR

TU WIEN

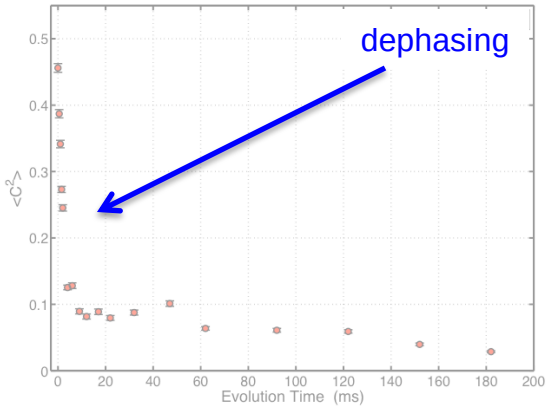
Open Questions

Thermalisation

What is thermalisation?

How does it occur in a 1d system?

It is a subtle process in our case, if it exists at all.



Generalized Gibbs Ensemble (GGE)

It is predicted that the prethermalised state can be described by a GGE.
e.g. Kollar, Wolf, Eckstein, Phys. Rev. B 84, 054304 (2011).

How can we prove this with an experiment? Can we prove this?

Prethermalization

What is the most general definition of prethermalization?

Berges, Borsányi, Wetterich, *Prethermalization*, PRL **93** 142002 (2004)
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