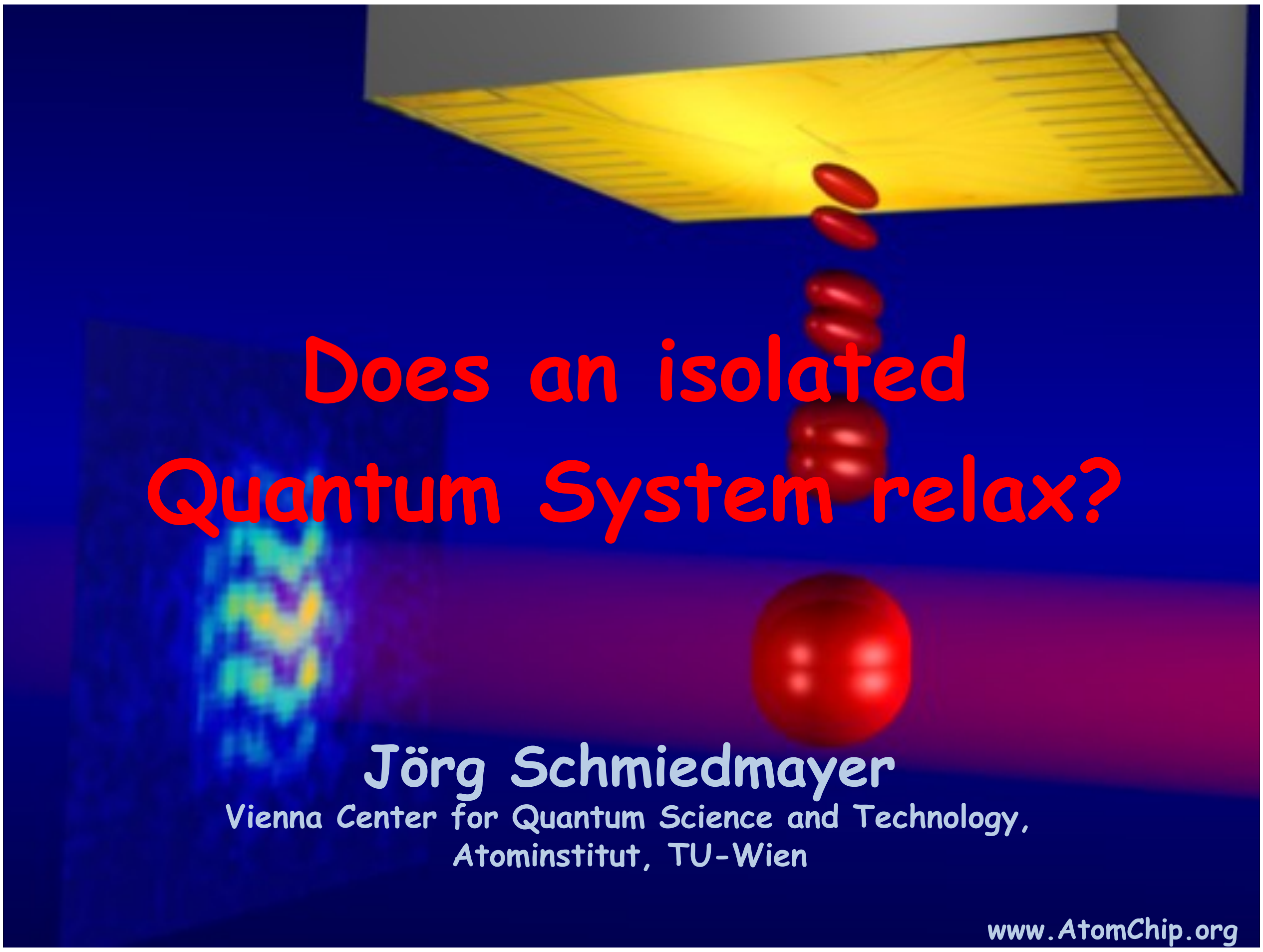


Does an isolated Quantum System relax?

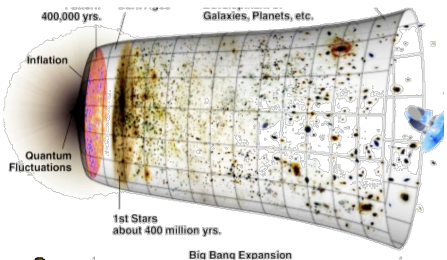
Jörg Schmiedmayer

Vienna Center for Quantum Science and Technology, Atominstitut, TU-Wien

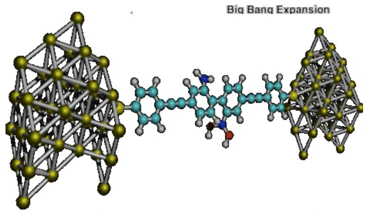
www.AtomChip.org

Non-equilibrium systems:
examples in quantum physics

- Particle creation and expansion in the early universe:
  - *Baryogenesis, Inflation*

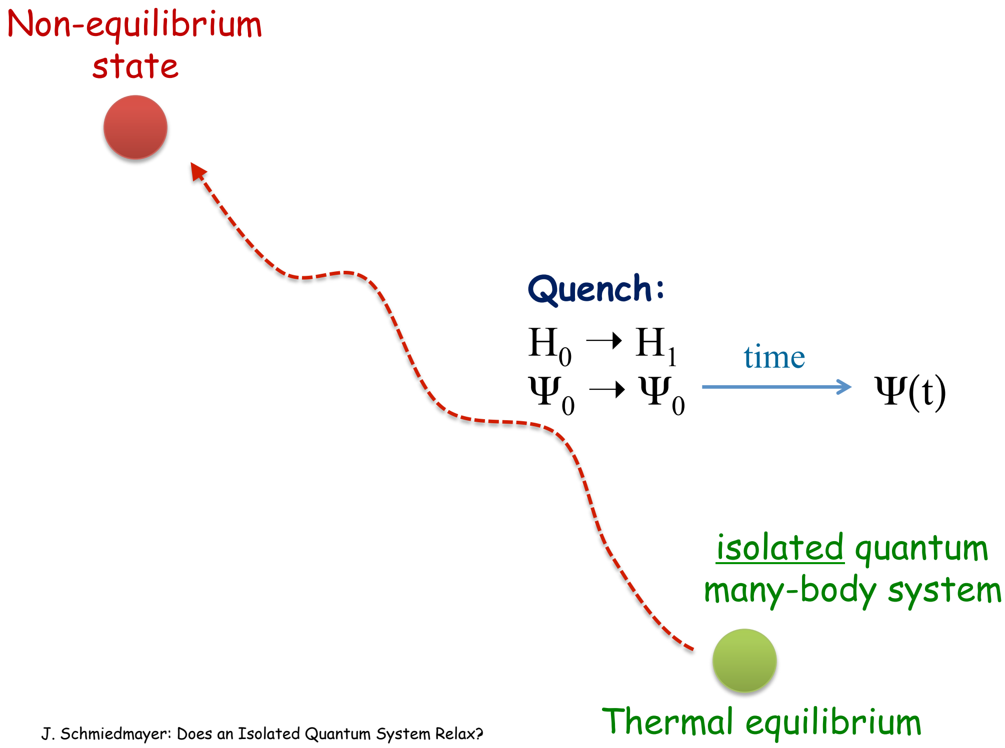


- Electron transport :
  - *molecular electronics*

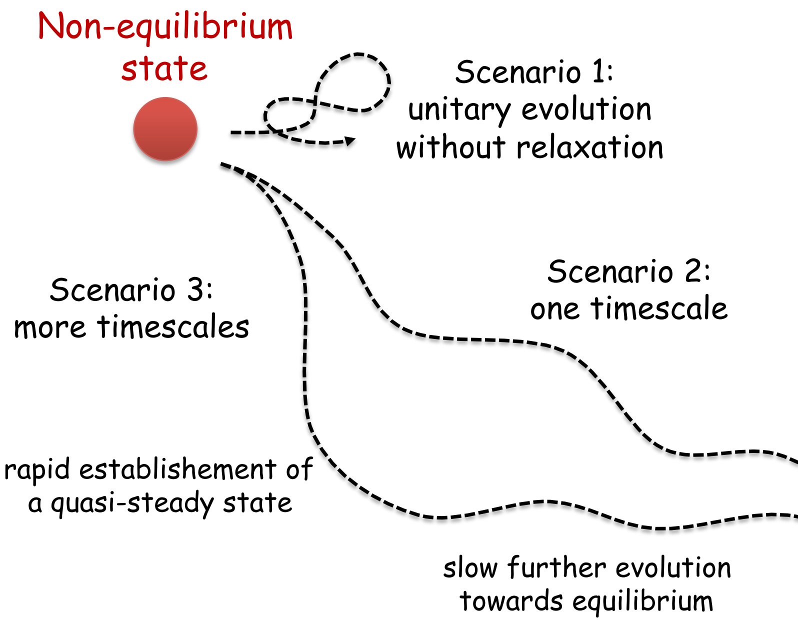


- De-Coherence :
  - *Measurement problem*
  - *Quantum Computer*

Motivation



Motivation



Open problem on vastly different energy, time and length scales!

Study using a model system:

1D Bose gas
isolated & controllable

Outline

Non-equilibrum system
- Coherently split 1d quantum gas

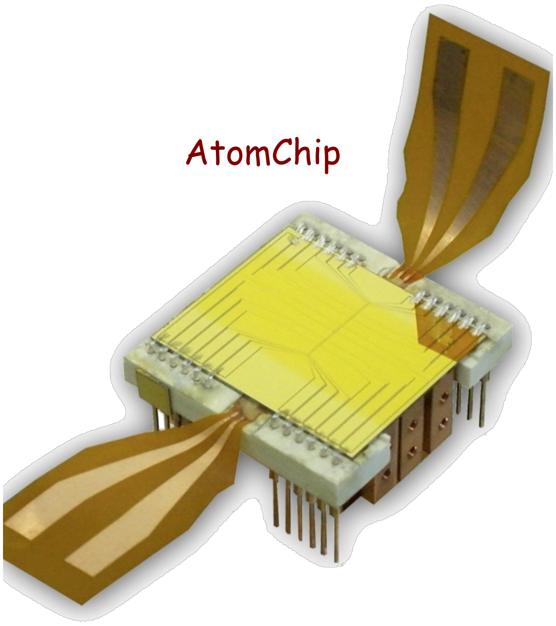
Tools to probe the quantum states
- Full distribution functions of interference

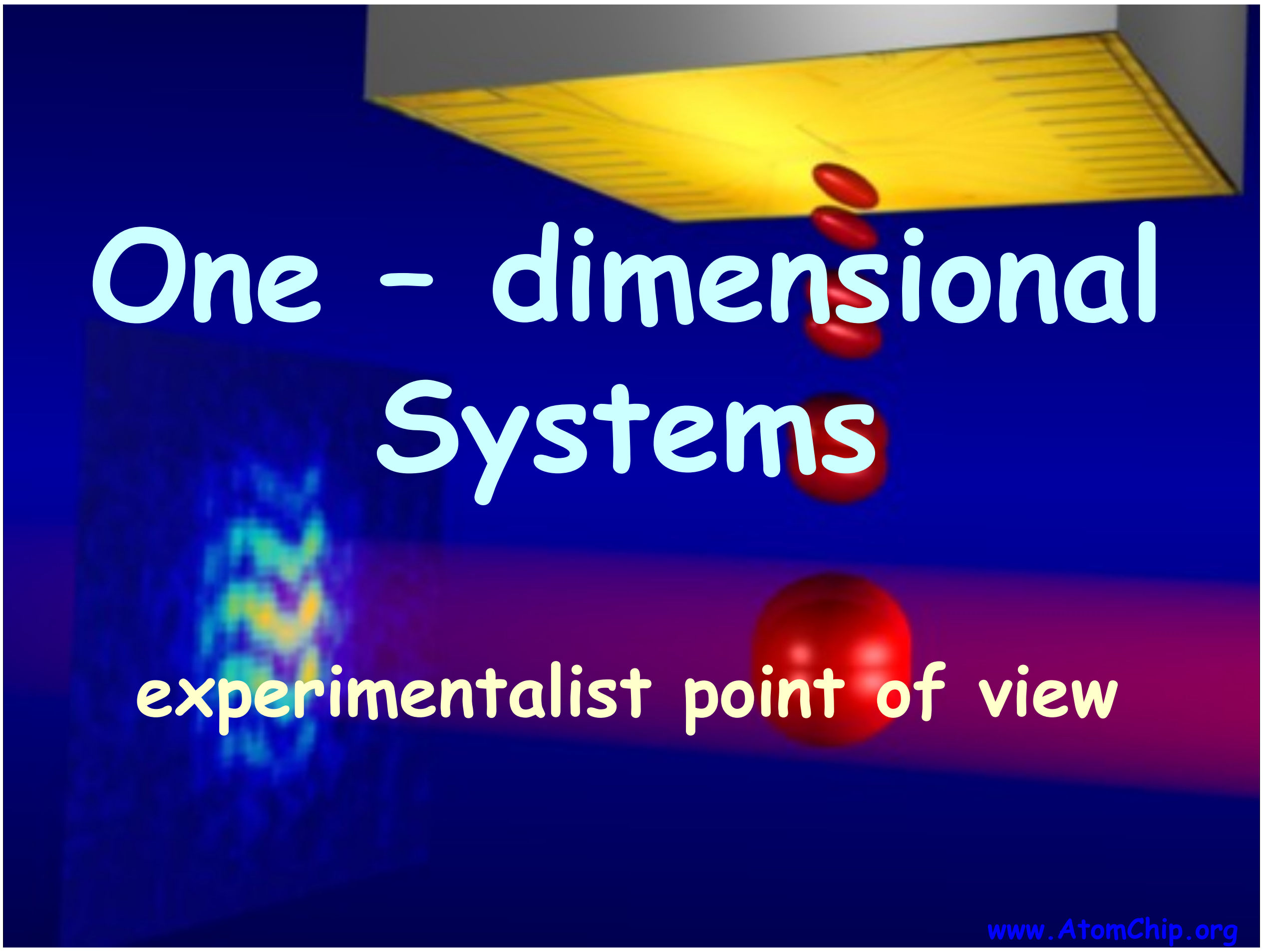
Approach towards equilibrium
- Probing dynamics
  - Pre-Thermalization
    Emergence of a new length scale
  - Light cone like spreading of de-coherence
  - Generalized Gibbs ensemble
  - Relaxation from the pre-thermalized state
- Improving Interferometry
  - Large spin squeezing and entanglement

Other Non-equilibrum systems
- Decay of excited state -> twin beams
- Fast cooling in 1d

Outlook

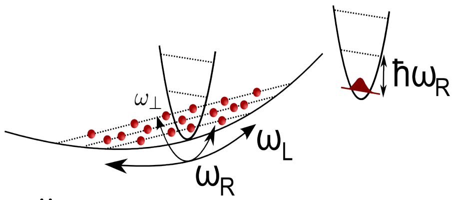
AtomChip





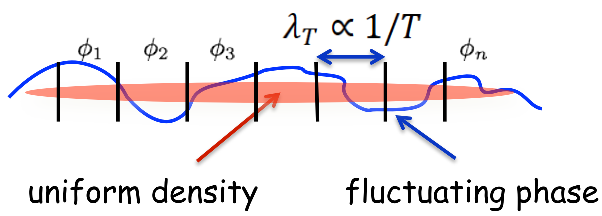
System under investigation

Weakly interacting 1d Bose gas



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

quasi-condensate



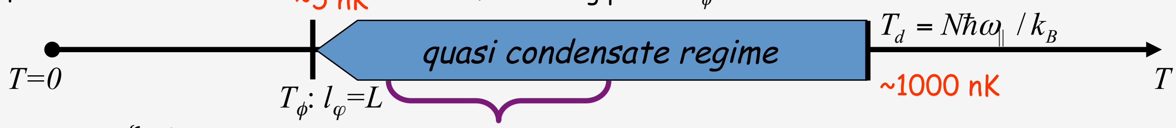
„true“ 1D condensate

- longe range phase coh.
- quantum fluctuations

1D „quasi condensate“

- macroscopic wave function
- fluctuating phase: $l_\phi < L$

thermal gas



experiments: 20-150 nK

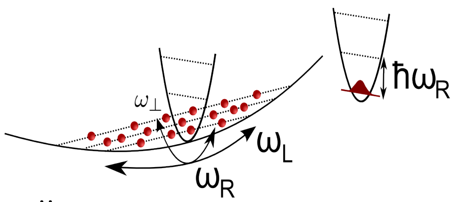
$T_\varphi \approx n_{1d}\ \xi_h\ \hbar\omega_{||}$

$\xi_h = \frac{\hbar}{\sqrt{m\ n_{1d} g_{1d}}}$

With interaction energy: $I = n_{1d} g_{1d}$ and 1d interaction strength: $g_{1d} = 2\hbar\omega_\perp a_s$

System under investigation

Weakly interacting 1d Bose gas



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

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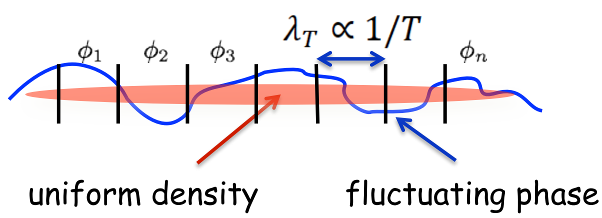


Theory: Lieb-Liniger model

- Exactly solvable Integrable theory

Luttinger-liquid

- excitations are soundwaves (phonons), which do NOT interact
- Linear dispersion relation
- dynamics described through the dephasing of the phonons

Model for interacting many body systems which can be described by a field theory with long lived excitations.

Excitations play an enhanced role in 1d

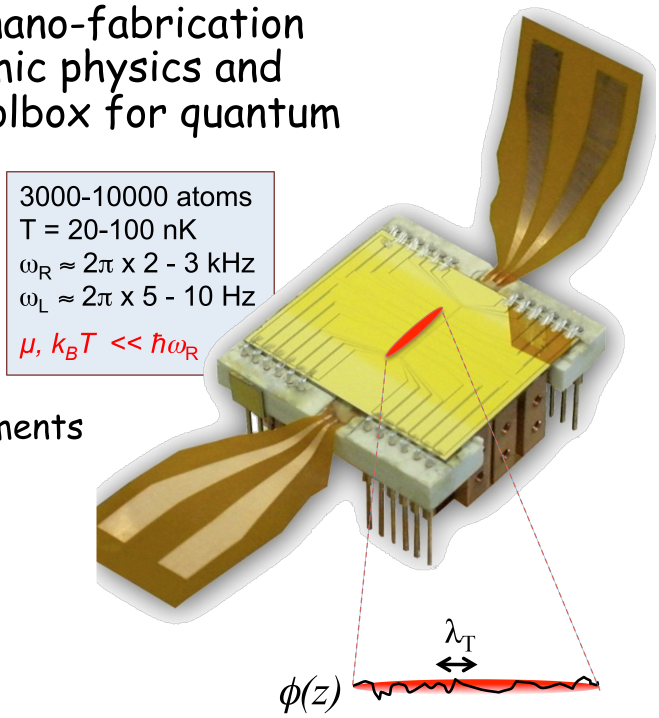
$$\hat{\psi}(x) = e^{i\hat{\phi}_1(x)}\sqrt{\rho + \hat{n}_1(x)}$$

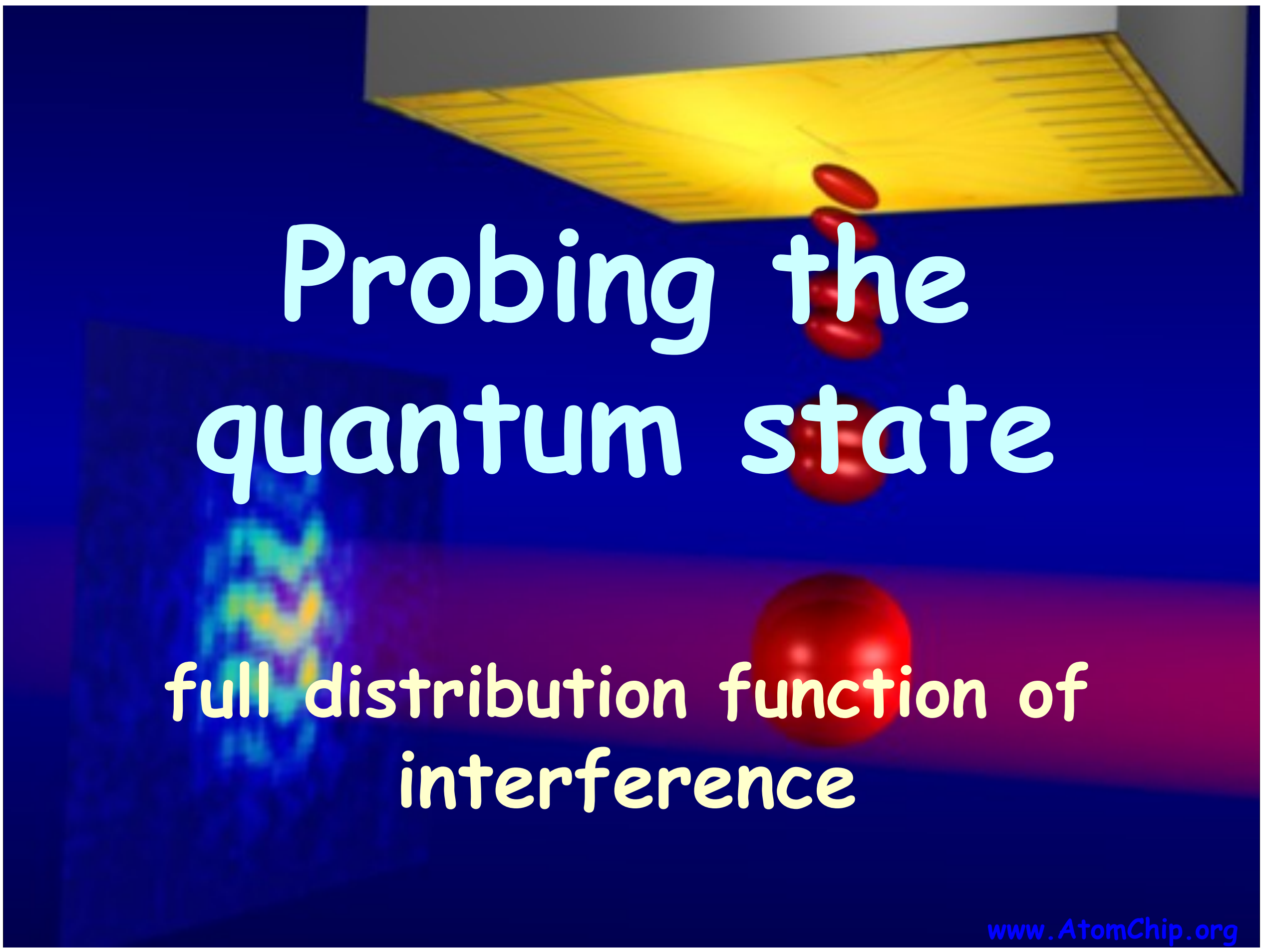
thermally populated

The longitudinal phase fluctuations are key for our experiments

Combine the robustness of nano-fabrication an the quantum tools of atomic physics and quantum optics to build a toolbox for quantum experiments

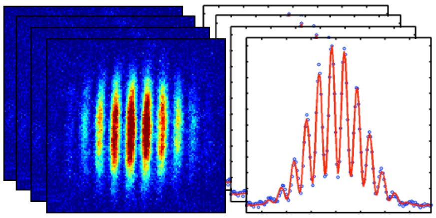
- 1d elongated traps
- Easy to create a BEC
- Very stable and reproducible laboratory for quantum experiments
- Fast operation
- Well controlled splitting and interference





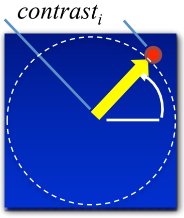
FDF of phase and contrast

- Matter-wave interferometry: repeat many times

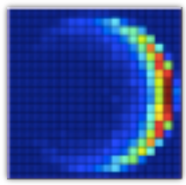


→ phase, contrast i>100

- Plot as circular statistics



→



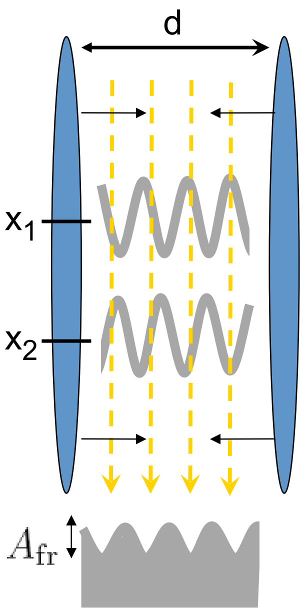
full distribution function of phase & contrast

Theory: Polkovnikov et al. PNAS **103**, 6125 (2006)
Gritsev et al. Nature Phys. **2**, 705 (2006)
Exp: Hofferberth et al. Nature Phys. **4**, 489 (2008)

FDF contains information about all order correlation functions
in solid state: **Full Counting Statistics**

Interfering independent 1d Quantum Liquids

A. Polkovnikov, et al., PNAS **103**, 6125 (2006)
V. Gritsev, et al., Nature Phys. **2**, 705 (2006)
A. Imambekov et al. Phys. Rev. A **77**, 063606 (2008)



A is a quantum operator.
Its measured value will fluctuate from shot to shot.

$$A = \frac{1}{n_{1d}} \int_{-L/2}^{L/2} a_1^+(z) a_2(z) dz$$

For independent BEC's: expectation value of contrast:
$\langle A \rangle = 0$ due to random rel. Phases

Look at $\langle |A|^2 \rangle$

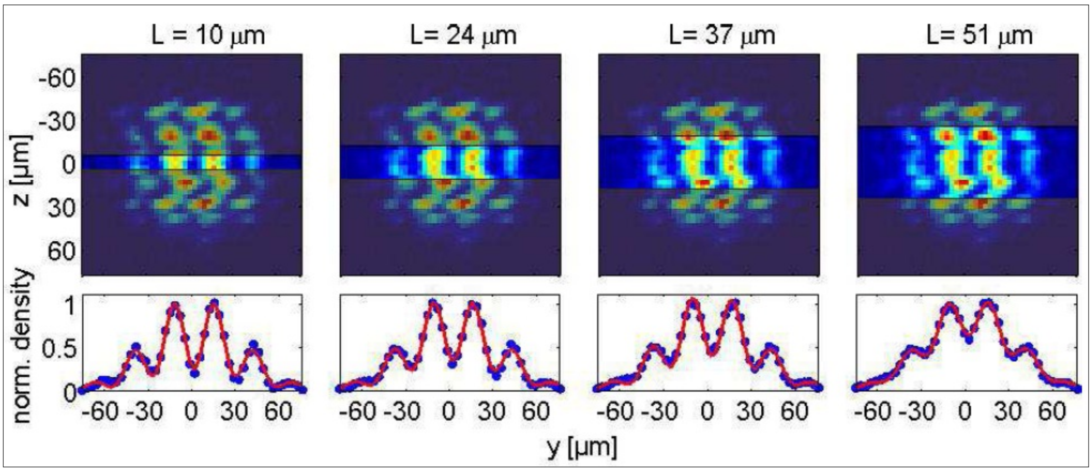
$$\underbrace{\langle |A|^2 \rangle}_{\text{2nd moment of fringe („average contrast“)}} = \frac{1}{n_{1d}^2} \int_{-L/2}^{L/2} dz_1 \int dz_2 \underbrace{\langle a_1^+(z_1) a_1(z_2) \rangle \langle a_2^+(z_2) a_2(z_1) \rangle}_{\text{2nd order correlation function}}$$

2nd moment of fringe („average contrast“)
2nd order correlation function

E. Demmler, A. Polkovnikov, V. Gritsev, A. Imambekov E. Altman

Analysis of interference patterns: contrast analysis

Hofferberth et al Nature Phys. 4, 489 (2008)



wave vector of fringe separation: $Q = md / \hbar t_{TOF}$

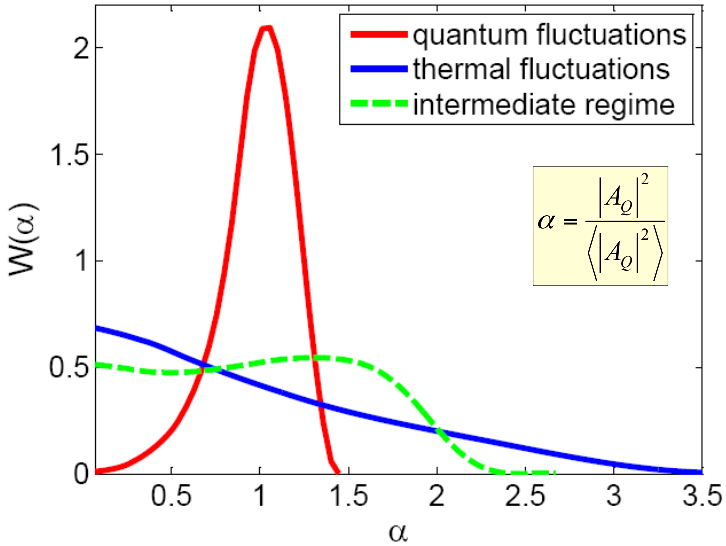
contrast of integrated profile: $A_Q = \frac{1}{n_{1d}} \int_{-L/2}^{L/2} a_1^+(z) a_2(z) dz$

expectation value of contrast: $\langle A_Q \rangle = 0$ due to random rel. phases

full contrast statistics
theory predictions

A. Polkovnikov, et al., PNAS **103**, 6125 (2006)
V. Gritsev, et al., Nature Phys. **2**, 705 (2006)
A. Imambekov et al. Phys. Rev. A **77**, 063606 (2008)

theoretically expected **distribution functions** for the average contrast:



quantum coherence:
asymetric Gumbel distribution
(low temp. T or short length L)

thermal fluctuations:
broad Poissonians distribution
(high temp T or long length L)

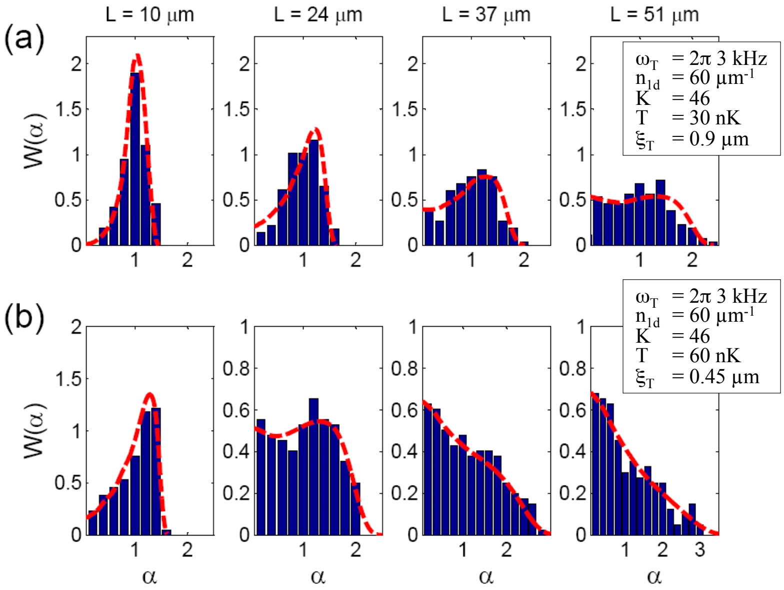
intermediate regime:
double-peak strukture

Semi-classical approach: Stimming et al. et al. PRL (2010)

full contrast statistics
experiment

experimentally measured distribution functions for the average contrast:

Hofferberth et al Nature Phys. **4**, 489 (2008)



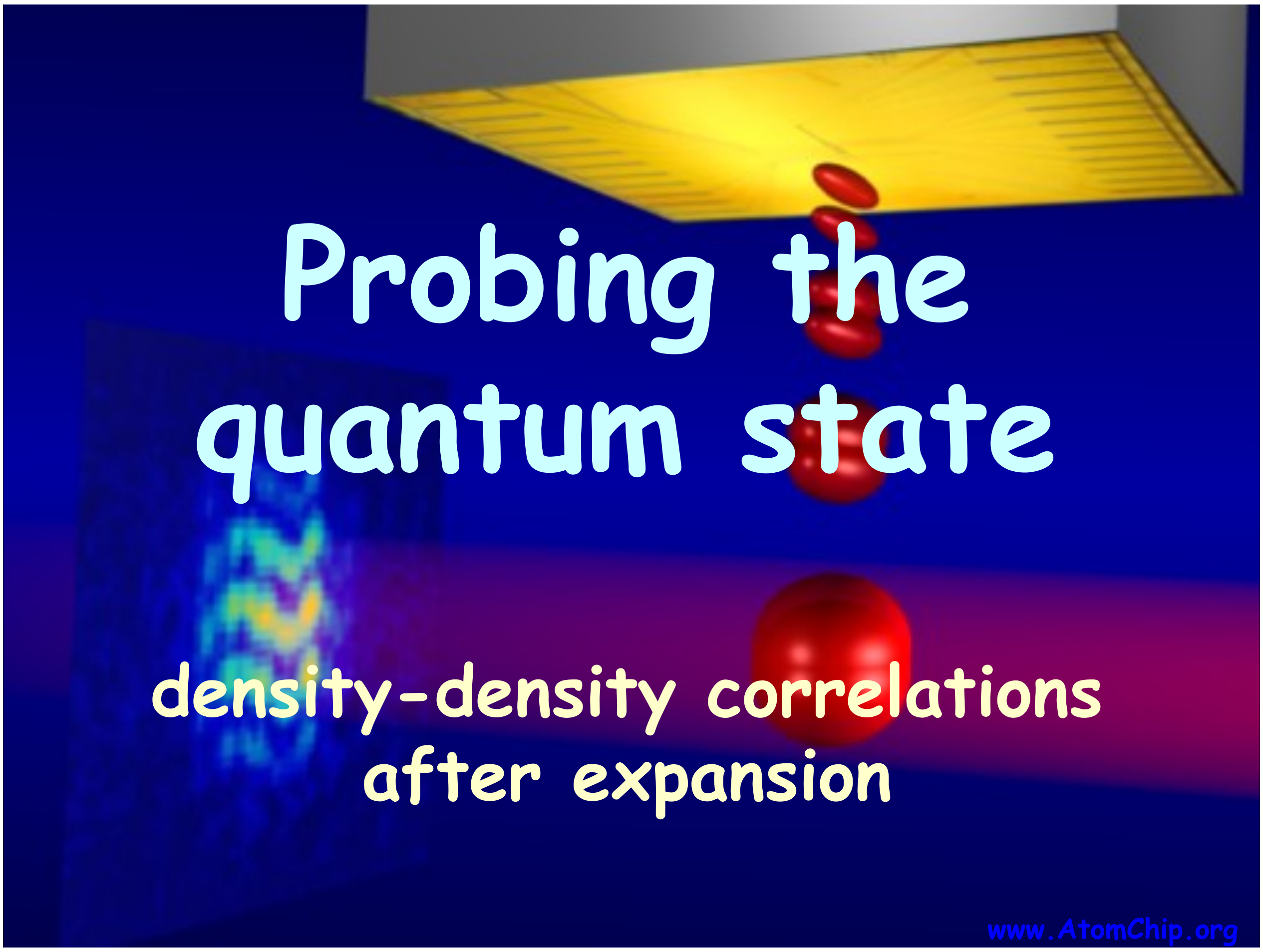
quantum coherence:
asymetric Gumbel distribution
(low temp. T or short length L)

thermal fluctuations:
broad Poissonians distribution
(high temp T or long length L)

intermediate regime:
double-peak strukture

No free parameters!

experiment records entire distribution function of interference contrast
→ high order correlations can be derived



Correlations as a probe

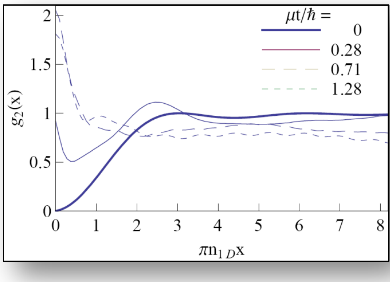
A. Imambekov et al PRA **80**, 33604 (2009)

Phase fluctuations in the trapped quantum gas will translate into density fluctuations

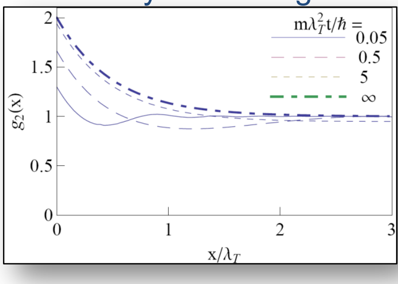
Interference leads to a **matter wave spackle pattern**

If the propagation is free (no final state interaction) one can infer back to the properties of the trapped quantum gas

strongly interacting



weakly interacting



relevant timescale: $m\lambda_c^2/\hbar$

strongly interacting: λ_c: particle distance

weakly interacting λ_c: coherence length

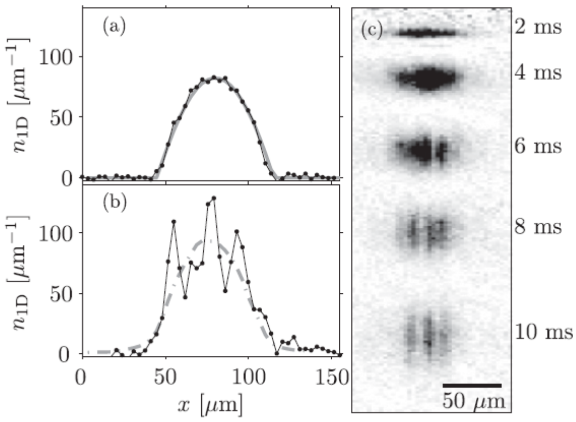
Conclusion:
don‘t take TOF too long or look in-situ

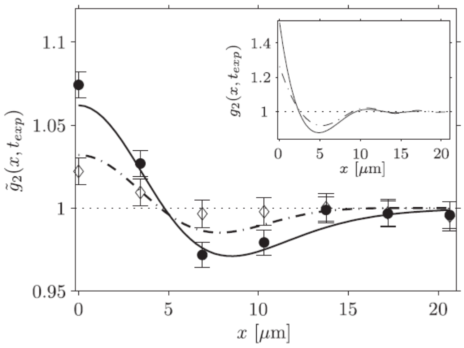
for long TOF, everything looks like an ideal gas

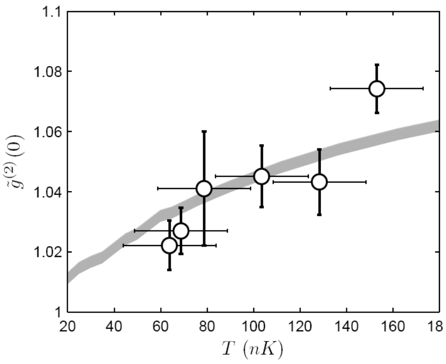
2nd order correlations of a BEC: “correlation thermometry”

Th: A. Imambekov et al PRA 80, 33604 (2009)
Exp: St. Manz et al Phys. Rev. A **81**, 031610 (2010)

absorption images of expanding BEC







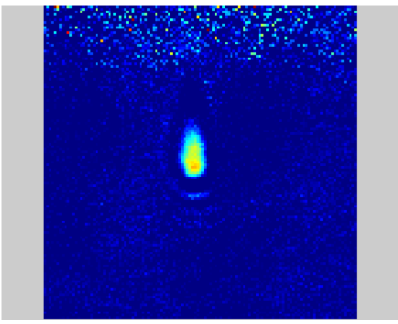
In 1d system we can neglect the interactions in expansion and get information about the properties of the trapped 1d gas

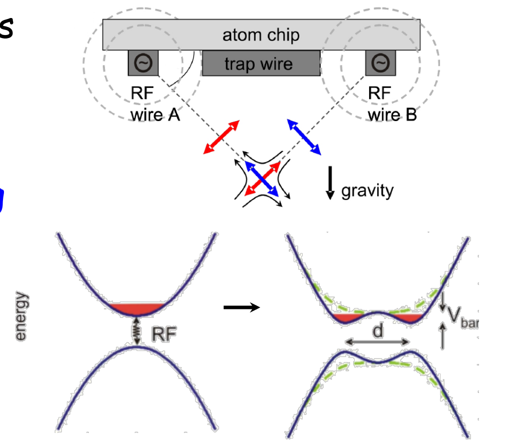
Recent experiments for 2d systems:
Jae-yoon Choi, Sang Won Seo, Woo Jin Kwon, Yong-il Shin
Probing Phase Fluctuations in a 2D Degenerate Bose Gas by Free Expansion

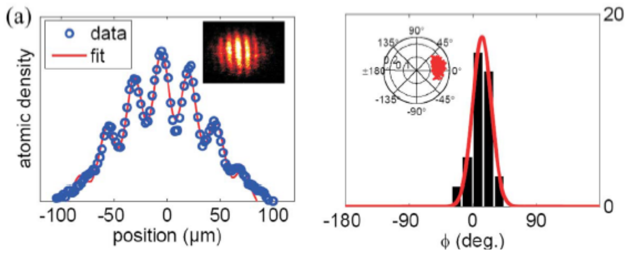
Coherent splitting of a 1d BEC
RF traps on a chip

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

- Deform the single trap into a double-well by coupling of atomic states by RF fields
- **A coherent beamsplitter for matterwaves!**
- ***Observe the interference by releasing the BEC and let it expand to overlap in time of flight***

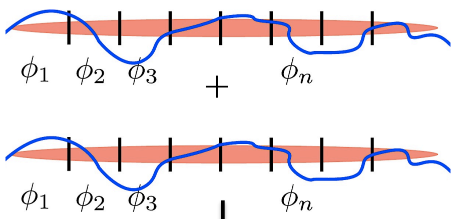






Split 1d-bose-gas as non-equilibrium system

Initial state
coherently split quantum gas



hold time

$\hat{n}_1(x),\ \hat{\phi}_1(x)$

$\hat{n}_2(x),\ \hat{\phi}_2(x)$

symmetric

$\hat{n}_s = \hat{n}_1 + \hat{n}_2, \quad \hat{\phi}_s = \hat{\phi}_1 + \hat{\phi}_2$

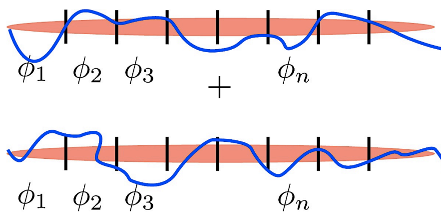
thermally populated

anti symm.

$\hat{n}_a = \hat{n}_1 - \hat{n}_2, \quad \hat{\phi}_a = \hat{\phi}_1 - \hat{\phi}_2$

populated by quantum fluctuations

Thermal equilibrium state
two independent quantum gases



equal (thermal) populated

symmetric

$\hat{n}_s = \hat{n}_1 + \hat{n}_2, \quad \hat{\phi}_s = \hat{\phi}_1 + \hat{\phi}_2$

equal thermal population

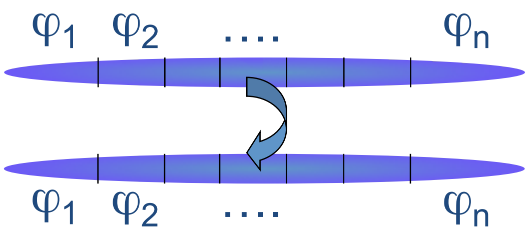
anti symm.

$\hat{n}_a = \hat{n}_1 - \hat{n}_2, \quad \hat{\phi}_a = \hat{\phi}_1 - \hat{\phi}_2$

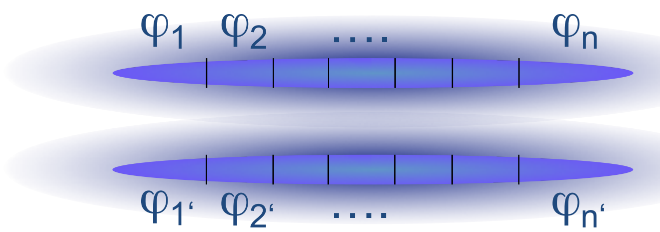
interference of phase fluctuating 1D condensates

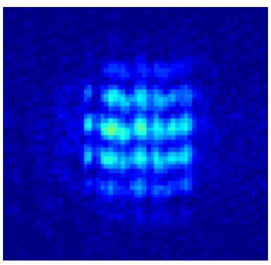
Study the dynamics of excitations on a quantum field

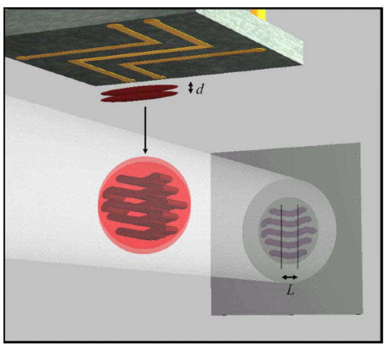
create a copy by splitting
quantum connected

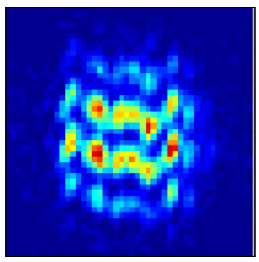


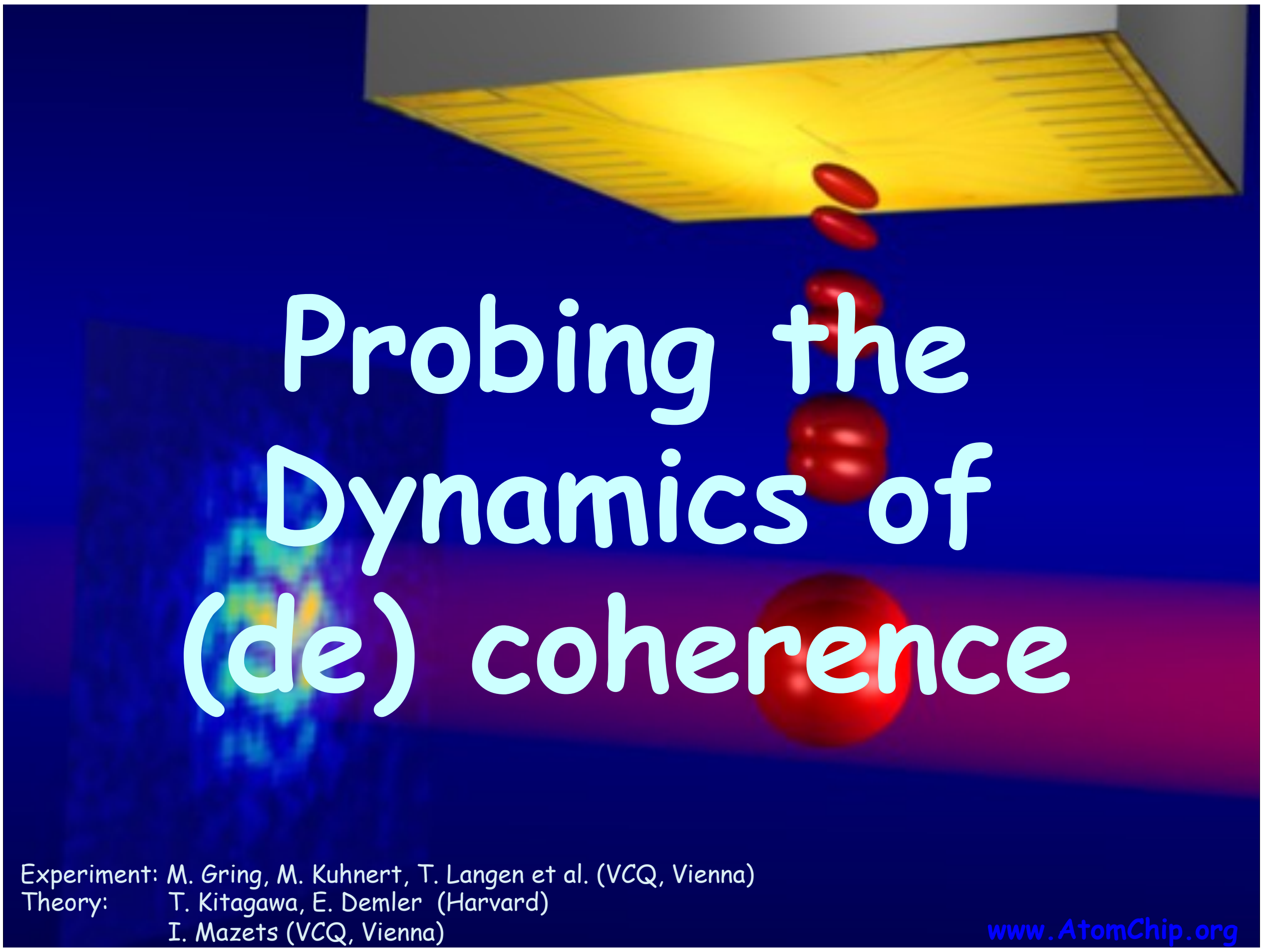
create two independet samples
classically separated











Probing the Dynamics of (de) coherence

Experiment: M. Gring, M. Kuhnert, T. Langen et al. (VCQ, Vienna)
Theory: T. Kitagawa, E. Demler (Harvard)
I. Mazets (VCQ, Vienna)

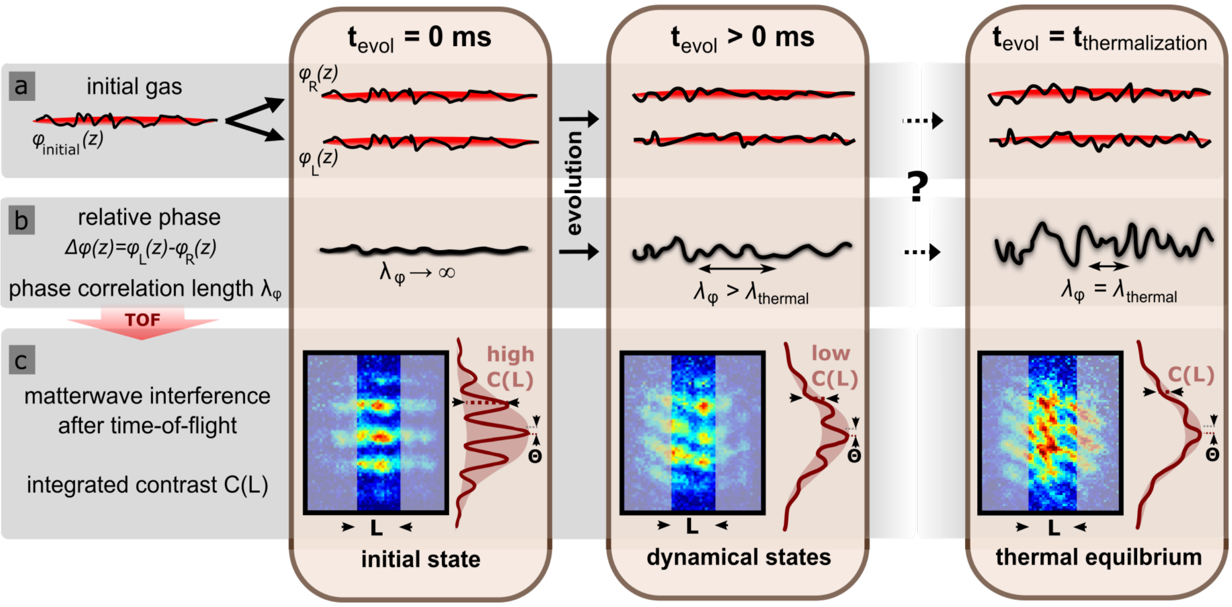
www.AtomChip.org

TU WIEN

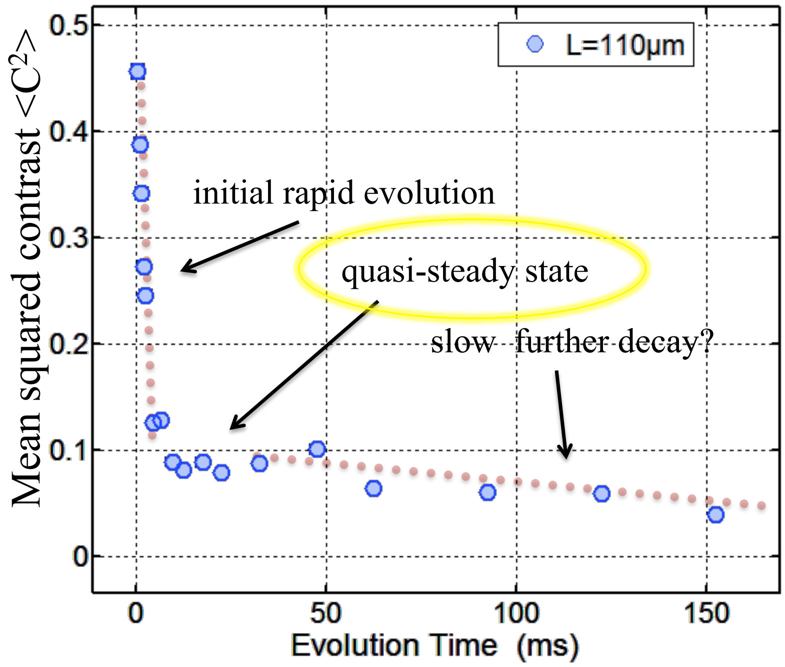
Experimental Procedure

VCQ Vienna Center for Quantum Science and Technology

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



Decay of the mean contrast



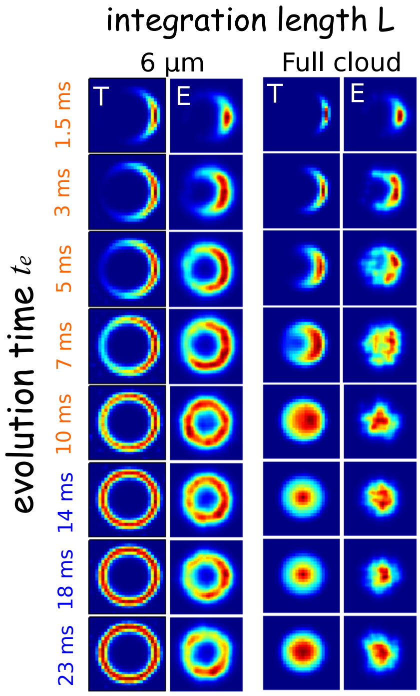
Experimental observation
two regimes

theory: Kitagawa et al., PRL **104**, 255302 (2010); NJP **13** 073018 (2011)
exp: Kuhnert et al., PRL **110**, 090405 (2013)

Initially reduced phase spread shows coherence of the splitting. Over time, two regimes emerge:

- **long length scale:**
  significant occupation of phonon modes with λ<L leads to random phaseswith in L and to loss of contrast on the same timescale as the phase diffuses
  contrast decay regime (spin decay)

- **short length scale:**
  only significant occupation of phonon modes with λ>L -> only phase diffusion
  phase diffusion regime (spin diffusion)



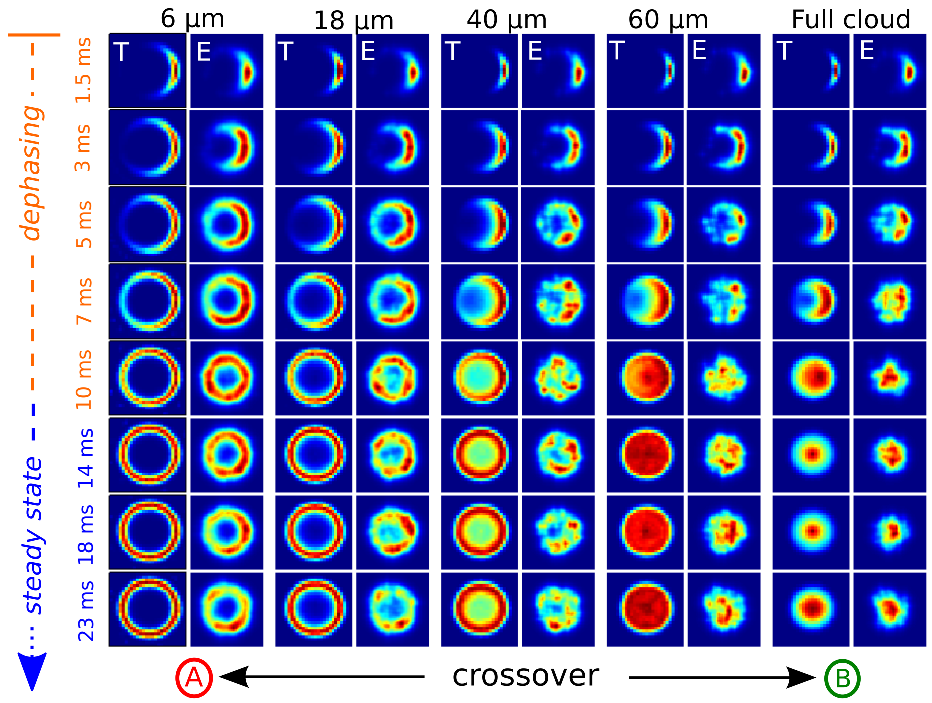
Theory description: Luttinger-liquid

- Excitations are soundwaves (phonons)
- dynamics described through the dephasing of the phonons
  does not describe a thermalisation process

FDF of Phase and Contrast
comparison to theory

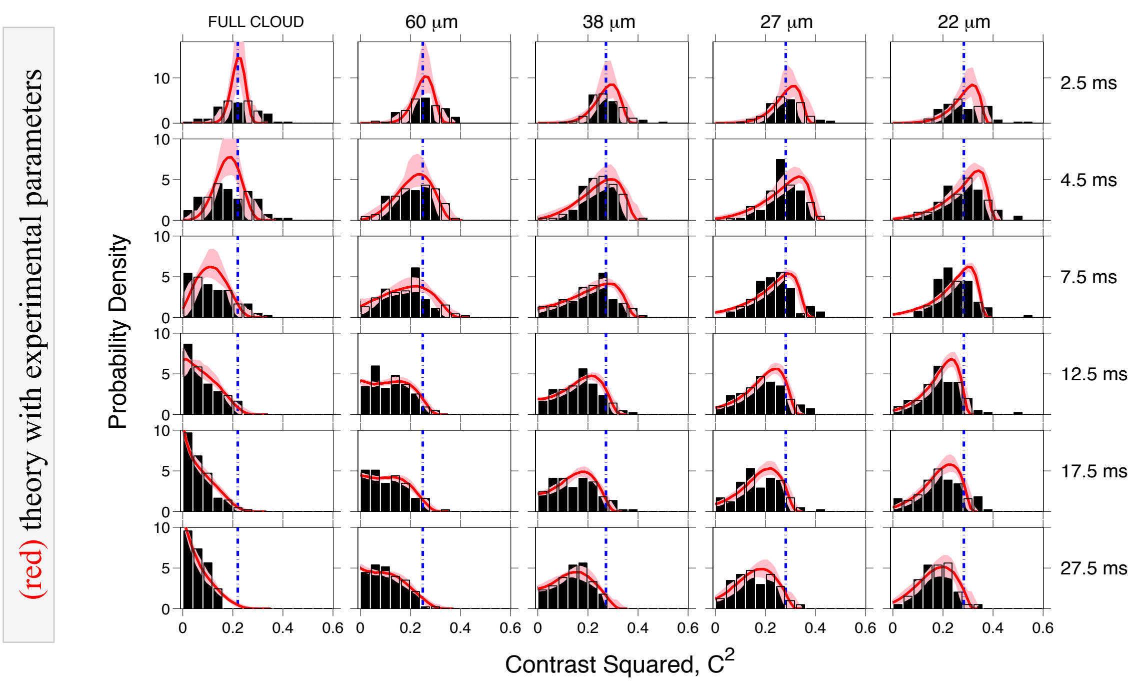
theory: Kitagawa et al.

Kuhnert et al., PRL **110**, 090405 (2013)



FDF of (Contrast)^2

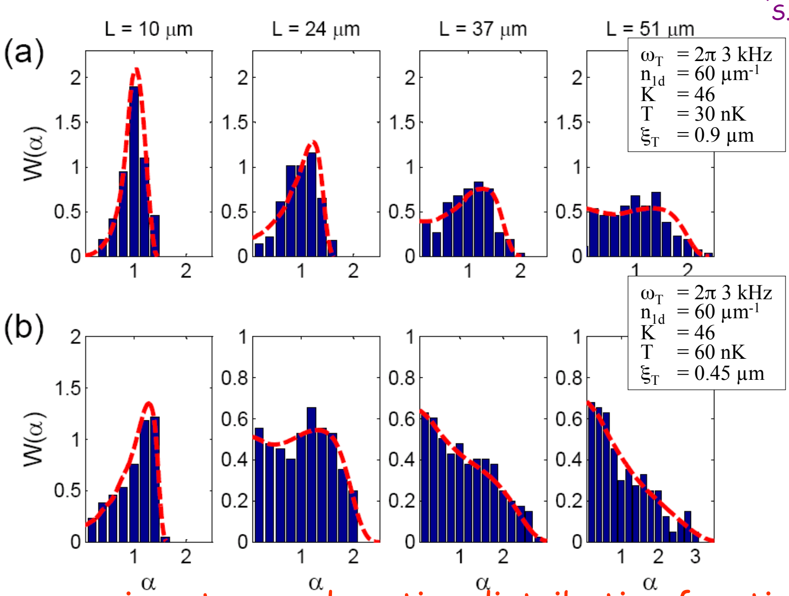
Gring et al., Science **337**, 1318 (2012)



full contrast statistics
experiment

experimentally measured distribution functions for the average contrast:

Theory:
A. Polkovnikov, et al., PNAS **103**, 6125 (2006).
V. Gritsev, et al., Nature Phys. **2**, 705 (2006).
Experiment:
S. Hofferberth et al Nature Phys. **4**, 489 (2008)



quantum coherence:
asymetric Gumbel distribution
(low temp. T or short length L)

thermal fluctuations:
broad Poissonians distribution
(high temp T or long length L)

intermediate regime:
double-peak strukture

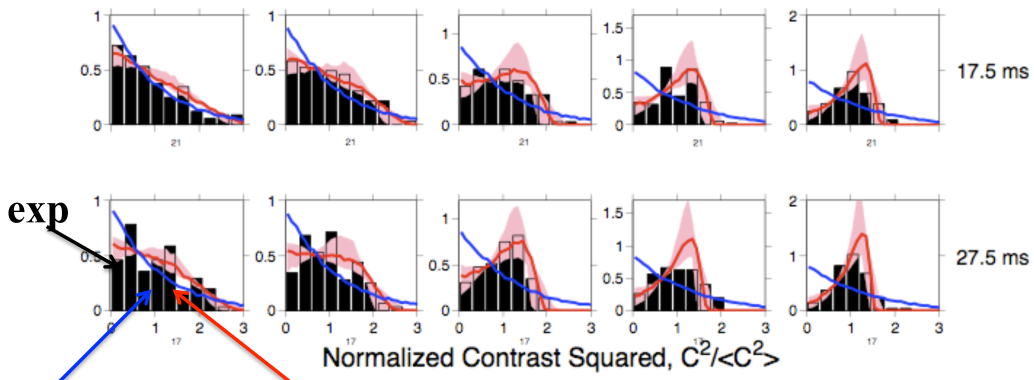
No free parameters!

experiment records entire distribution function of interference contrast
→ high order correlations can be derived

Steady state
thermal like

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

Measure effective temperature by comparing to equilibrium distributions:



T_{kin}~ 100nK T_{eff}=12 ± 3 nK $L_{th}(T_{eff})$ = 12 ± 4 μm ~ L_0

Effective temperature is ~ 8 times colder than the initial kinetic temperature!

Theory for equilibrium :
A. Polkovnikov, et al., PNAS **103**, 6125 (2006).
V. Gritsev, et al., Nature Phys. **2**, 705 (2006).
Experiment for equilibrium:
S. Hofferberth et al Nature Phys. **4**, 489 (2008)

Interpretation

theory: Kitagawa et al., PRL **104**, 255302 (2010); NJP **13** 073018 (2011)

Gring et al., Science **337**, 1318 (2012)
Kuhnert et al., PRL **110**, 090405 (2013)
Smith et al., NJP **15**, 075011 (2013)

- Our 1d many body quantum system is close to an integrable system (perfect 1d system)
- Fast evolution is the de-phasing of the phonon modes of the initial state of the split 1d system ('relaxation' in an integrable system)
- (quasi) steady state is the quantum state the integrable system relaxes to. It can be described by a generalized Gibbs ensemble
  - Quasi steady state is determined by the conserved quantities in the 1d Luttinger liquid model (phonon occupation numbers)
  - The fast splitting process leads to equipartition of energy in the (antisymmetric) modes ⇒ thermal like state
  - Prediction: effective temperature for the quasi steady state given by the quantum shot noise introduced by the splitting process

$$k_B T_{\text{eff}} = g\rho/2\,,$$

- Expect: - Revivals by re-phasing of the phonons
  - Over long times the quasi steady state should slowly decay
- Example of a Pre-thermalized state (Berges 2004)

Scaling of T_{eff}

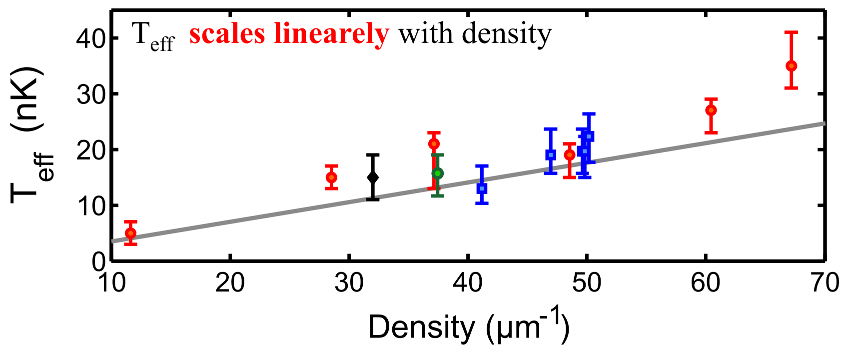
theory: Kitagawa et al., PRL **104**, 255302 (2010); NJP **13** 073018 (2011)

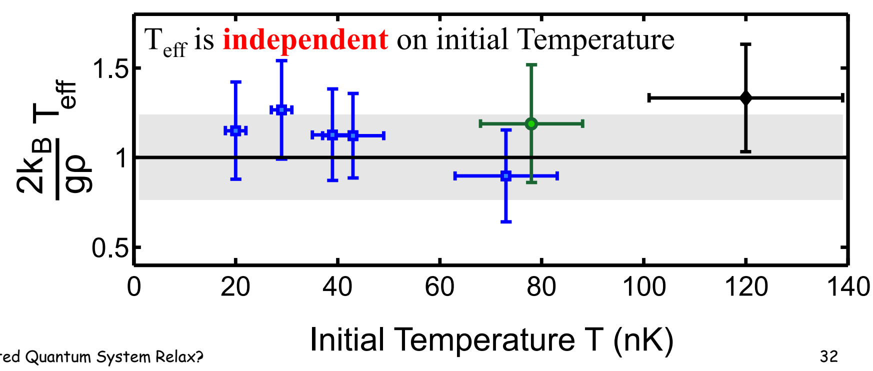
Gring et al., Science **337**, 1318 (2012)

Luttinger liquid prediction

$$k_B T_{\text{eff}} = g\rho/2\,,$$

effective temperature for the quasi steady state given by the quantum shot noise introduced by the splitting process



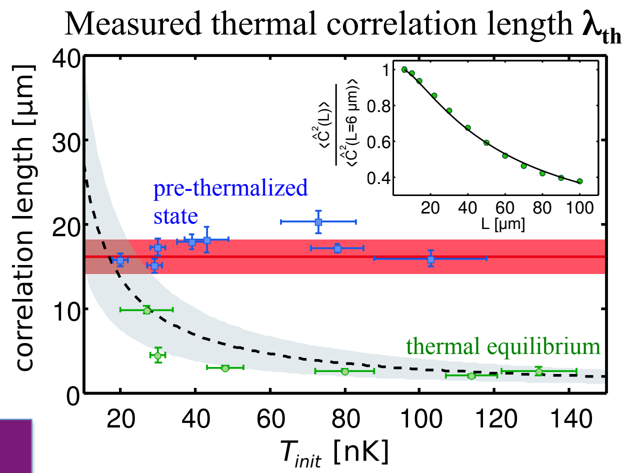


Pre-Thermalization
Effective length scale

Kuhnert et al., PRL **110**, 090405 (2013)
theory: Kitagawa et al., PRL **104**, 255302 (2010);
NJP **13** 073018 (2011)

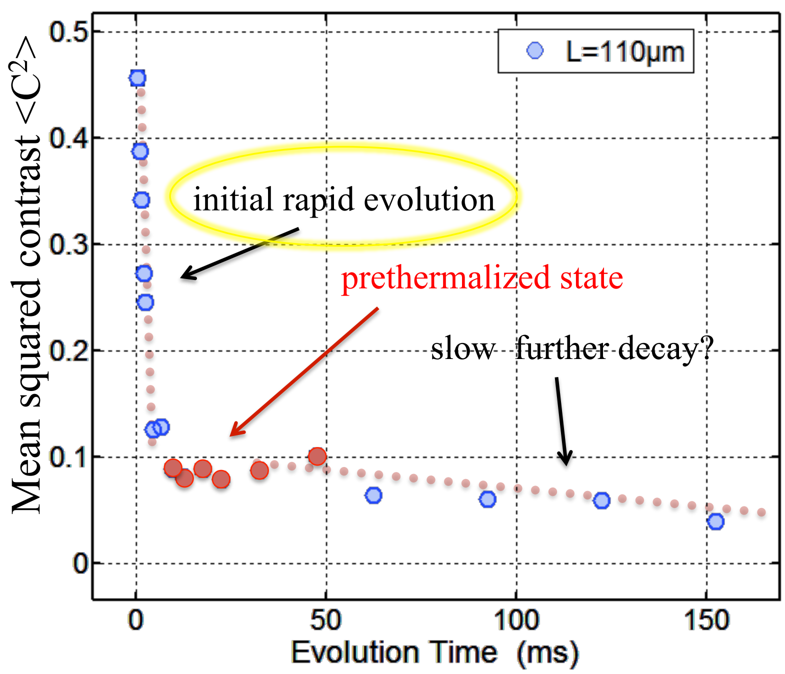
Theory introduces a new characteristic "thermal-like" length scale L_0:

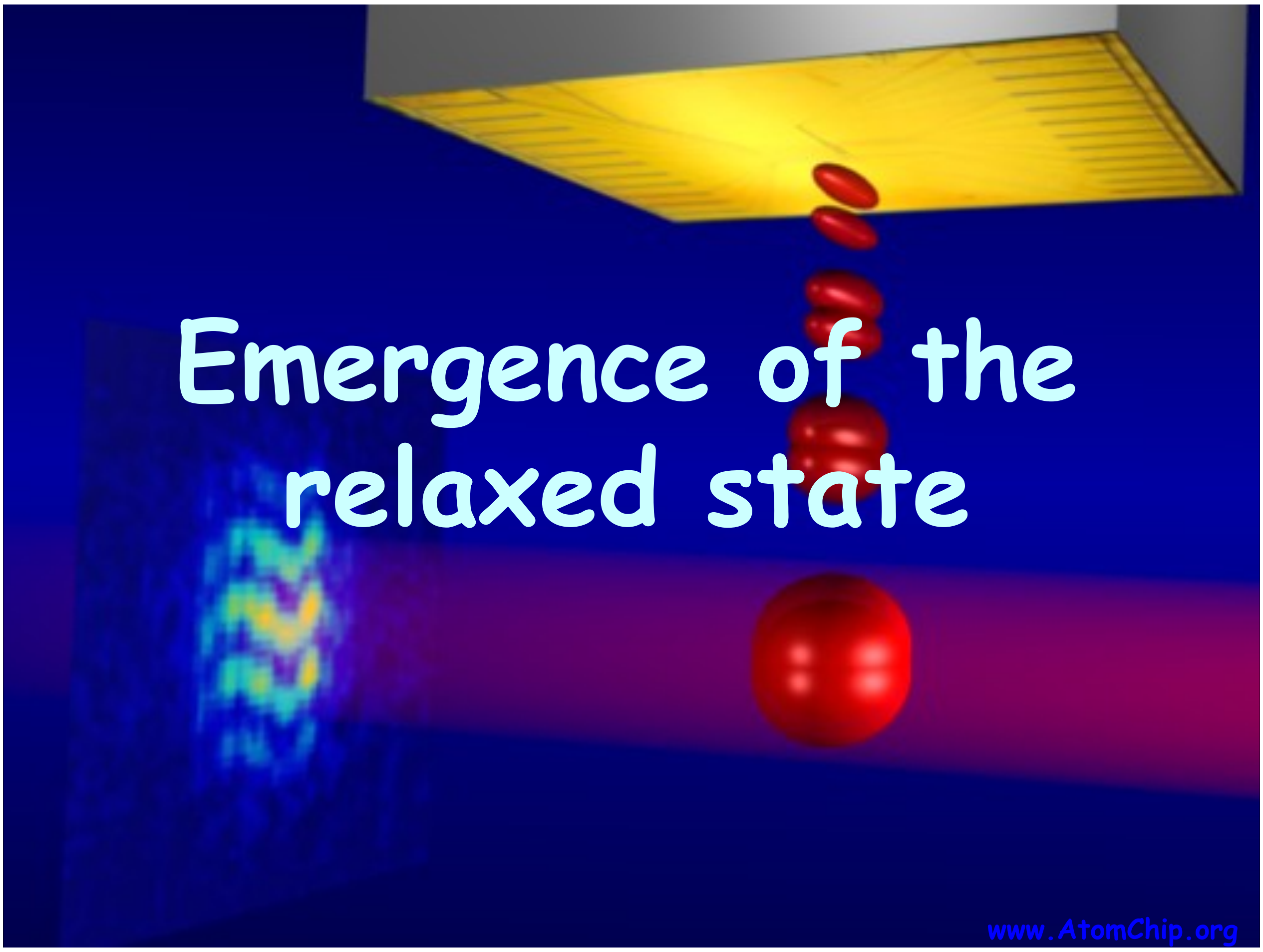
- Transition between decay and diffusion regime occurs around integration length $L_0 = 8K^2/\pi^2 n_{1d}$
- This is much longer than the thermal coherence length:



Theory:	$L_0 = 15.8 \pm 0.9$ µm
Measured:	$\lambda_{th}(T_{eff}) = 16.9 \pm 0.9$ µm ~ L_0
Initial T :	$\lambda_{th} \sim 1/T = 1.5 \rightarrow 10$ µm

Decay of the mean contrast

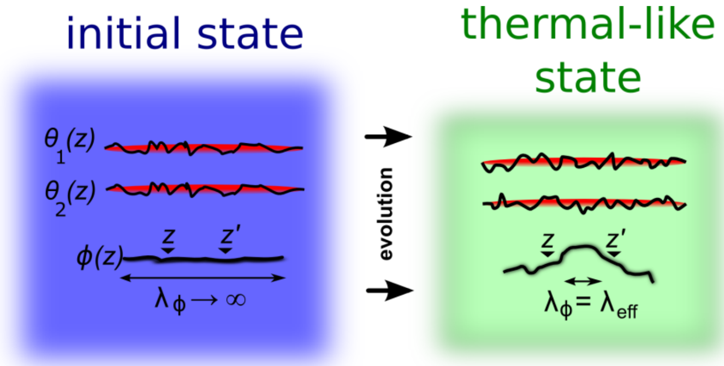




Local observation of relaxation

T. Langen et al NatPhys **9**, 460 (2013)

How does the system acquire thermal-like properties?

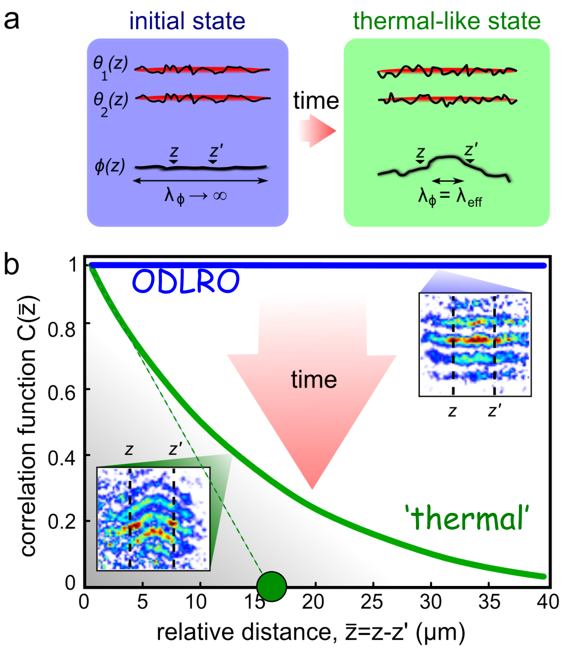


(prethermalized)

Linear disperison relation of the phonons relates this to the questions asked by:
Calabrese, P. & Cardy, J. Phys. Rev. Lett. **96**, 011368 (2006)

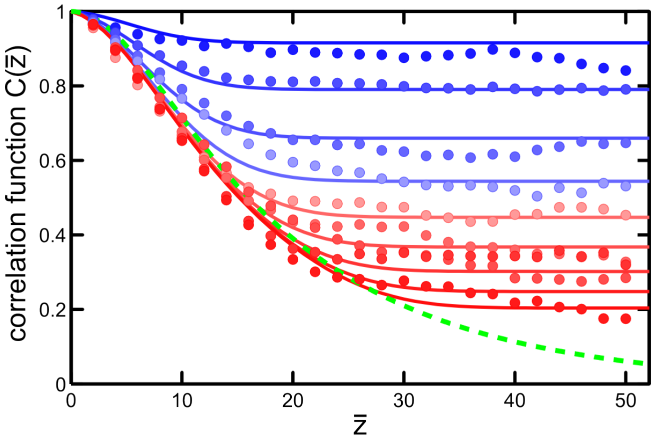
Decay of coherence

T. Langen et al NatPhys **9**, 460 (2013)



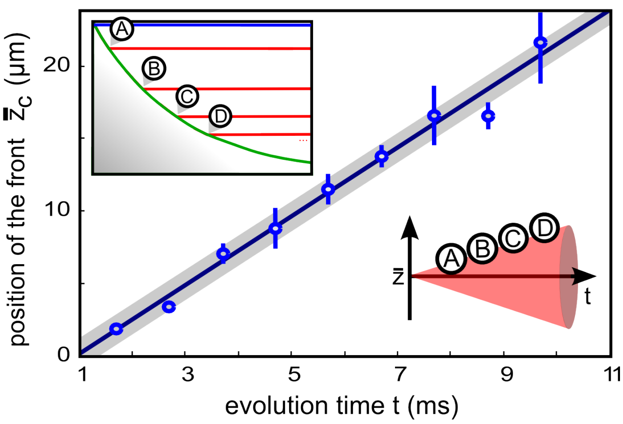
Time evolution of the phase correlation function

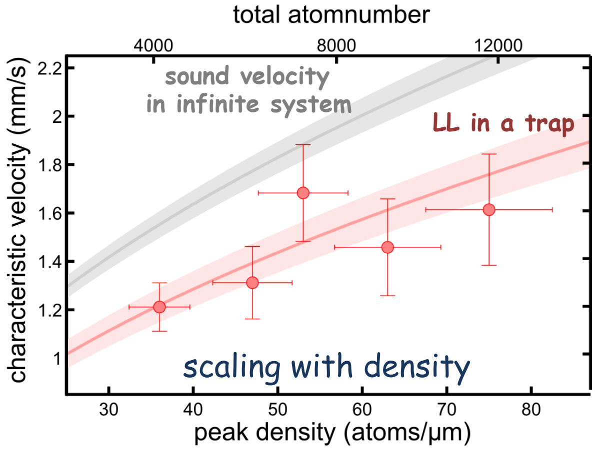
$$C(\bar{z} = z - z') = \left\langle e^{i(\varphi(z)-\varphi(z'))} \right\rangle$$



Light-Cone dynamics in the decay of coherence

T. Langen et al NatPhys **9**, 460 (2013)
LL theory in trap: R. Geiger et al. arXiv:1312.7568





Linear dispersion relation -> Light-Cone dynamics

The region with the final form of the phase correlation function expands with **sound velocity**

Linear disperison relation of the phonons relates to the questions asked in:

CFT: Calabrese, P. & Cardy, J. Phys. Rev. Lett. **96**, 011368 (2006)

Lattice model: Cramer, M., et al. Phys. Rev. Lett. **100**, 030602 (2008).

Emergence of Light-Cone

Phase correlation function:

R. Geiger et al. NJP **16** 053034 (2014)
arXiv:1312.7568

$$C(z,z',t) = \exp(-\tfrac{1}{2}\langle\Delta\phi_{zz'}(t)^2\rangle)$$

Initially the spitting process creates excitations (phonons with $\omega_k = c_0 k$) in the density quadrature. (density fluctuations from the beam splitter)

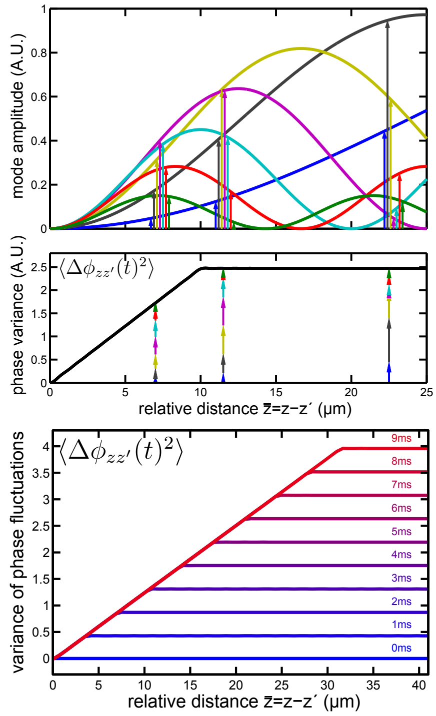
With time the density quadrature of the phonons oscillate into the phase quadrature (with ω_k)

Equipartition created by a fast splitting results in a $1/k$ population of the modes

Time evolution of the phase variance:

$$\langle\Delta\phi_{zz'}(t)^2\rangle = \frac{2\pi^2}{LK^2}\sum_{k\neq 0}\frac{\sin(\omega_k t)^2}{k^2}(1-\cos(k\bar{z}))$$

Fourier decomposition of a ramp with a flat plateau starting at $z=c_0 t$

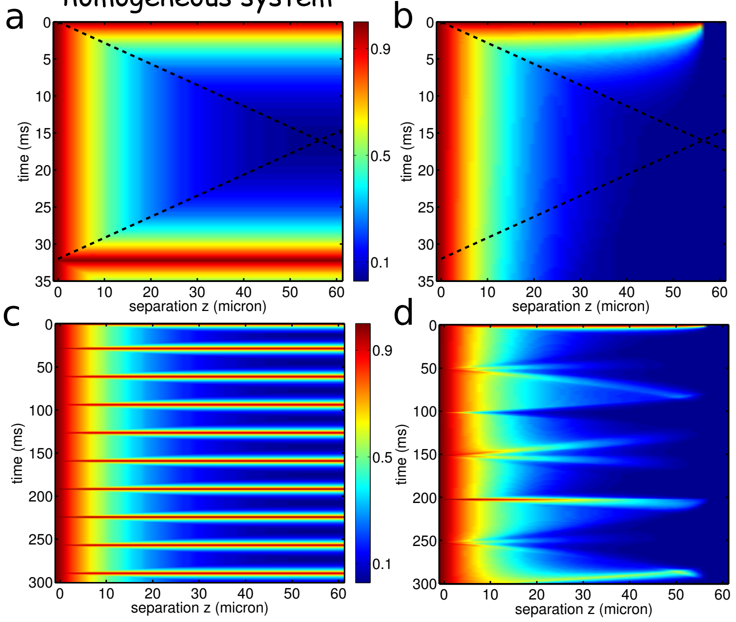


Revivals of Quantum Interferences

R. Geiger et al. NJP **16** 053034 (2014)
arXiv:1312.7568

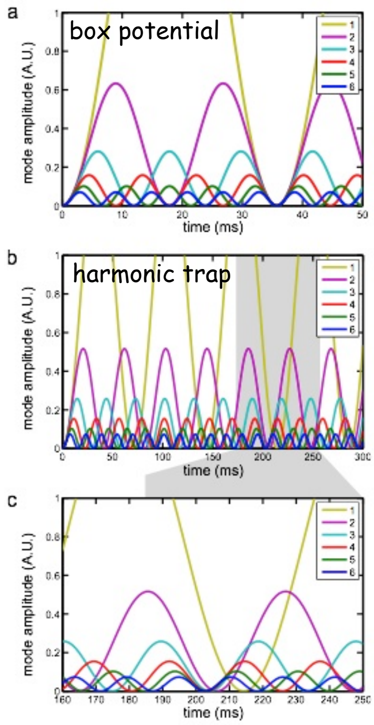
Box potential
homogeneous system

harmonic trap

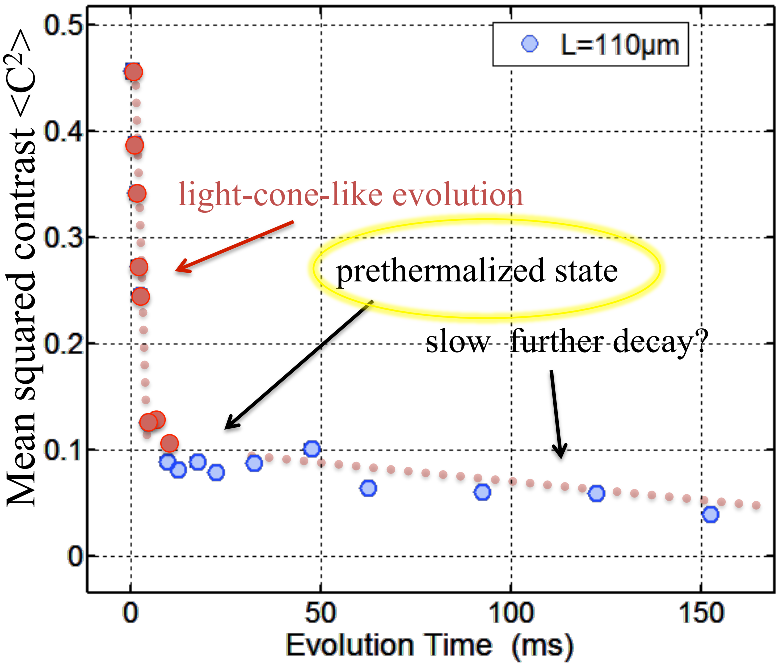


clear revivals with an 'inverse light cone'

complicated dynamics due to unequal spacing of phonon frequencies



Decay of the mean contrast



The generalized Gibbs ensemble

1D Bose gas is a (nearly) integrable system

→ many conserved quantities inhibit thermalization

Conjecture:
Quantum system to **relax to maximum entropy state** decribed by a generalized Gibbs ensemble:

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

partition function

Lagrange multiplier $\lambda_m \rightarrow \beta_m = 1/k_B T_m$

conserved quantities: mode occupations

striking feature: a temperature for every mode!

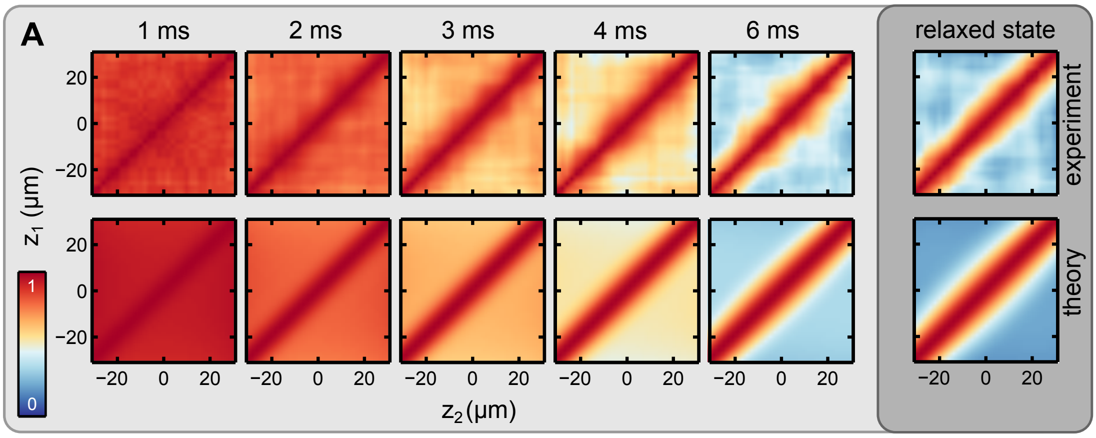
2d phase correlation function for 'Light Cone'

T. Langen et al. (2014)

Choose different starting points to evaluate the phase correlation function $C(z_1, z_2)$ $C(z_1,z_2) = \left\langle e^{i(\varphi(z_1)-\varphi(z_2))} \right\rangle$

Observation: the decay of phase correlation function is independent on starting point z_1

Data is described by a model with a single temperatures for ponon modes in the *anti symmetric* state.



Generalized Gibbs Ensemble

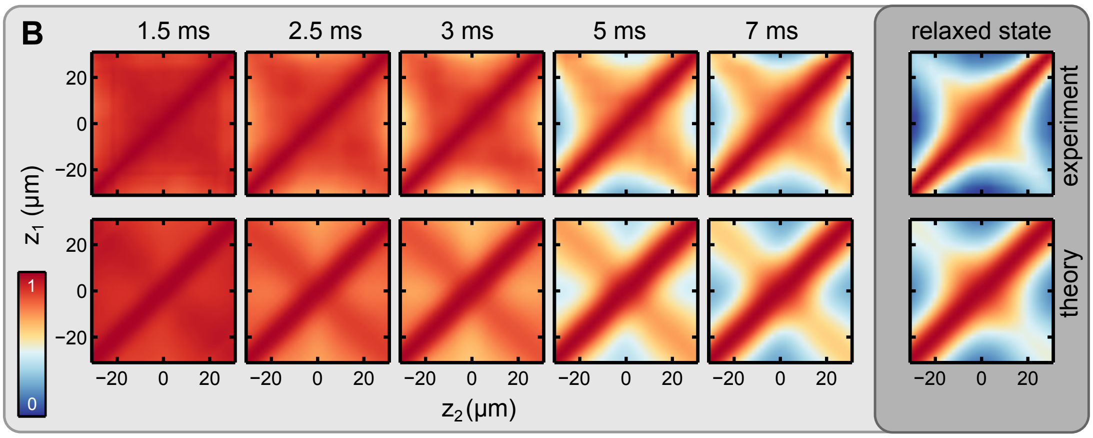
T. Langen et al. (2014)

Choose different starting points to evaluate the phase correlation function $C(z_1, z_2)$

$$C(z_1,z_2)=\left\langle e^{i(\varphi(z_1)-\varphi(z_2))}\right\rangle$$

Observation: For specific splitting procedures (=initial conditions) the decay of phase correlation function depends on starting point z_1 and shows ‚revivals' of coherence

Data is described by a model with different temperatures for *even* phonon modes and *odd* phonon modes in the *anti symmetric* state.

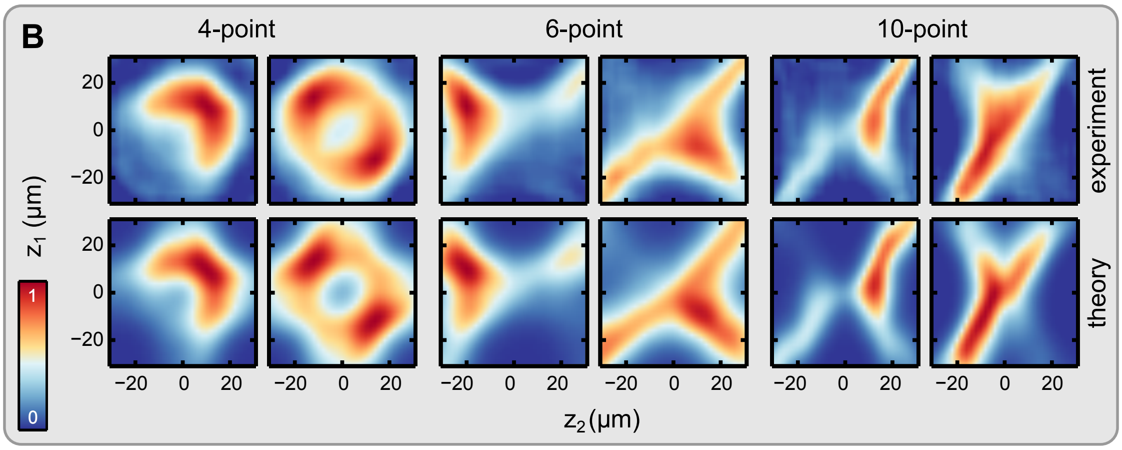


need at least 3 temperatures

Higher order phase correlation functions

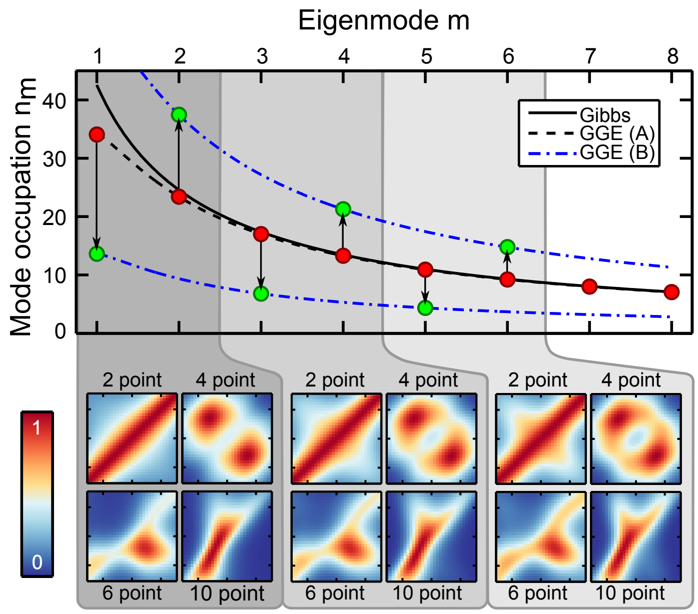
Evaluation of higher order correlation functions

Data is well described by GGE

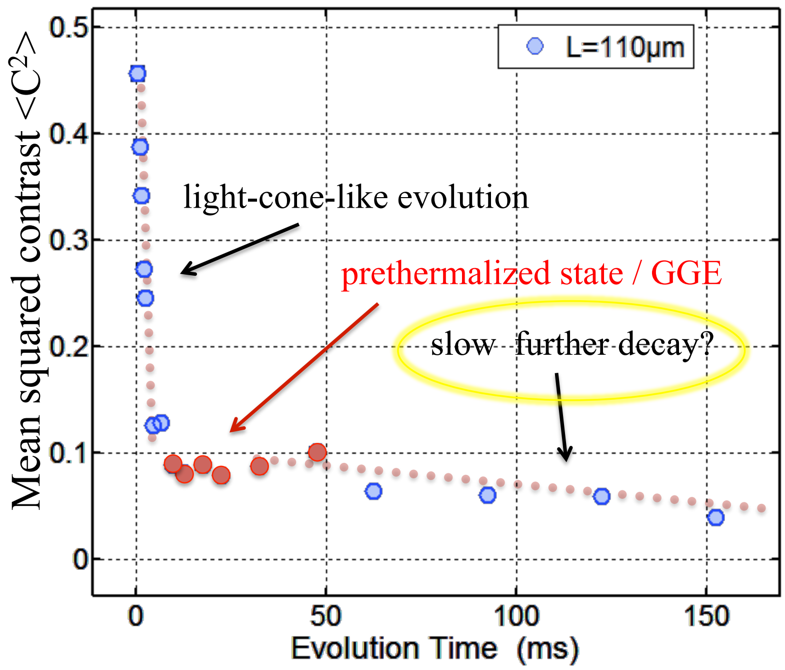


Higher order phase correlation functions

Which modes contribute to GGE



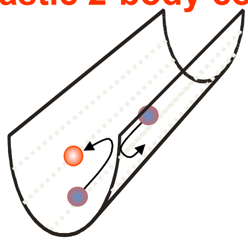
Decay of the mean contrast



Possible sources of thermalization in 1d systems

Elastic 2-body collisions

…can only contribute to thermalization if they lead to **transverse excitations** in the final state



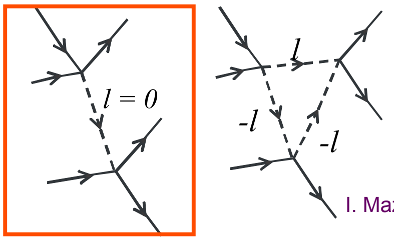
$$\Gamma_{2b} \approx \sqrt{8}\omega_\perp \, \zeta \, e^{-\frac{2\hbar\omega_\perp}{k_B T}}$$

$$\zeta = \frac{n_{1D} a_0^2}{a_\perp}$$

drops exponentially for $k_B T < \hbar\omega_\perp$

Experiment: $\Gamma_{2b} \approx 0.02\, s^{-1}$

Effective 3-body collisions via virtual excited states



effective 3-body colissions lead to **thermalization**

$\Gamma_{3b} \approx C_{3b}\, \omega_\perp \, \zeta^2$ $\quad C_{3b} \approx 5.57$ independent of temp.

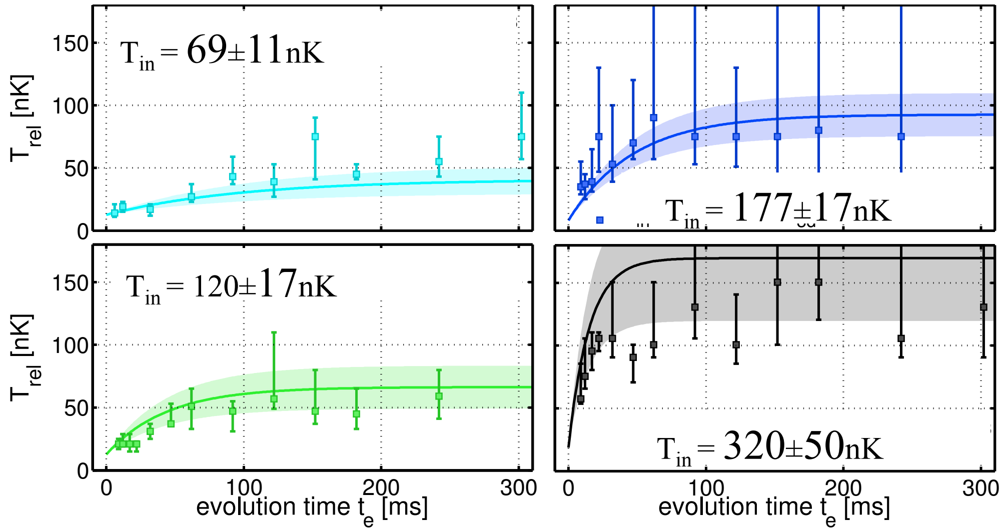
I. Mazets et al. PRL **100**, 210403 (2008), PRA **79**, 061603 (2009), NJP **12**, 055023 (2010)
see also: Shina Tan et al. PRL **105**, 090404 (2010)

Phonon – Phonon scattering

Linear dispersion relation prevents thermalizing phonon phonon scattering in LL.
Andreev: Assume k-state with finite width and determine width self-consistently:
-> $\Gamma_k \sim k^{3/2}$

A.F. Andreev, Sov. Phys. JETP **51**, 1038 (1980)

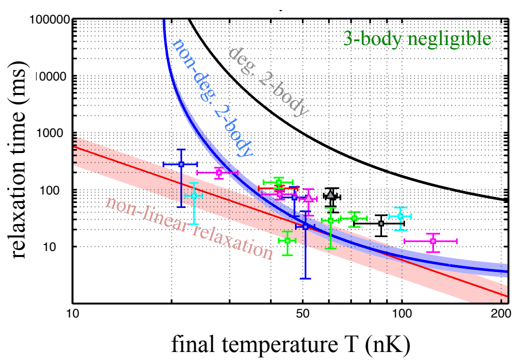
Time evolution of the relative phase

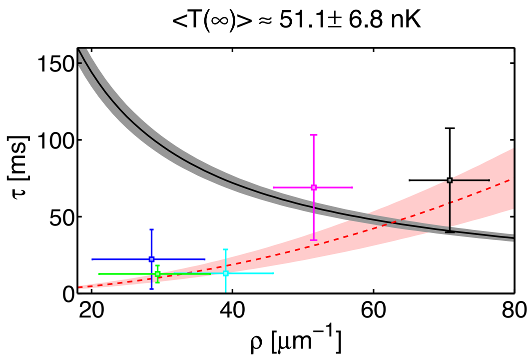


System reaches final steady state!

Relaxation rate

M. Kuhnert et al., in preparation
Theory by I. Mazets





Phonon-phonon scattering:

Assume that each k-state has its finite width and determine this width self-consistently:

$$\Gamma_k \sim k^{3/2}$$

Relaxation of 1D Bose gas:

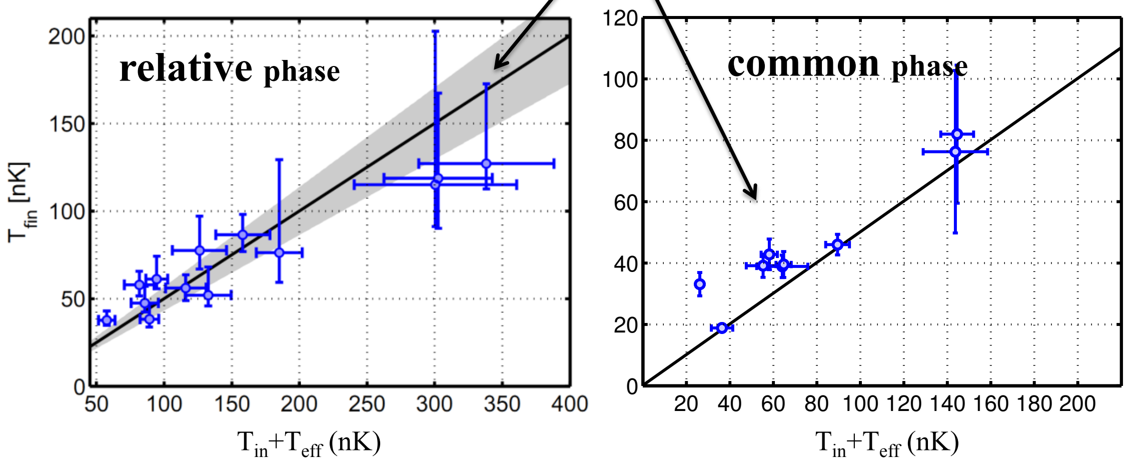
1) Dephasing of excitations
2) Damping of excitations from effective phonon-phonon scattering

I. E. Mazets, PRA 83, 023618 (2011)
A.F. Andreev, Sov. Phys. JETP 51, 1038 (1980)

Steady state

long time limit $T_{fin} = (T_{com,in} + T_{rel,in})/2$

M. Kuhnert et al., in preparation
Theory by I. Mazets

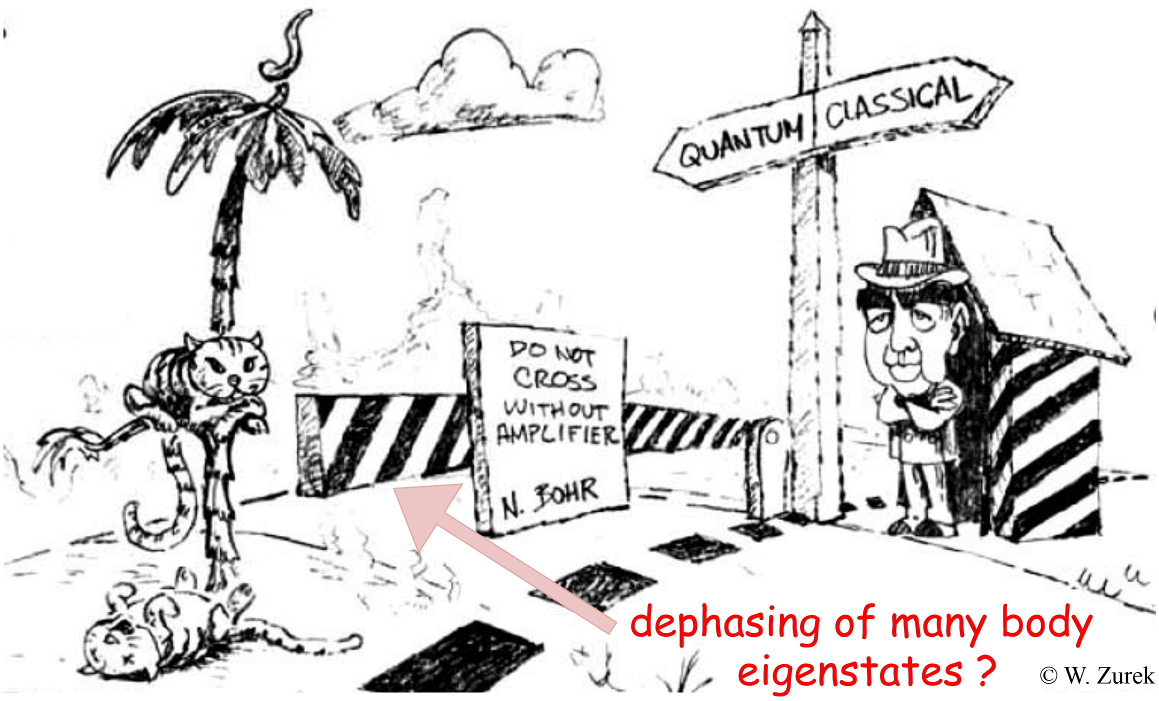


Relaxation of 1D Bose gas:

1) Dephasing of excitations -> Prethermalized State
2) Damping of excitations from effective phonon-phonon scattering

After relaxation the system looks like **two separaely created 1d quantum gases**

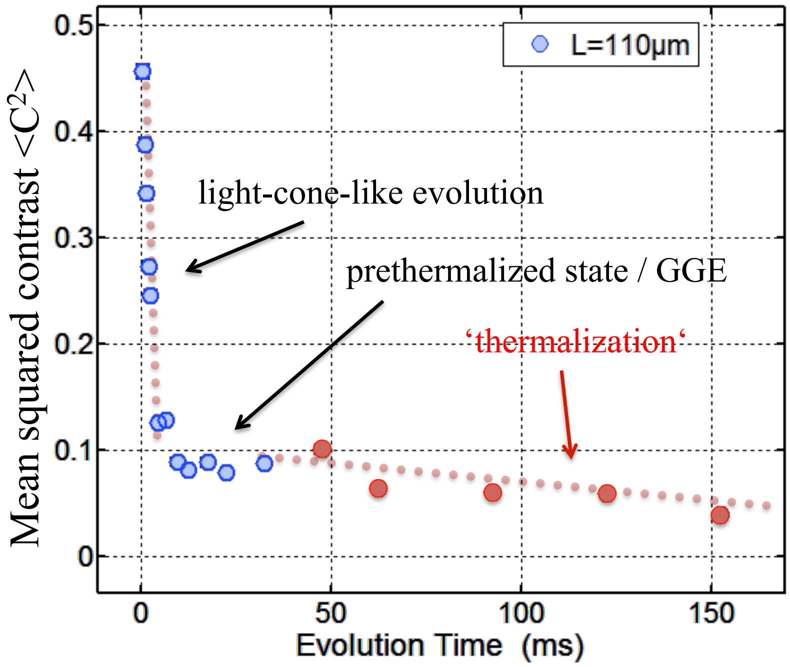
Emergence of classical world from quantum evolution

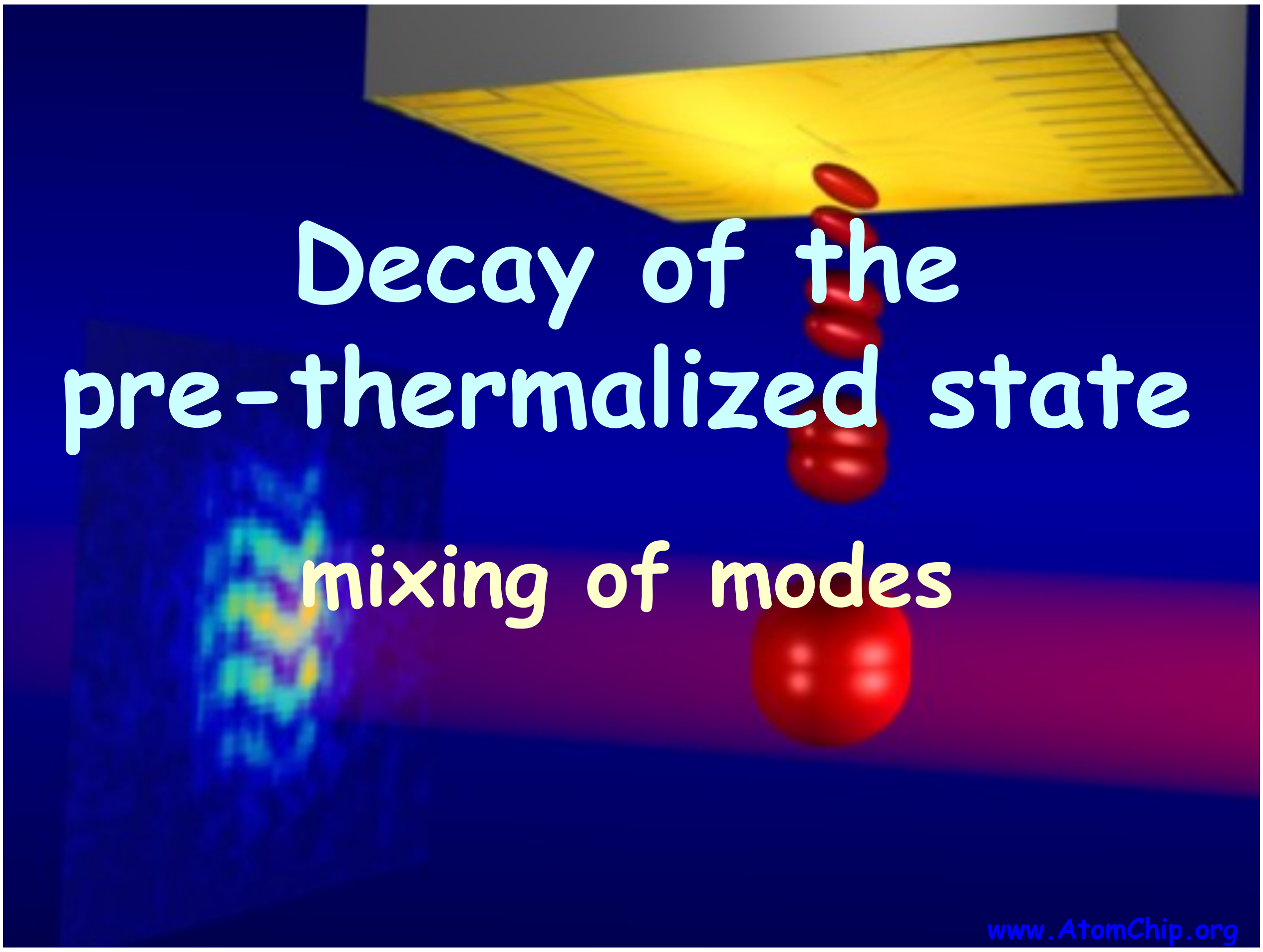


dephasing of many body eigenstates ?

© W. Zurek

Decay of the mean contrast

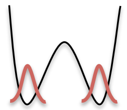




Imbalanced double well

T. Langen preliminary

Balanced double well

H_L  H_R

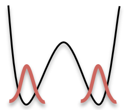
$\phi_L(z),\ n_L(z)$ $\phi_R(z),\ n_R(z)$

H_+ *common phase* $\phi = [\phi_L(z) + \phi_R(z)]/2$

H_- *relative phase* $\Delta\phi = \phi_L(z) - \phi_R(z)$

Phonon modes are '*identical*' in left and right mode ($n_L \approx n_R$)
Mixing between H_+ and H_- only though processes ***beyond*** the 1D model

Imbalanced double well

H_L  H_R

$\phi_L(z),\ n_L(z)$ $\phi_R(z),\ n_R(z)$

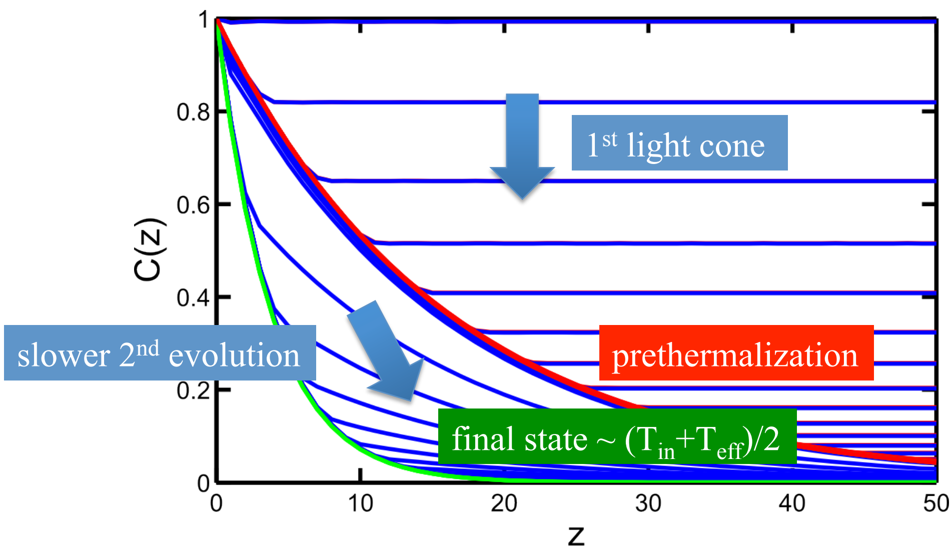
H_+ *common phase* $\phi = [\phi_L(z) + \phi_R(z)]/2$

H_- *relative phase* $\Delta\phi = \phi_L(z) - \phi_R(z)$

Phonon modes are different in left and right mode ($n_L \neq n_R$)
H_+ and H_- are *not* eigenmodes $\Rightarrow$ ***mixing though dephasing***
$H_{mix} \sim (n_1 - n_2)\ T$

Imbalanced double well
Evolution of phase correlations

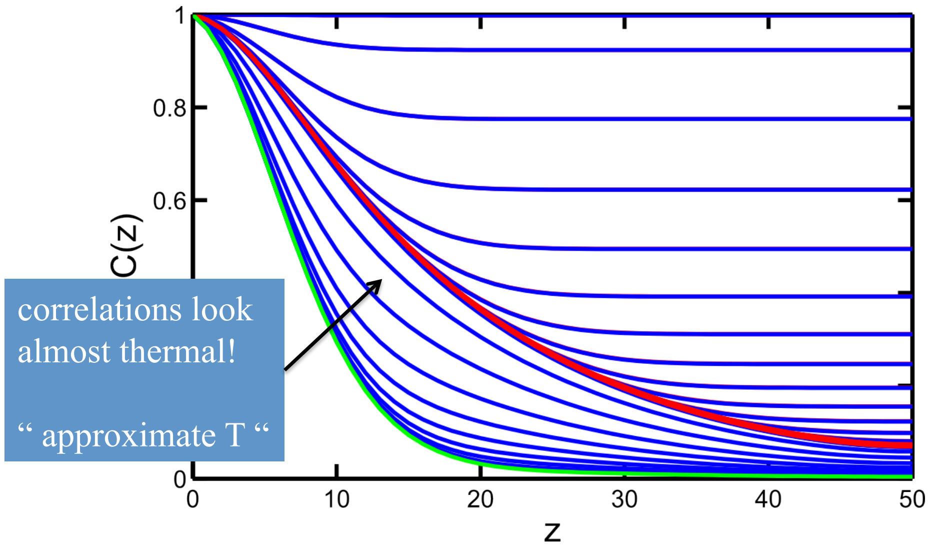
T. Langen preliminary



How can we probe this?

Phase correlations
with imaging resolution

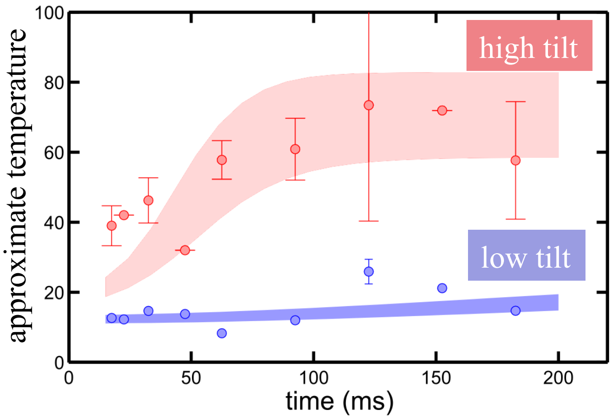
T. Langen preliminary



Optical resolution works in our favour!

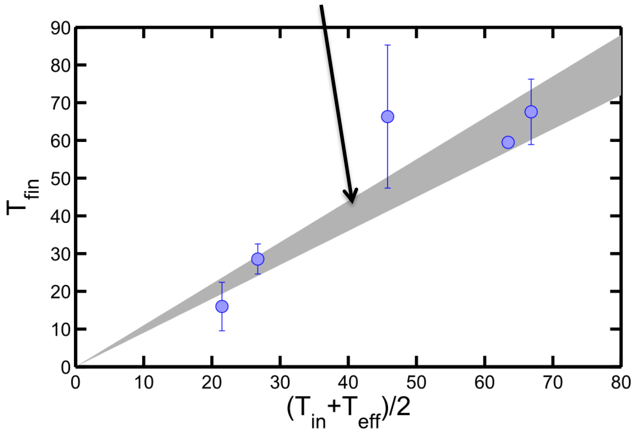
Apparent thermalization by dephasing

T. Langen preliminary



long time limit

$T_{fin} \approx (T_{in}+T_{eff})/2$



A non-equilibrium system approaches to appears thermal,
if one looks at an observable *not connected* to conserved quantities

Optimal Control of Splitting

fast squeezing in a multi mode system

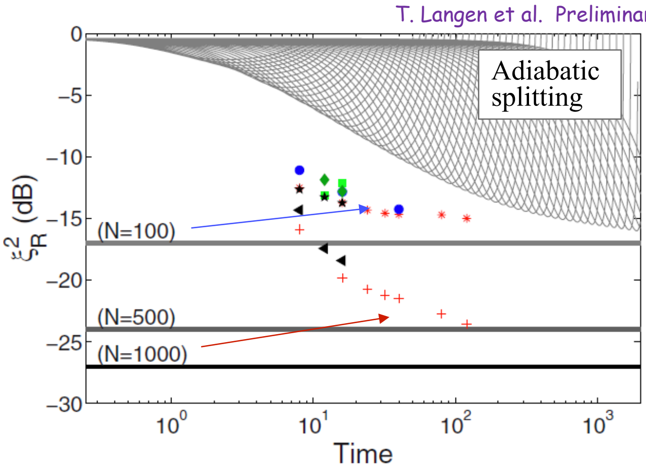
Vienna Center for Quantum Science and Technology

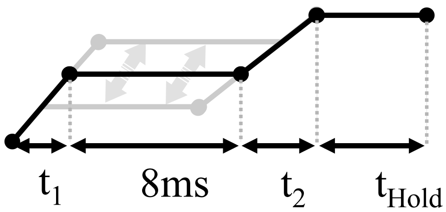
T. Langen et al. Preliminary

Optimal Controll applied to the problem of the fluctuation properties in splitting a BEC

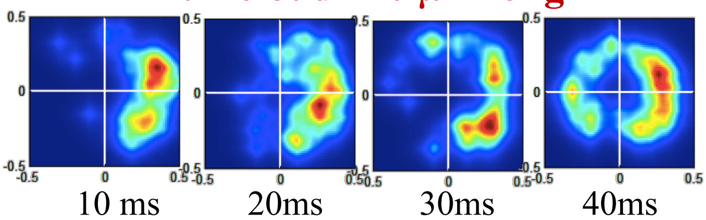
J. Grond et al. PRA **79**, 021603 R (2009)
J. Grond et al. PRA **80**, 053625 (2009)

- Fancy splitting ramps inspired by OCT: t_1+t_2 = 17ms
- Leads to dramatic change of statistical distribution of interference





full cloud 140 μm long



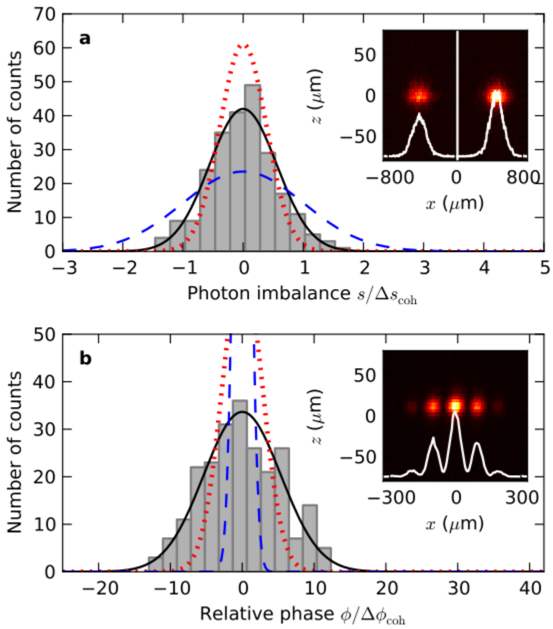
Squeezing

$N = 1200$ atoms, $\mu \simeq 0.5\,\mathrm{kHz}$, $T \simeq 25\,\mathrm{nK}$ (0.5 kHz)

T. Berrada, et al., Nat. Comm **4**, 2077 (2013)

number and phase distribution

(black: measured, blue: binomial, red: detection noise)



RMS fluctuations of the **number difference**

$$n \equiv N_L - N_R$$

$$\Delta n = 14(3) \text{ atoms}$$

Whereas $\sqrt{N} = 35$

Spin squeezing: $\xi_S^2 \equiv \dfrac{\xi_N^2}{\langle \cos\phi \rangle^2} = -7.7\,\mathrm{dB}$

Implies that ≈ 150 atoms are entangled!

RMS fluctuations of the **phase**

$$\Delta\phi = 0.168(8)\,\mathrm{rad}$$

Whereas $1/\sqrt{N} = 0.03$

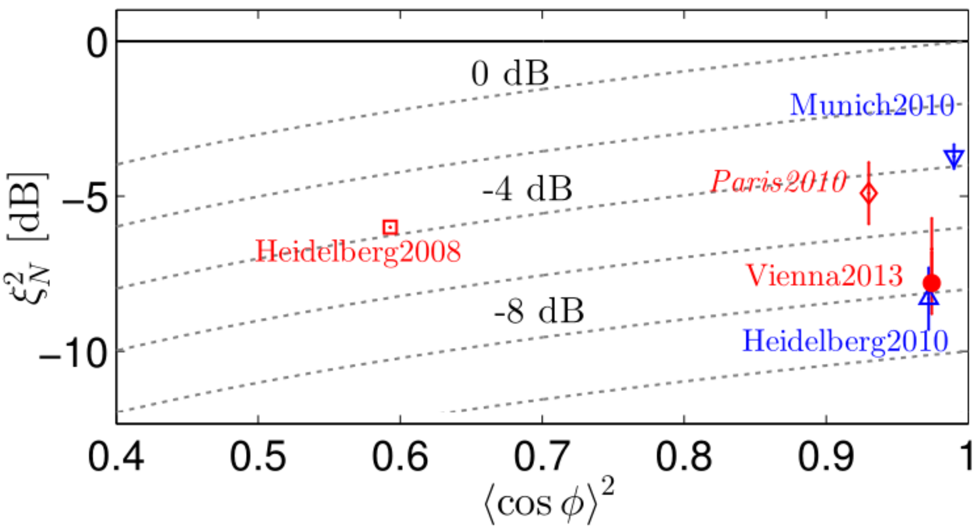
$$\Delta n\,\Delta\phi = 2.3(7)$$

Almost ground state

Squeezing

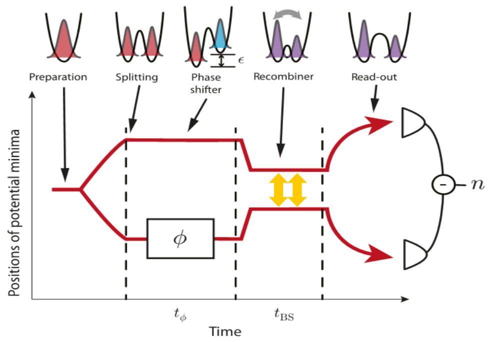
$N = 1200$ atoms, $\mu \simeq 0.5\,\mathrm{kHz}$, $T \simeq 25\,\mathrm{nK}$ (0.5 kHz)

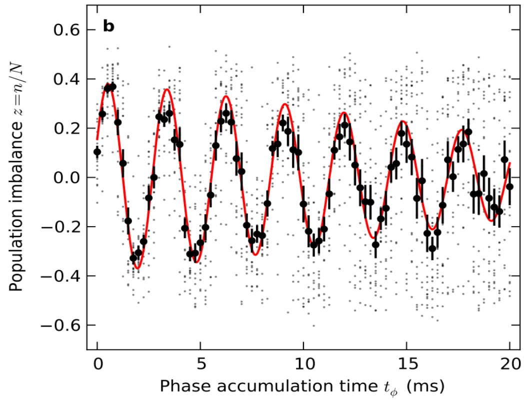
T. Berrada, et al., Nat. Comm **4**, 2077 (2013)



Interferometer
trapped 1d quantum gas

T. Berrada, et al., Nat. Comm **4**, 2077 (2013)





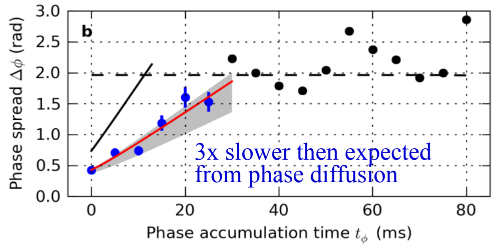
Phase diffusion

Castin & Dalibard, PRA 55, 4330 (1997)
Javanainen & Wilkens, PRL 78, 4675 (1997)

$$\Delta\phi^2 = \Delta\phi_0^2 + (R t_\phi)^2$$

$$\text{with} \quad R = \frac{\xi_N \sqrt{N}}{\hbar} \left. \frac{\partial \mu}{\partial \mathcal{N}} \right|_{\mathcal{N}=N/2}$$

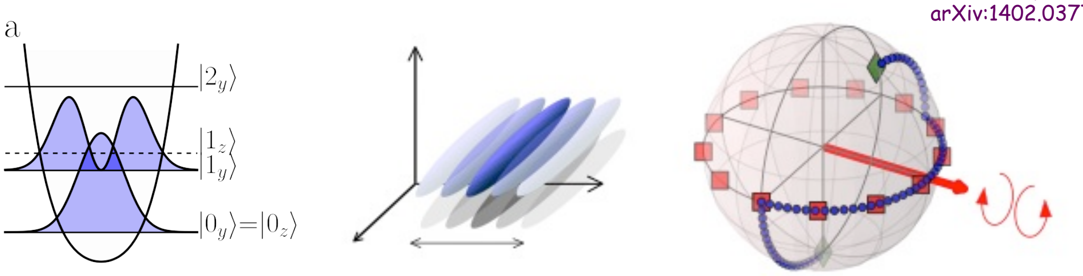
Number squeezing reduces phase diffusion



Interferometer signal stays with full contrast for t>80ms ! -> 1d dephasing is irrelevant
=> **emerging prethermalized lengthscale >> system size**

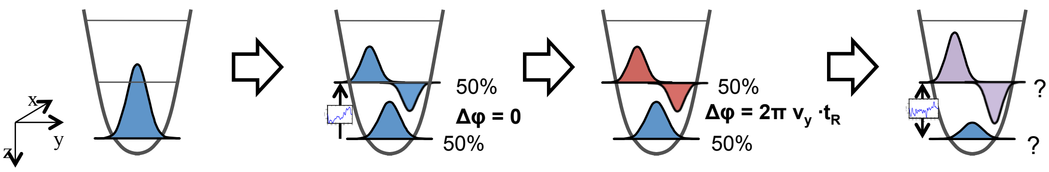
Ramsey interferometer trapped many body states

S. Van Frank NatureComm **5**, 4009 (2014)
arXiv:1402.0377



Together with T. Calarco, we developed an OCT sequence to build a Ramsey interferometer with trapped atoms, the two arms being internal motional states of the trap.

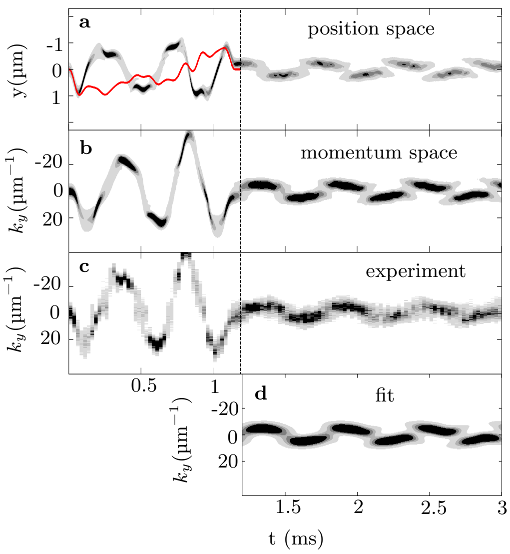
<u>Challenge</u>: design an OCT sequence that is a pi/2 pulse for any initial condition in an interferometer.



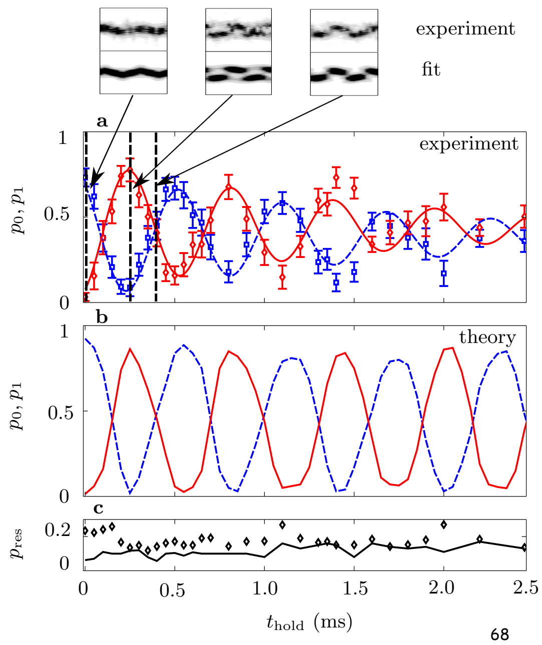
Ramsey interferometer trapped many body states

S. Van Frank NatureComm **5**, 4009 (2014)
arXiv:1402.0377

π/2 pulse

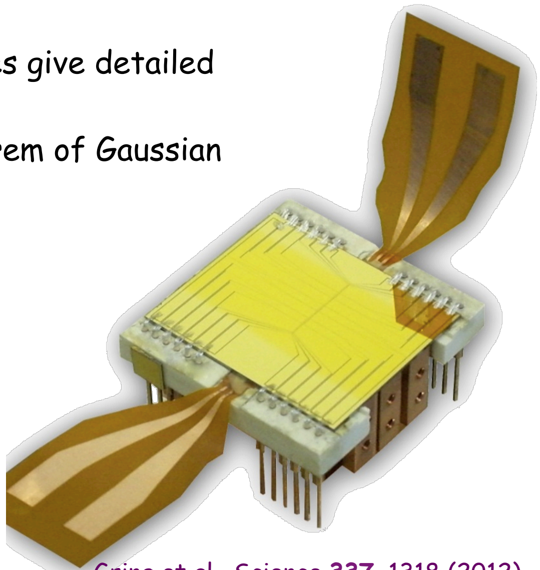


final interferometer sequence



What have we learned

- generalization of homodyne measurement: the full distribution functions of observables give detailed insight into (quantum) physics
- in ensemble averages the central limit theorem of Gaussian statistics hides the (quantum) physics
- Relaxation in quantum systems does not proceed through a simple path.
- establishment of a ‘prethermalized’ state Generalized Gibbs Ensemble
- Relaxed state emerges localy and spreads throughout the many body system in a light cone like fashion
- ‘prethermalized’ state decays by non trivial phonon-phonon processes
- Experiments allow to probe how classical statistical properties emerge from microscopic quantum evolution through dephasing of many body eigenstates.



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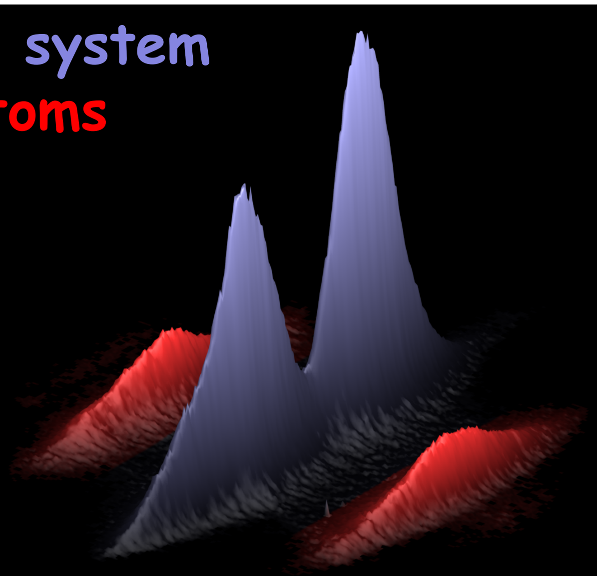
Kuhnert et al., PRL **110**, 090405 (2013)
Smith et al. NJP **15**, 075011 (2013)
Langen et al., Nature Physics **9**, 460 (2013)
R. Geiger et al. NJP **16** 053034 (2014)
T. Berrada, et al., Nat. Comm **4**, 2077 (2013)
S. Van Frank, et al., Nat. Comm **5**, 4009 (2014)

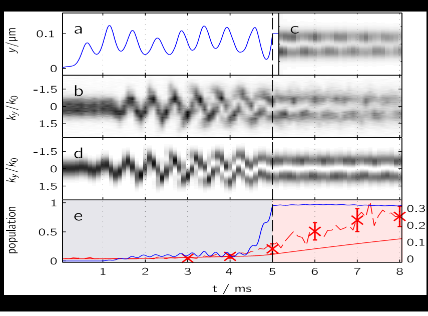
Decay of an excited 1d system
-> Single mode Twin Atoms

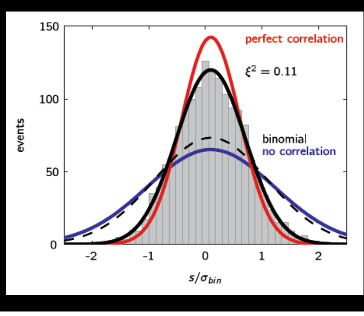
- Use OCT to create a BEC in transverse excited state
- Trap level design and Bose statistics ensures a single decay channel
- Collisions between atoms create pairs
- Sub shot noise atom number statistics better then 0.11 x shot noise
- dynamics of a matter wave OPO

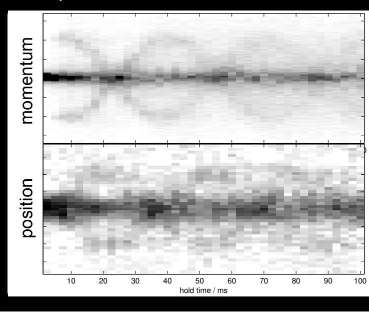
Outlook:
two-particle interference
CV entanglement



Bücker et al. Nature Physics **7**, 608 (2011)
Bücker et al. Phys. Rev. A **86**, 013638 (2012)

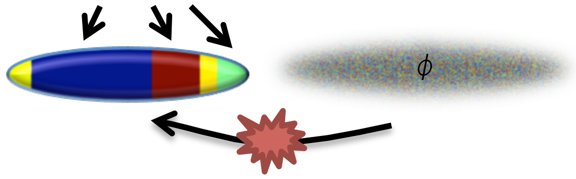


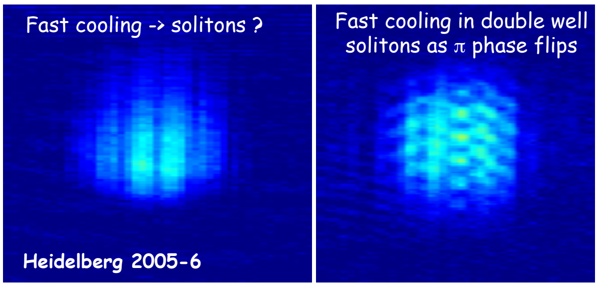




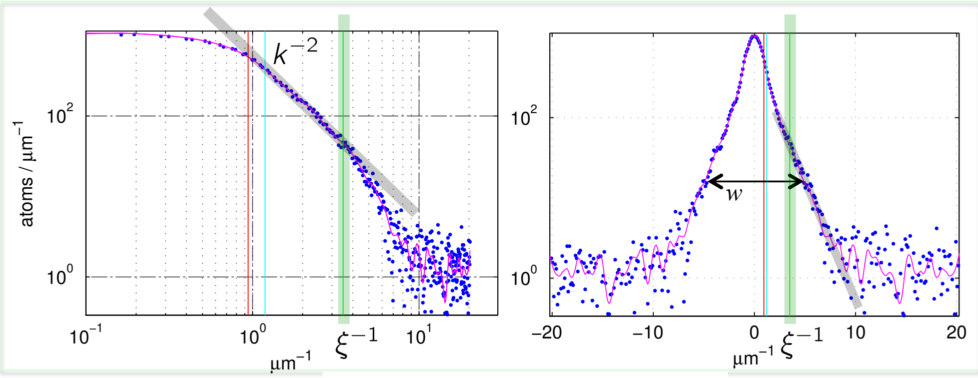
Non-equilibrium condensation in a 1d-Bose gas

collaboration with S.Erne, B.Nowak, T.Gasenzer





Expect: Power law k^{-2} for $k<\xi^{-1}$
and exponential drop-off beyond



momentum distribution (focused)

Atom Chip Experiment

S. Manz, T. Betz, R. Bücker, T. Berrada, S. vanFrank, M. Pigeur, A. Perrin, T Schumm, JF Schaff R. Wu , M. Bonneau

T. Langen, M. Kuhnert, M. Gring, B. Rauer, Th. Sch... D. Smith, Remi Geiger, T. Langen

Atom Chip Fabric...

D. Fischer, M. Trinker, M... S. Groth (HD), Israe...

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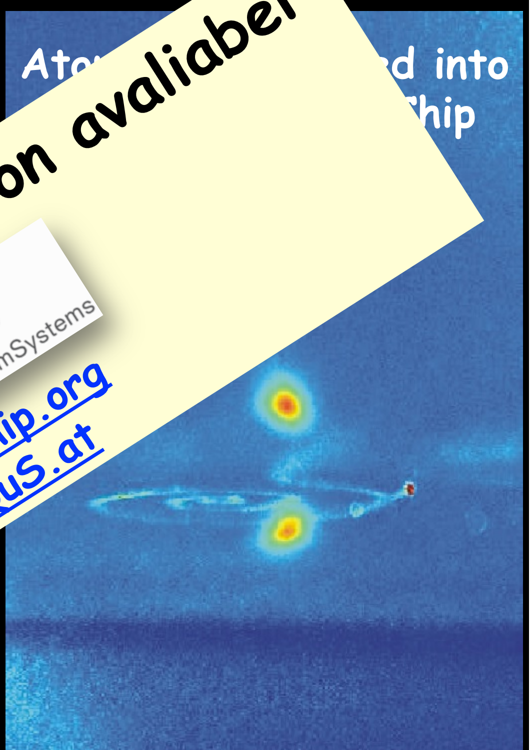

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