Lecture IV
Probing Quantum Physics in 1d

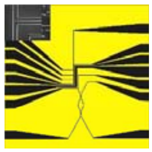
Regimes of 1d physics
Building 1d systems
Phase fluctuations
Dynamics of decoherence
Probing the noise by interference statistics
Integarbility in 1d quantum systems

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002 www.AtomChip.org

Physics in 1d

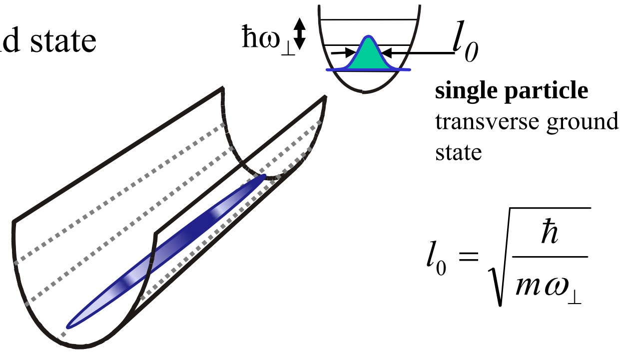
AtomChip Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002 www.AtomChip.org

Quantum degeneracy in one dimension



The world is 3D:

1D means: system is „frozen“ to the ground state in two spatial directions:



$$l_0 = \sqrt{\frac{\hbar}{m\omega_\perp}}$$

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

3D density of the wave function:

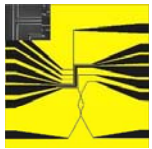
$$n_{3D}(r,z) = n(z) \cdot \frac{1}{\sqrt{\pi l_0^2}} e^{-\frac{r^2}{l_0^2}}$$

remember the Gross-Pitaevskii equation (now in 1D):

$$i\hbar \frac{d\psi}{dt} = \underbrace{-\frac{\hbar^2}{2m}\nabla^2\psi}_{\text{kinetic energy}} + V(z)\psi + \underbrace{g|\psi^2|\psi}_{\text{interaction energy}}$$

the interplay of **kinetic** energy and **interaction** energy determines the physics

Quantum degeneracy in one dimension



interaction energy: $I = ng$

kinetic energy: $K = \hbar^2 / \bar{r}^2 m \approx \hbar^2 n^2 / m$

We define $\gamma = \frac{I}{K} = \frac{mg}{\hbar^2 n}$

counter-intuitive: gas gets „more interacting“ for lower density! (in contrast to 2D and 3D gases)

γ<1: the „usual“ **weakly interacting regime** allowing Bose condensation, „quasi condensates“ etc. p.p.

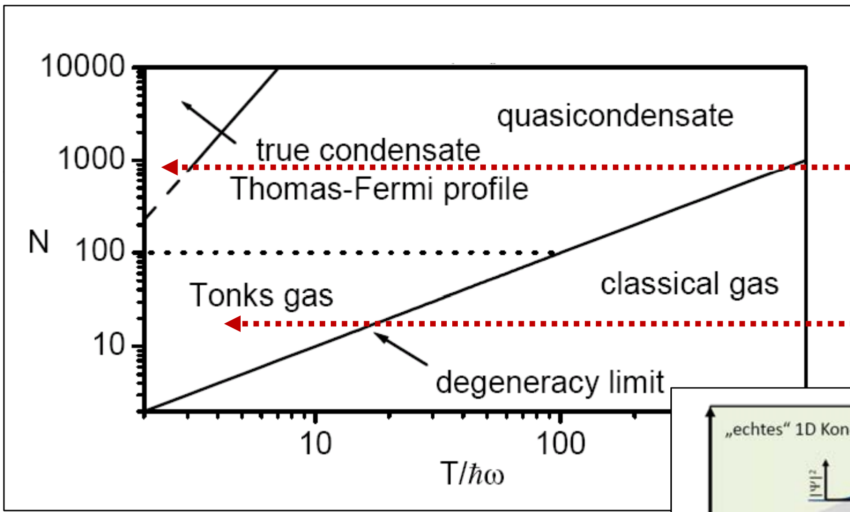
γ>1: **strongly interacting regime**: aka.
gas of inpenetrable Bosons, **Tonks-Girardeau gas**

Completely new properties:

- bosons behave like fermions („fermionization“)
- different correlations („antibunching“)
- different collisions (3 body suppressed)
- …

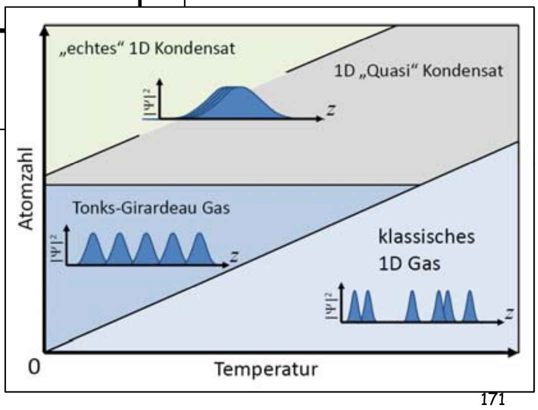
} exclusively in 1D systems

1d Bose Gas
Phase diagram for finite temperature



weakly interacting regime

strongly interacting regime



none of these lines are phase transitions, it's all smooth cross over

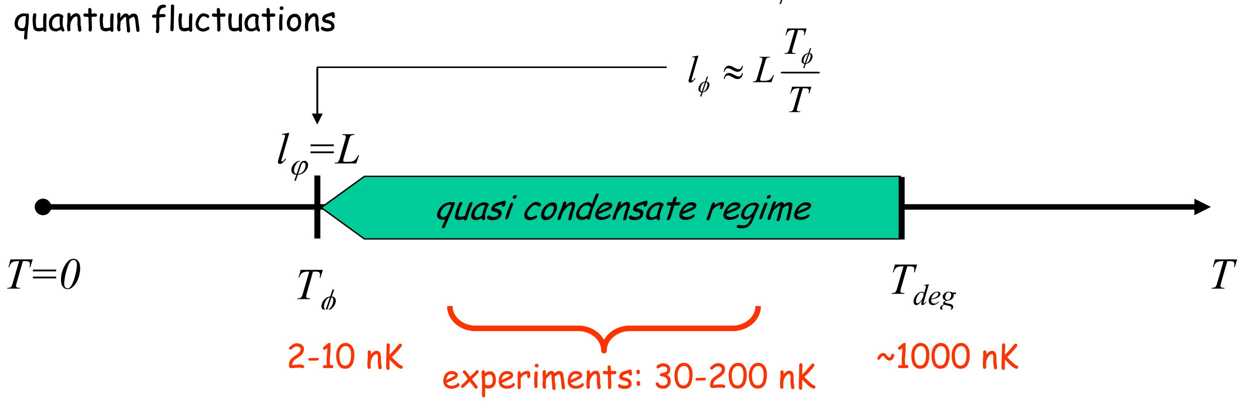
in 1D, the bose gas drastically changes its **quantum statistics**

The weakly interacting 1D regime

„true" 1D condensate
- longe range phase coherence
- quantum fluctuations

1D „quasi condensate"
- macroscopic wave function
- fluctuating phase: $l_\phi < L$

thermal gas

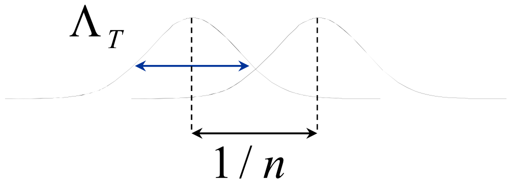


The weakly interacting 1D regime

We define the **degeneracy temperature** T_d with

$$T_d = N\hbar\omega_{\|} / k_B$$

(usual overlap of wavefunctions compare phase diagram...)



for $T < T_d$ we find a order parameter with a fluctuating phase: **1D quasi condensate**

Coherence length of 1D phase fluctuations:

Condensate field operator: $\hat{\Psi}(z) = \sqrt{n_0(z)} e^{i\hat{\phi}(z)}$ ← this has now a z dependence!

First order correlation function: $g_1(z,z') \equiv \langle \hat{\Psi}^+(z')\hat{\Psi}(z) \rangle = \sqrt{n_0(z)n_0(z')} e^{-\frac{1}{2}\langle \delta\phi^2_{z,z'} \rangle}$

„exponential decay of the correlation function“

With the expectation value of phase fluctuations $\langle \delta\phi^2_{z,z'} \rangle = \frac{4T\mu}{3T_d\hbar\omega_{\|}} \left| \ln \frac{(1-z')(1+z)}{(1+z')(1-z)} \right|$

In a finite system :
define the temperature T_ϕ for which
$<\delta\phi^2_{z,z'}>$ vanishes over a length z-z‘ ≈ R_{TF}

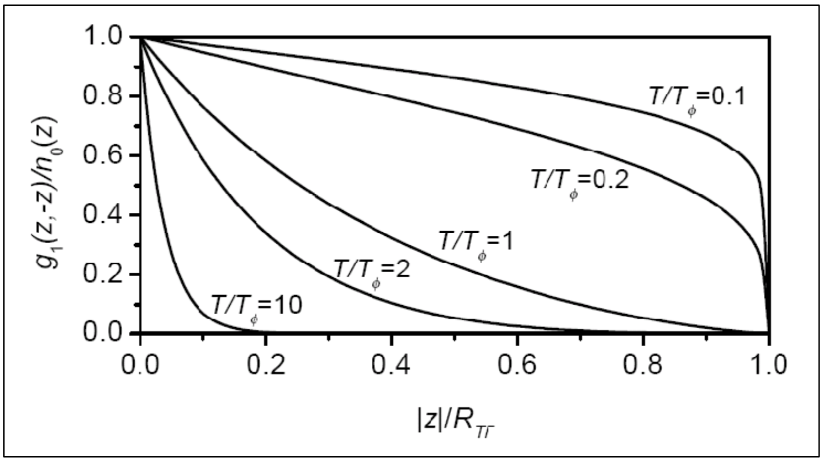
$$T_\phi = T_d \frac{\hbar\omega_{\|}}{\mu}$$

(compare phase diagram)

The weakly interacting 1D regime

for $T_D >> T >> T_\phi$ phase fluctuating 1D quasi condensate
$T << T_\phi$ true condensate of uniform phase

Correlation length of phase fluctuations: $l_\phi \approx R_{TF} \frac{T_\phi}{T}$

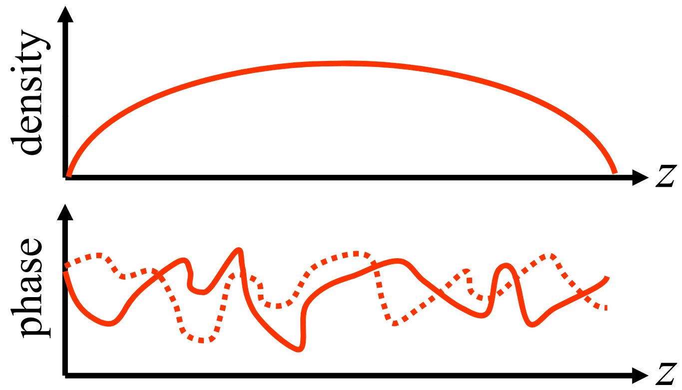


$T < T_\phi$ has **never been reached** in an experiment with weakly interacting 1D bose gases

Note: phase fluctuations occur also in **elongated 3D condensates** as they are due to low lying excitations in the longitudinal direction

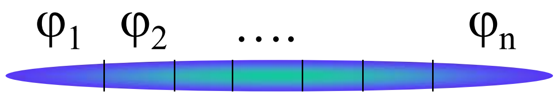
Quasi condensates
weakly interacting 1D regime

a one-dimensional Bose gas in the quasi condensate regime:



$$\Psi = \sqrt{n_0}\, e^{i\phi(z,t)}$$

- what is the density profile of a 1D quasi condensate?
- what are the spatial correlations of the phase?
- what are the timescales of phase fluctuations?

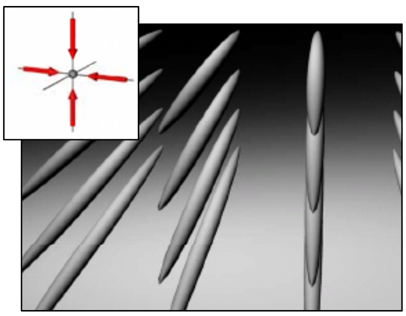


$$l_\phi \approx L \frac{T_\phi}{T}$$

consider as a chain of condensate blocks (10 to 50) with **locally uniform phase**

Experimental realizations of 1D systems

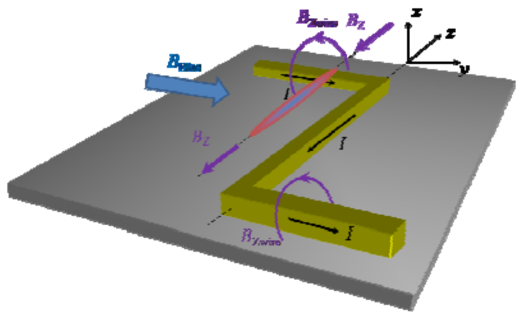
2D optical lattice + weak trap



about 5000 realizations:
- each tube: **20-50** atoms
- aspect ratio 200-1000
- typical $\omega_\perp \approx 2\,\pi$ x 50 kHz
- essentially **T=0** (ground state)
- γ between **0.1 and 100**
- **strongly interacting 1D gases**

1D lattice groups: D. Weiss, I. Bloch, W. Phillips, H. C. Nägerl, T. Esslinger,...

single trap on atom chip

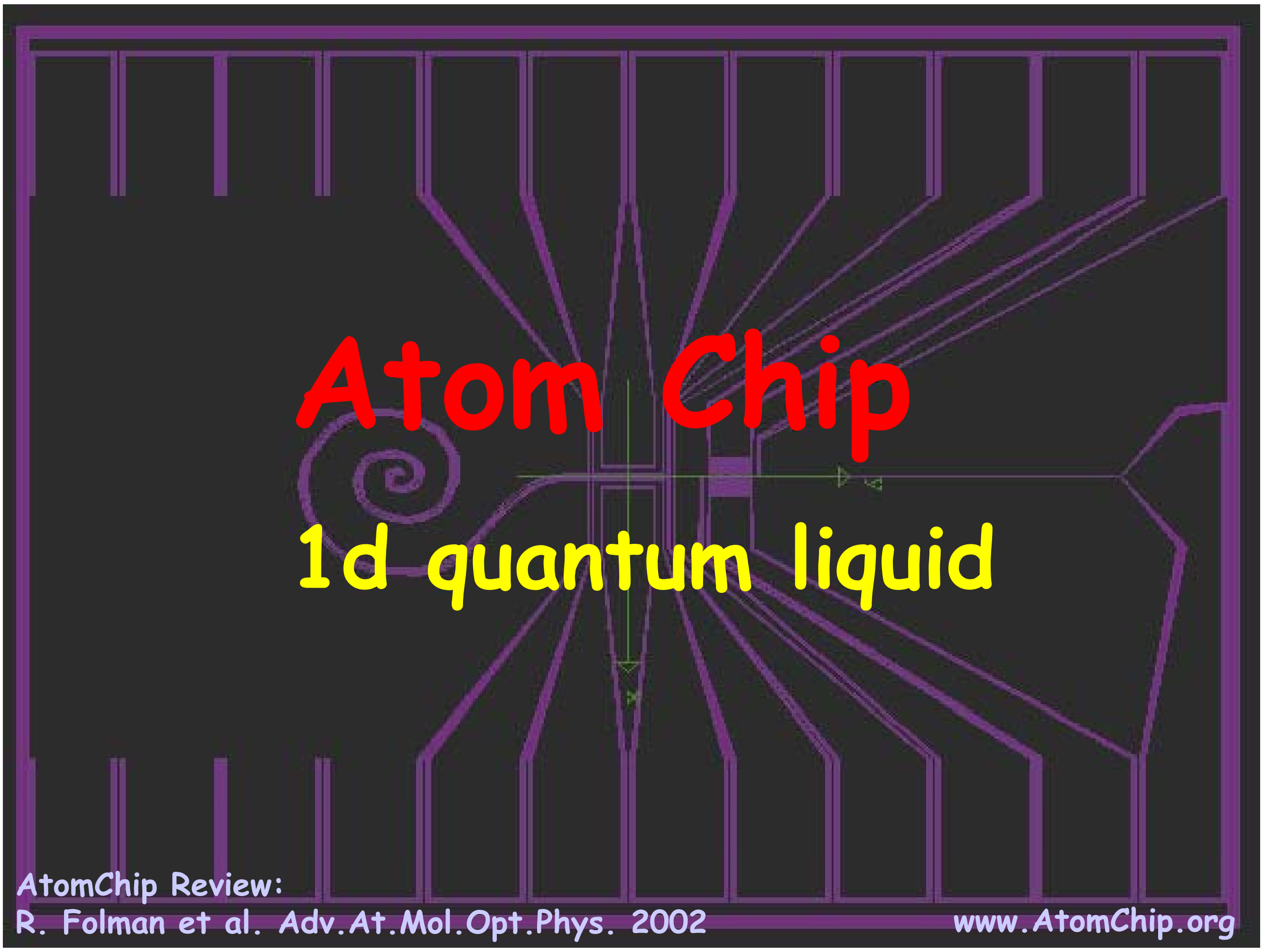


a single sample
- **5000 to 50.000** atoms
- aspect ratio 100-1000
- typical $\omega_\perp \approx 2\,\pi$ x 5 kHz
- **T ≈ 50 nK** (≅ 2 π x 1 kHz)
- γ **below 0.01**
- **weakly interacting 1D gases**

1D chip groups: J. Schmiedmayer, K. vanDruten, A. Aspect, W. Ketterle...

1d Systems
Motivation

- 1d systems are an ideal testing ground for many body quantum physics
- precise analytical models
  (Lieb-Lindinger theory of Luttinger Liquids)
- We can look at the coherence and its dynamics and study the interplay between
  fundamental quantum fluctuations
  thermal fluctuations
  by observing the evolution of interference between two 1d superfluids



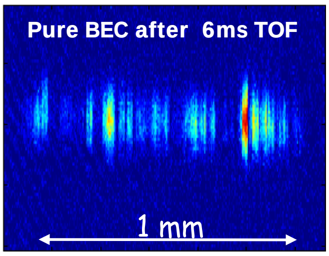
1d – Bose Gas

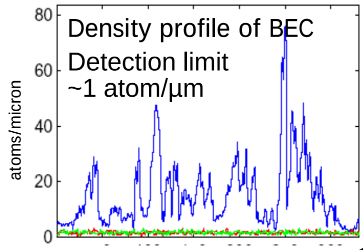
1d BEC: $\mu, T < \hbar\omega_{trans}$

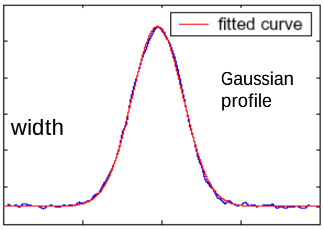
Smooth atom chip potentials allow creation of continuous 1d BEC in tightly confining traps

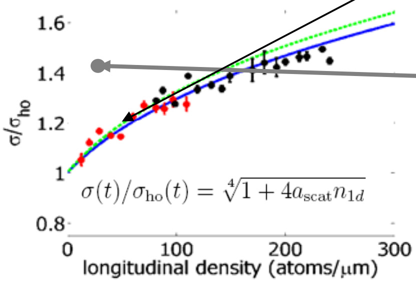
l>1mm $\omega_{transv} > 2\pi$ 5 kHz aspect ratio >1:1000

$$\mu_{\text{l.e.}}[n_1] = \hbar\omega_\perp\sqrt{1+4an_1}$$

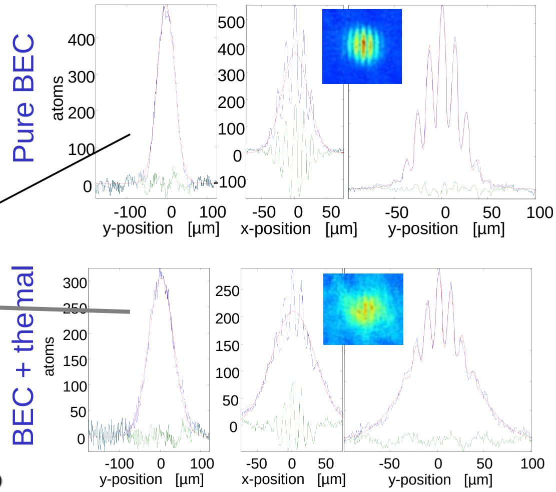




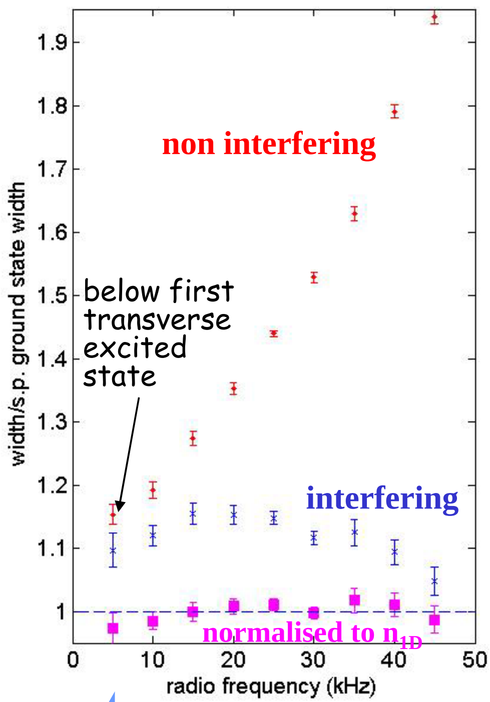


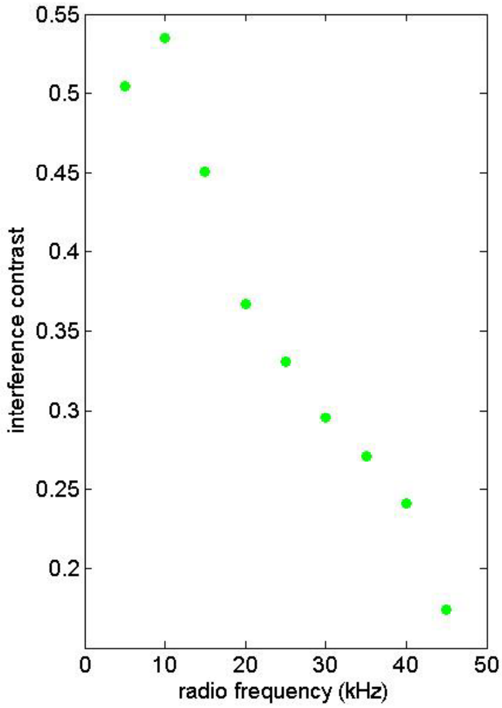


Measuring the order parameter with interference



Effect of Temperature

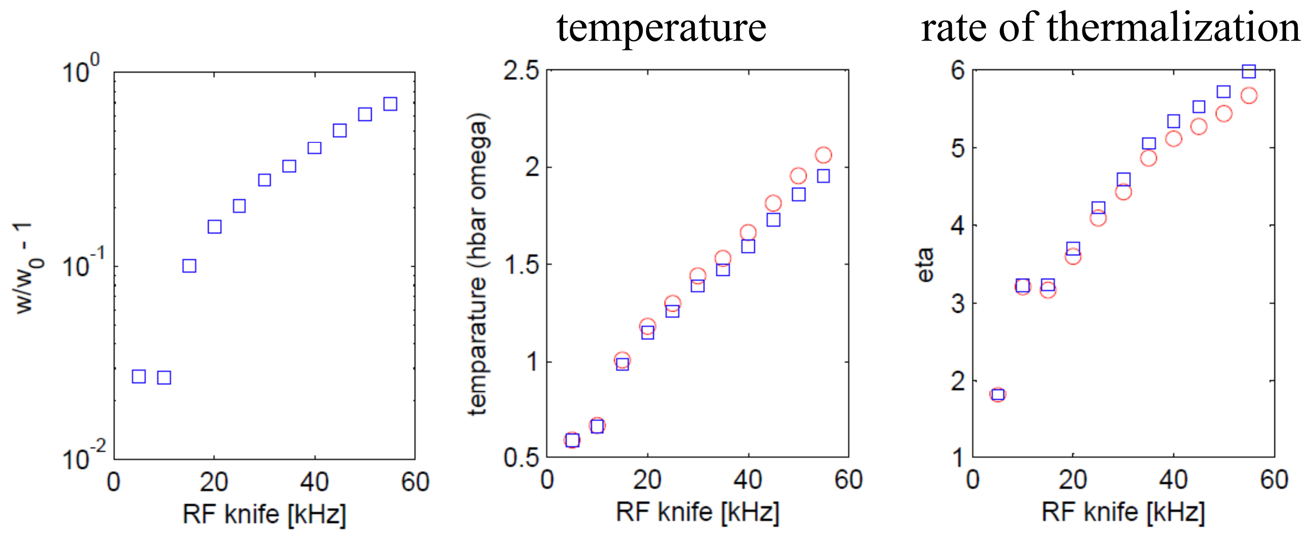




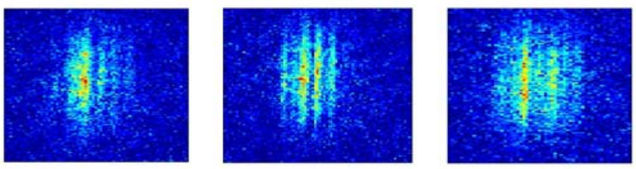
work in this regime

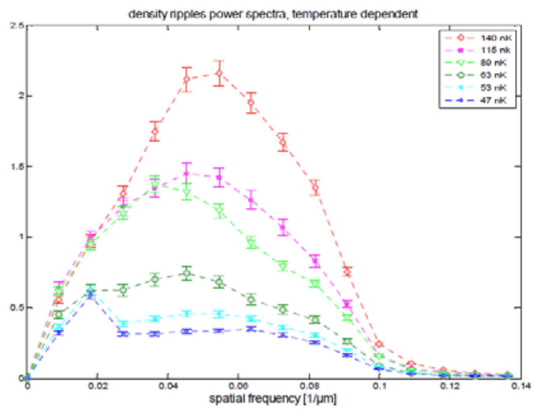
Transverse expansion in 1d
temperature and collisions

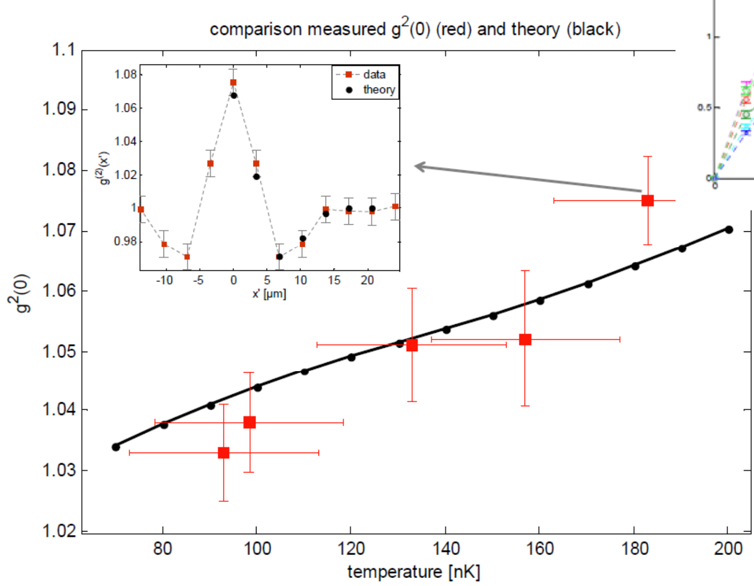
From the difference between the expansion width of the interfering and he not interfering component together with n1d we can extract:

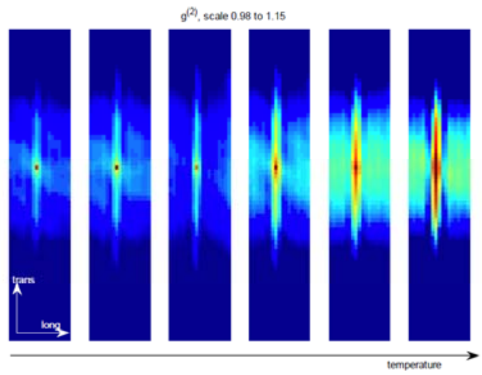


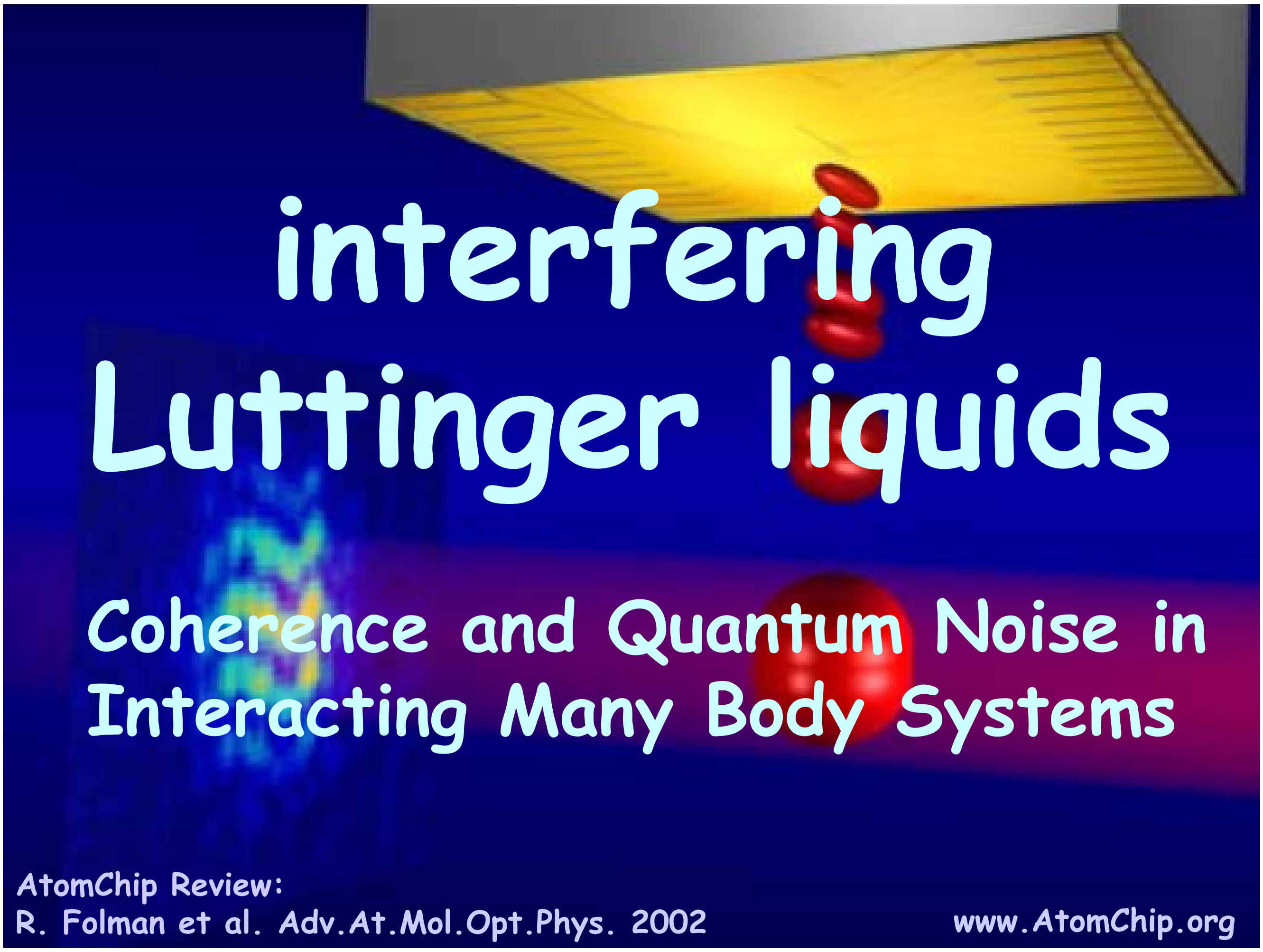
Density correlations in TOF
experiment











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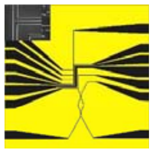
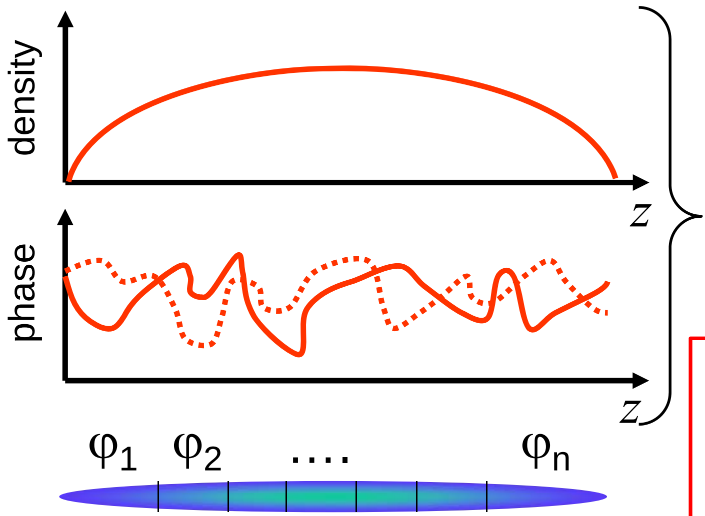
Phase Fluctuating 1d Condensates



a one-dimensional Bose gas in the quasi condensate regime:



$$l_\phi \approx L\frac{T_\phi}{T}$$

consider as a chain of condensate blocks (10 to 50) with **locally uniform phase**

$$\Psi = \sqrt{n_0}\, e^{i\phi(z,t)}$$

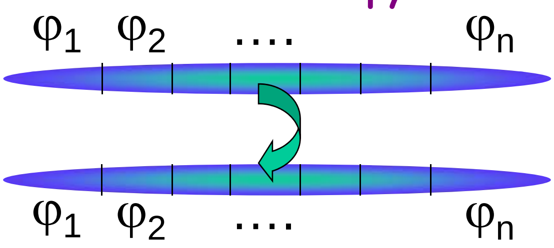
what are the **dynamics** of these phase fluctuations?

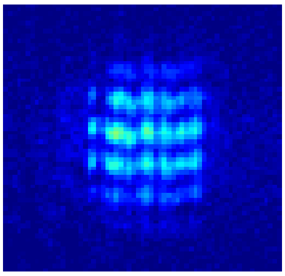
$\omega_{x,y} = 2\pi \times 3...5$ kHz
$\omega_z = 2\pi \times 5$ Hz
$N = 2...10 \times 10^3$ Rb^{87} atoms
$\mu, T \approx 1$ kHz
$n_{1d} = 20...100\mu m^{-1}$
$\gamma = \frac{m g_{1d}}{\hbar^2 n_{1d}} \approx 0.001$

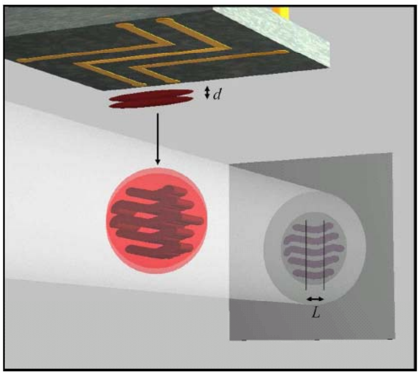
interference of phase fluctuating 1D condensates

How can we study the dynamics and noise of phase fluctuations

create a copy







interference of phase fluctuating 1D condensates

How can we study the dynamics and noise of phase fluctuations

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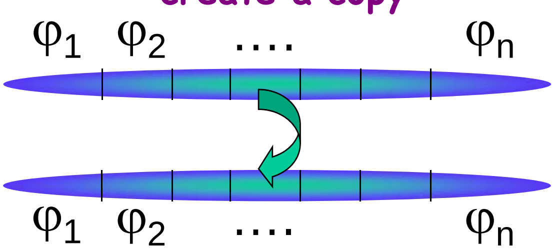
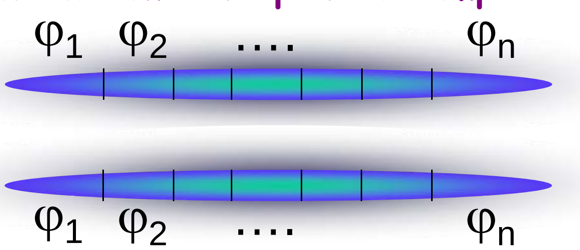
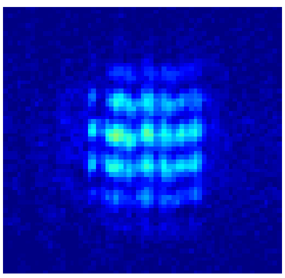
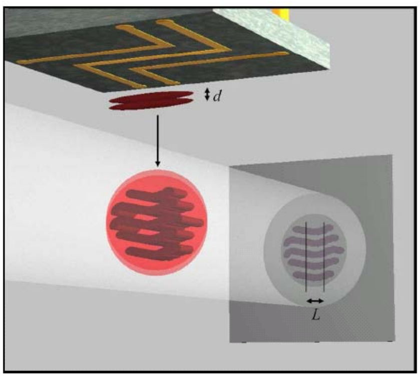
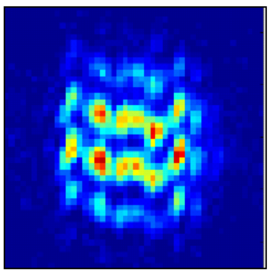


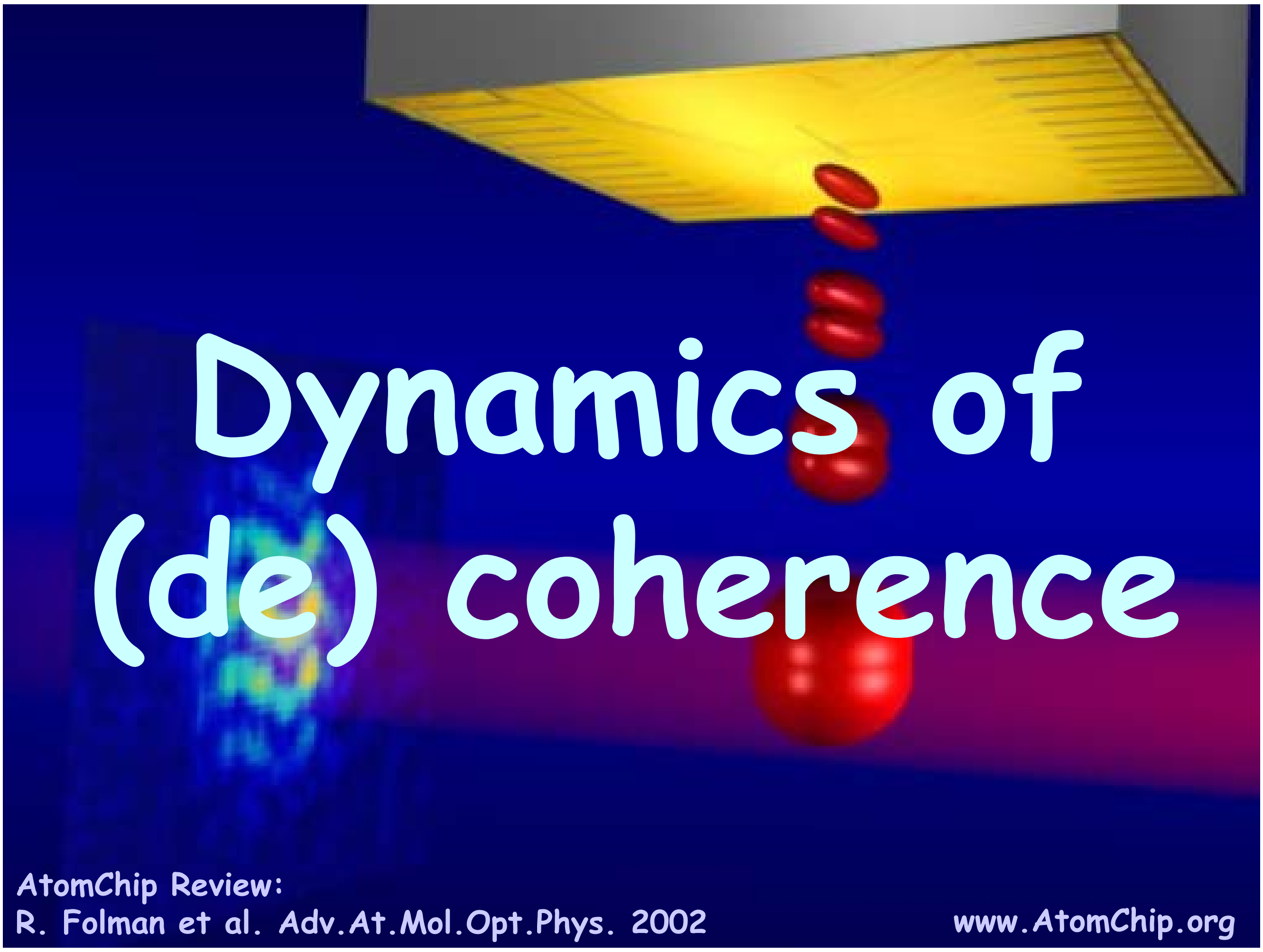
create two independet samples





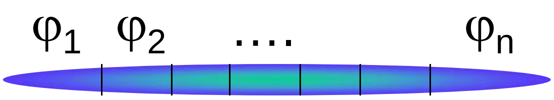






interference of phase fluctuating 1D condensates

How can we study the dynamics of phase fluctuations?



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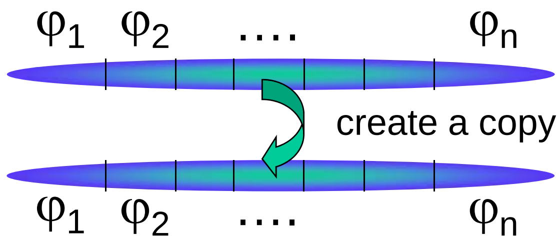

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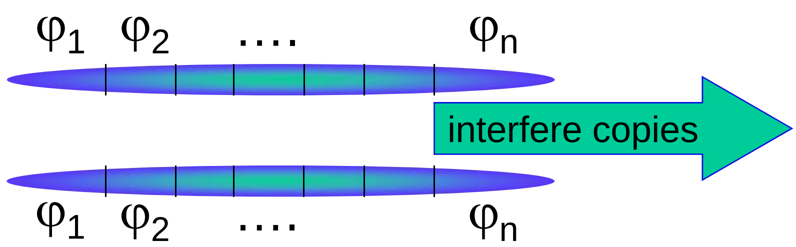

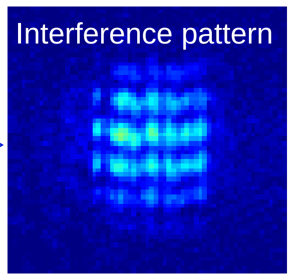

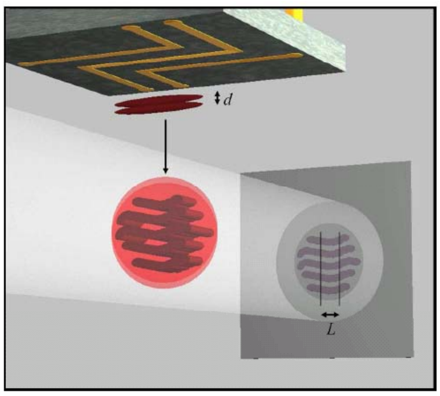

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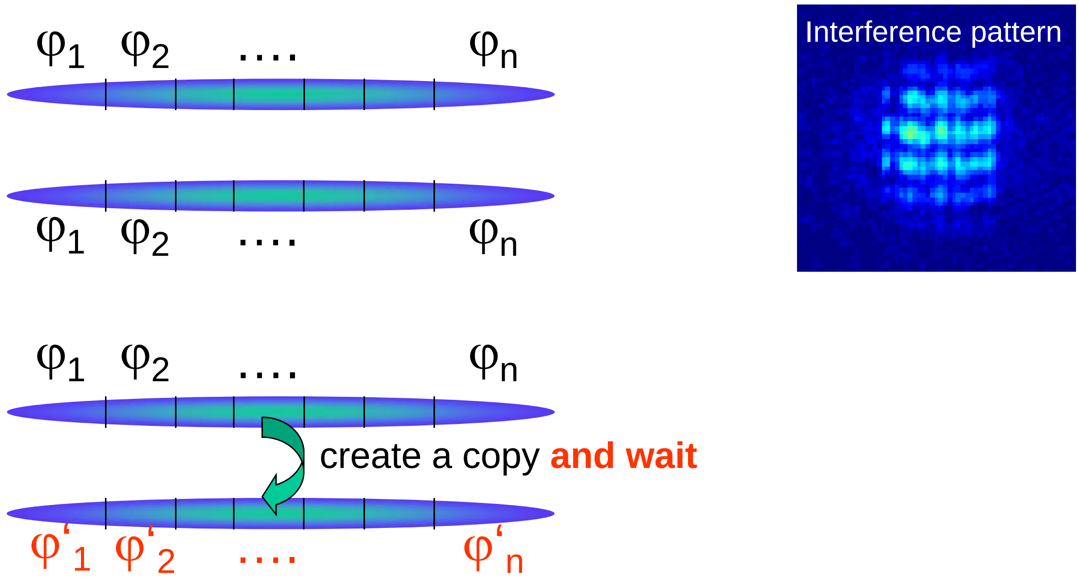

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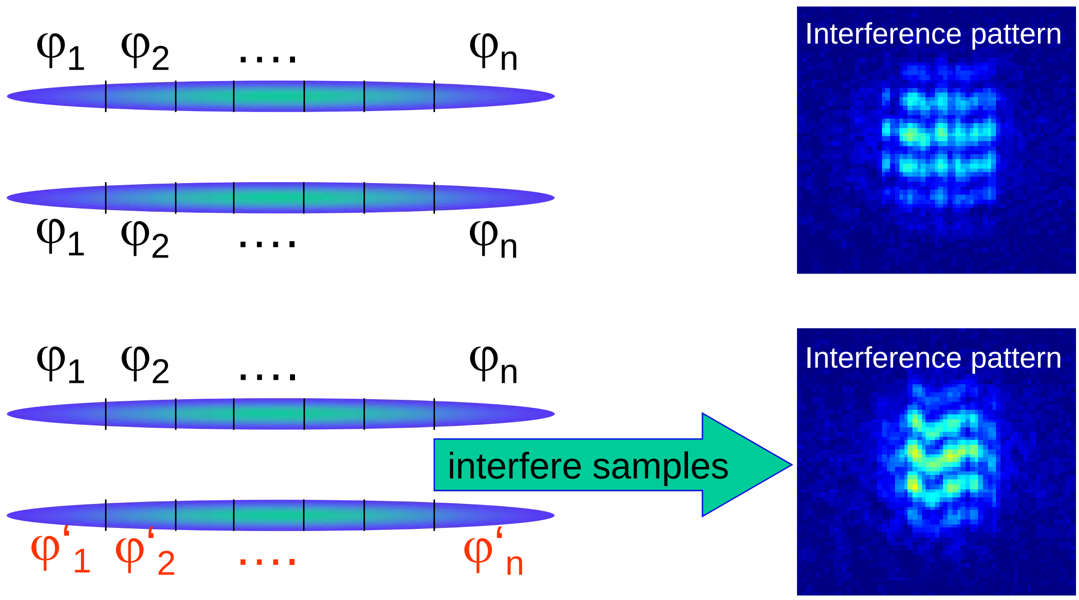

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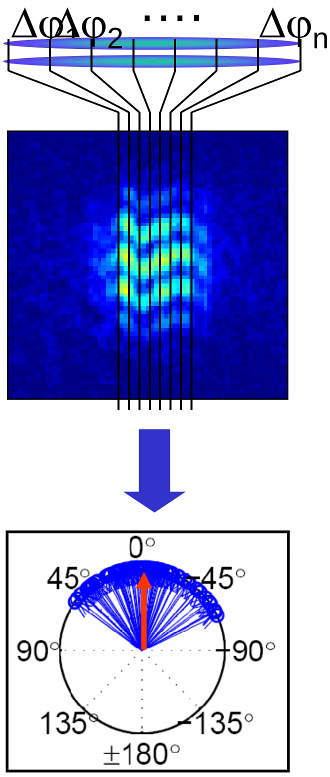
quantify phase fluctuations: circular statistics



- determine the (local) relative phase $\theta(z,t)$ of the two condensates for each vertical pixel slice
- calculate the **coherence factor**

$$\Psi(t) = \frac{1}{N}\sum_{N}\left\langle e^{i\theta(z,t)}\right\rangle$$

- **compare to theory by**
  - *A. Burkov et.al.*: luttinger liquids, PRL **98**, 200404 (2007)
  - *I. Mazets et al.:* Bogoliubov excit. EPJ-B **68**, 335 (2009)
- theoretical prediction for the coherence decay:

$$\Psi(t) \propto e^{-(t/t_0)^{2/3}}$$

decoherence dynamics of 1D bose gases

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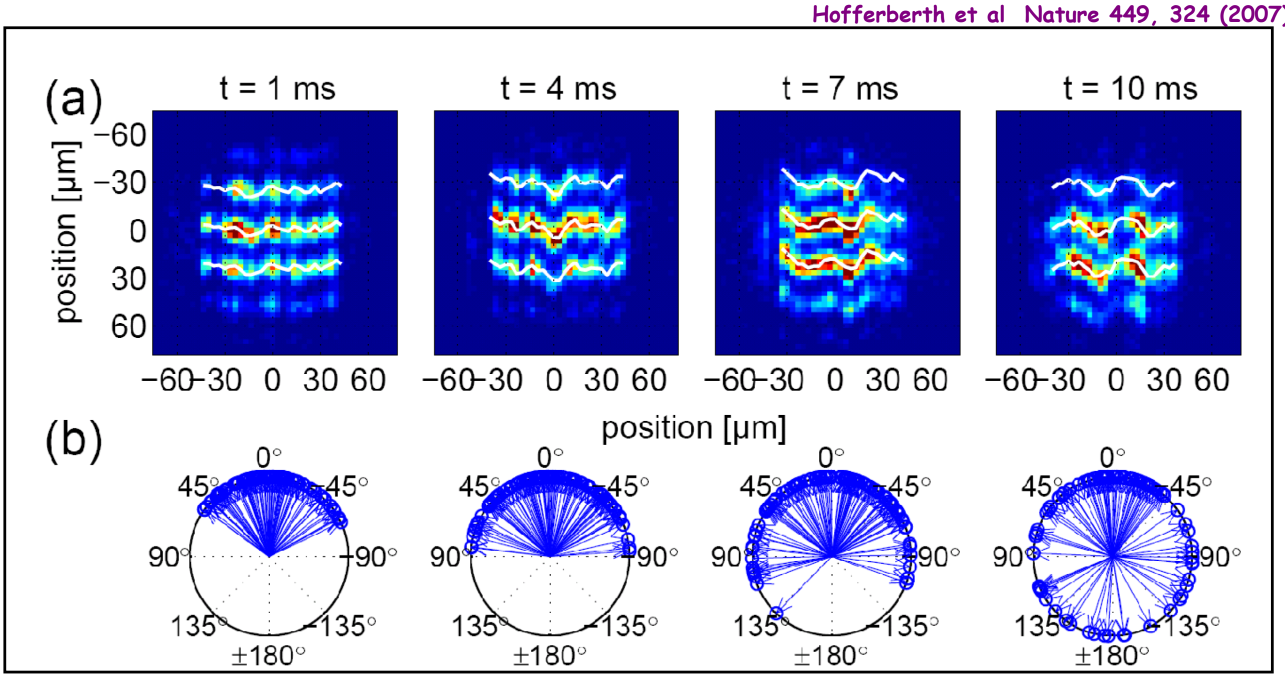
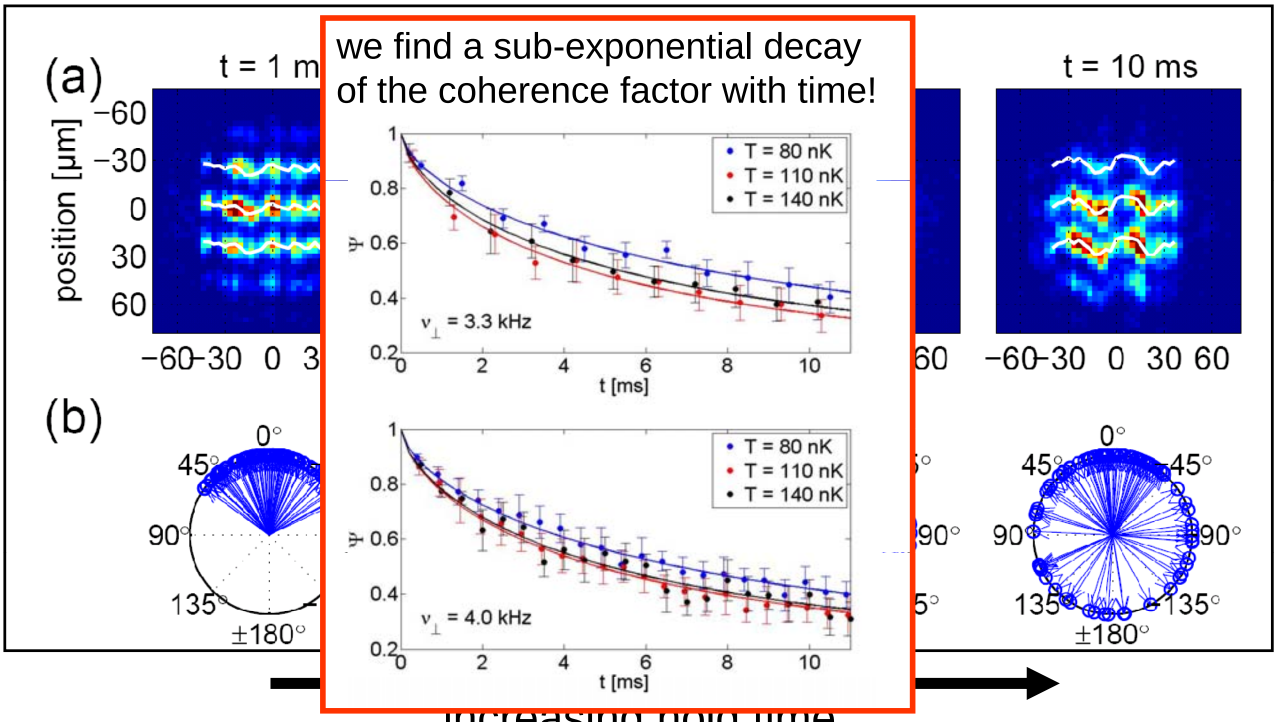


increasing hold time

decoherence dynamics of 1D bose gases



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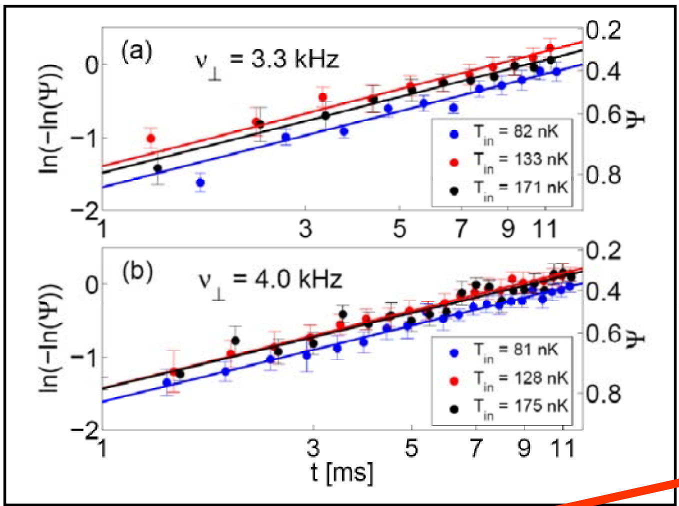
decoherence dynamics of 1D bose gases



$$\Psi(t) \propto e^{-(t/t_0)^{\alpha}}$$

linearized coherence factors plotted over time yield the exponent of coherence decay

six different realizations (trap, atom density, temperature)

we find excellent agrement with the prediction of 2/3

T_{in} [nK]	n_{1d} [$1/\mu m$]	$\omega_\perp$ 2π [kHz]	α	t_0 [ms]	T_f [nK]
82(28)	20(4)	3.3	0.64(8)	9.0(4)	76(10)
133(25)	34(5)	3.3	0.65(7)	5.5(3)	145(13)
171(19)	52(4)	3.3	0.64(4)	6.4(3)	186(15)
81(31)	22(4)	4.0	0.65(3)	8.1(2)	85(10)
128(23)	37(4)	4.0	0.66(3)	5.9(2)	153(13)
175(20)	51(5)	4.0	0.64(6)	6.1(4)	194(17)

determining the decay constant t_0, we can measure the „temperature“ of the system

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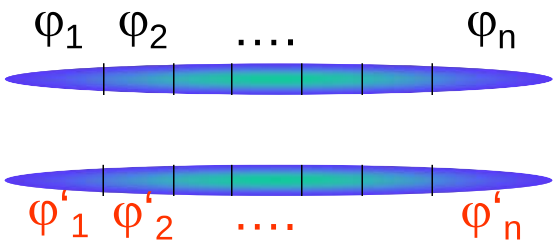
de-coherence dynamics? coupled 1d condensates



• **phase fluctuations scramble** the relative phase
• on a timescale of 10 ms we recover two independent systems
→ „phase memory" is lost

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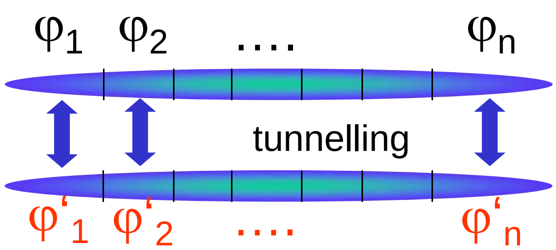
~~de~~-coherence dynamics? coupled 1d condensates



• **phase fluctuations scramble** the relative phase
• on a timescale of 10 ms we recover two independent systems
→ „phase memory" is lost

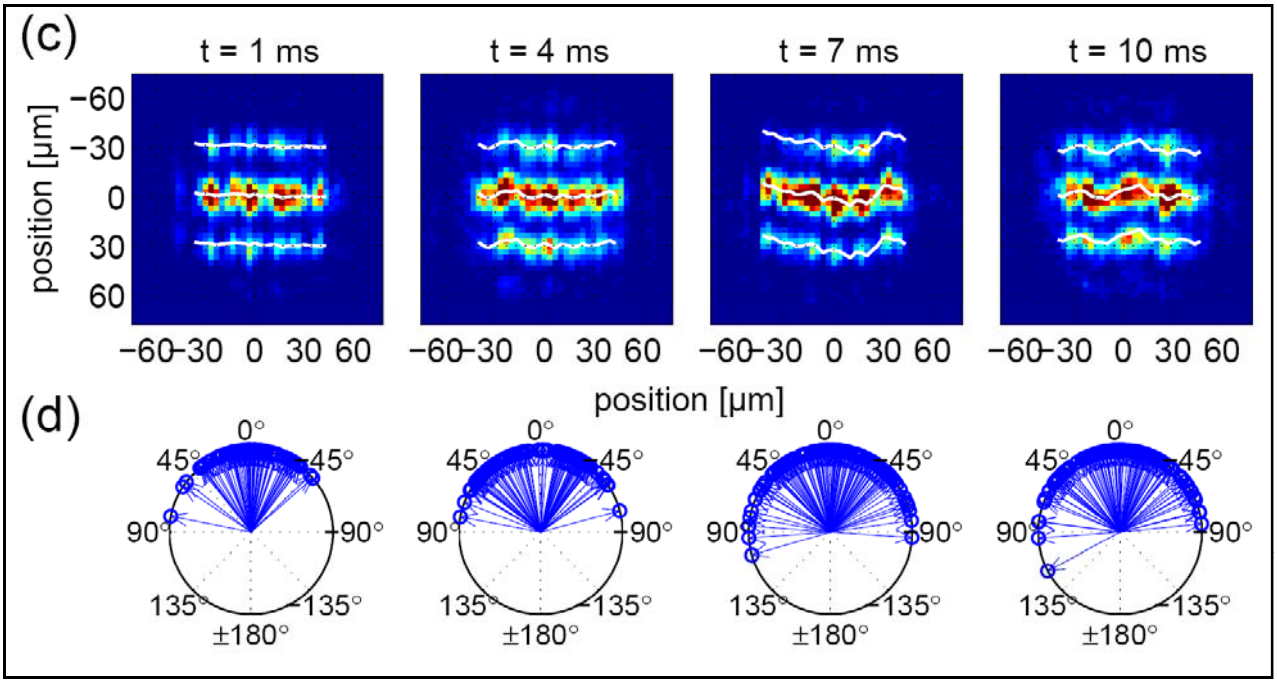
• coupling both systems via **tunnelling** may to **lock** the relative phases

What is the „equlibrium" situation for the coupled system?

• We expect an equilibrium of **finite coherence factor** depending on tunnel coupling strength

Hofferberth et al Nature 449, 324 (2007)

coherence dynamics coupled 1d condensates

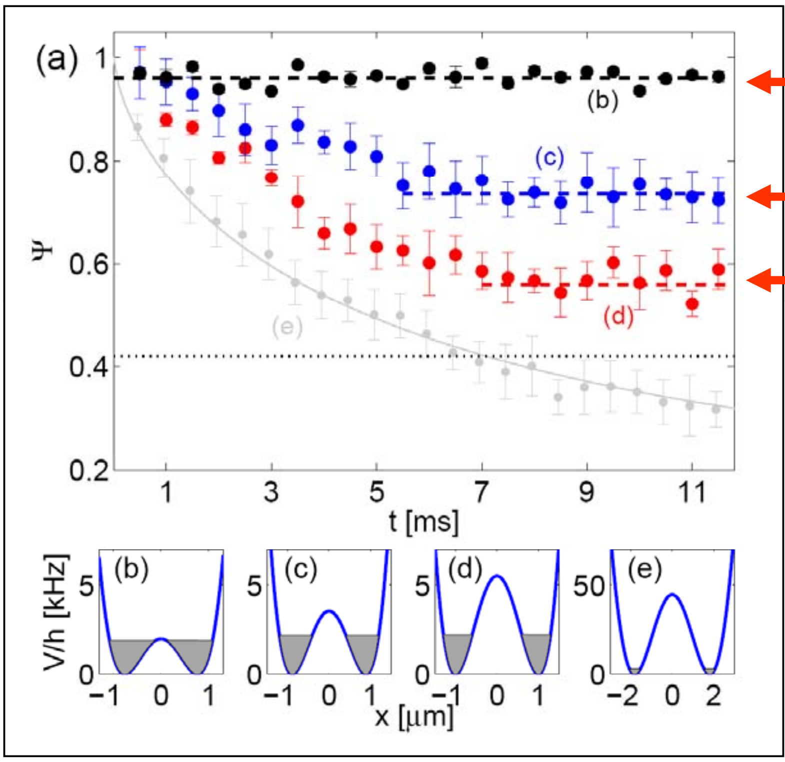


increasing hold time

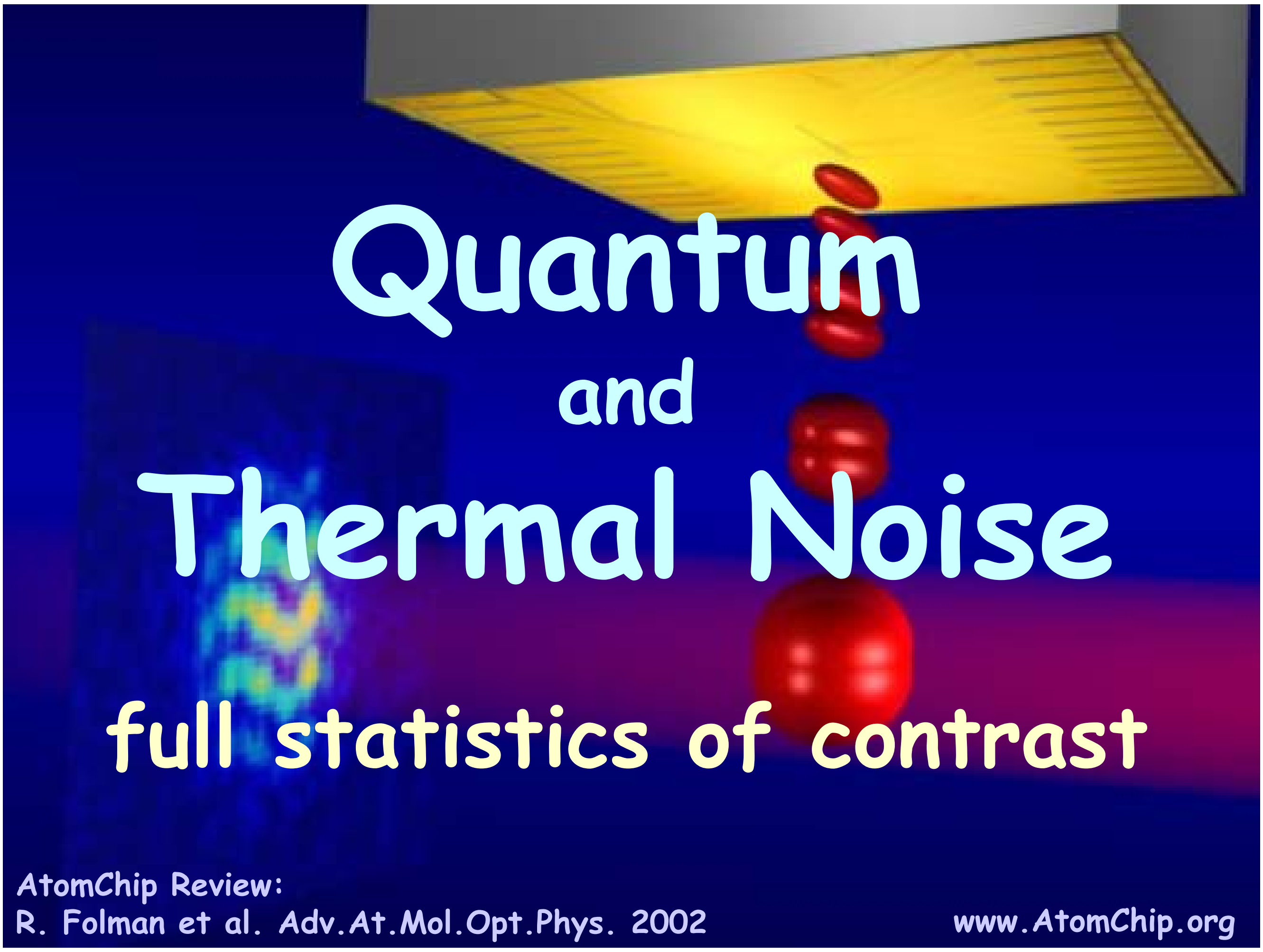
Hofferberth et al Nature 449, 324 (2007)

coupled 1d condensates: „equilibrium“ situation

Hofferberth et al Nature 449, 324 (2007)

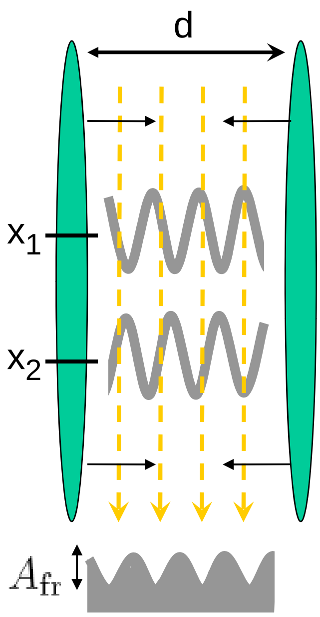


- „equilibrium“ situation characterized by finite and constant coherence factor
- strength of tunnel coupling determines the „equilibrium“ level (measure coupling)
- the system only needs one or few Josephson oscillations to reach „equilibrium“ (dynamics unclear, no theory available yet)



Interfering independent 1d Quantum Liquids

E. Demmler (Harvard)
E. Altman (WIS)



A_{fr} is a quantum operator. Its measured value will fluctuate from shot to shot.

expectation value of contrast:

$\langle A_{fr} \rangle = 0$ due to random rel. phases

How to predict the distribution function of A_{fr}

Quantum impurity problem:

interacting one dimensional electrons scattered on an impurity

Conformal field theories with negative central charges

For identical condensates

$$\langle |A_{fr}|^2 \rangle = L \int_0^L dx \, (\, G(x) \,)^2$$

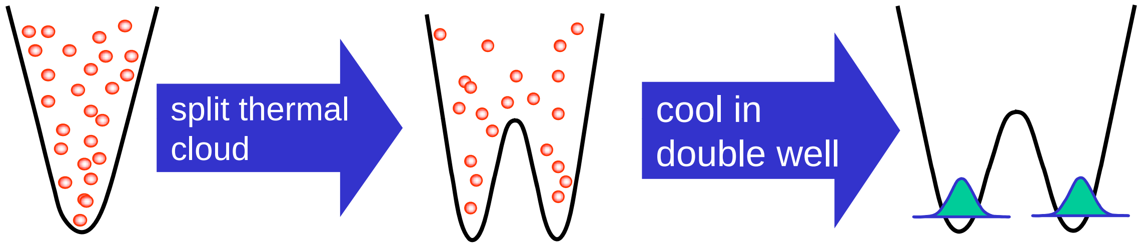
Instantaneous correlation function

$$G(x) = \langle \, a(x) \, a^\dagger(0) \, \rangle$$

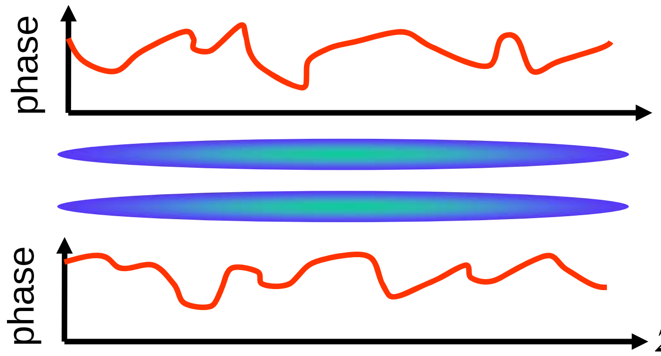
Interference of independent 1d systems

Hoffererth et al. Naure Physics 2, 710 (2006)

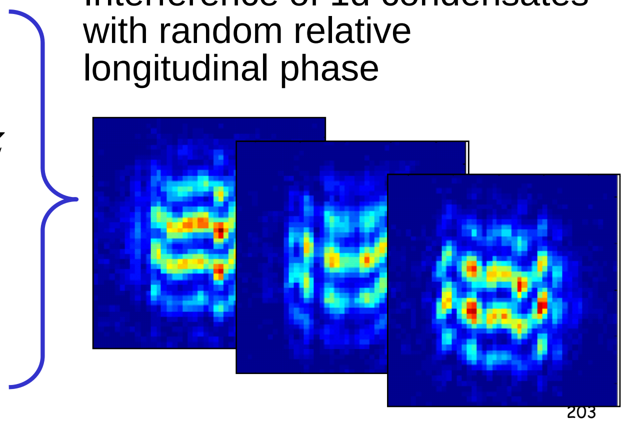
transverse trapping potential



longitudinal relative phase

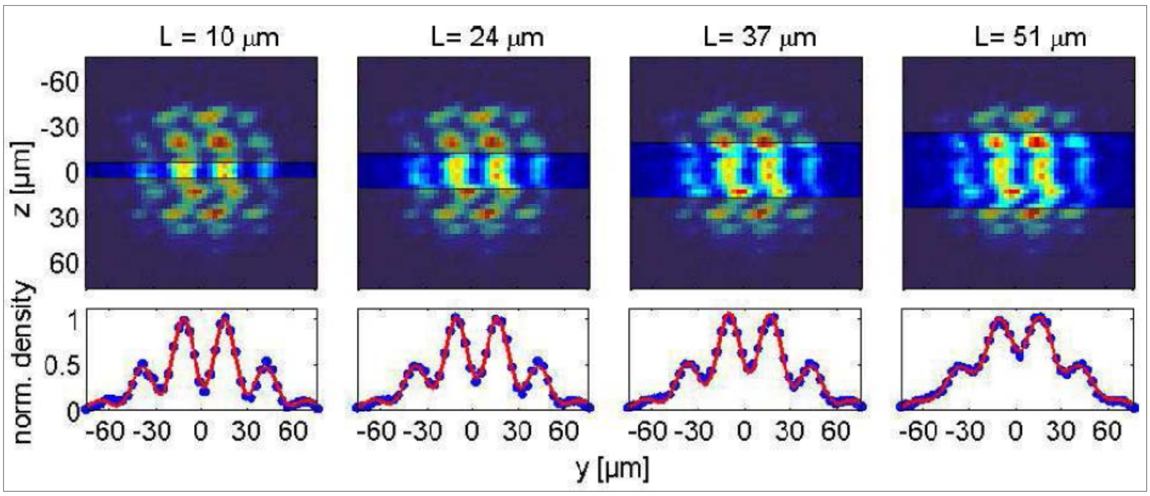


Interference of 1d condensates with random relative longitudinal phase



Analysis of interference patterns: contrast analysis

Hofferberth et al arXiv:0710.1575 (2007)



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

contrast analysis: second order correlations

Theory: E. Demer (Harvard 2007)

$$\left\langle \left|A_Q\right|^2 \right\rangle = \frac{1}{n_{1d}^2} \int_{-L/2}^{L/2} dz_1 \int dz_2 \left\langle a_1^+(z_1) a_1(z_2) \right\rangle \left\langle a_2^+(z_2) a_2(z_1) \right\rangle$$

2^{nd} moment of fringe („average contrast“)

2^{nd} order correlation function

(…as used by Hadzibabic et.al to identify the B.K.T. transition in 2D) Nature 441, 1118 (2006)

We now look at it in 1d:

again Luttinger liquid theory (A. Polkovnikov *et.al*…)

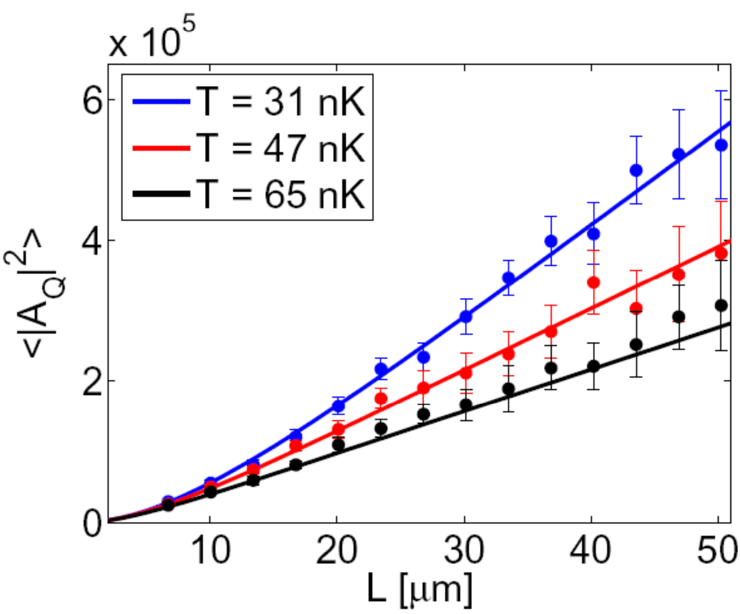
$$\left\langle \left|A_Q(L)\right|^2 \right\rangle = C_1 \xi_h L + C_2 \left(\frac{L}{\xi_h}\right)^{2-1/K} f\left(\frac{\xi_\Phi}{L}, K\right)$$

…can be calculated from trap parameters, 1d atomic density and temperature

PNAS USA **103**, 6125 (2006)

Coherence and correlations in 1d Bose gases

Hofferberth et al arXiv:0710.1575 (2007)



- only free parameter: Temperature
- curve takes into account thermal and quantum fluctuations
- shot noise negligible even for shortest system size

length dependence of average contrast gives information on two-point correlations in the 1d Bose gase

higher order correlations: full contrast statistics

Theory: E. Demer (Harvard 2007)

$$\frac{\left\langle |A_Q|^{2m} \right\rangle}{\left\langle |A_Q|^{2} \right\rangle^{m}} \equiv \left\langle \alpha^m \right\rangle = \int_0^\infty W(\alpha)\alpha^m d\alpha$$

normalized moment of order m

full distribution of fringe contrast

to reconstruct the full distribution, one has to calculate ALL moments of interference contrast

mapping to „a generalized Coulomb gas model and a related problem of fluctuating random surfaces“

$$W(\alpha) = \prod_{n=1}^{\infty} \frac{\int_{-\infty}^{\infty} dt_n e^{-t_n^2/2}}{\sqrt{2\pi}} \delta[\alpha - g(\{t_n\})g(\{-t_n\})]$$

$$\alpha = \frac{|A_Q|^2}{\left\langle |A_Q|^2 \right\rangle}$$

this can be computed using a Monte-Carlo algorithm…

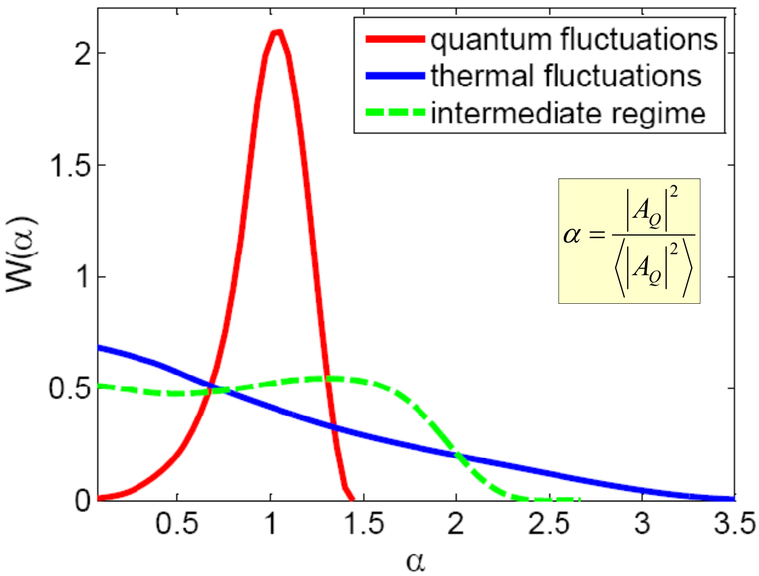
V. Gritsev, *et.al* Nature Phys. 2, 705 (2006)

full contrast statistics

therory predictions

Theory: E. Demer (Harvard 2007)

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



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

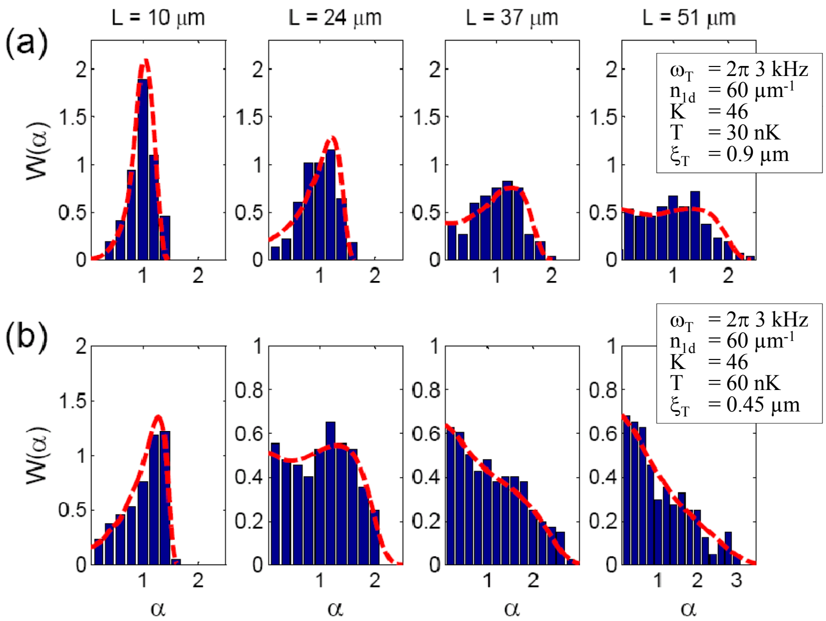
thermal fluctuations:
broad Poissonians distribution
(high temp T or long length L)

intermediate regime:
double-peak strukture

full contrast statistics
experiment

Hofferberth et al arXiv:0710.1575 (2007)

experimentally measured distribution functions for the average contrast:



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

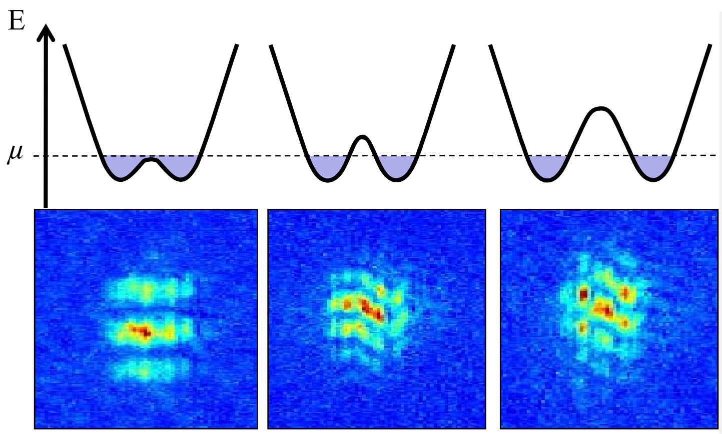
thermal fluctuations:
broad Poissonians distribution
(high temp T or long length L)

intermediate regime:
double-peak strukture

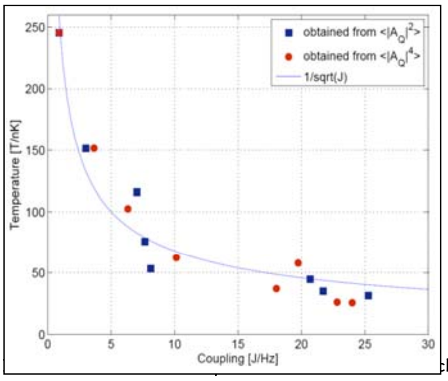
No free parameters!

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

Coupled 1D quasi condensates identical analysis...



- Prepare systems with different coupling strengths, same chemical potential
- take interference images (bin for different fringe spacing to ensure identical tunneling, post-select for chemical potential)
- Plot distribution function of $|A_Q|^2$
- extract $\langle|A_Q|^2\rangle$, $\langle|A_Q|^4\rangle$,...
- compare to theory...
- we have no theory for the full distribution functions yet, only heavy numerics

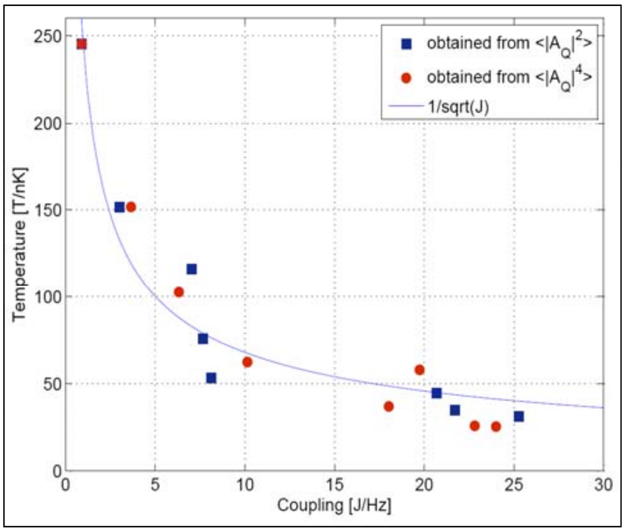


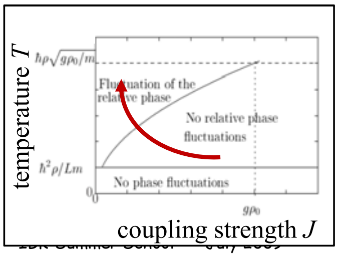
theoretical model for relative phase (Whitlock/Bouchoule PRA 2002; only thermal fluctuations) allows to determine both: **temperature *T*** and tunnel **coupling *J*:**

⇒strong dependence of temperature on coupling!

possible explanations: better thermalization in a strongly coupled system?

Coupled 1D quasi condensates temperature dependence???





We find a **strong dependence of temperature on coupling!**

(...despite identical preparation of the samples...)

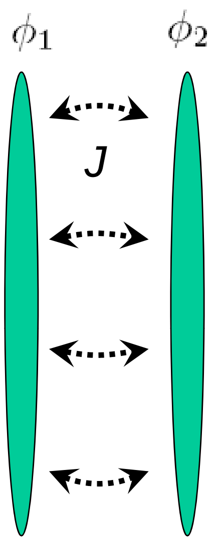
possible explanations:
better thermalization in a strongly coupled system?

coupling breaks integrability of 1D system?

Further experiments neccesary!

Coupled 1d Bose liquids

E. Demmler (Harvard)



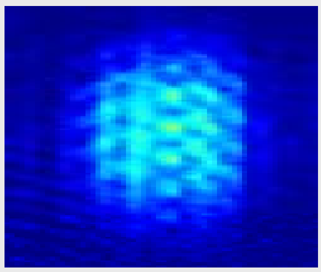
- Interactions lead to phase fluctuations within individual condensates
- The tunneling term favors aligning of the two phases
- Interference experiments measure only the relative phase

Quantum Sine-Gordon model for the relative phase

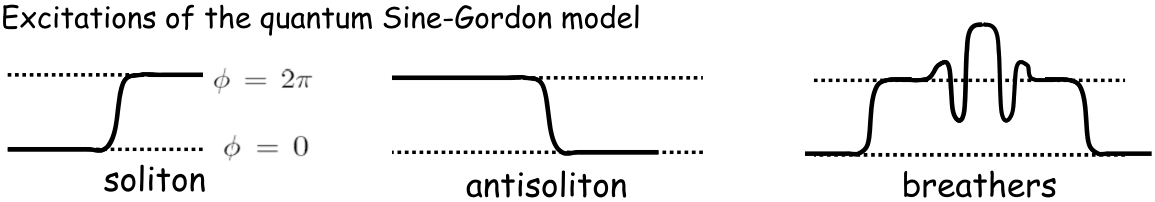
$$\phi = \phi_1 - \phi_2$$

$$\mathcal{H}[\phi] = \int dx\, d\tau \left[\frac{1}{2K}(\Delta n)^2 + \frac{K}{2}(\partial_x \phi)^2 \right] - J \int dx\, d\tau\, \cos\phi$$

Experiment HD: soliton excitations in coupled 1d BEC ?



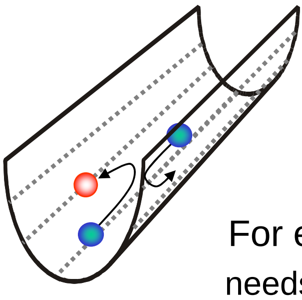
Excitations of the quantum Sine-Gordon model



Possible sources of thermalization in 1d systems

ATOMINSTITUT

Elastic 2-body collisions



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

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

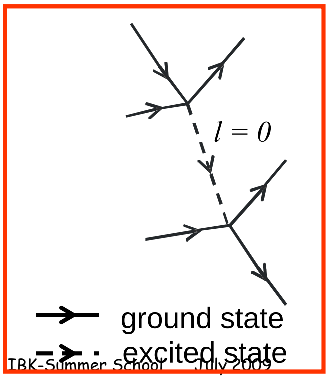
$$\zeta = \frac{n_{1D} a_0^2}{a_\perp}$$

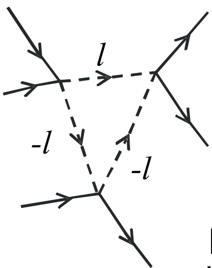
drops exponentially for $k_B T < \hbar\omega_\perp$

For experimental parameters: $\Gamma_{2b} \approx 0.02\, s^{-1}$

needs > 100 s to thermalize (~ 3 colissions to thermalize also in 1D)

Effective 3-body collisions via virtual excited states





… yield effective 3-body colissions, which lead to **thermalization**

$$\Gamma_{3b} \approx C_{3b}\, \omega_\perp \, \zeta^2$$

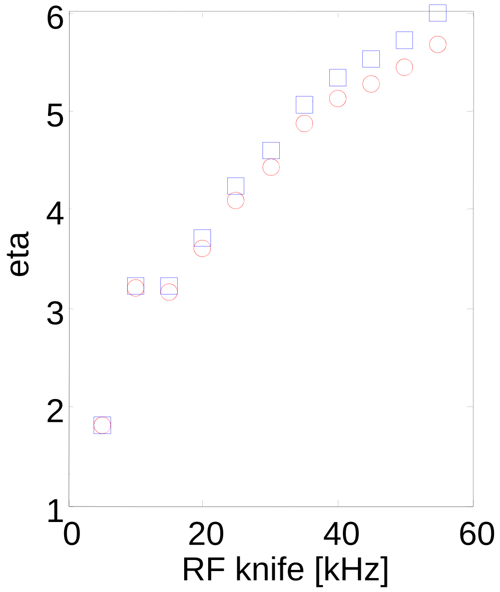
with $C_{3b} \approx 5.57$ independent of temperature

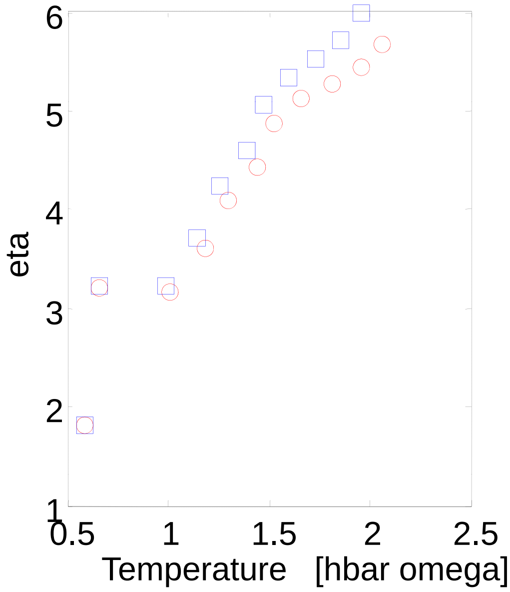
For experimental parameters: $\Gamma_{3b} = 5.0\, s^{-1}$

system thermalizes in 0.6 s, **compatible with experiment**

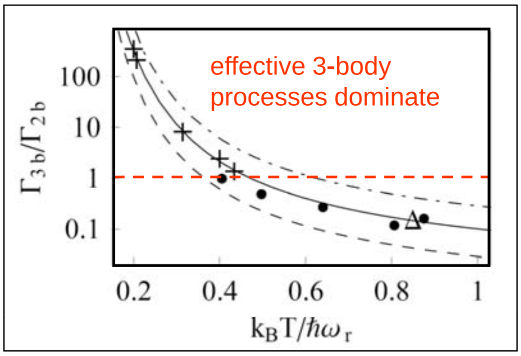
I. Mazets et al. Phys. Rev. Lett. **100**, 210403 (2008)
I. Mazets et al. Phys. Rev. A **79**, 061603(R) (2009)

Freezout of 2-body collisions in 1d





Possible sources of thermalization in 1d systems

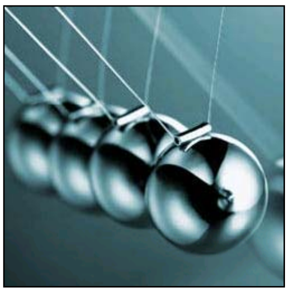


I. Mazets et al. Phys. Rev. Lett. **100**, 210403 (2008)
I. Mazets et al. Phys. Rev. A **79**, 061603(R) (2009)

• S. Hofferberth *et.al*, Nature **499**, 324-327 (2007)
Δ A.H. van Amerongen *et.al*, PRL **100**, 090402 (2008)
+ S. Hofferberth *et.al*, nature Physics **4**, 489 (2008)

effective 3-body colissions can be a **dominant source of thermalization** in weakly interacting 1D systems even for $k_B T < \hbar\omega_\perp$
-> break integrability

Physics:
- The virtual excitations are only suppressed by a ‚detuning'
- The real excitations are suppressed by the exponential Boltzmann factor



Quantum Newtons Cradle T. Kinoshita, et al., Nature **440**, 900 (2006)
demonstrates that in the strongly correlated regime thermalizaton is inhibited

in this regime the virtual 3-body collisions are supressed by $g^3(0)$ ~0 (<< 1)
-> integrability is ensured by the quantum correlation

what have we learned

- we can look at dynamics of decoherence
- generalization of homodyne measurement: statistics of the full distribution functions give detailed insight into (quantum) physics
- in ensemble averages the central limit theorem of Gaussian statistics hides the (quantum) physics
- integrability in 1d quantum systems is NOT related to freeze out of two body collisions, but to the behavior of $g^3(0)$

Atom Chip Future

- Mesoscopic physics
- Bosons – Fermion and mixed systems
- Model Systems (Analog quantum computing)
  - Superconductivity
  - Spin systems
  - Quantum Field theories
  - Excitations
  - Low dimensional systems
- Precision measurements
- Many more things we don't think of

Exiting science in small groups

www.AtomChip.uni-hd.de

Atom Chip Experiment

S. Hofferberth, I. Lesanovsky, S. Manz, T. Betz,
R. Bücker, W. Rohringer, A. Perrin, Thorsten Schumm

Atom Chip Detector

M. Wiltzbach, D.Heine, T. Raub, Bjorn Hessmo

Atom Chip Fabrication

S. Groth (HD), Israel Bar Joseph (WIS)
M. Trinker, D. Fischer (ATI)

Atom Microscope

Simon Aigner, Leonardo Della Pietra (HD)
Yoni Yaffa, Ron Folman (BenGurion Univ)

Atom-Light Interface

Y-A Chen, S Chen, Z-S Yuan, T. Strassel, Jian-Wei Pan

Theory Collaboration

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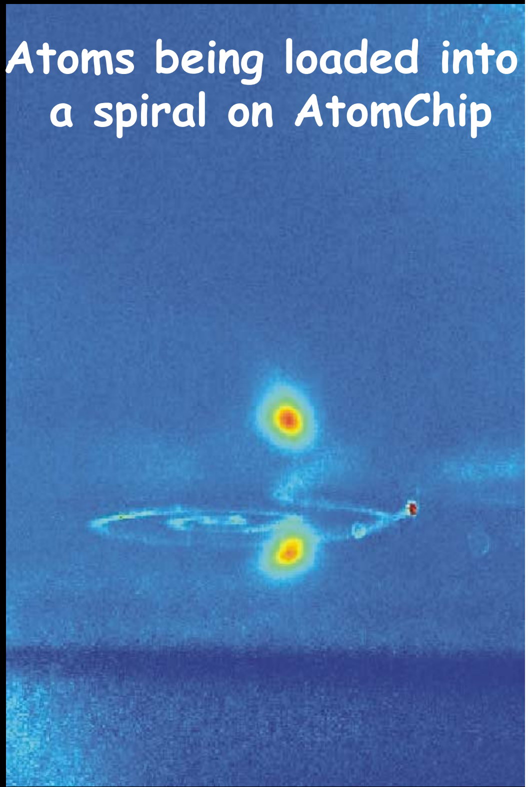
Ehud Altman + ... (WIS)

Former:

M. Anderson, K. Brugger, D. Cassetari, R. Folman, A. Haase,
P. Krüger, X. Lou, St. Wildermuth, T. Fernholz
series of undergrad students in Heidelberg

EU: SCALA, ACQP, FASTnet, AtomChip
DFG, Humboldt, Landesstiftung BW, DIP
FWF, Wittgenstein



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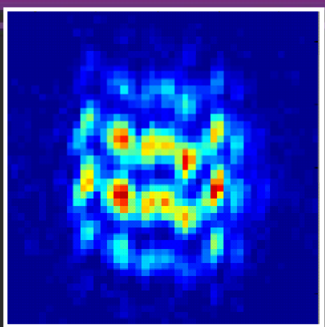
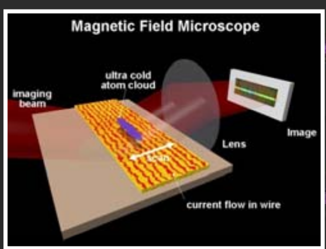
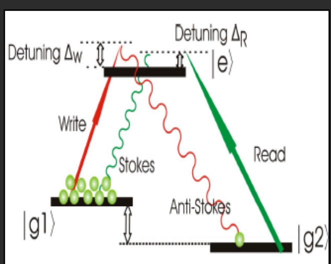


- *Atom Chip quantum physics*
  - Matter-wave interferometry in a double well on an atom chip
    Nature Physics **1**, 57 (2005)
  - Radiofrequency-dressed-state potentials for neutral atoms
    Nature Physics **2**, 710 (2006)
  - Non-equilibrium coherence dynamics in one-dimensional Bose gases
    Nature **449**, 324 (2007)
  - Probing quantum and thermal noise in an interacting many-body system
    Nature Physics **4**, 489 (2008)



- **Magnetic Field Microscope**
  - Bose-Einstein condensates - Microscopic magnetic-field imaging
    Nature **435**, 440 (2005)
  - Long-Range Order in Electronic Transport through Disordered Metal Films
    Science **319**, 1226 (2008)



- *Quantum Communication*
  Quantum memory: connecting photons to atoms
  - Experimental quantum teleportation of a two-qubit composite system
    Nature Physics **2** 678 (2006)
  - Memory-built-in quantum teleportation with photonic and atomic qubits
    Nature Physics **4**, 103-107 (2008)
  - Entanglement Swapping with Storage and Retrieval of Light: A Building Block of Quantum Repeaters
    Nature in print (2008), arXiv:0803.1810