Quantum many-body dynamics of ultracold atoms

Near equilibrium dynamics: collective modes

Observation of the amplitude Higgs mode in the superfluid state of bosons in optical lattices

Experiment: Manuel Endres, Immanuel Bloch and MPQ team
Theory: David Pekker (Caltech), Eugene Demler

Far from equilibrium dynamics: collective modes

Quantum dynamics of split one dimensional condensates. Prethermalization

Experiment: David Smith, Joerg Schmiedmayer and Vienna team
Theory: Takuya Kitagawa et al.,

Supported by NSF, DARPA OLE, AFOSR MURI, ARO MURI

Near equilibrium dynamics: Observation of the amplitude Higgs mode in the superfluid state of bosons in an optical lattice

Experiment: Manuel Endres, Immanuel Bloch and MPQ team
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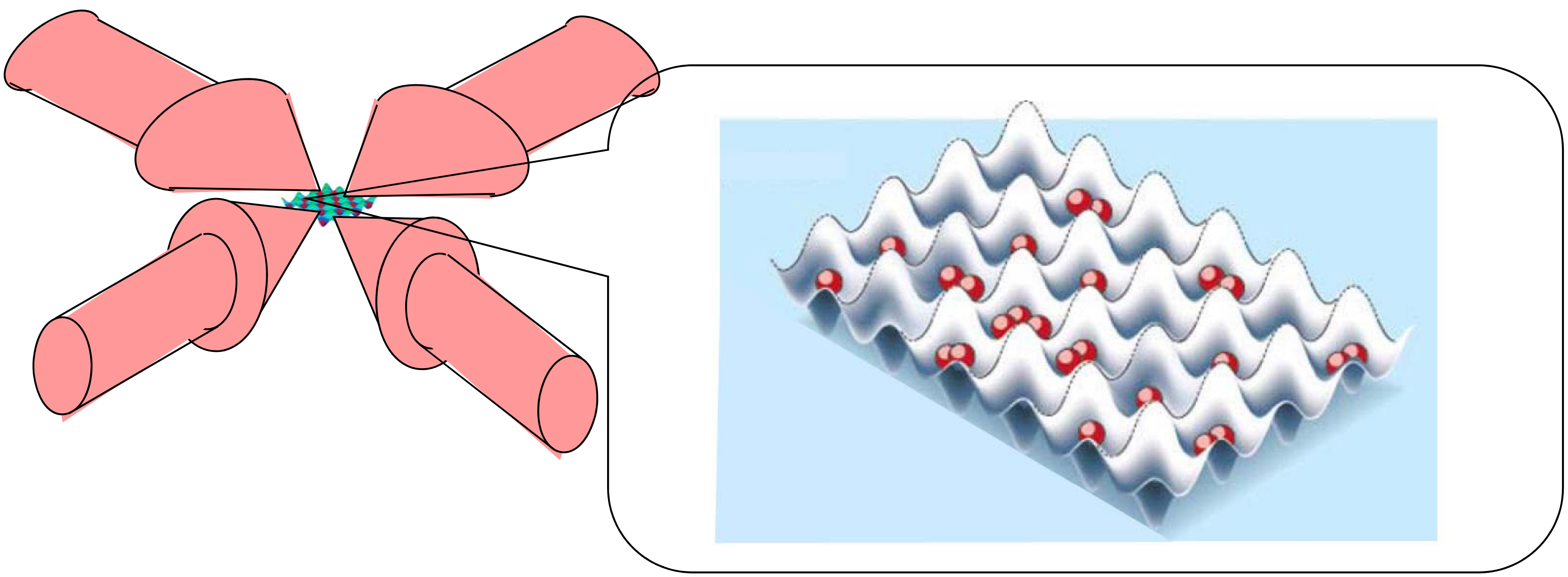
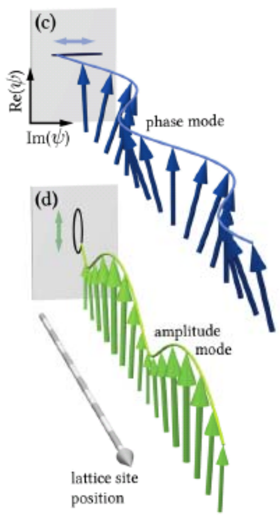


Collective modes of strongly interacting superfluid bosons

Order parameter $\langle b_i \rangle = \Phi = |\Phi| \; e^{i\theta}$ Breaks U(1) symmetry



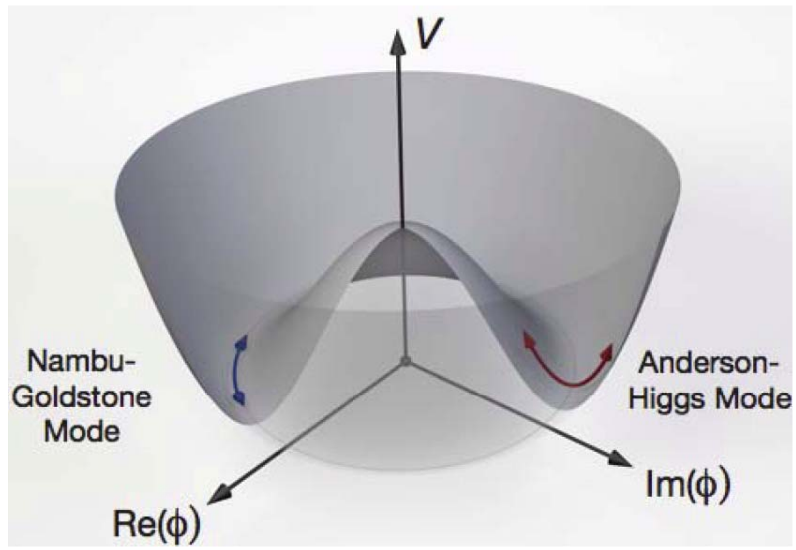
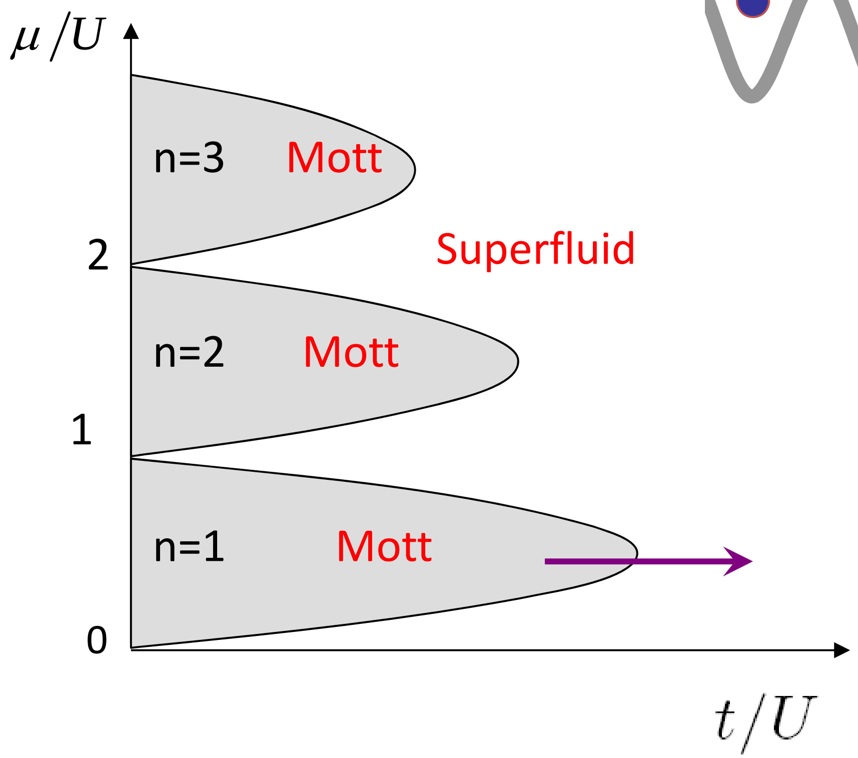


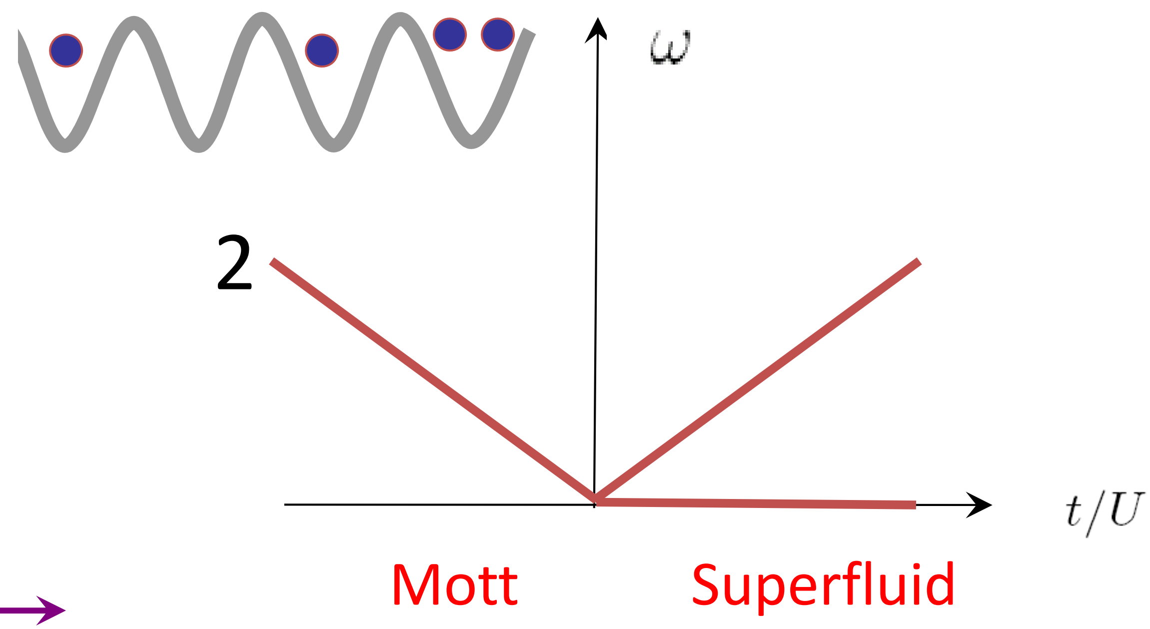
Figure from Bissbort et al. (2010)

Phase (Goldstone) mode = gapless Bogoliubov mode $\omega = c \mid \vec{q} \mid$

Gapped amplitude mode (Higgs mode) $\omega = \sqrt{\Delta^2 + c^2 q^2}$

Excitations of the Bose Hubbard model



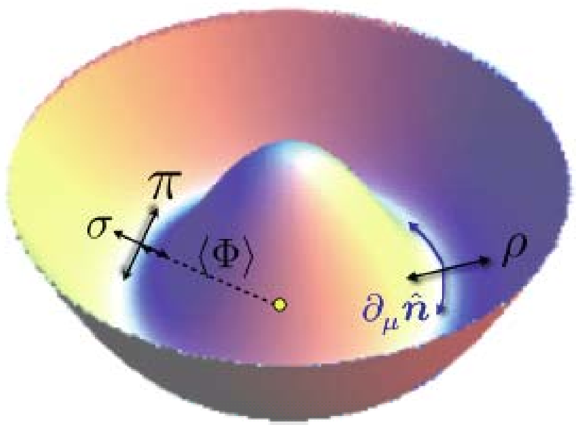


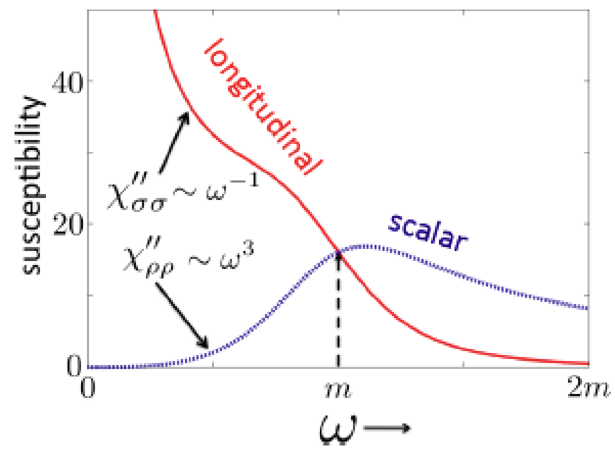
Softening of the amplitude mode is the defining characteristic of the second order Quantum Phase Transition

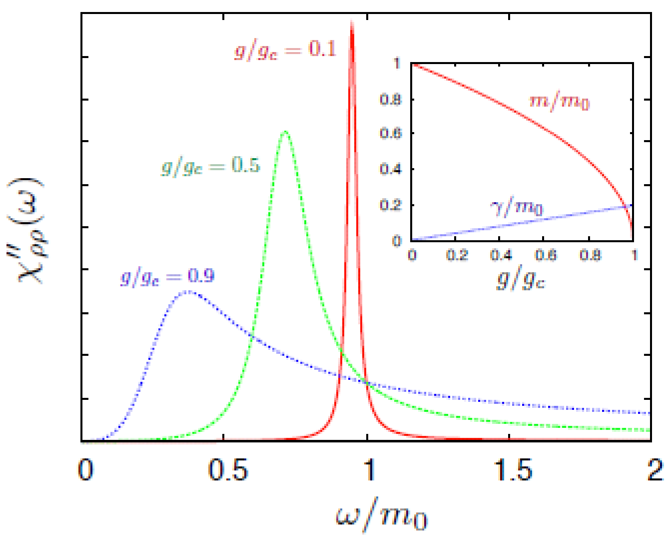
Is there a Higgs resonance 2d?

D. Podolsky et al., arXiv:1108.5207

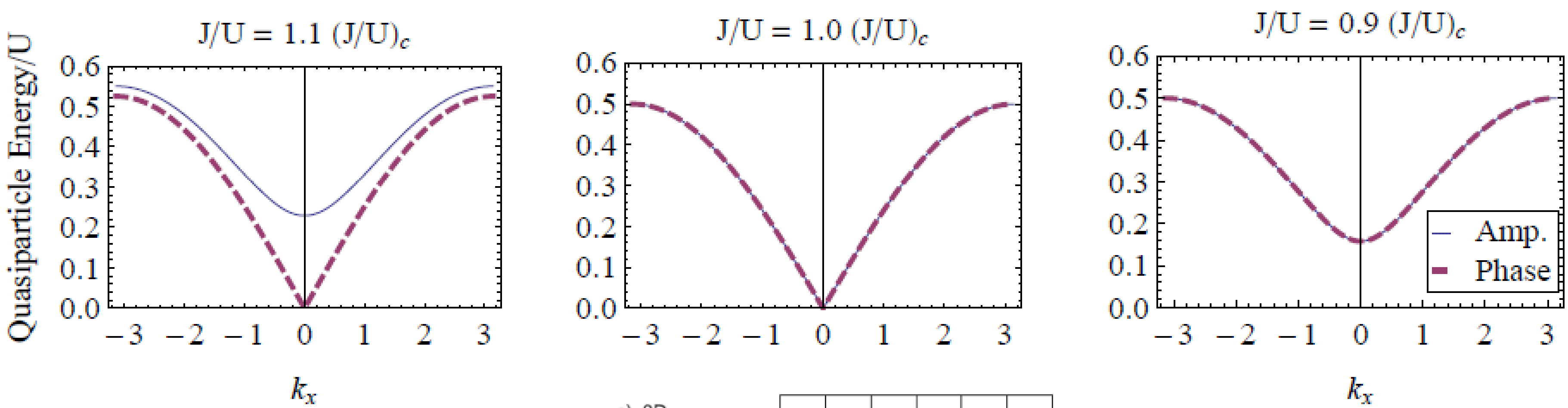
Earlier work: S. Sachdev (1999), W. Zwerger (2004)



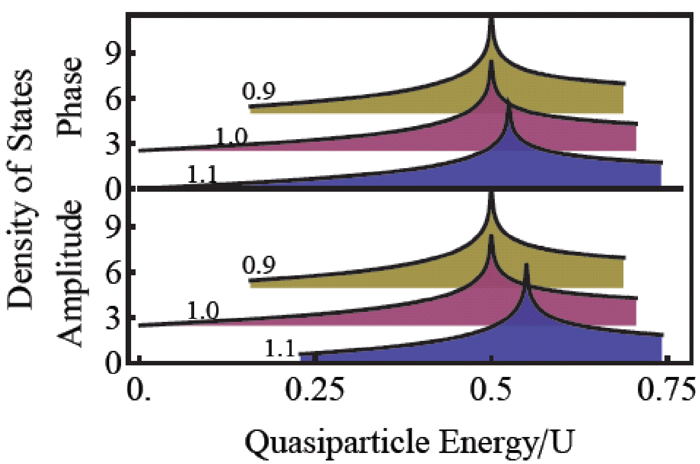


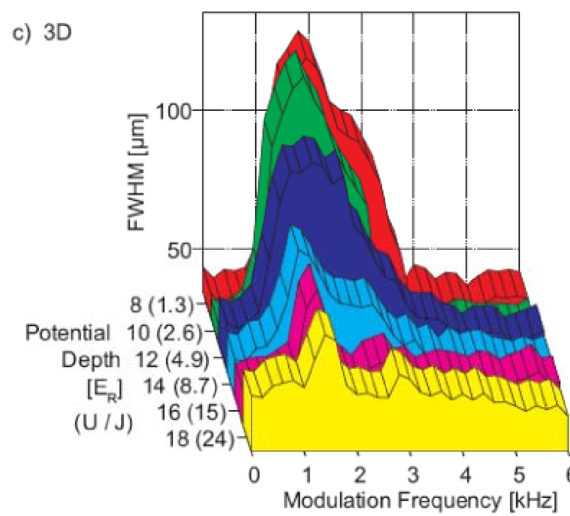


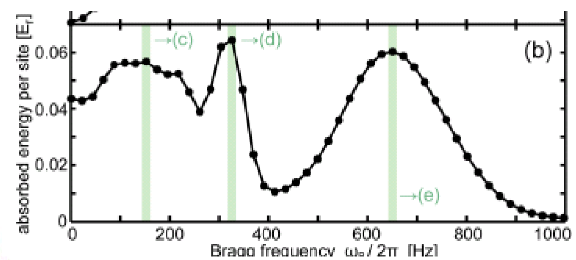
Why it is difficult to observe the amplitude mode



Bissbort et al., PRL(2010)



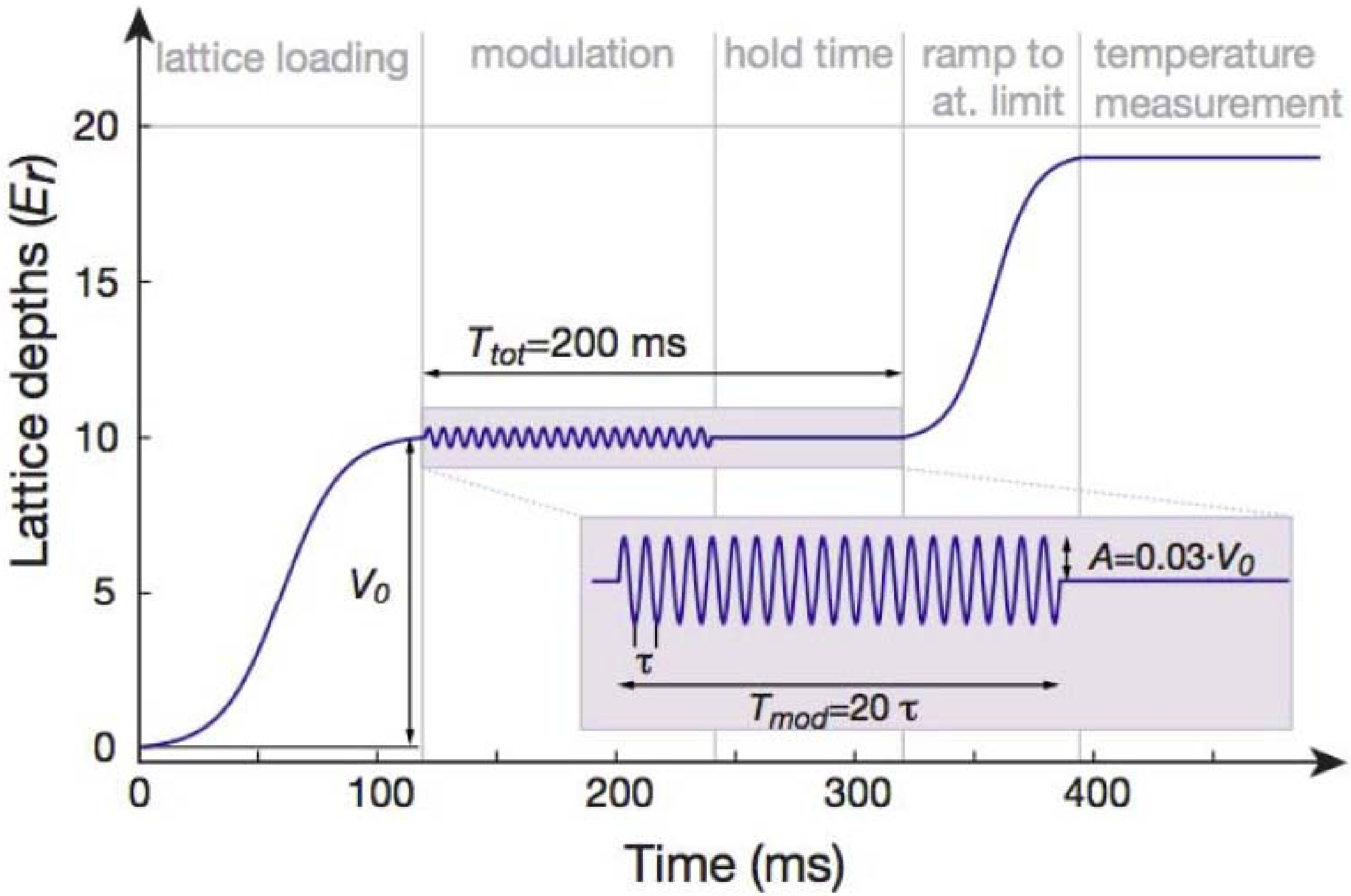




Stoferle et al., PRL(2004)

Peak at U dominates and does not change as the system goes through the SF/Mott transition

Exciting the amplitude mode

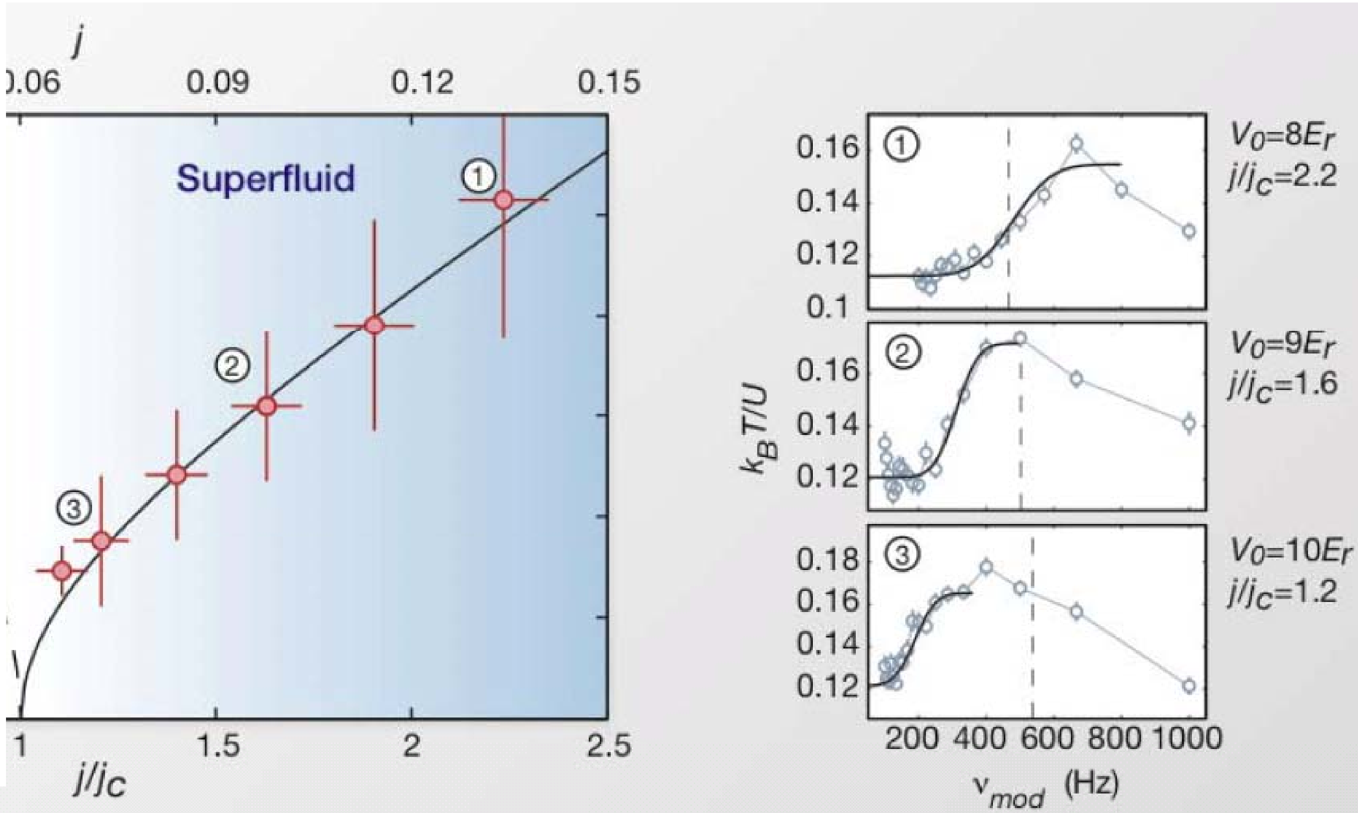


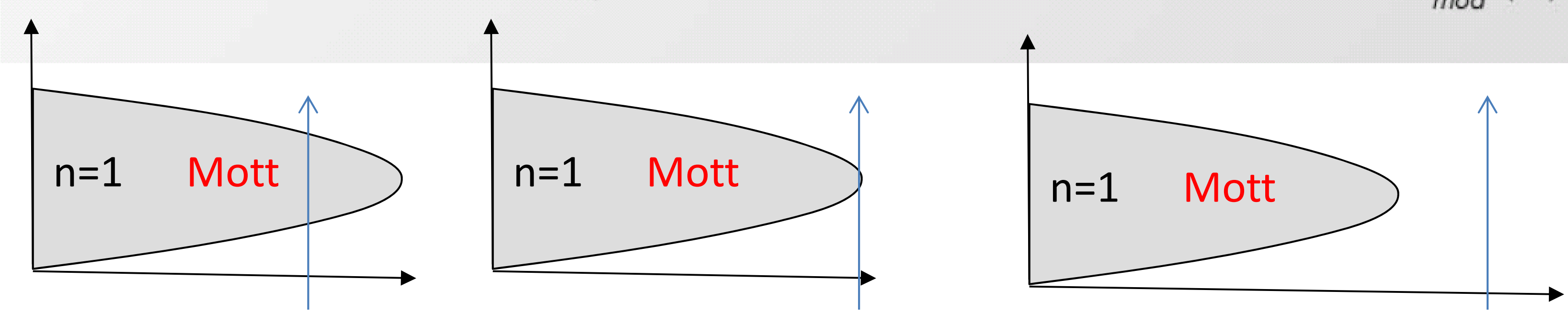
Absorbed energy

$$E = 2\pi(\delta J)^2 S(\omega)\omega T_{\mathrm{mod}}$$

Exciting the amplitude mode

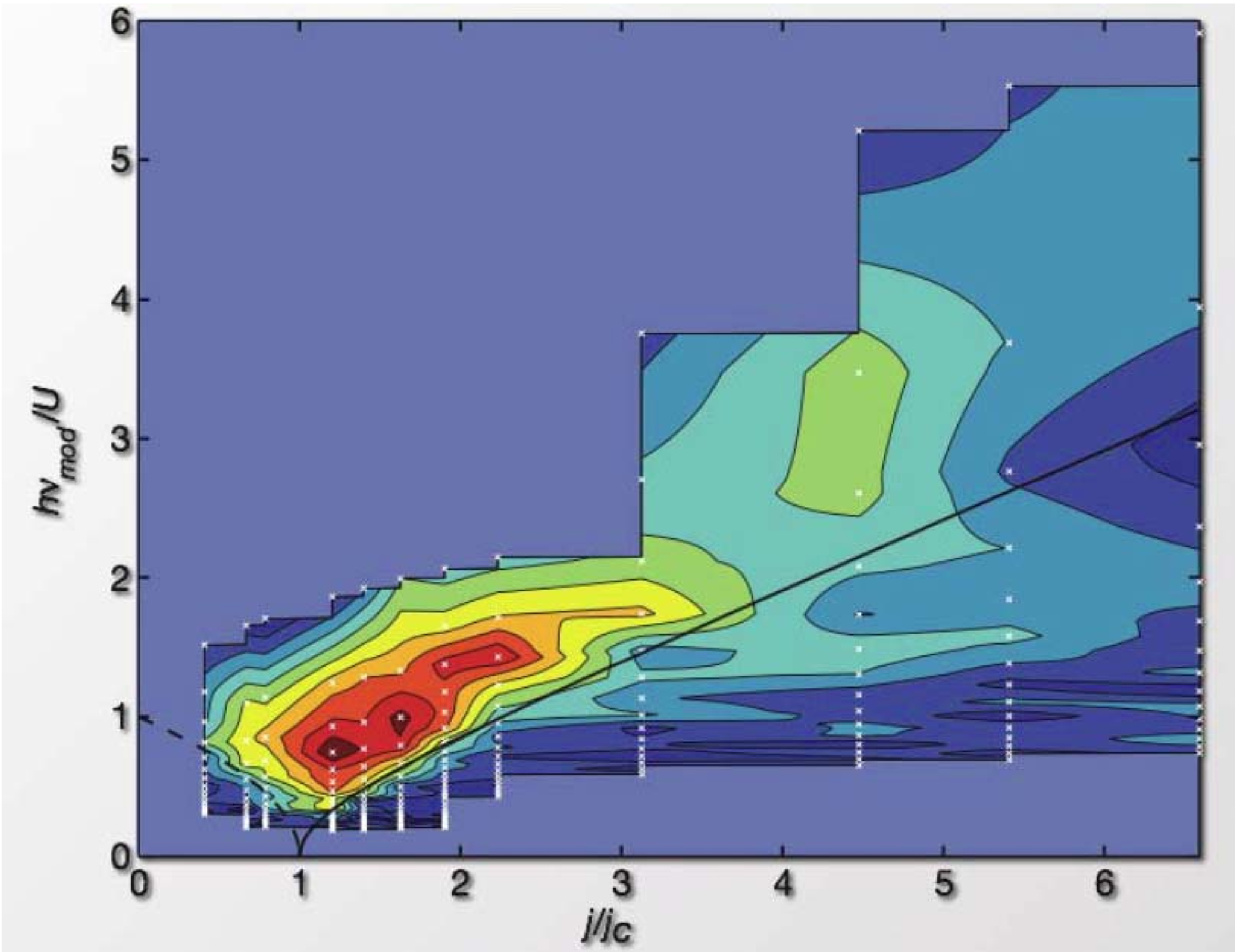
Manuel Endres, Immanuel Bloch and MPQ team





Experiments: full spectrum

Manuel Endres, Immanuel Bloch and MPQ team



Theory. Time dependent mean-field

Semiclassical equations of motion

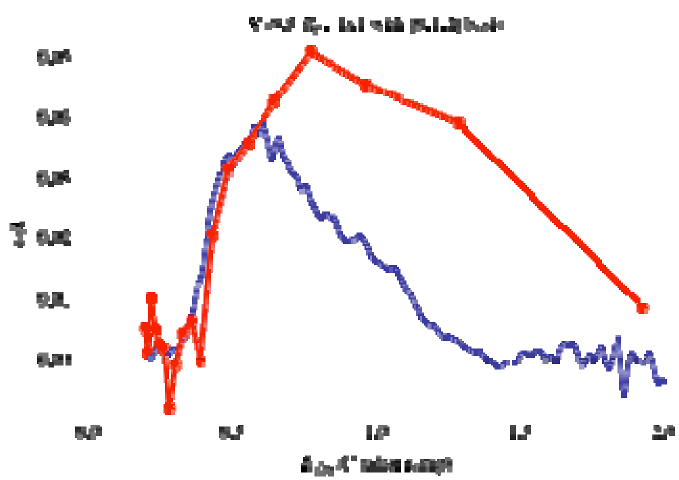
Time-dependent variational wavefunction

$$|\Psi\rangle = \prod_i \left[\sin\frac{\theta_i}{2}\, e^{-\varphi_i/2} \,|\downarrow\rangle_i + \cos\frac{\theta_i}{2}\, e^{\varphi_i/2} \,|\uparrow\rangle_i \right]$$

Landau-Lifshitz equations

$$\frac{d}{dt}\langle S_i^x \rangle = \sum_{\langle j \rangle} \left(-J_\perp \langle S_i^z \rangle \langle S_j^y \rangle + J_z \langle S_i^y \rangle \langle S_j^z \rangle \right)$$

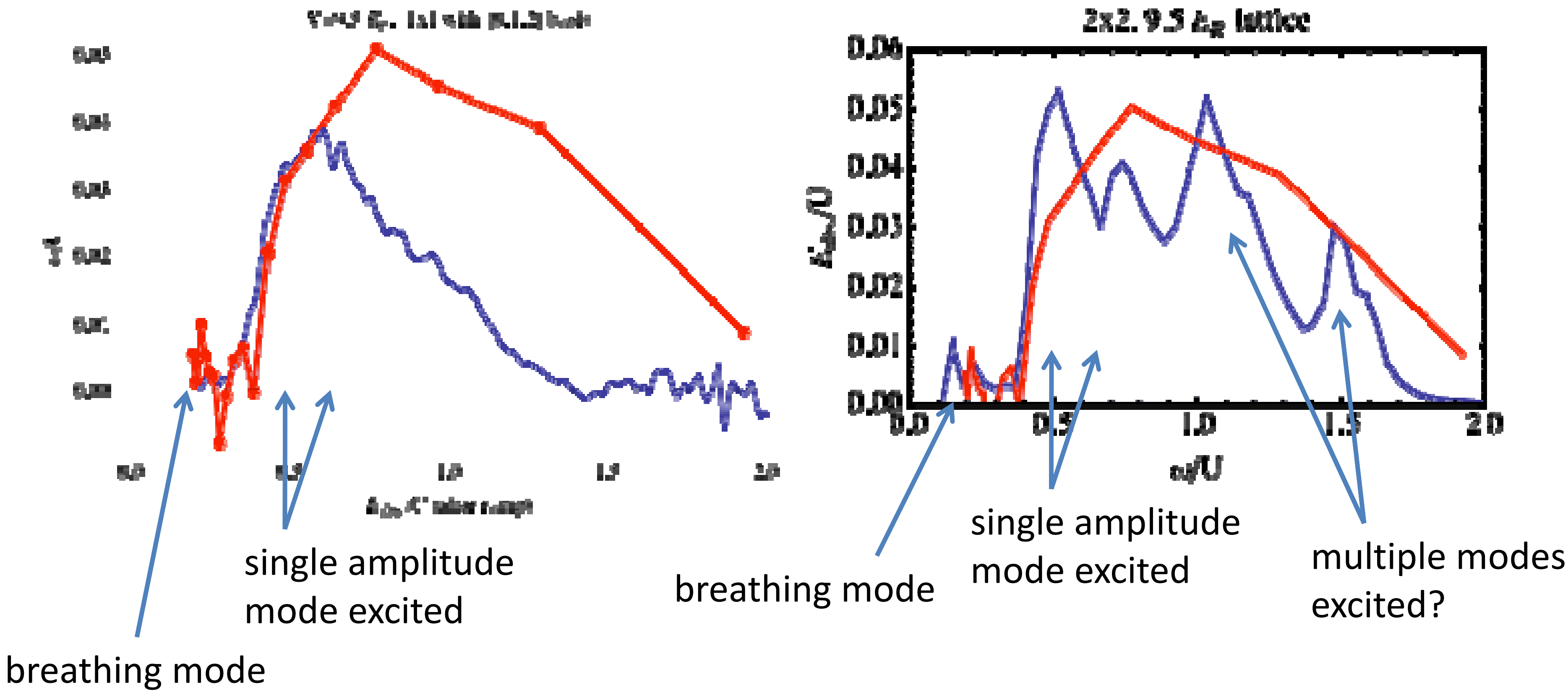
$$\frac{d}{dt}\langle S_i^y \rangle = \ldots \qquad \frac{d}{dt}\langle S_i^z \rangle = \ldots$$



Threshold for absorption is captured very well

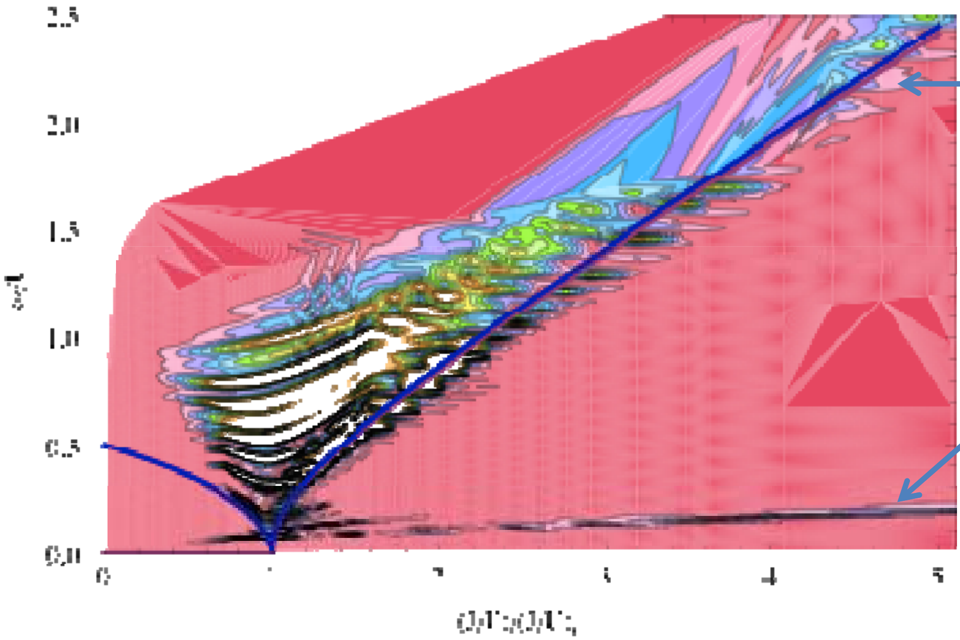
Time dependent cluster mean-field

Lattice height 9.5 Er: (1x1 vs 2x2)



2x2 captures width of spectral feature

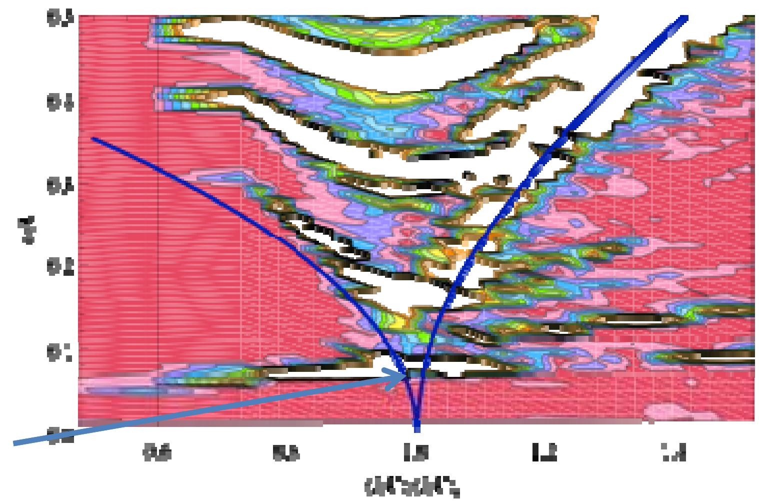
Absorption spectra. Theory (1x1 calculations)



disappearing amplitude mode

Breathing mode

details at the QCP



spectrum remains
gapped due to trap

Far from equilibrium dynamics:
Quantum dynamics of split one dimensional condensates Prethermalization

Theory: Takuya Kitagawa et al.

Phys. Rev. Lett. 104:255302 (2010)

New J. Phys. 13 (2011) 073018

Experiments: D. Simith, J. Schmiedmayer, et al.

arXiv:1112.0013

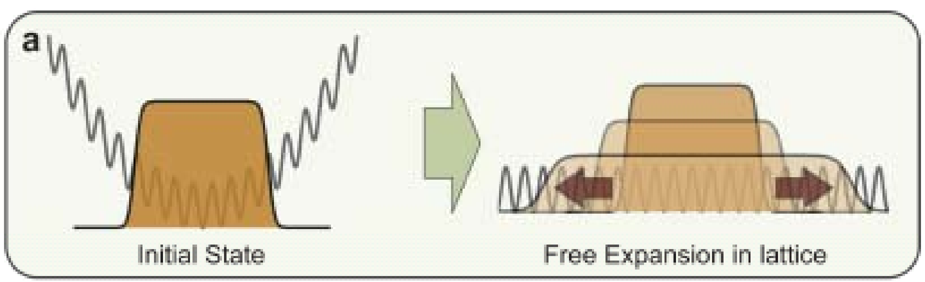
Relaxation to equilibrium

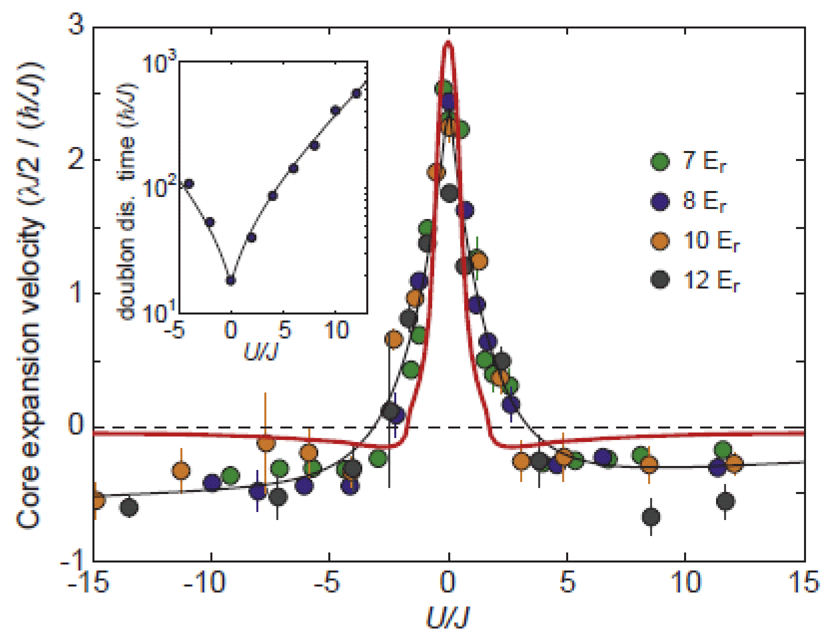
Thermalization: an isolated interacting systems approaches thermal equilibrium at long times (typically at microscopic timescales). All memory about the initial conditions except energy is lost.

Bolzmann equation

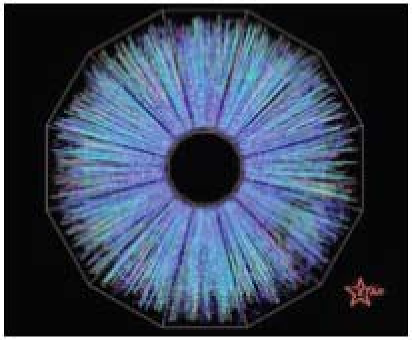
$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial \vec{x}}\vec{v} + \frac{\partial f}{\partial \vec{x}}\vec{F} = -\frac{1}{\tau}(f - f_0)$$

U. Schneider et al., arXiv:1005.3545





Prethermalization



Heavy ions collisions
QCD

PHYSICAL REVIEW D, VOLUME 60, 105026

Time evolution of correlation functions and thermalization

Gian Franco Bonini* and Christof Wetterich†

VOLUME 93, NUMBER 14 PHYSICAL REVIEW LETTERS week ending 1 OCTOBER 2004

Prethermalization

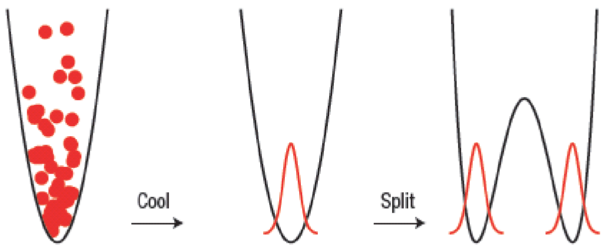
J. Berges, Sz. Borsányi, and C. Wetterich
Institute for Theoretical Physics, Heidelberg University, Philosophenweg 16, 69120 Heidelberg, Germany
(Received 6 April 2004; published 28 September 2004)

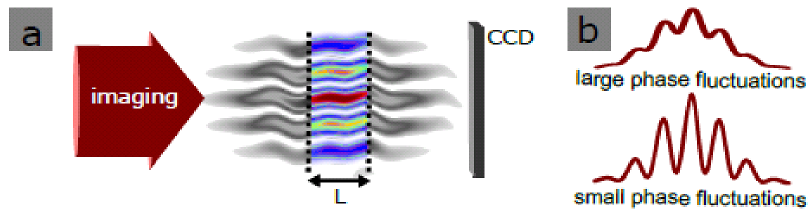
We observe irreversibility and approximate thermalization. At large time the system approaches stationary solution in the vicinity of, but not identical to, thermal equilibrium. The ensemble therefore retains some memory beyond the conserved total energy…This holds for interacting systems and in the large volume limit.

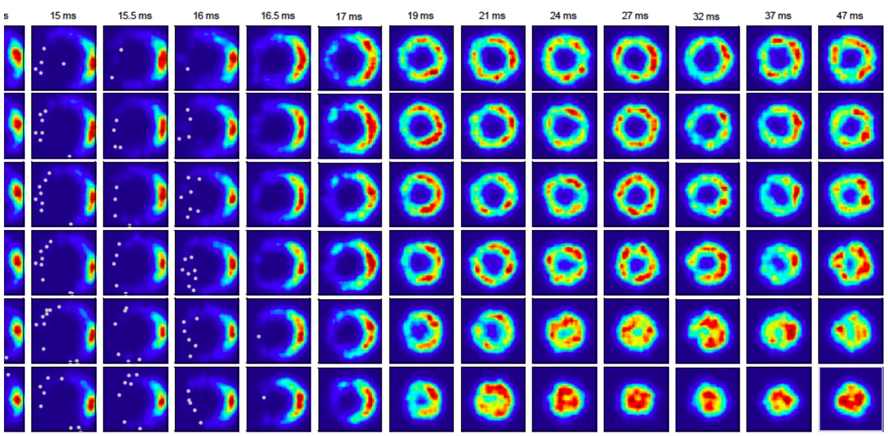
Prethermalization in ultracold atoms, theory: Eckstein et al. (2009); Moeckel et al. (2010), L. Mathey et al. (2010), R. Barnett et al.(2010)

Experimental demonstration of prethermalization

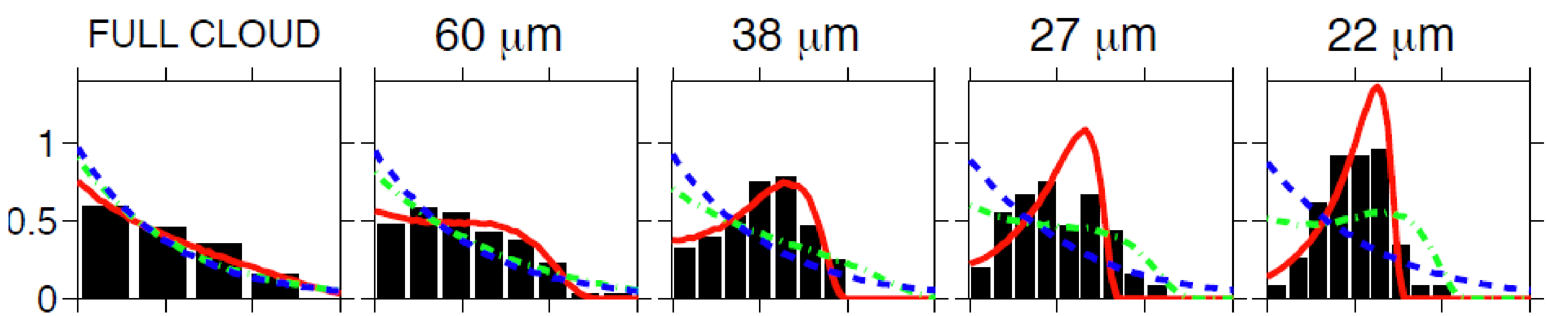
Probing thermolization using local resolution and complete characterization of quantum noise





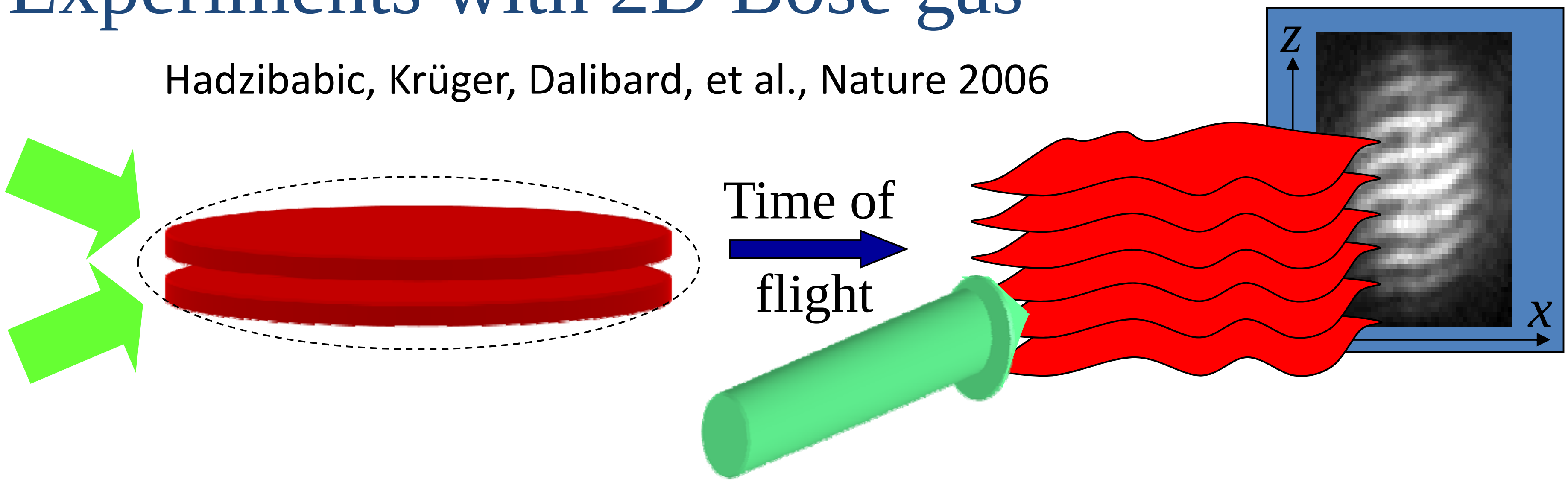


Initial T=120 nK (blue line).
After 27.5 ms identical to thermal system at T= 15 nK
At all lengthscales
In all correlation functions

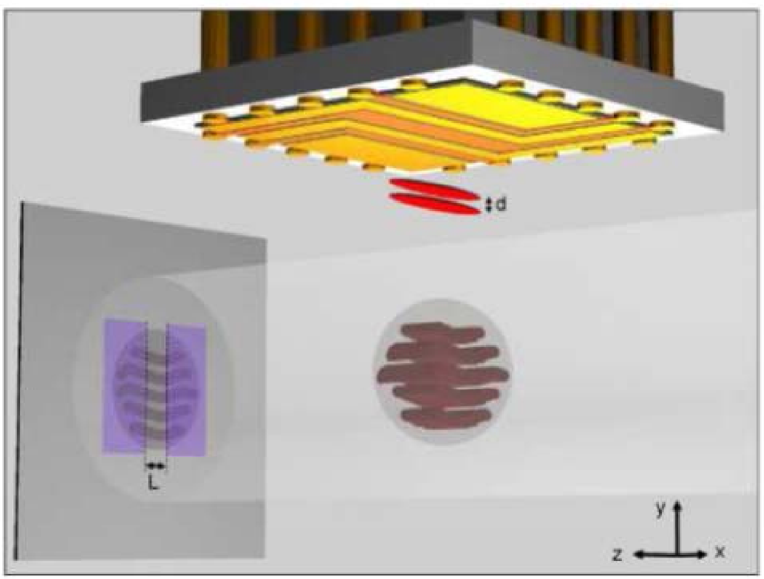


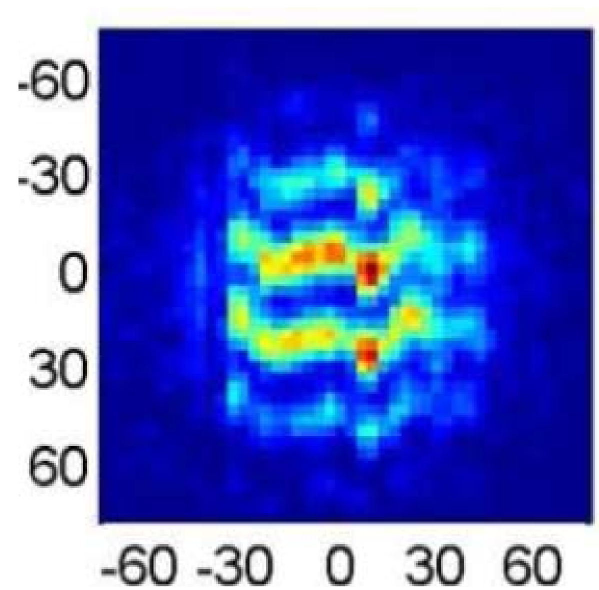
Experiments with 2D Bose gas

Hadzibabic, Krüger, Dalibard, et al., Nature 2006

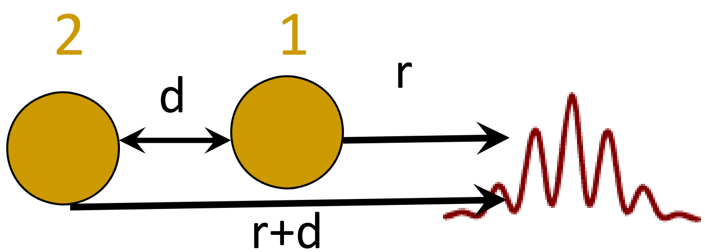


Experiments with 1D Bose gas Hofferberth et al., Nat. Physics 2008





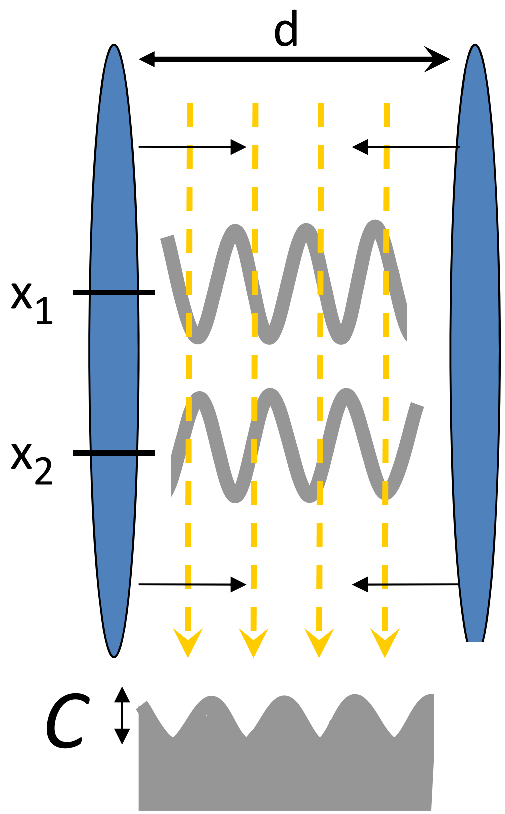
Interference experiments with condensates



$$\psi(r) = \psi_1(r) + \psi_2(r)$$

$$\rho_{\text{int}}(r) = e^{i\frac{m\,d\,r}{\hbar\,t}}\, e^{i(\phi_2 - \phi_1)} + \text{c.c.}$$

Assuming ballistic expansion



Interference of fluctuating condensates

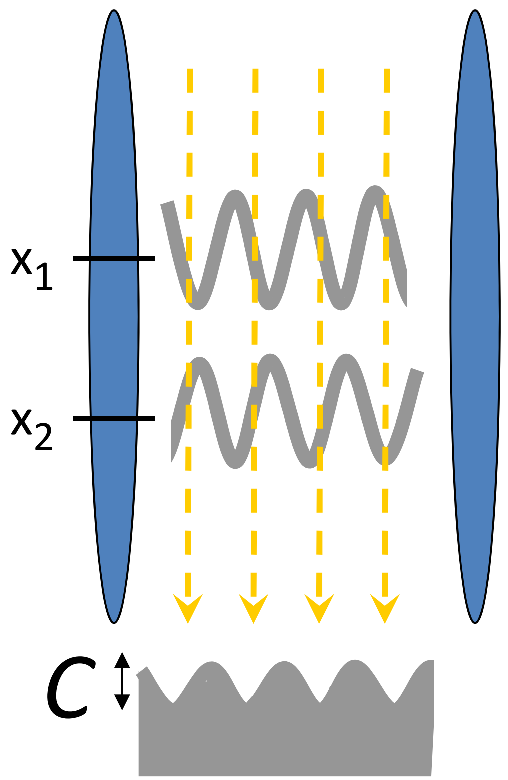
Polkovnikov et al. (2006)

Amplitude of interference fringes

$$C = \int_0^L dx\, e^{i(\phi_1(x)-\phi_2(x))}$$

Distribution function of fringe amplitudes for interference of fluctuating condensates

Polkovnikov et al. (2006), Gritsev et al. (2006), Imambekov et al. (2007)



C is a quantum operator.

The measured value of C will fluctuate from shot to shot

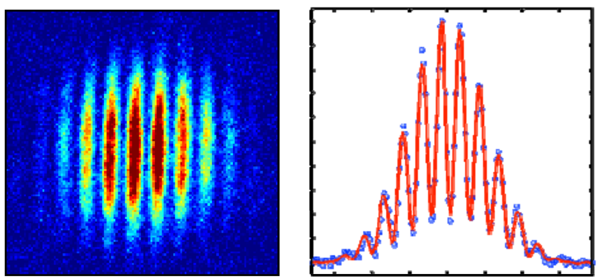
$$< C^n > = \int dz_1 \cdots dz_n \langle e^{i\phi(z_1)} \ldots e^{i\phi(z_n)} \rangle$$

Higher moments reflect higher order correlation functions

Experiments analyze distribution function of C

FDF of phase and contrast

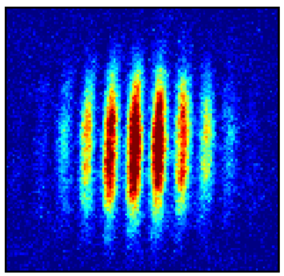
- Matter-wave interferometry

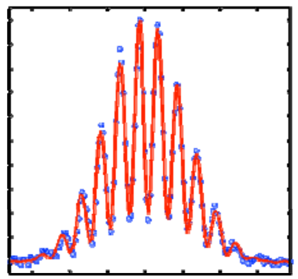


phase, contrast

FDF of phase and contrast

- Matter-wave interferometry

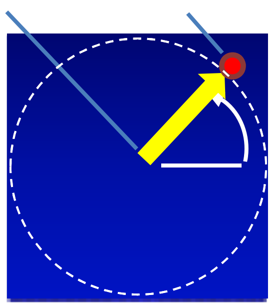




→ phase, contrast

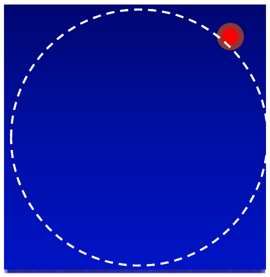
- Plot as circular statistics

contrast



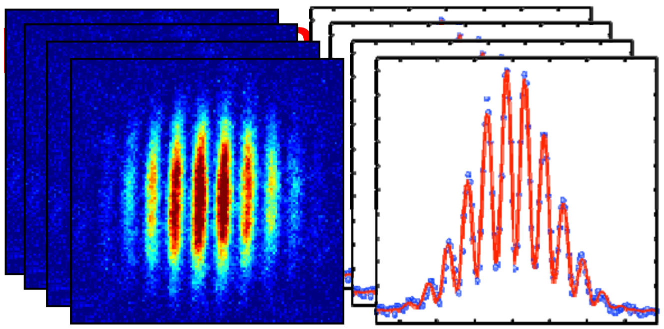
phase

→



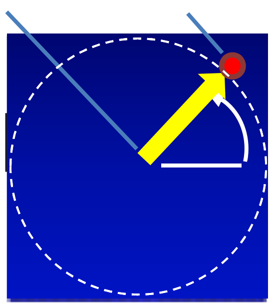
FDF of phase and contrast

- Matter-wave interferometry: repeat

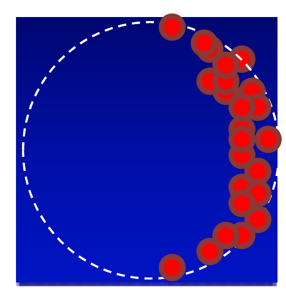


→ phase, contrast i>100

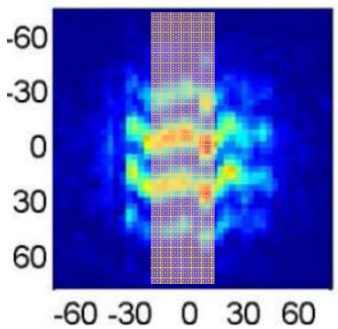
contrast$_i$

-  *phase* →

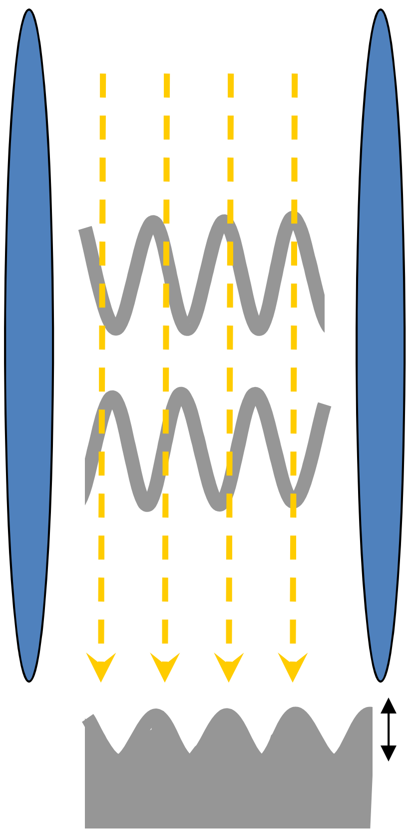
accumulate statistics



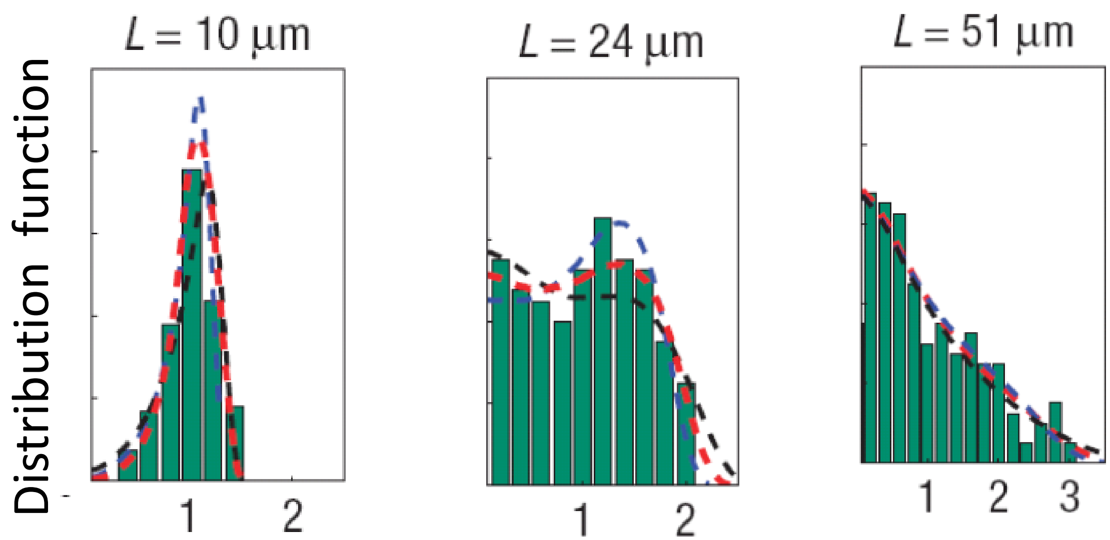
Equilibrium. Interference of independent 1d condensates



Theory: Altman, Imambekov, Gritsev, Polkovnikov, Demler
Experiments: Hofferberth et al., Nature Physics (2008)

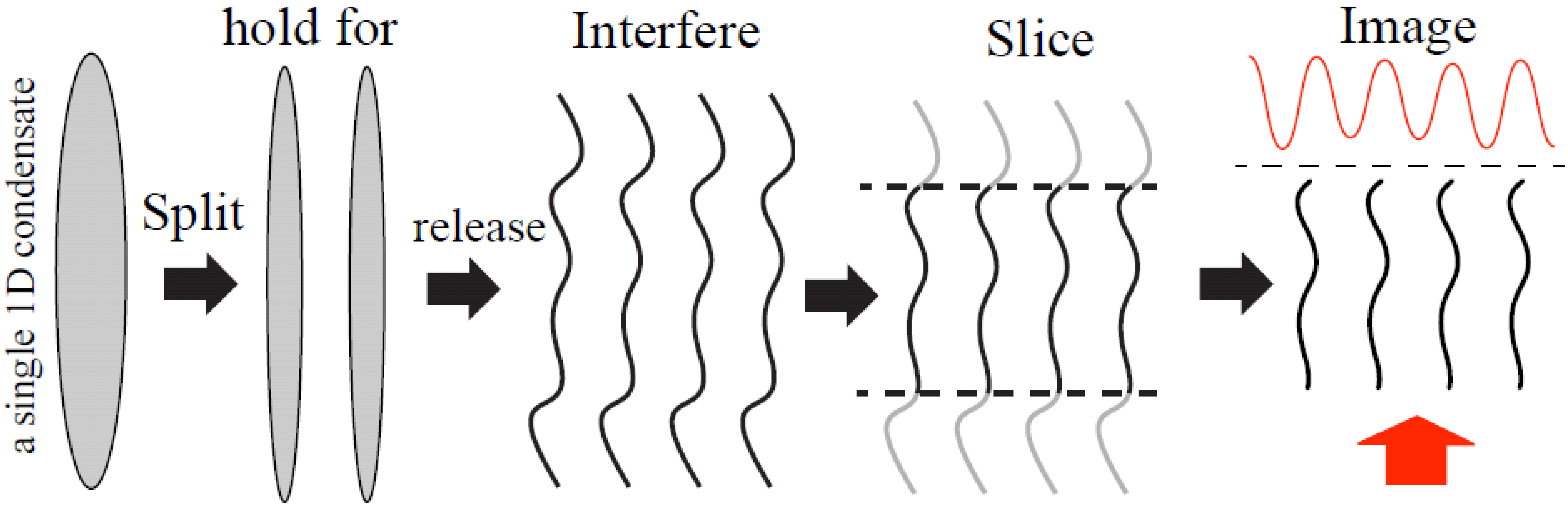


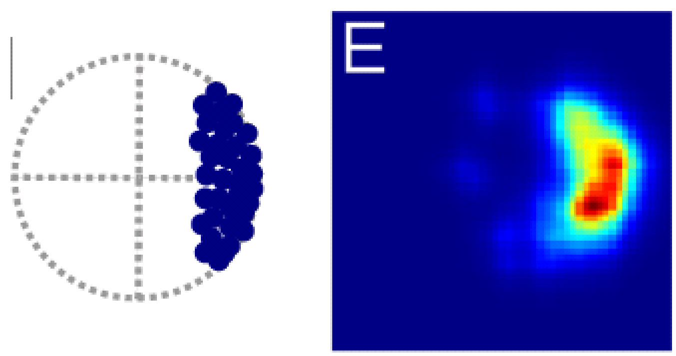
fringe contrast



contrast normalized by the average value

Measurements of dynamics of split condensate

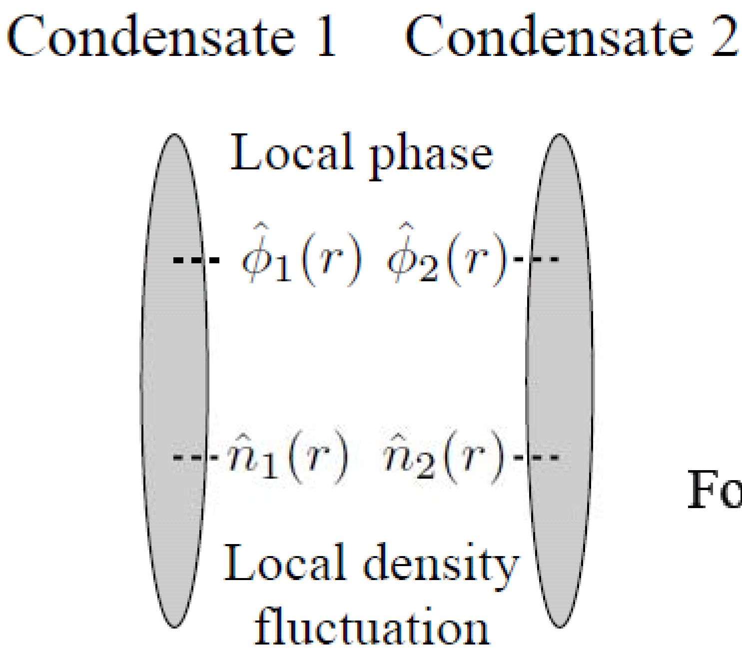




Theoretical analysis of dephasing

Luttinger liquid model

Luttinger liquid model of phase dynamics



$$\hat{\phi}_s(r) = \hat{\phi}_1(r) - \hat{\phi}_2(r)$$

$$2\hat{n}_s(r) = \hat{n}_1(r) - \hat{n}_2(r)$$

$$[\hat{n}_s(r), \hat{\phi}_s(r')] = -i\delta(r - r')$$

For identical average densities, phase difference modes decouple from the phase sum mode

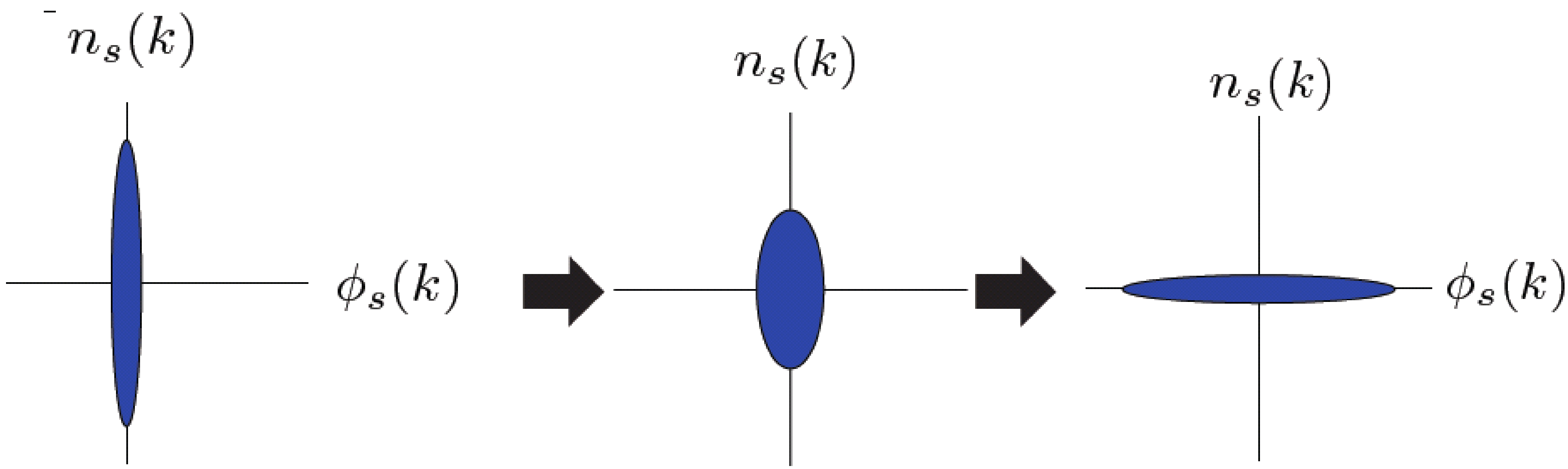
$$H_s = \frac{c_s}{2} \int \left[\frac{K_s}{\pi} (\nabla \hat{\phi}_s(r))^2 + \frac{\pi}{K_s} \hat{n}_s^2(r) \right] dr$$

Luttinger liquid model of phase dynamics

$$H_s = \frac{c_s}{2}\int \left[\frac{K_s}{\pi}(\nabla\hat{\phi}_s(r))^2 + \frac{\pi}{K_s}\hat{n}_s^2(r) \right] dr$$

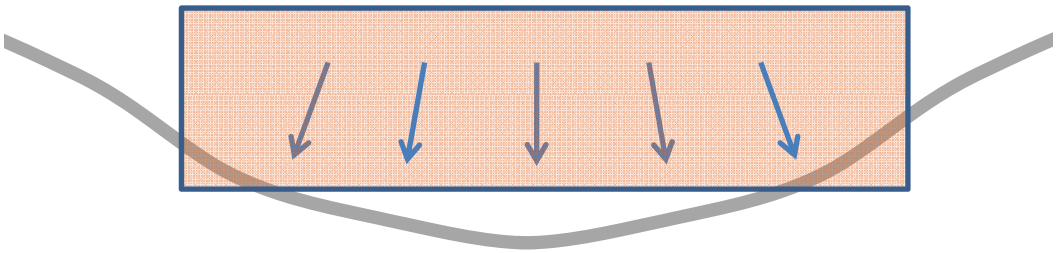
$$= \frac{c_s}{2}\sum_k \left[\frac{K_s k^2}{\pi}\hat{\phi}_s^\dagger(k)\hat{\phi}_s(k) + \frac{\pi}{K_s}\hat{n}_s^\dagger(k)\hat{n}_s(k) \right]$$

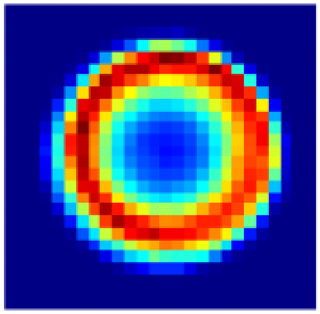
For each k-mode we have simple harmonic oscillators



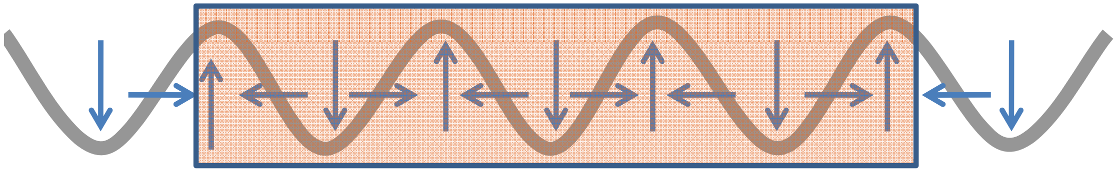
Phase diffusion vs Contrast Decay

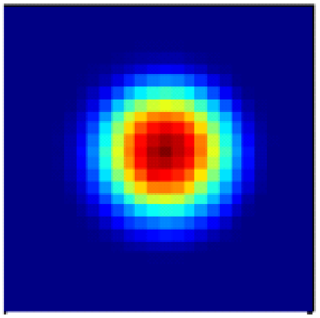
Segment size is smaller than the fluctuation lengthscale





Segment size is longer than the fluctuation lengthscale



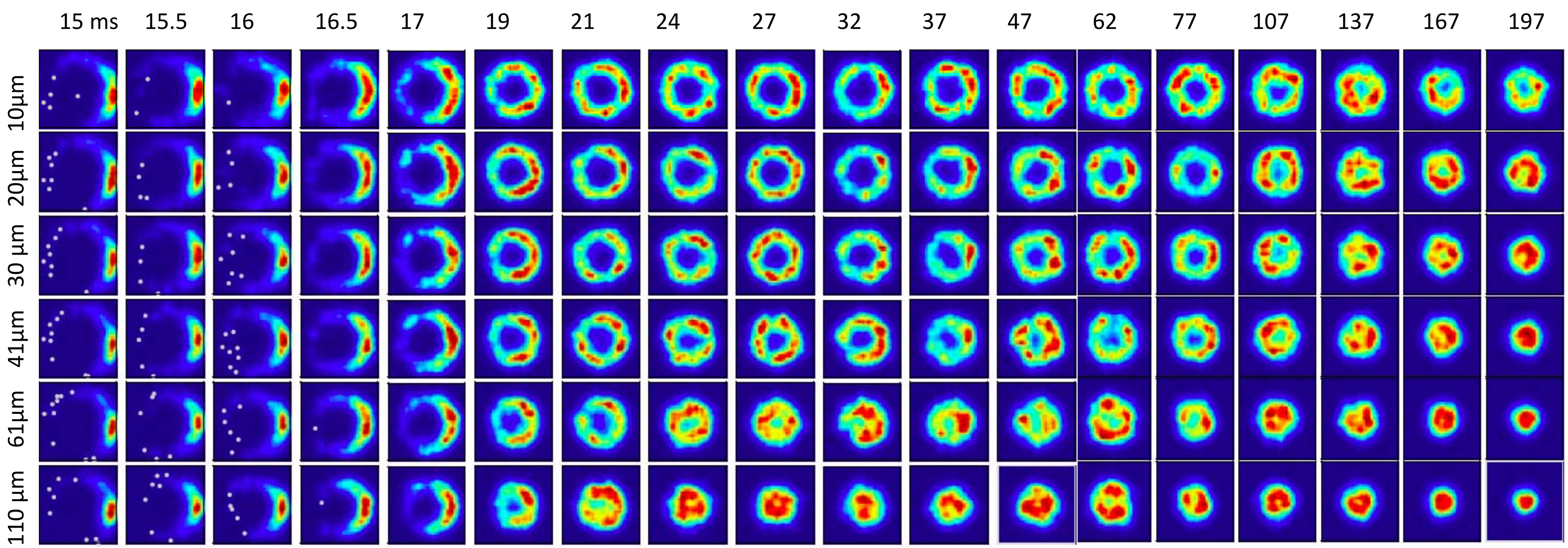


At long times the difference between the two regime occurs for

$$l_0 = \frac{8\,K^2}{\pi^2\,\rho}$$

Length dependent phase dynamics

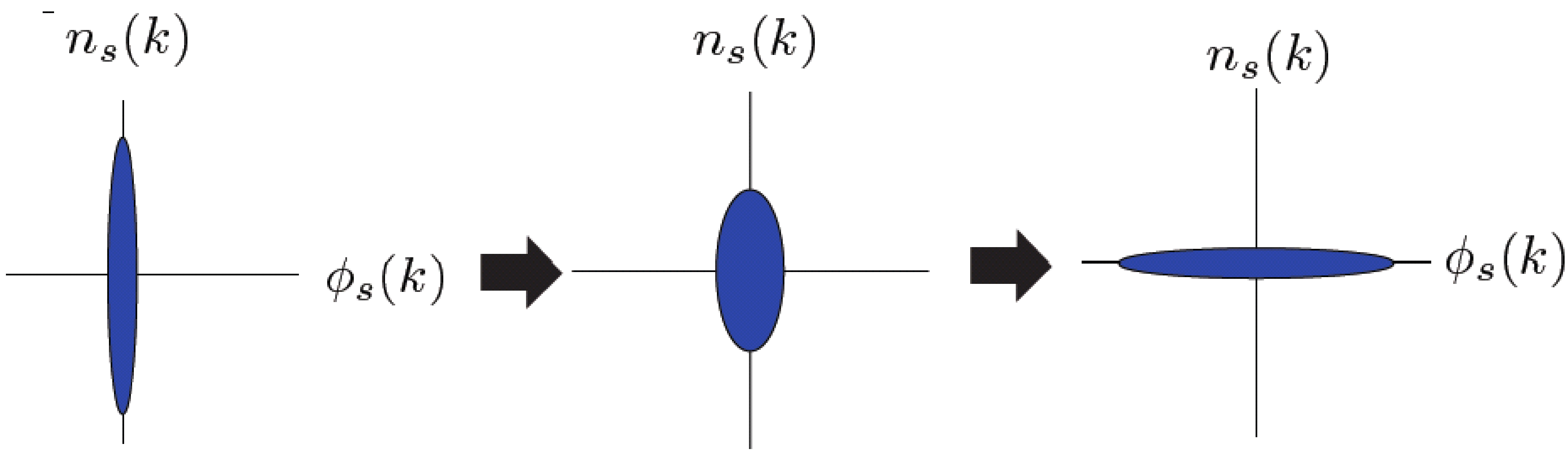
"Short segments" = phase diffusion



"Long segments" = contrast decay

Energy distribution

Initially the system is in a squeezed state with large number fluctuations



Energy stored in each mode initially

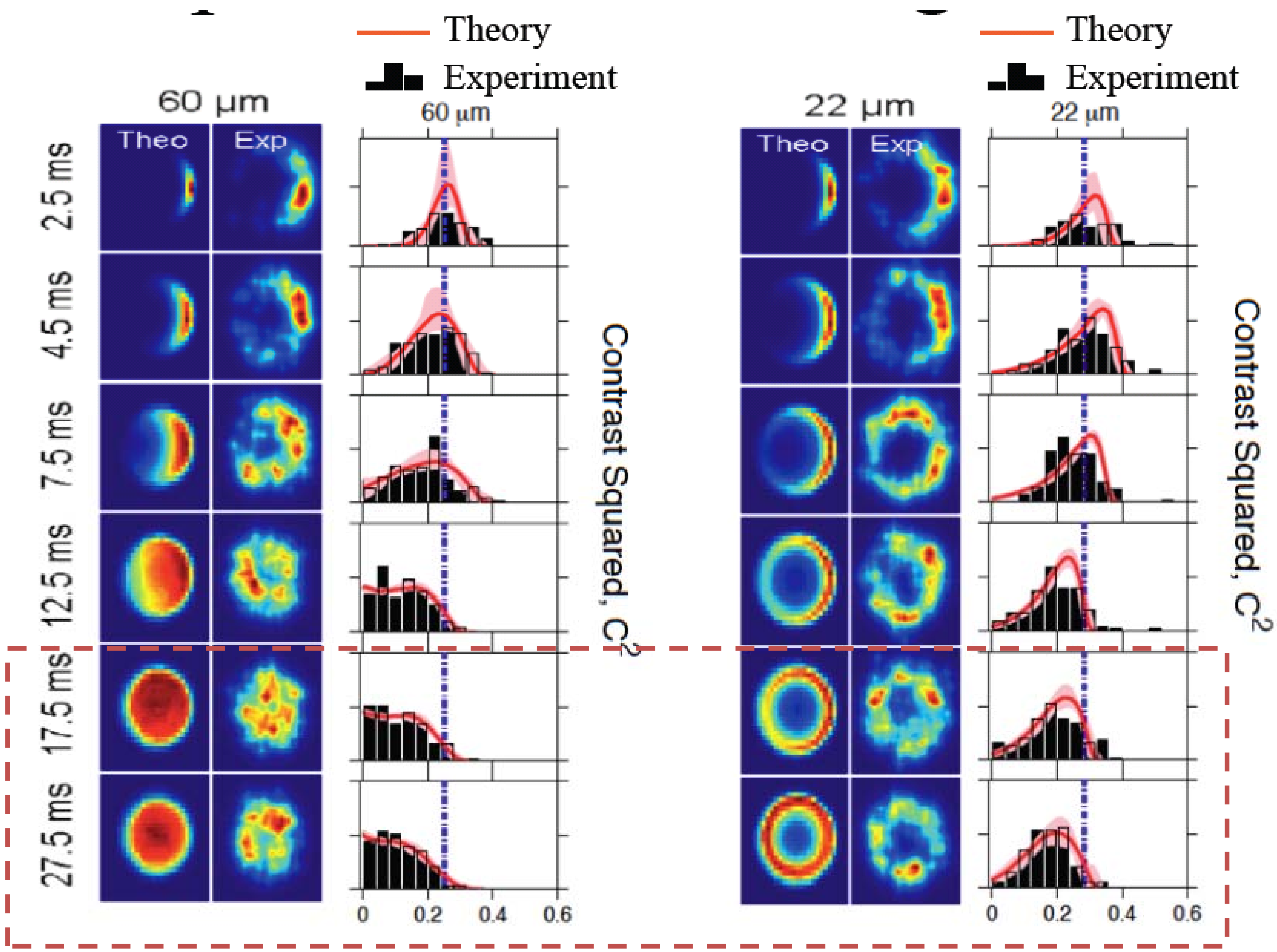
$$E_k = g\, n_s^2(k, t=0) = \frac{g}{\phi_0^2}$$

Equipartition of energy

For 2d also pointed out by Mathey, Polkovnikov in PRA (2010)

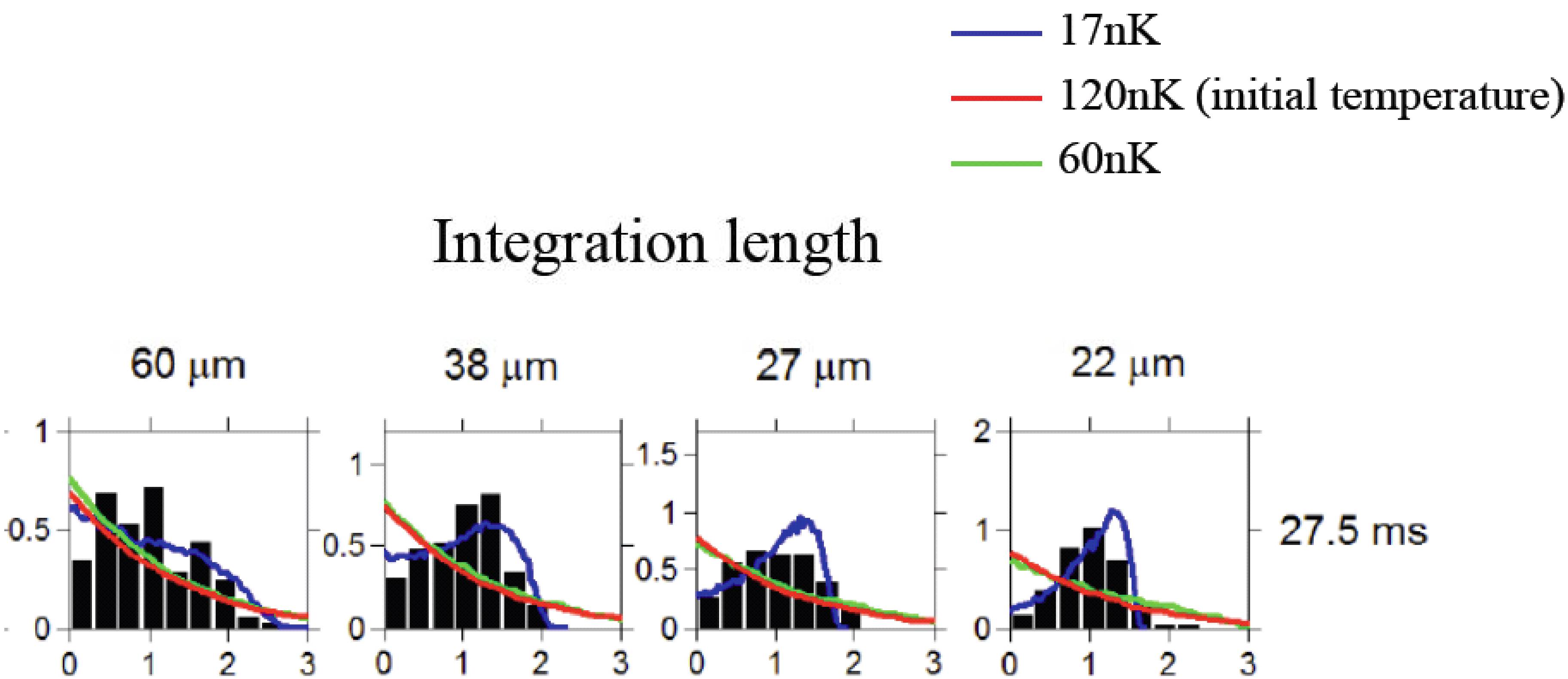
The system should look thermal like after different modes dephase.
Effective temperature is not related to the physical temperature

Comparison of experiments and LL analysis



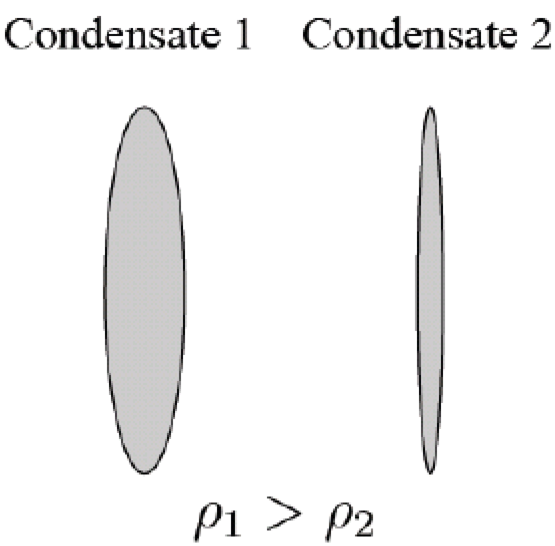
Do we have thermal-like distributions at longer times?

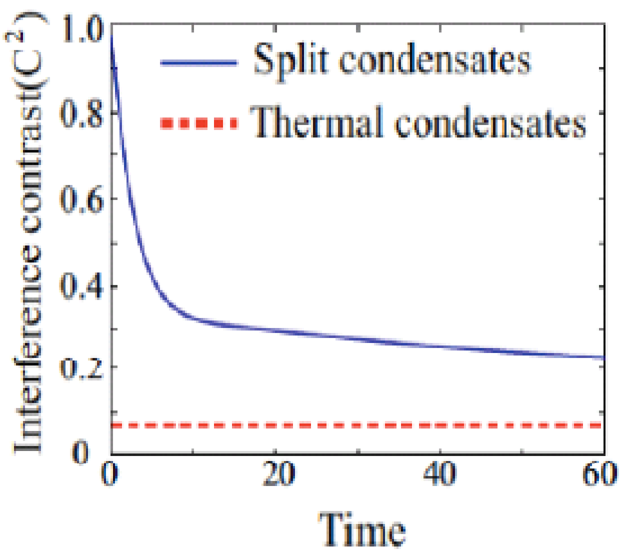
Prethermalization

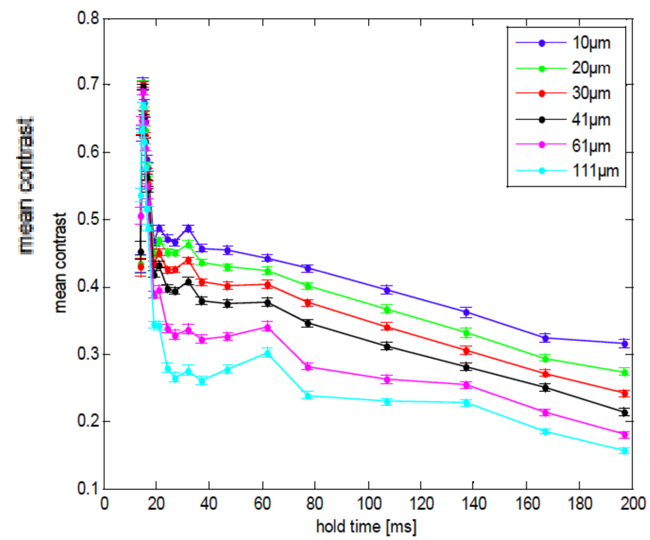


Interference contrast is described by thermal distributions but at temperature much lower than the initial temperature

Long time transient







When the average densities of two condensates are different, the interference contrast relaxes to smaller value as time progresses.

Quantum many-body dynamics of ultracold atoms

Near equilibrium dynamics: collective modes

Observation of the amplitude Higgs mode in the superfluid state of bosons in optical lattices

Experiment: Manuel Endres, Immanuel Bloch and MPQ team
Theory: David Pekker (Caltech), Eugene Demler

Far from equilibrium dynamics: collective modes

Quantum dynamics of split one dimensional condensates. Prethermalization

Experiment: David Smith, Joerg Schmiedmayer and Vienna team
Theory: Takuya Kitagawa et al.,

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