Low-dimensional quantum gases

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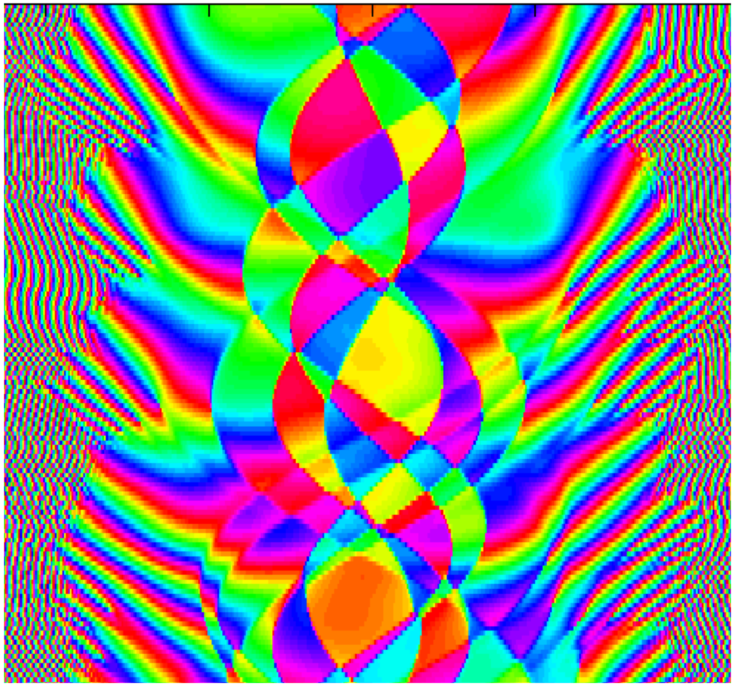
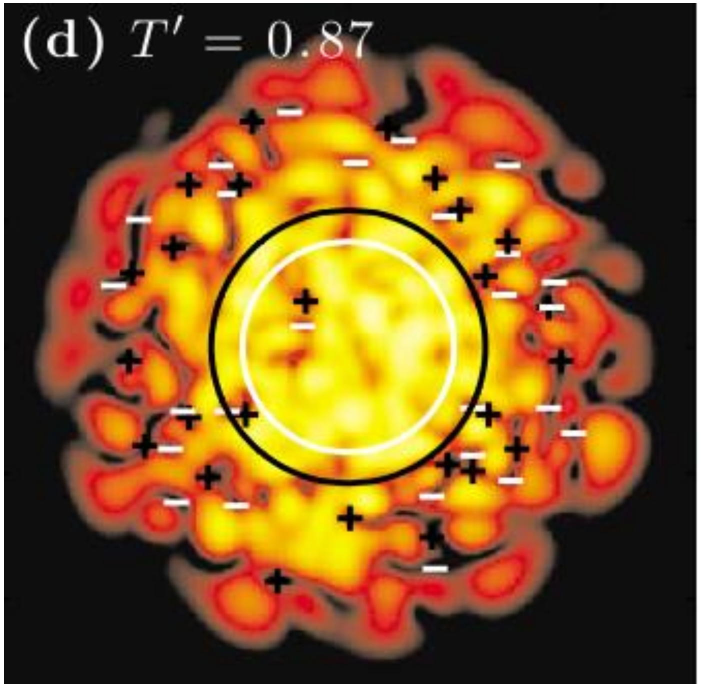
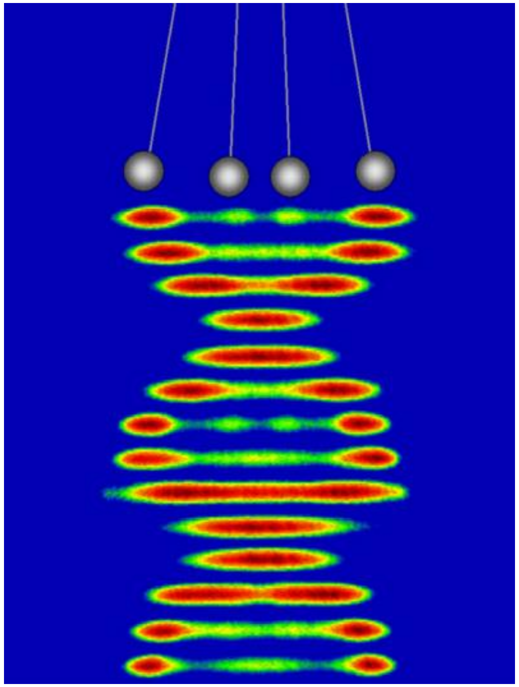




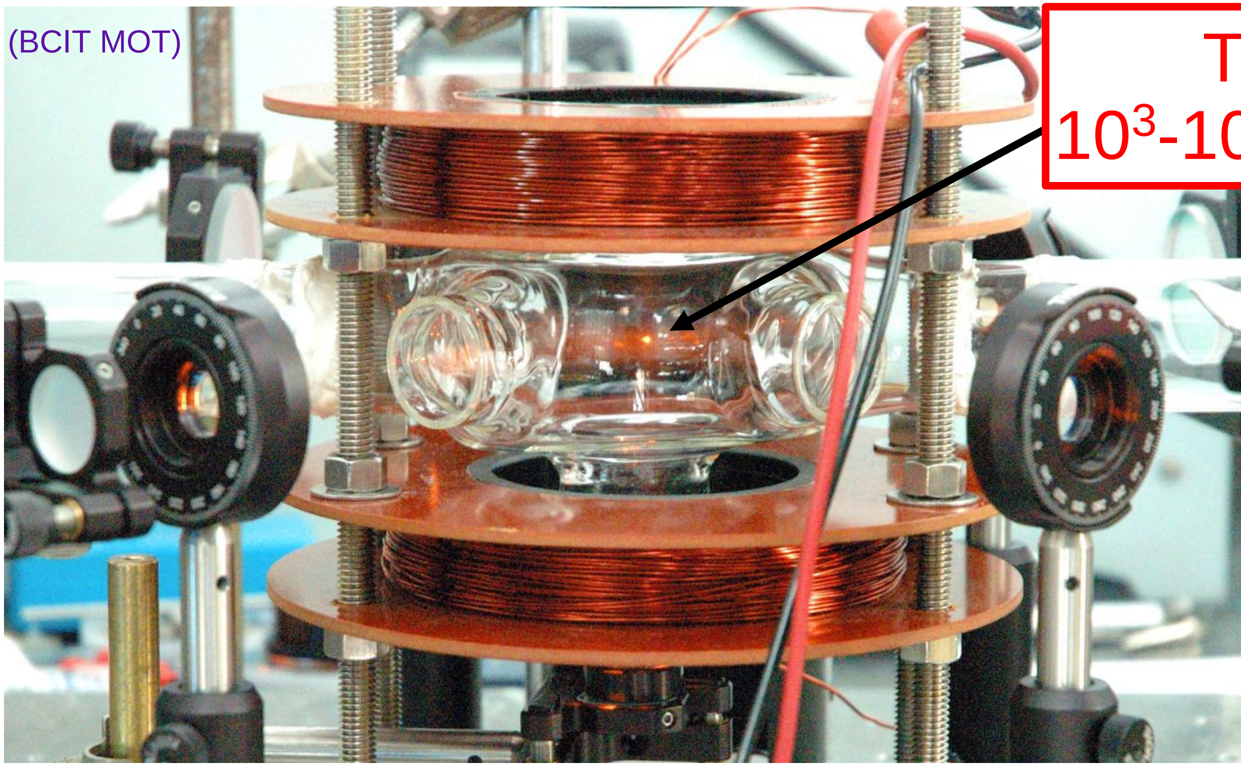


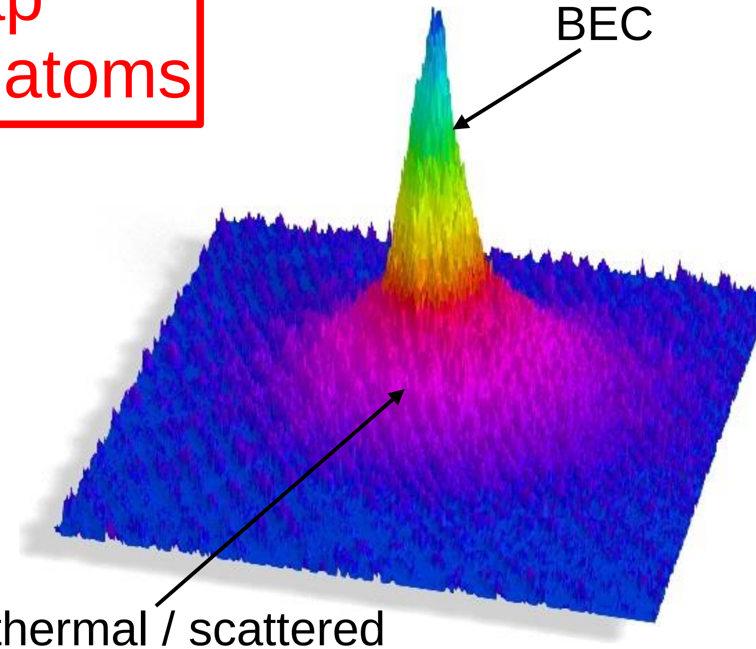
Outline

1. General features of the ultracold gas
2. Reduced dimensions
3. Intergability
4. Quasicondensate
5. Thermal solitons
6. Anderson localization
7. 2D gas – Berezinskii-Kosterlitz-Thouless transition

Ultracold gas - features

"most atoms are concentrated in a small subset of states"





$$\widehat{H} = \int d^3\mathbf{x} \left\{ \widehat{\Psi}^\dagger(\mathbf{x}) \left[V(\mathbf{x}) - \frac{\hbar^2}{2m}\nabla^2 \right] \widehat{\Psi}(\mathbf{x}) + \frac{g}{2} \widehat{\Psi}^\dagger(\mathbf{x})^2 \widehat{\Psi}(\mathbf{x})^2 \right\}$$

(2nd quantization)

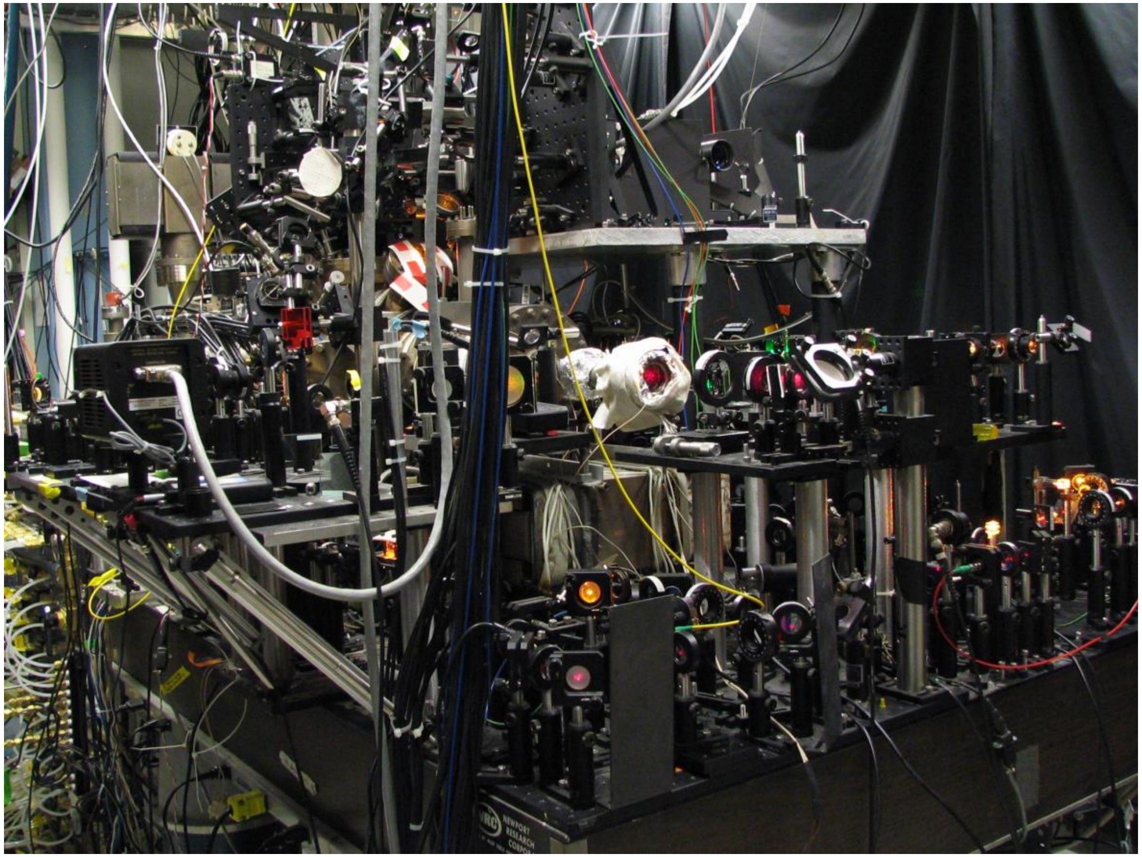
Boson field $\left[\widehat{\Psi}(\mathbf{x}), \widehat{\Psi}^\dagger(\mathbf{x}') \right] = \delta^{(3)}(\mathbf{x} - \mathbf{x}')$

low T → low E
dilute
→ contact, s-wave interactions

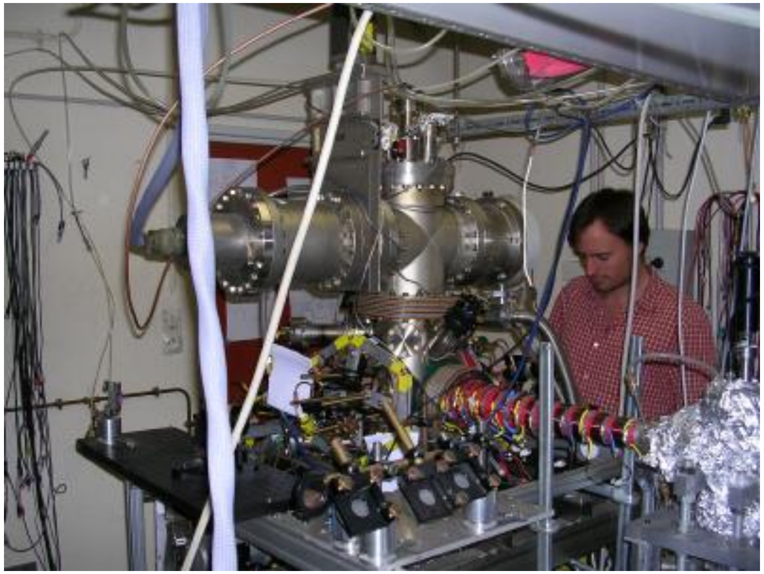
Experiments

Newer look

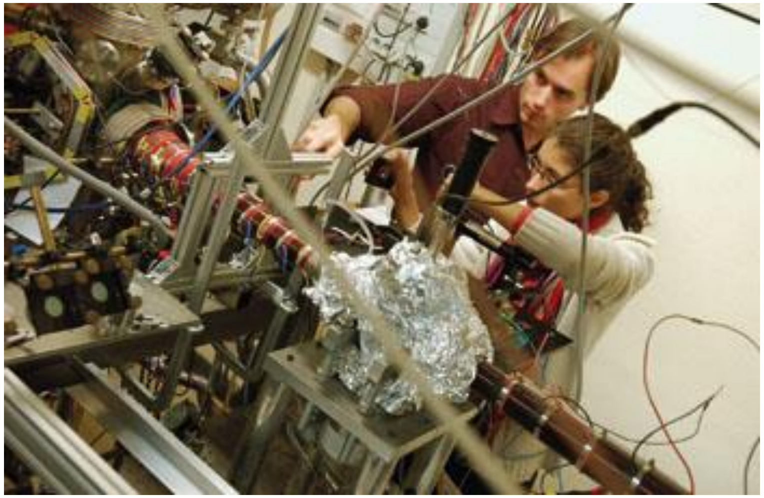
Old-style look



Ketterle expt. MIT



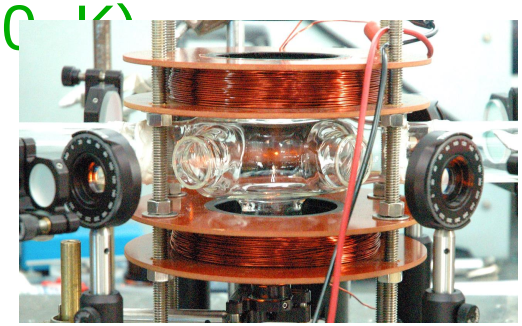
Westbrook expt. Institut d'Optique

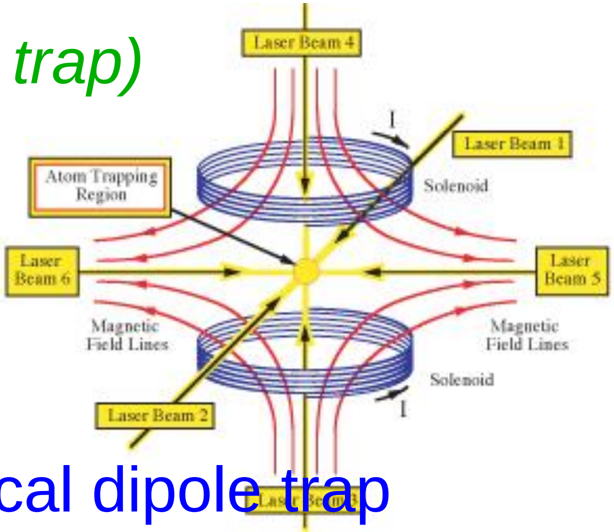


Ultracold gas – cooling

1. Laser cooling + MOT *(Magneto-optical trap)*
(≈100μK)

MOT:

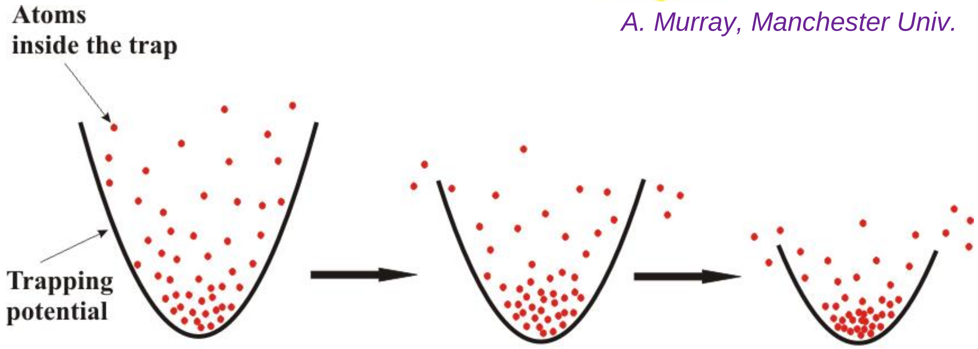




A. Murray, Manchester Univ.

2. Evaporative cooling + magnetic or optical dipole trap
(≈100nK)

Optical dipole trap



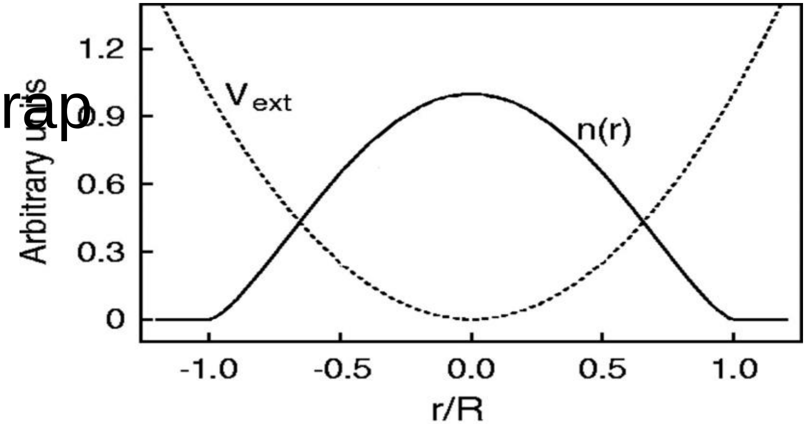
G. Raithel, Univ. Michigan

Traps usually well approximated by a parabolic potential

Typically, 10^5-10^7 atoms in a 3D trap

density 10^{12}-10^{14} cm^{-3}

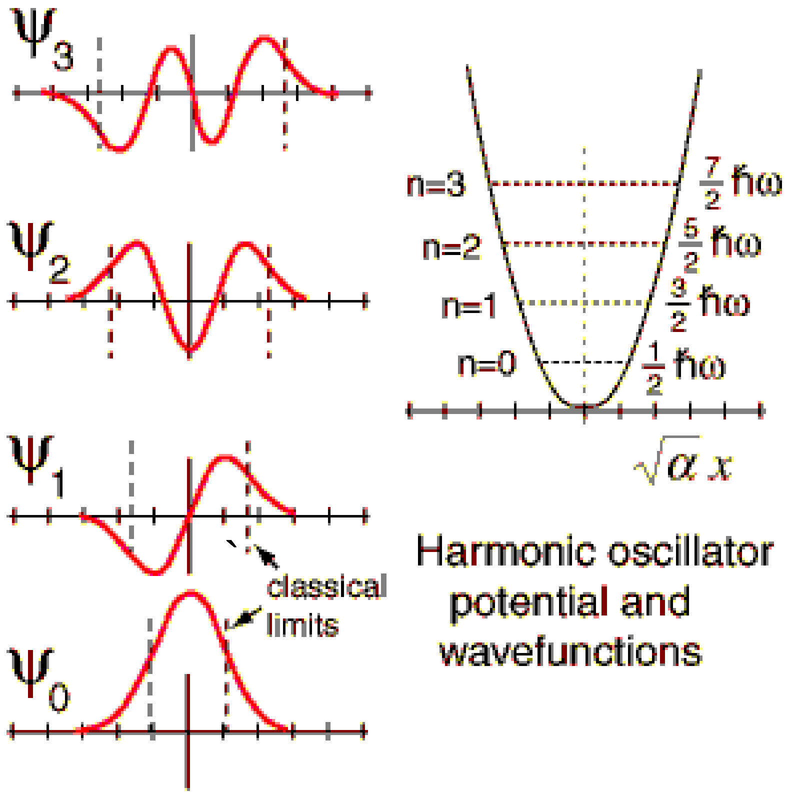
[air : $3X10^{19}$ cm^{-3}]



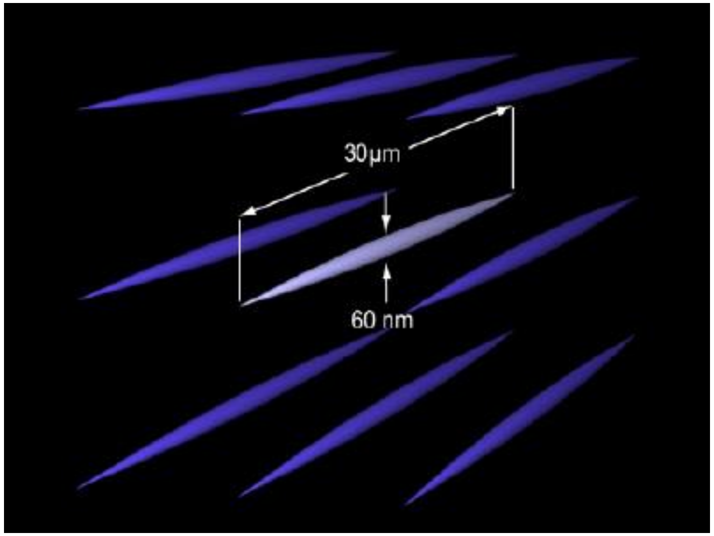
Reduction of dimensions

Requirements in the narrow directions

NOT OCCUPIED

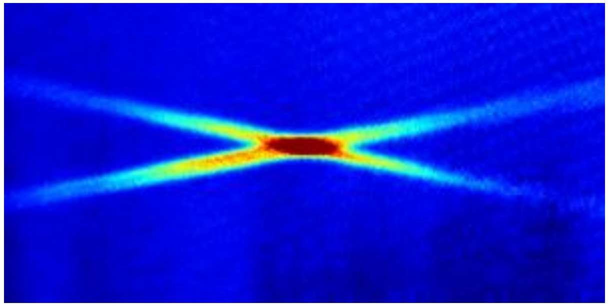


OCCUPIED - Ground state of transverse motion ONLY



Moritz, Kohl, Esslinger, PRL **91**, 250402 (2003)

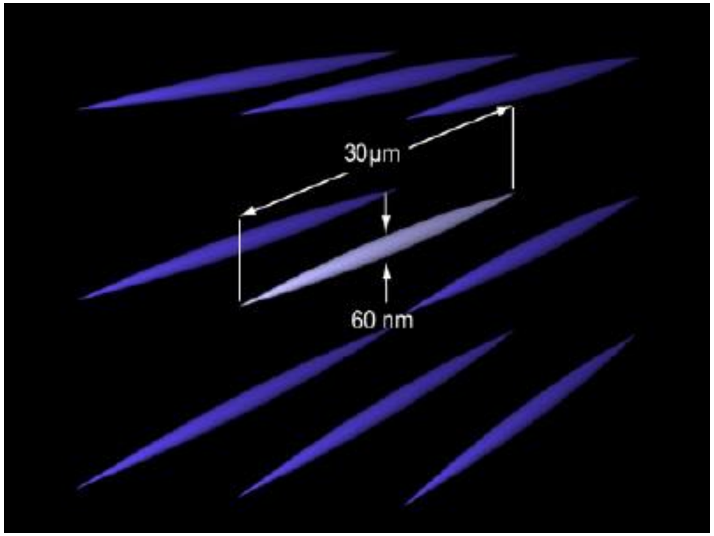
"Crossed" dipole trap



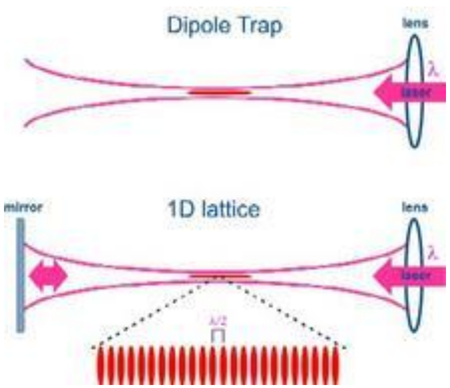
Noether expt. Stuttgart

Need $\hbar\omega_{long} \ll k_B T, \mu \ll \hbar\omega_{narrow}$

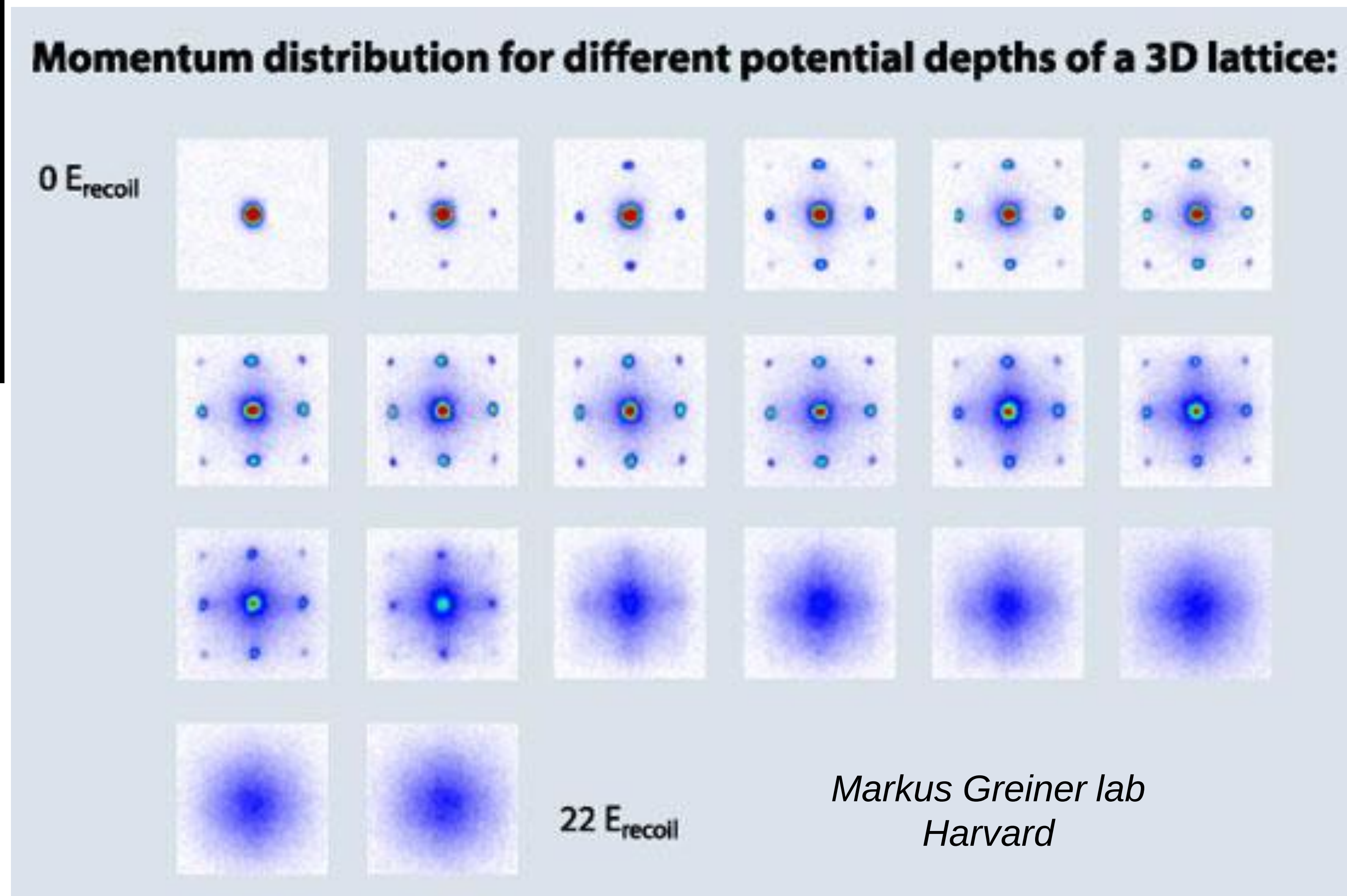
Lattices



Moritz, Kohl, Esslinger, PRL **91**, 250402 (2003)



Katori *et al*, PRL **91**, 173005 (2003)



Markus Greiner lab
Harvard

Ideal 1D gas

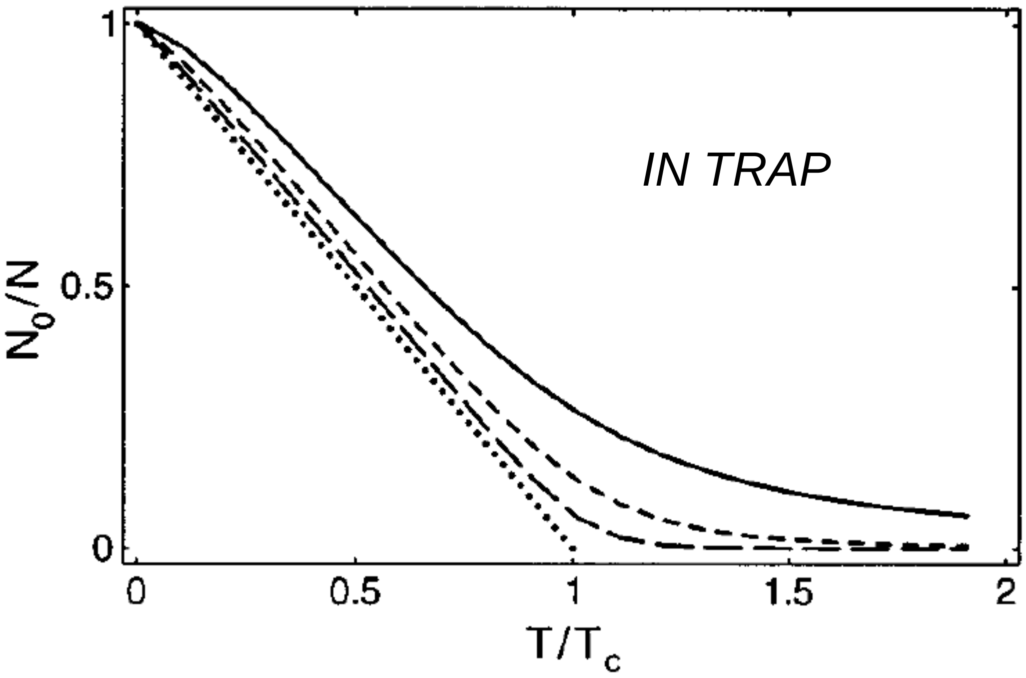
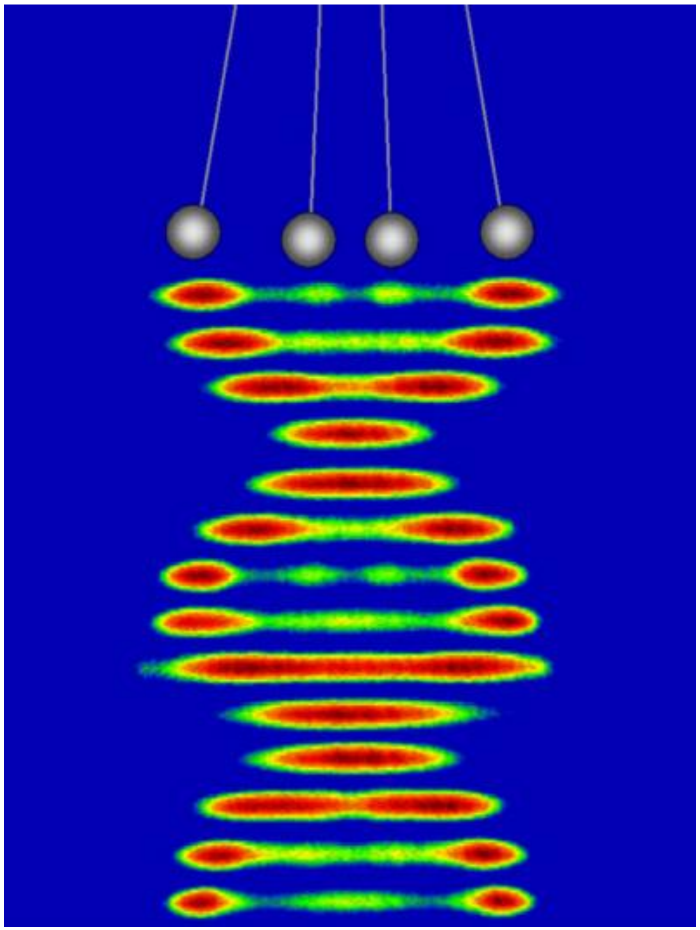


FIG. 4. The condensate fraction for a finite number N of atoms in a one-dimensional harmonic potential versus temperature. Plots are shown for $N=100$ (solid line), 10^4, 10^8, and infinite (dotted).

Ketterle, van Druten, PRA **54**, 656 (1996)

Integrability

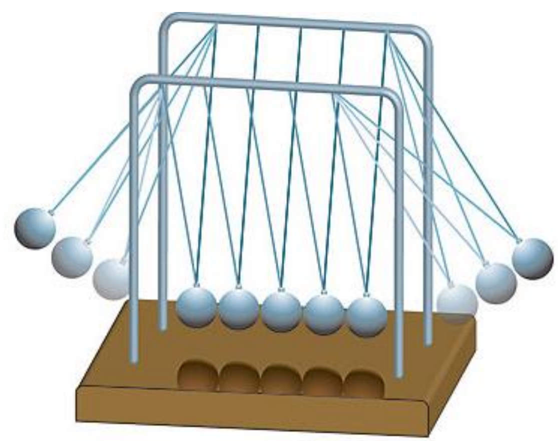
Quantum "Newton's cradle"



Kinoshita, Wenger, Weiss, Nature 440, 900 (2006)

Even in the *INTERACTING* uniform gas,
the momentum distribution is invariant
Because collisions create no dispersion

Apparently, this remains
a good approximation
in the trap



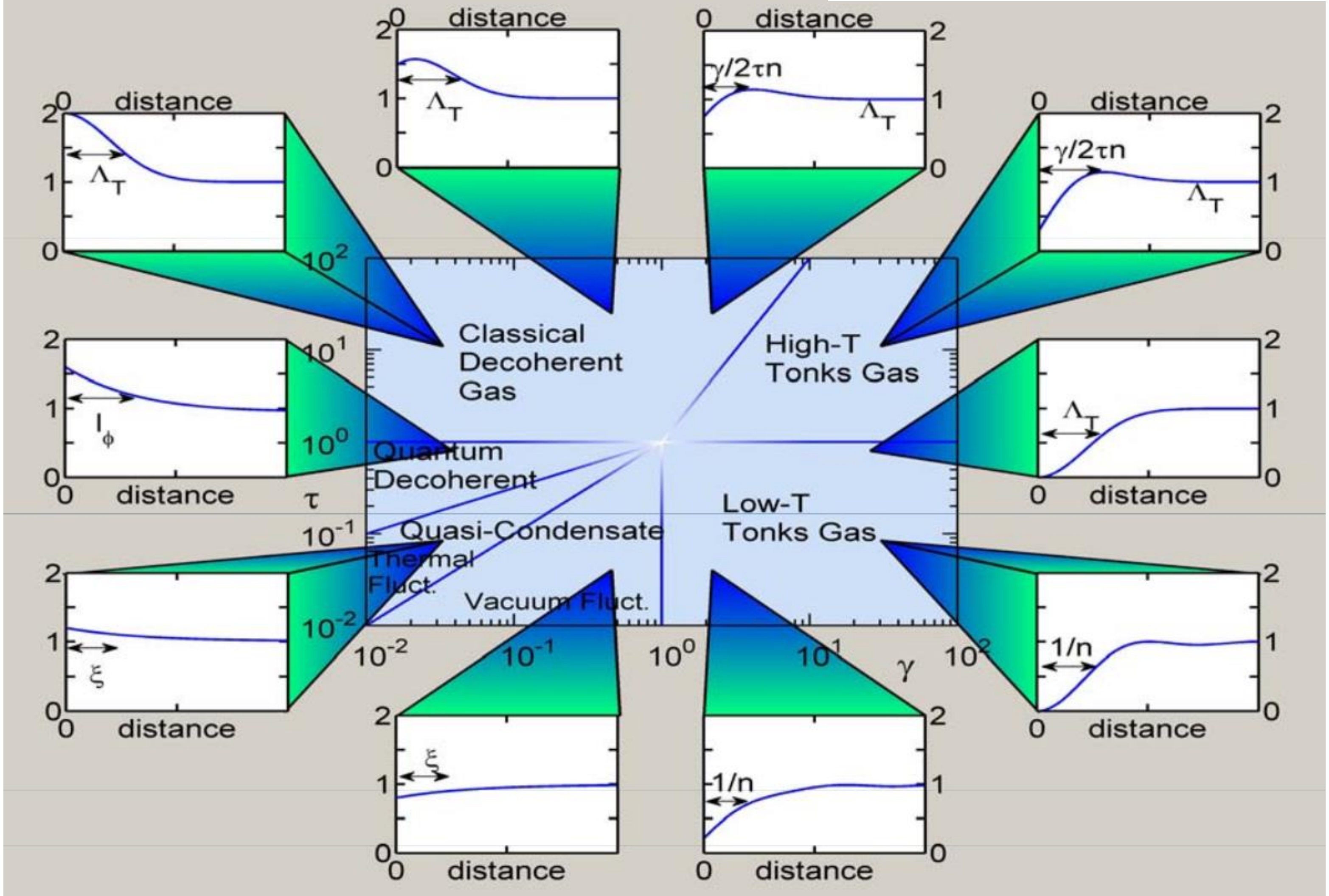
NARODOWE CENTRUM NAUKI

Interacting Bose gas

Uniform case is exactly solvable:

T = 0: Lieb & Liniger, Phys. Rev. **130**, 1605 (1963)
T>0: Yang & Yang, J. Math. Phys. **10**, 1115 (1969)

Pair correlation function $g^{(2)}(x, x+y) = \frac{1}{N^2}\langle \widehat{\Psi}^\dagger(x)\widehat{\Psi}^\dagger(x+y)\widehat{\Psi}(x)\widehat{\Psi}(x+y)\rangle$



$$\gamma = \frac{mg}{\hbar^2 n}$$

Deuar, Sykes, Gangardt, Davis, Drummond, Kheruntsyan, PRA **79**, 043619 (2009)

Quasicondensate

- In the uniform 1D gas, there is no true condensate for T>0
- ***However:*** finite coherence length l_ϕ and small density fluctuations

$$g^{(1)}(x,x') \sim \exp\left[-\frac{|x-x'|}{l_\phi}\right] \quad ; \quad l_\phi \sim \frac{N^{2/3}}{T}$$

$$g^{(1)}(0,x) = \frac{\langle \widehat{\Psi}^\dagger(0)\widehat{\Psi}(x)\rangle}{[\rho(0)\rho(x)]^{1/2}}$$

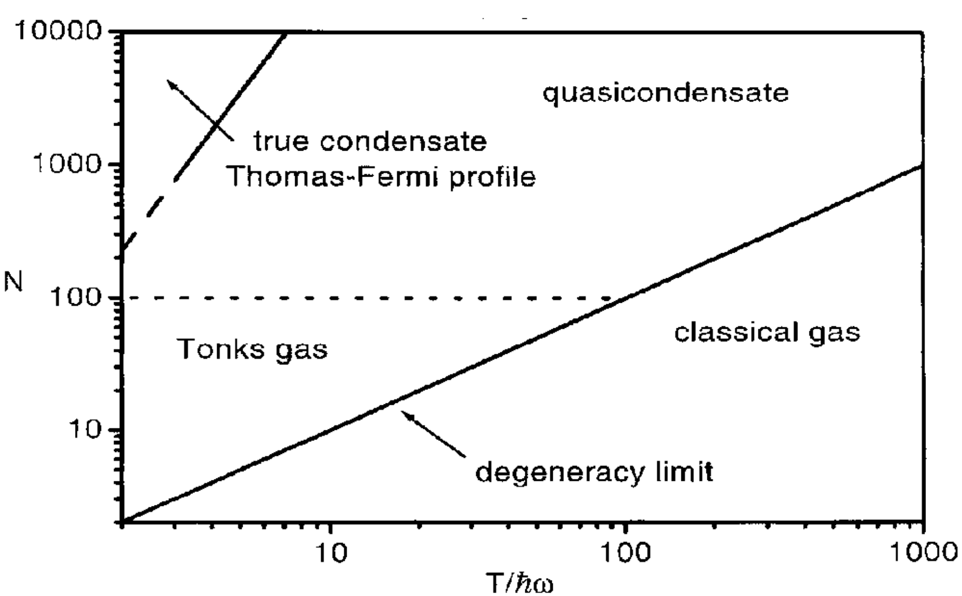
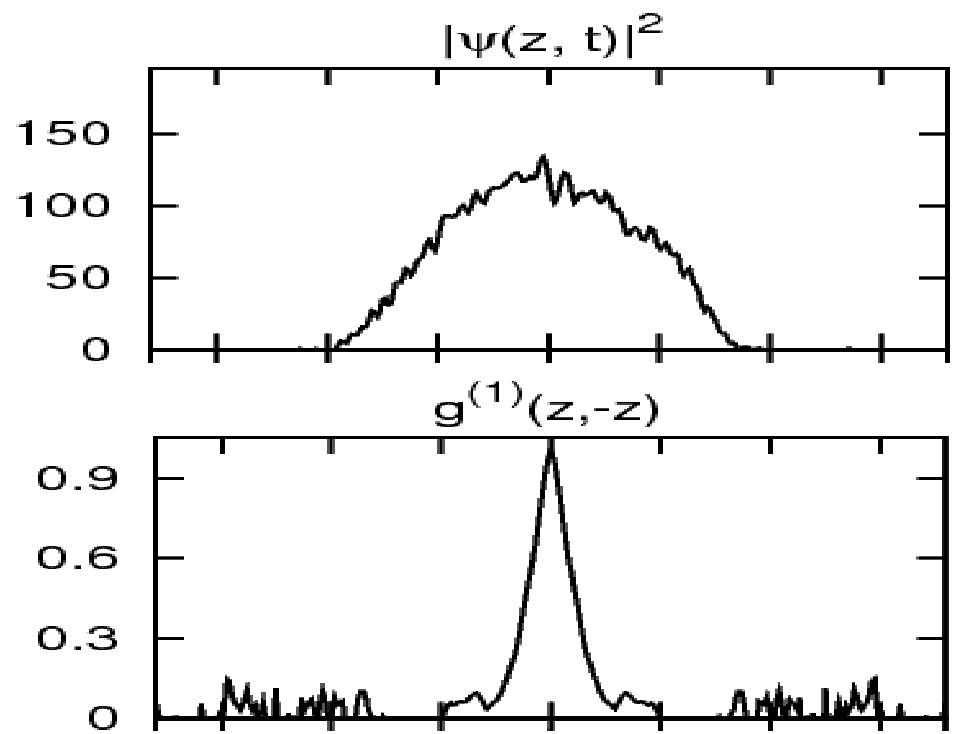


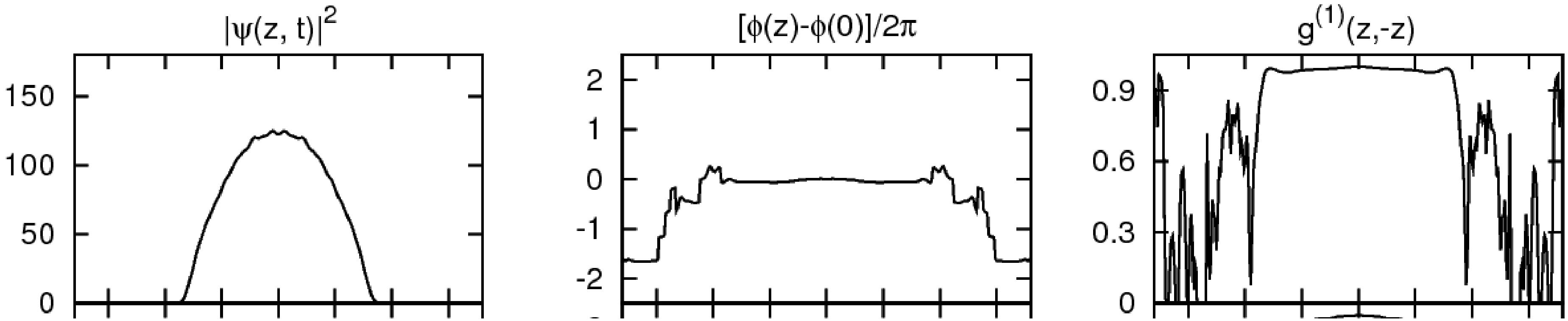
FIG. 1. Diagram of states for a trapped 1D gas.

D. Petrov, G. Shlyapnikov, J. Walraven, PRL **85,** 3745 (2000)

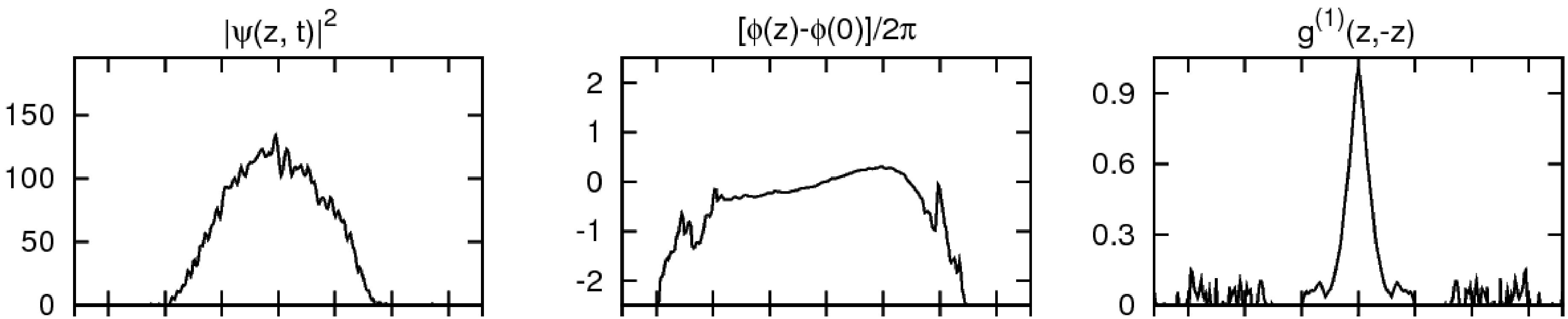


Quasicondensate

BEC



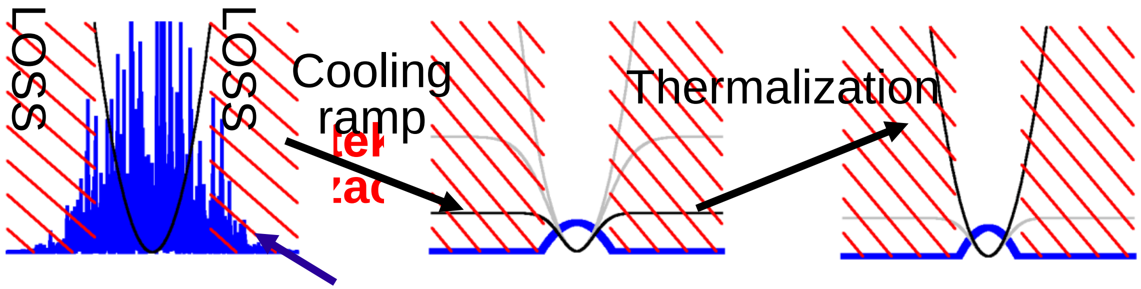
Quasicondensate

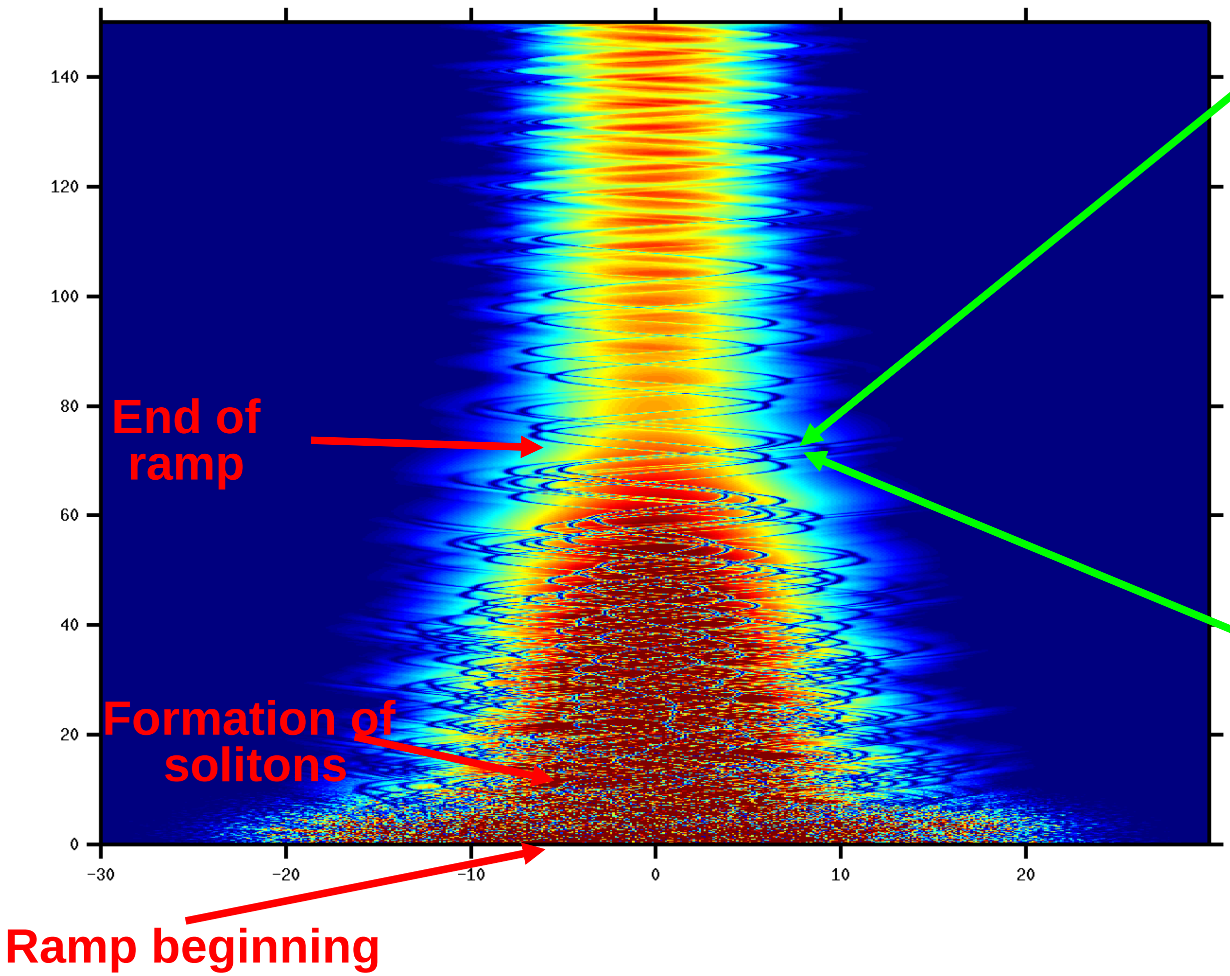


E. Witkowska, PD, M. Gajda, K. Rzążewski PRL **106**, 135301 (2011)

1D Bose gas cooling

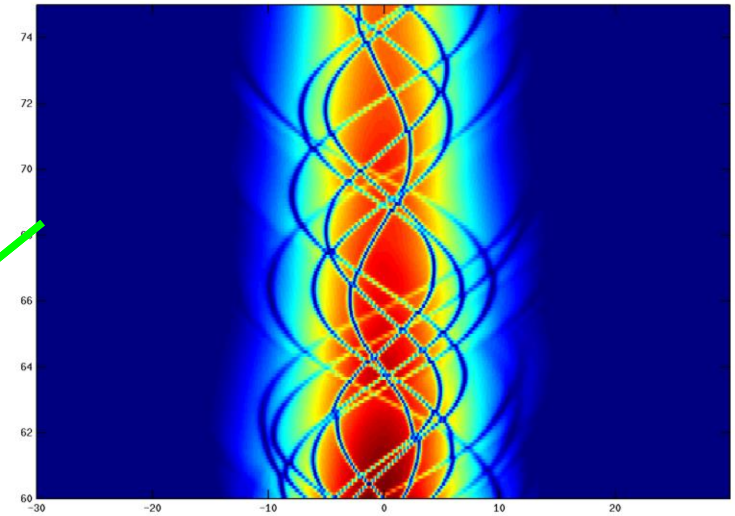
E. Witkowska, PD, M. Gajda, K. Rzążewski PRL **106**, 135301 (2011)



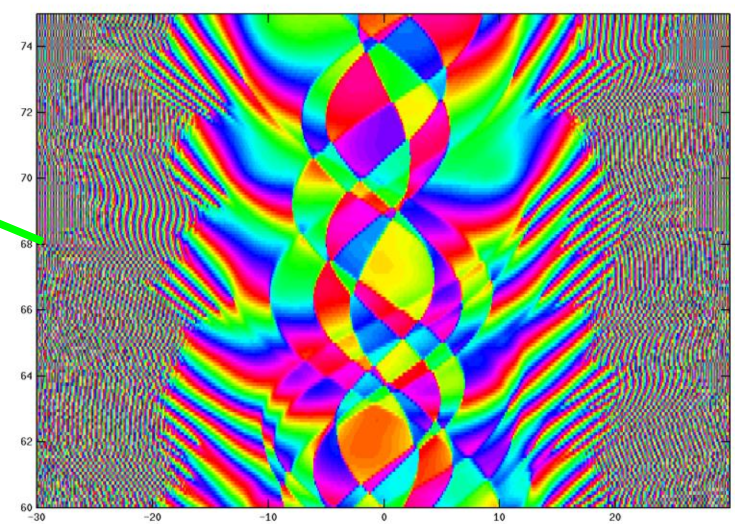


Creation of defects via Kibble-Zurek mechanism

DENSITY



PHASE



NARODOWE CENTRUM NAUKI

Long time after cooling, thermalization

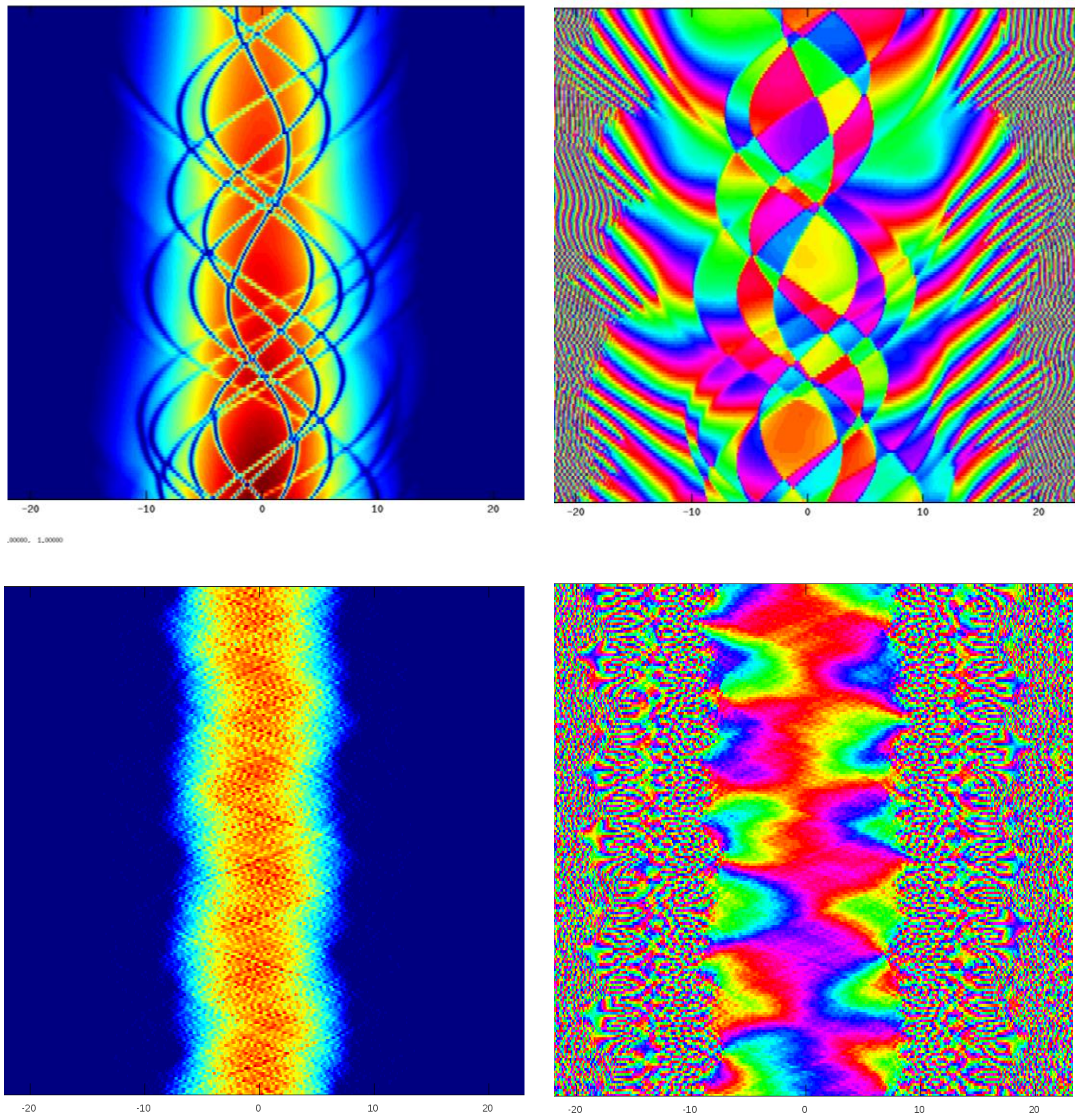
F

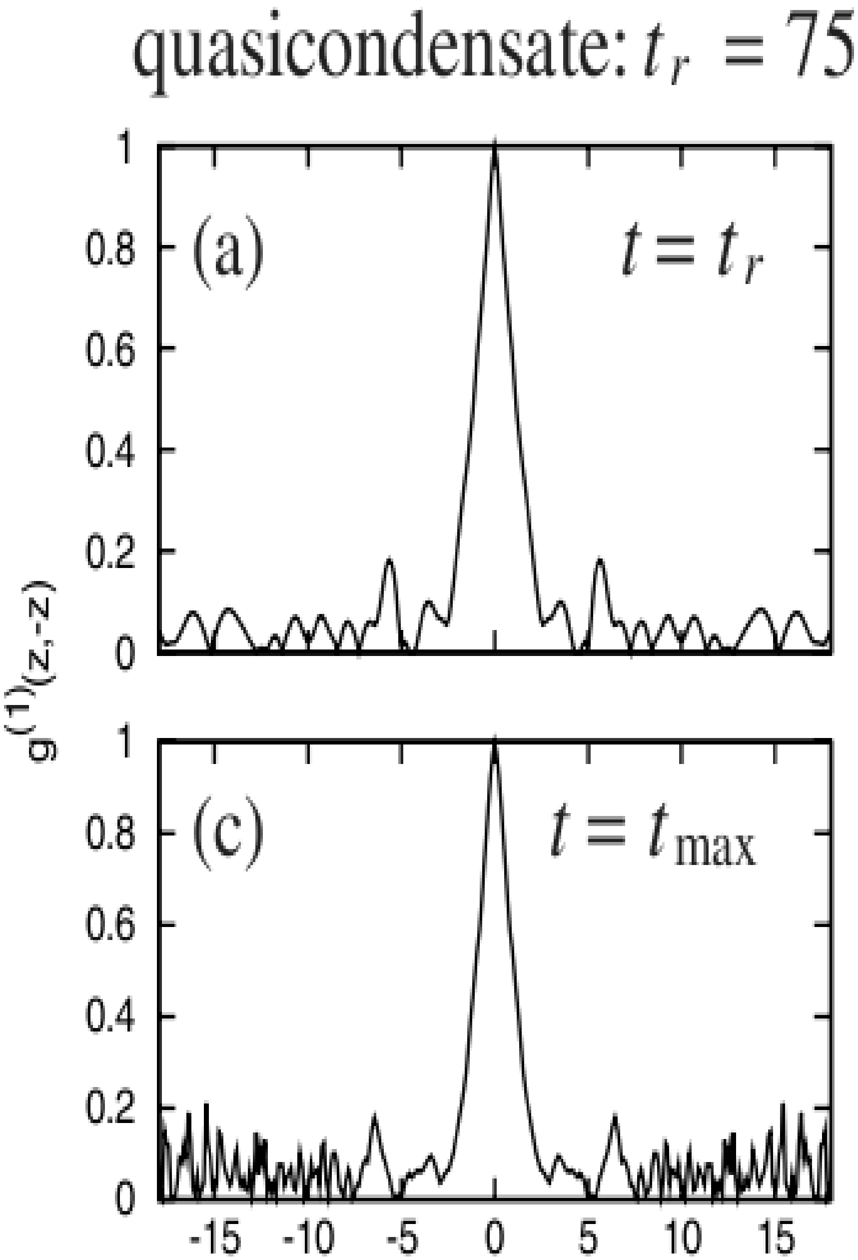
E. Witkowska, PD, M. Gajda, K. Rzążewski. PRL **106**, 135301 (2011)

DENSIY PHASE

END OF COOLING

THERMALISED





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