Negative Absolute Temperature for Motional Degrees of Freedom

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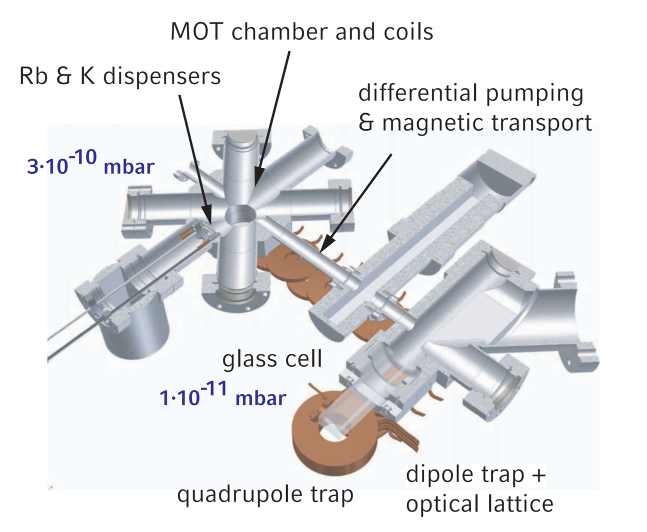
MPQ

The Apparatus

Vacuum chamber



Species:

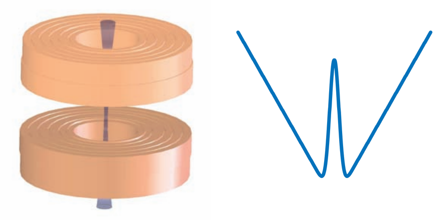
- ^{87}Rb (bosonic)
- ^{39}K (bosonic)
- ^{40}K (fermionic)

Experimental Sequence:

- MOT
- magnetic transport
- evap. in plugged quadrupole trap
- evap. in crossed dipole trap
- loading to blue lattice

Optically plugged quadrupole trap

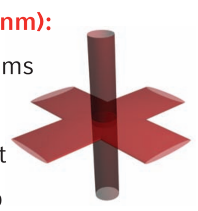
- blue-detuned light to prevent Majorana losses in center
- tapered amplifier with 1W at 780 nm
- cloud centered on symmetry axis, coils also usable for Feshbach field



Crossed optical dipole trap and blue-detuned lattice

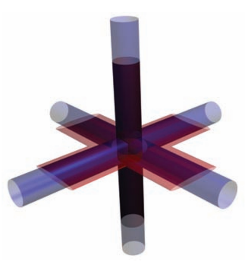
Crossed Dipole Trap (1064 nm):

- 2 elliptical horizontal beams
- round vertical beam
- tight vertical confinement
- good overlap of K and Rb



Blue Lattice (736.65 nm):

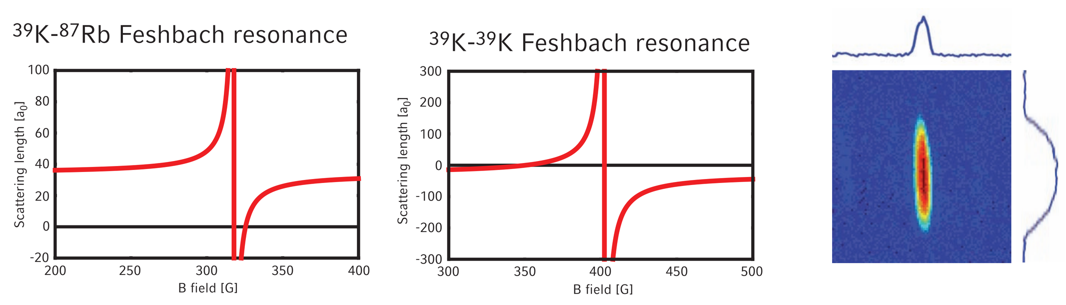
- anti-trapping potential
- control of K vs. Rb mobility
- creation of random defects by "freezing out" K



Independent **control** of lattice **depth** and harmonic **confinement**!

BEC with Tunable Interactions

both atoms in absolute ground state:

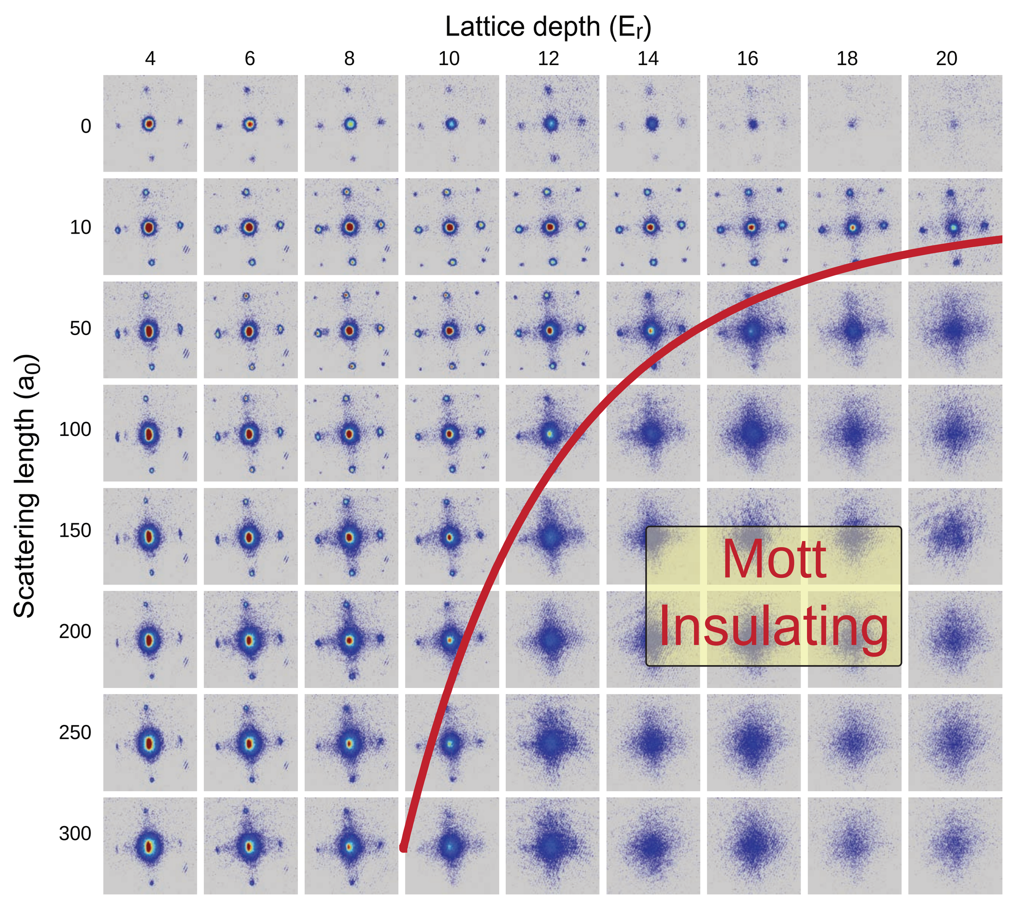


Cooling scheme for ^{39}K:

- **Sympathetic MW evaporation** in plugged quadrupole trap
- **Sympathetic cooling** in dipole trap on interspecies Feshbach resonance
- **Direct evaporative cooling** in dipole trap on intraspecies Feshbach resonance

^{39}**K BEC** of $100\cdot10^3$ atoms at a condensate fraction of above 90%

Feshbach Induced Mott Insulator



Preliminary, see also M.J. Mark et.al. arXiv: 1107.1803

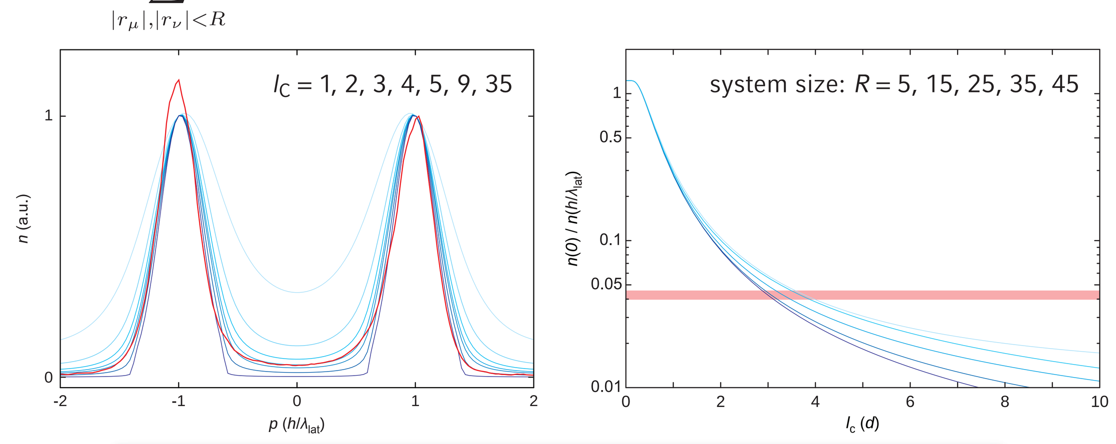
Qualitative agreement with QMC

Coherence Length

modelling 1D distribution after finite TOF with Gaussian envelope times **interference term**:

$$S(k) = \sum_{|r_\mu|,|r_\nu|<R} e^{ik(r_\mu - r_\nu) - i\frac{m}{2\hbar t}(r_\mu^2 - r_\nu^2) - \frac{|r_\mu - r_\nu|}{l_C}}$$

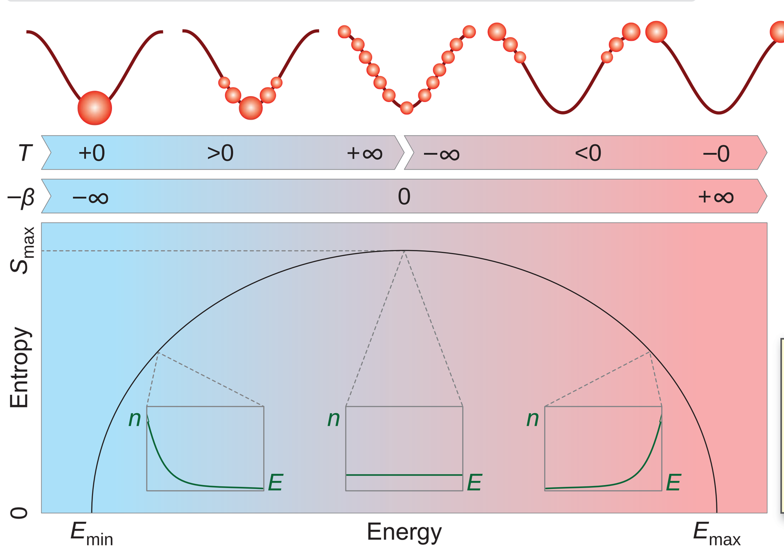
l_C: coherence length



background signal: **coherence length 3-4 lattice sites** (underestimate)

Creation of Negative Temperature States in Optical Lattices

What is negative absolute temperature?



$$P_i = \frac{g_i e^{-E_i/k_B T}}{Z(T)}$$

$$Z(T) = \sum_i g_i e^{-E_i/k_B T}$$

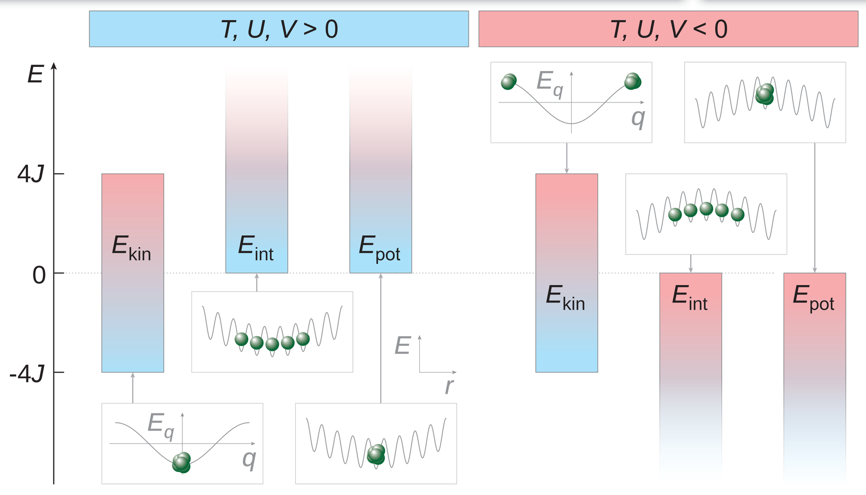
$$\frac{1}{T} = \left(\frac{\partial S}{\partial E}\right)_V$$

T>0: Hamiltonian must be bounded from **below**
T<0: Hamiltonian must be bounded from **above**

Energy bounds of the Bose-Hubbard Hamiltonian

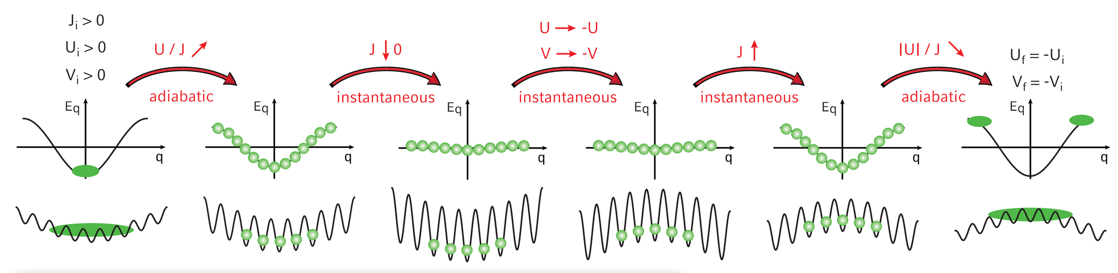
$$H = -J\sum_{\langle ij\rangle}\hat{b}_i^\dagger\hat{b}_j + \frac{U}{2}\sum_i \hat{n}_i(\hat{n}_i - 1) + V\sum_i \mathbf{r}_i^2\hat{n}_i$$

U, *V* < 0 necessary for upper bound!



Scheme for creation of negative temperature states

Quench of interaction U and external confinement V of a bosonic Mott insulator:



Thermalization at negative temperature in the attractive BHM leads to **condensation around** *q*=*π*/*d* **!**

Rapp et al., PRL 105, 220405 (2010)
Allard P. Mosk PRL 95, 040403 (2005)

Phase diagram and negative pressure

density matrix: $\rho = e^{-\frac{H}{k_B T}} = e^{-\frac{(-H)}{k_B(-T)}}$

sequence: $U \to -U \quad V \to -V$

dispersion: $E_q = -2J\cos(qd)$

momentum shift: $q \to q + \pi/d \;\hat{=}\; J \to -J$

Phase diagram for **repulsive BHM at** *T*>0 = PD for **attractive BHM at** *T*<0 **with shifted** *q*

general stability condition: $\left.\frac{\partial S}{\partial V}\right|_E \geq 0$

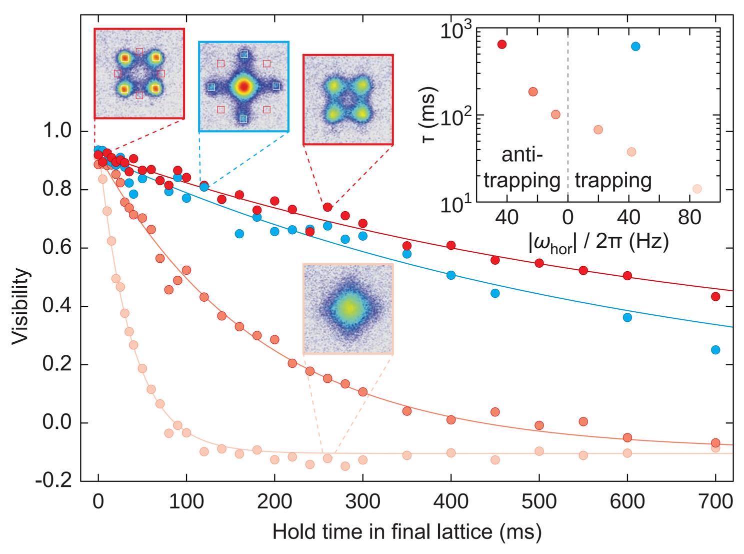
energy differential: $dE = T\,dS - P\,dV$

$$\left.\frac{\partial S}{\partial V}\right|_E = \frac{P}{T} \geq 0$$

negative pressure is stabilized by negative temperature! **stable condensate at attractive interactions!**

Stability

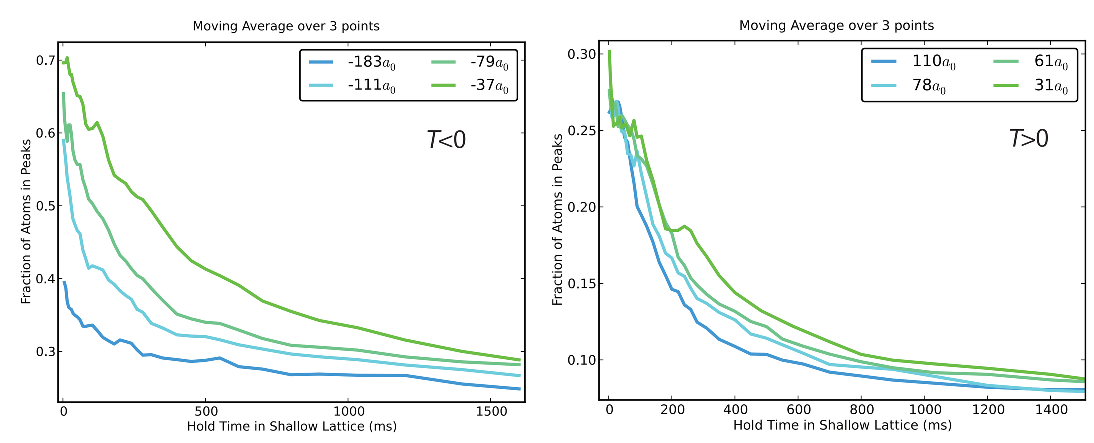
Coherence lifetime vs. horizontal trap frequency

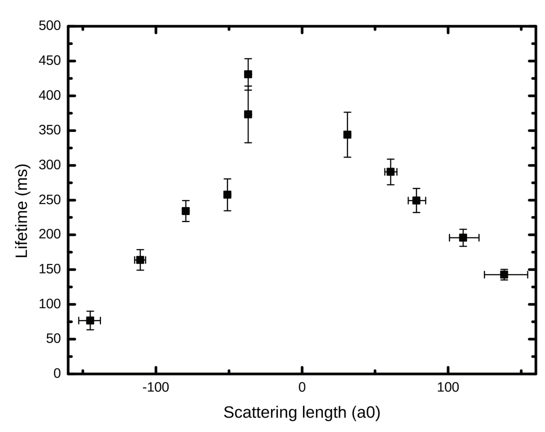


visibility: $\mathcal{V} = \frac{N_{\boxtimes} - N_{\boxdot}}{N_{\boxtimes} + N_{\boxdot}}$

- lifetime exceeding **600ms!**
- **same lifetime** as for **positive temperature**
- non-ideal confinement leads to **dephasing**

Coherence lifetime vs. interaction

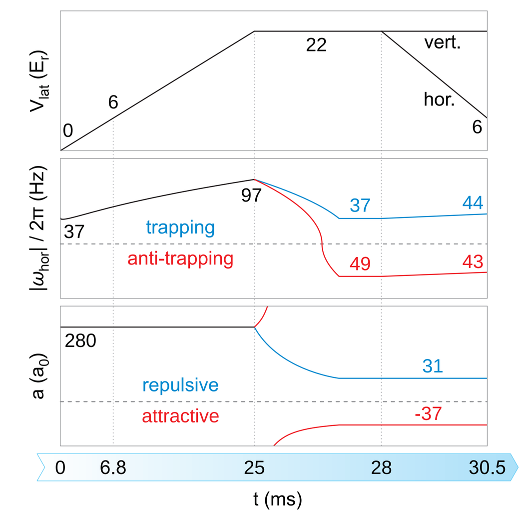




- **lifetime decreasing with interaction** for both positive and negative temperatures
- scaling qualitatively consistent with **three-body loss rates**

Experimental Realization

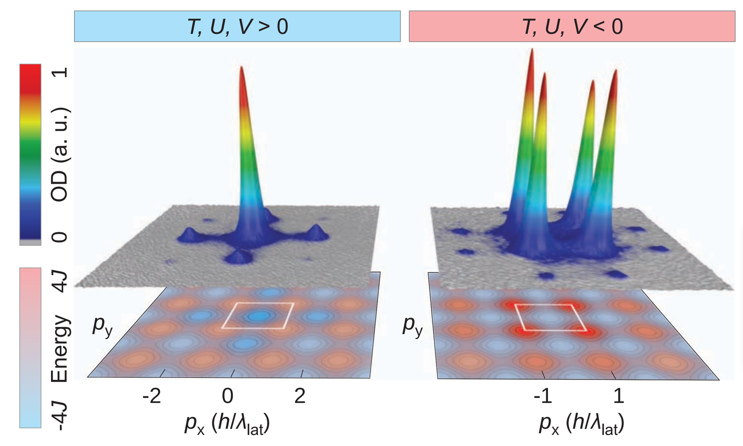
Experimental sequence and results



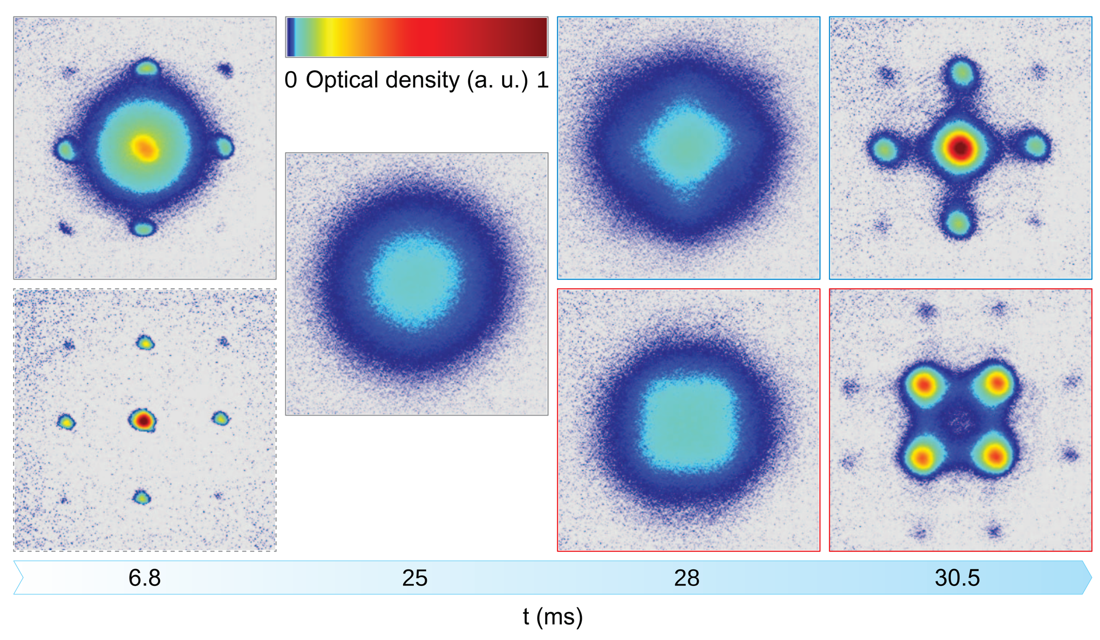
final negative (positive) temperature state prepared in **2D**:

- avoiding gravitation effects
- enabling strong anti-trapping potentials

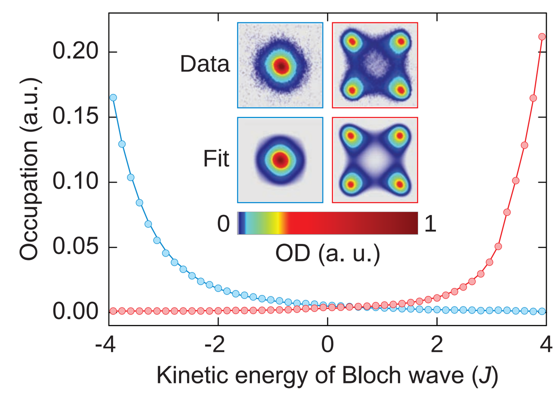
initially **strong interactions** to prevent double occupancies



macroscopic occupation of **maximum** kinetic energy!



Quasi-momentum distribution



fit: convolution with Gaussian

Bose-Einstein distribution, non-interacting and homogeneous:

$$n(q_x, q_y) = \frac{1}{e^{(E_{kin}(q_x,q_y)-\mu)/k_BT} - 1} + o$$

$$E_{kin}(q_x, q_y) = -2J\left[\cos(q_x d) + \cos(q_y d)\right]$$

very good reproduction with **Bose-Einstein distribution!**

- fitted temperature: ***T* = -2.2*J*/k_B** (+2.7*J*/k_B) (overestimate)
- theor. 2D superfluid transition (QMC): **|T_{BKT}| = 1.8*J*/k_B** (PRA 77, 015602 (2008))
- theor. condensation temperature in 2D harmonic trap (non-interacting): **|T_C| = 3.4(2)*J*/k_B**