Certifying the adiabatic preparation of ultracold lattice bosons in the vicinity of the Mott transition

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C. Carcy et al., preprint arXiv:2010.14352 (2020)

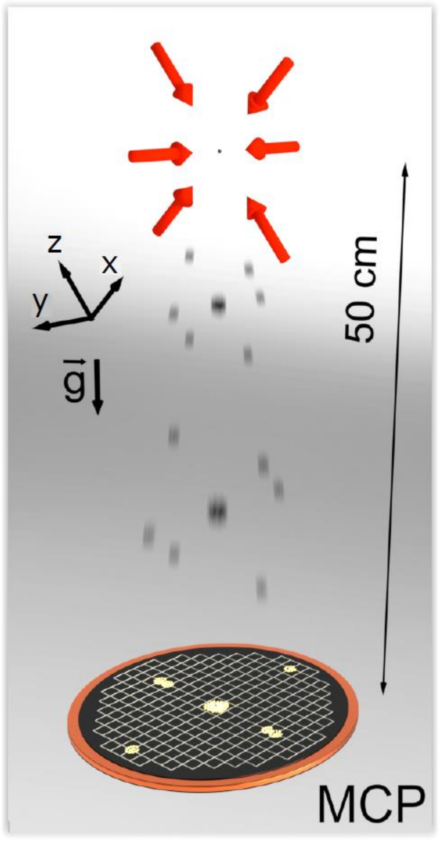
Measuring 3D (far-field) momentum distributions of individual atoms

Bose-Einstein condensates (BECs) of metastable Helium atoms $^4He^*$

3D optical lattice (λ=1550 nm)

He* detector (micro-channel plates and delay lines):

1. Reconstruction of **3D positions of individual atoms**
2. **Large dynamic range** in densities (no background)
3. **Excellent resolution**
4. **Saturation** at high flux



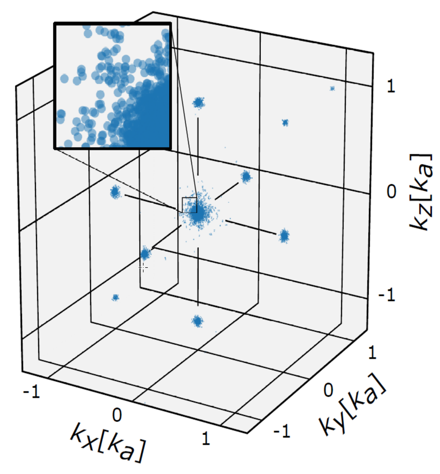
Single-atom-resolved 3D distribution in far-field

- Detection in far-field regime of expansion [1]:

$$t_{\rm tof} \simeq 300 \text{ ms} > t_{\rm FF} = \frac{mL^2}{2\hbar} \simeq 60 \text{ ms}$$

- Ballistic expansion:
  - mean-field effect negligible ($\hbar\omega_{\rm site} \gg \mu$)
  - two-body collisions negligible

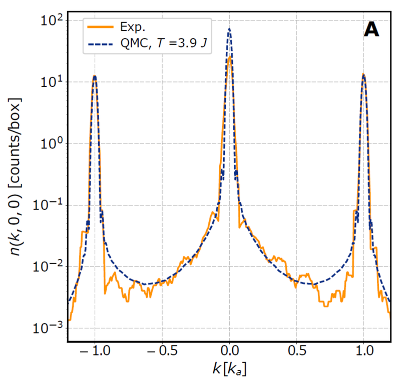
A. Tenart et al., Phys. Rev. Research 2, 013017 (2020)



Benchmarking the experiment with ab-initio Quantum Monte-Carlo (QMC)

Excellent match between measured TOF densities and QMC calculations of the in-trap momentum distributions by G. Carleo (Flatiron Institute) [2,3]

H. Cayla et al., Phys. Rev. A 97, 061609(R) (2018)



Bose-Hubbard Hamiltonian

Bosons in optical lattices emulate the Bose-Hubbard Hamiltonian :

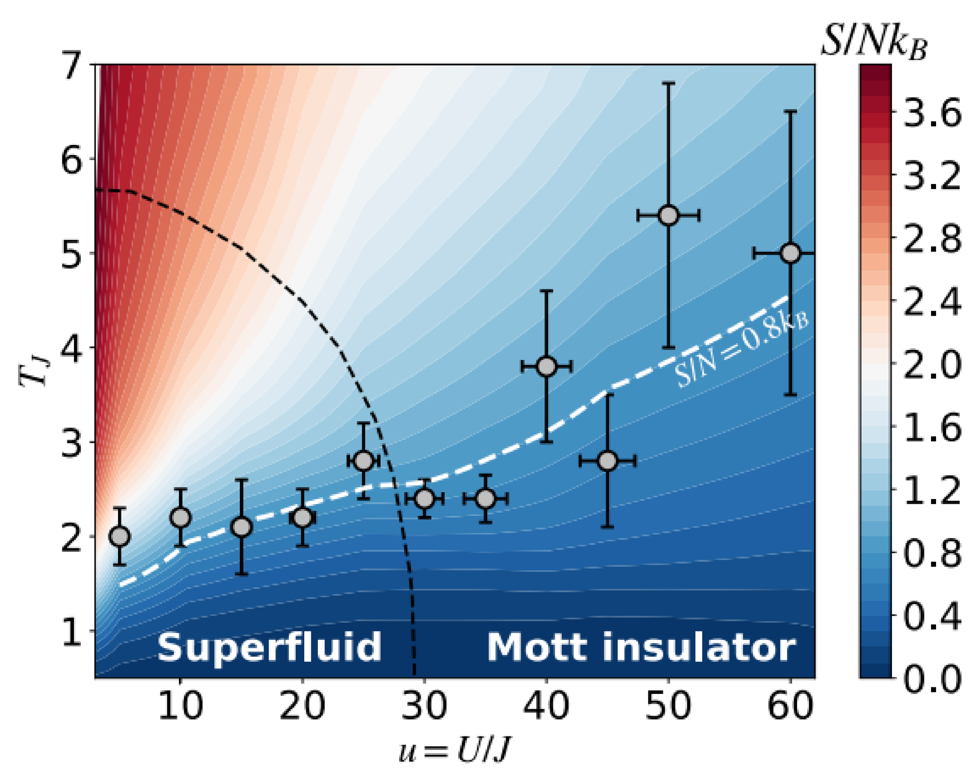
$$\mathcal{H} = -J\sum_{\langle ij\rangle}\left(b_i^\dagger b_j + \text{h.c.}\right) + \sum_i \left[\frac{U}{2}n_i(n_i-1) + V_i n_i\right]$$

Known to exhibit a many-body quantum phase transition at $T = 0$ driven by the parameter $u = U/J$ [4]. Critical point of the transition at $u_c^{MF} \sim 29.34$ [5].

Context : quantum simulators and adiabatic preparation.

⇒ Can strongly correlated states be prepared close to many-body quantum phase transition ?

Entropy map of the trapped (3D) Bose-Hubbard model



Within error bars, almost all temperatures are compatible with the isentropic range $S/Nk_B = 0.8(1)$. Moreover, the entropy of the initial BEC was measured to be $S_0/Nk_B = 0.72(7)$.

⇒ Both the loading and the ramping up of the lattice conserve the entropy of the initial BEC.

⇒ <u>Ensure the adiabatic preparation of any finite-entropy state of the 3D Bose-Hubbard model.</u>

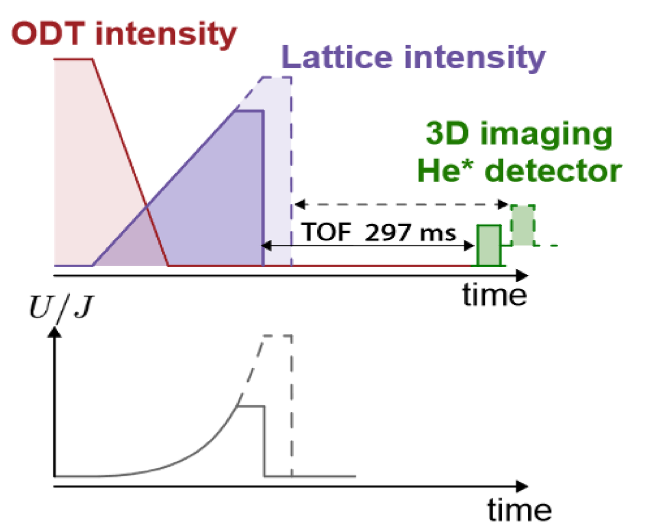
⇒ <u>This property holds even in the vicinity of a many-body quantum phase transition like the Mott transition.</u>

Exploring the Bose-Hubbard phase diagram

Varying the parameter $u = U/J$

Linear increase ($0.3\,Er/s$) of the lattice intensity ⇒ exponential increase of u.

Reaching $u' > u$ is identical to start from the equilibrium at u and then further increase the lattice intensity to reach u'.

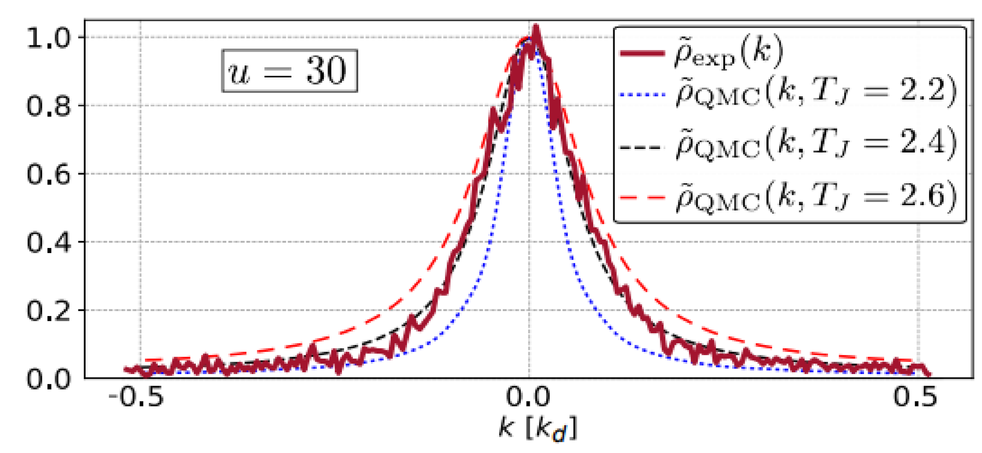


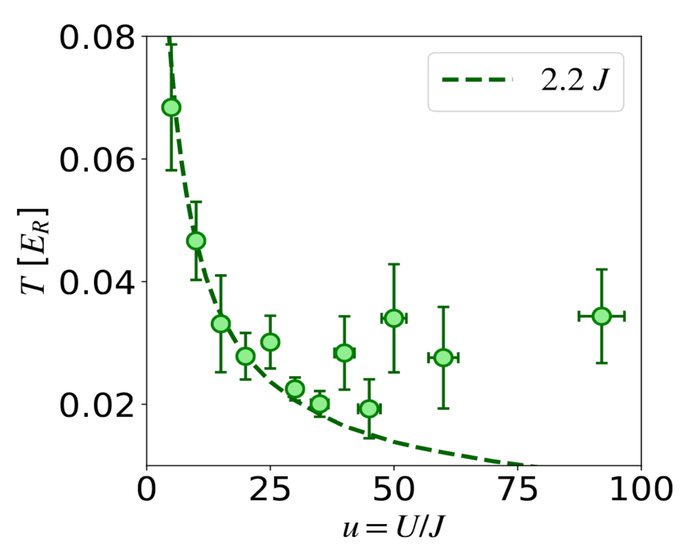
Thermometry from comparison with QMC

Working with clouds of $3.0(5) \times 10^3$ atoms allows to compare the measured k-space densities with exact QMC calculations.

- Simulations using our experimental parameters, with fixed atom number $N = 3000$.
- Temperature set as the only adjustable parameter.

⇒ Best agreement gives the temperature.





Superfluid regime : T follows the exponential decrease of J as $u = U/J$ is increased, this being due to the narrowing of the Bloch band.

Mott regime : no decrease of the temperature because opening of the gap.

The precision of our temperature measurement is inherently bounded by the Cramér-Rao limit [6] :

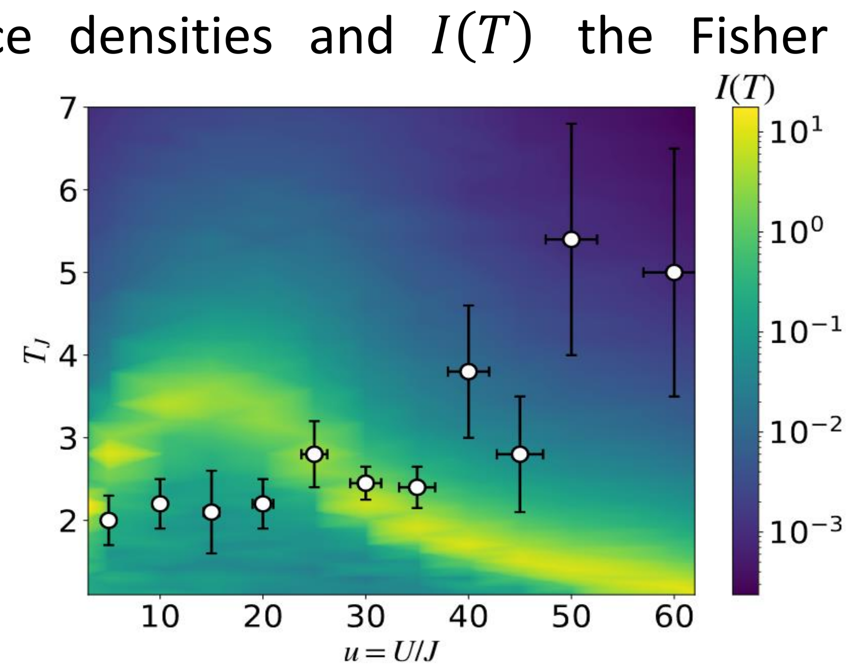
$$\delta T_J = \frac{k_b\,\delta T}{J} \leq (\delta T_J)_{min} = \frac{1}{\sqrt{I(T)M}}$$

with M the sample size of the k-space densities and $I(T)$ the Fisher information [6] related to the temperature.

Qualitatively : good concordance between variations of $I(T)$ and experimental error bars.

Quantitatively : at $u = 30$, $\delta T_J = 0.03$ while $(\delta T_J)_{min} = 0.03$.

⇒ Highest precision close to the transition.



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3. S. Trotzky *et al. Nat Phys* 6, 998–1004 (2010).
4. M. Greiner *et al. Nature 415*, 39-44 (2002).
5. B. Capogrosso-Sansone *et al. Phys. Rev. B* 75, 134302 (2007)
6. A. Van den Bos, *Parameters Estimation for Scientists and Engineers* (Wiley,2007)