Quantum simulation with ultracold bosons in frustrated optical lattices

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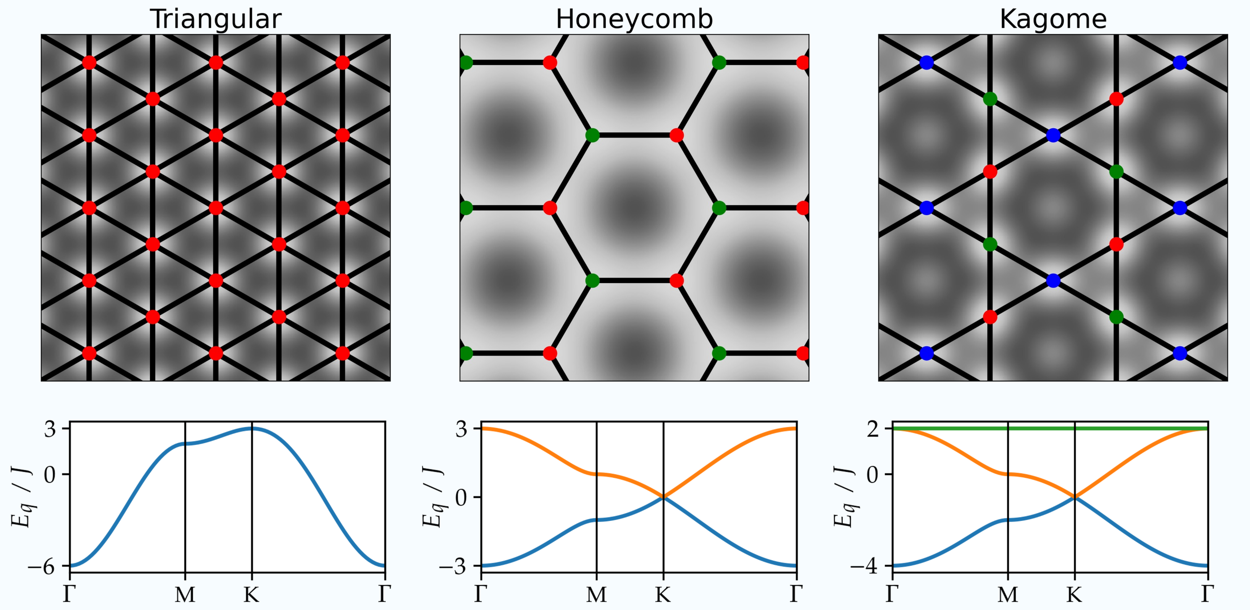
Introduction

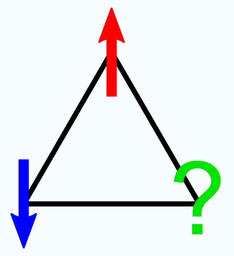
We present an ultracold-atom setup implementing a variety of hexagonal lattices including triangular and kagome. Both display geometric frustration. We show results on the Bose-Hubbard model with 39K.

Bose-Hubbard model

$$H = -J\sum_{\langle ij\rangle}(\hat{b}_i^\dagger \hat{b}_j + h.c.) + \frac{1}{2}U\sum_i \hat{n}_i(\hat{n}_i - 1) + \sum_i \varepsilon_i \hat{n}_i$$

- Flat band
- Topological phases
- Spin liquids





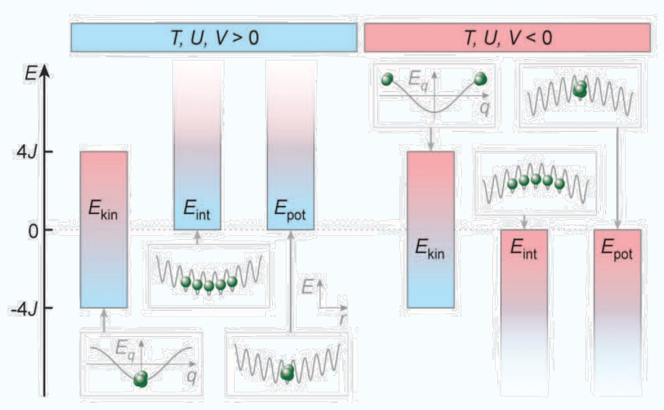
Left: The triangular, honeycomb and kagome lattices, with the lowest set of tight-binding subbands for each lattice type.

Negative absolute temperature

Negative temperature allows to probe the physics at the upper band edge.

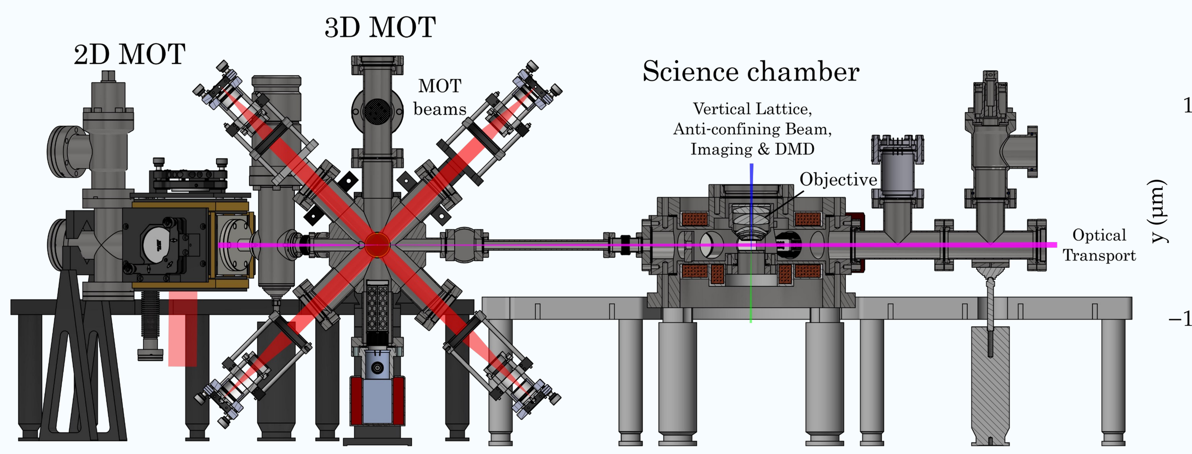
A negative-temperature state is stable provided there is an upper energy bound

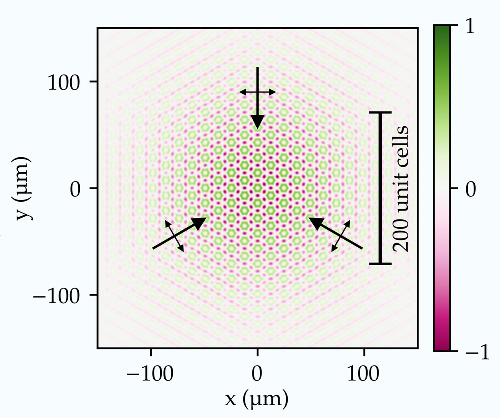
- lattice band gap
- attractive interaction
- anti-confining potential



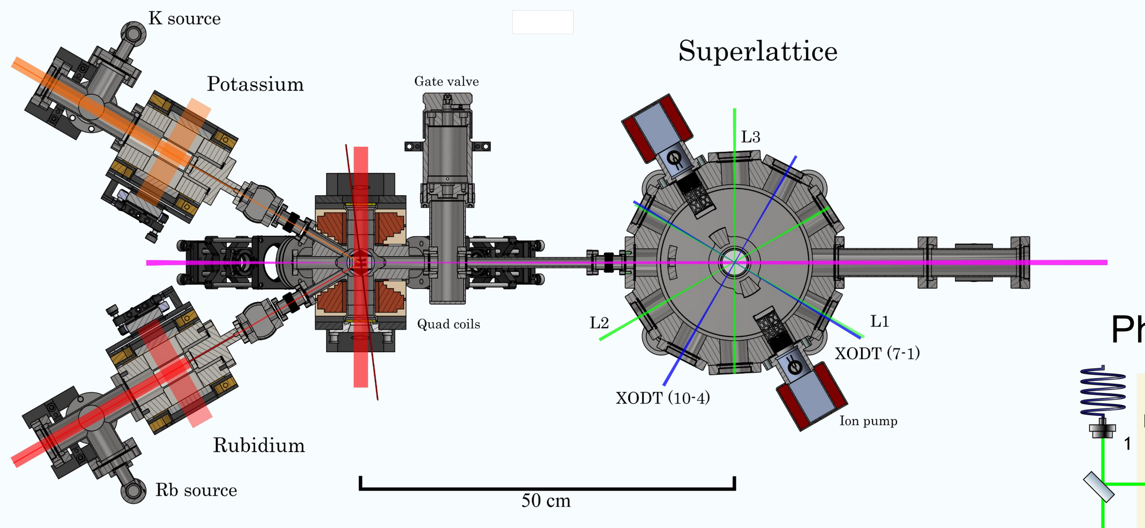
S. Braun et al., Science 339(6115), 52-55 (2013)

Experimental set-up

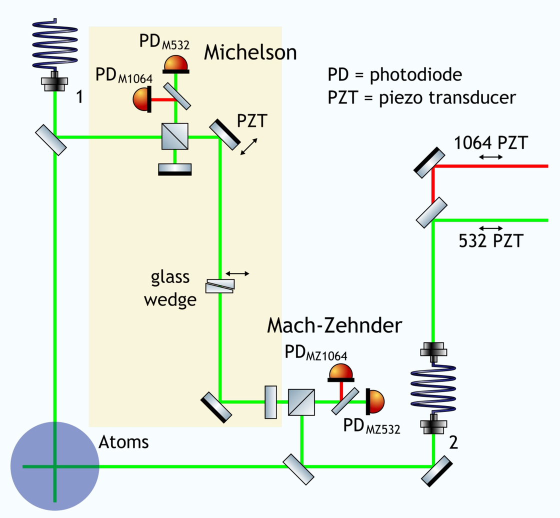




Kagome lattice beams and potential (lattice spacing scaled 20x)



Phase stabilisation scheme



Experimental highlights

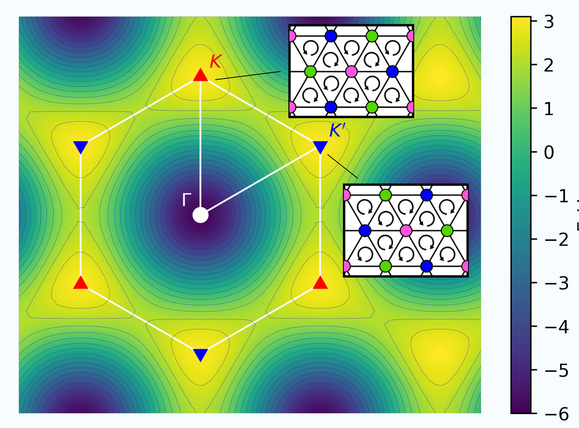
- ^{87}Rb, ^{39}K, ^{40}K
- Kagome is formed as bichromatic superlattice
- Active stabilisation of the lattice phase
- Quantum gas microscope

Triangular lattice

Geometric frustration

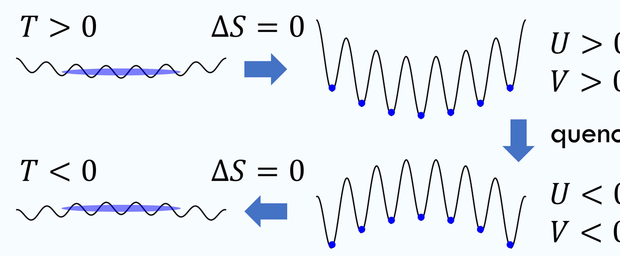
- ground band has two degenerate but inequivalent maxima at K and K'
- probe frustration with negative temperature

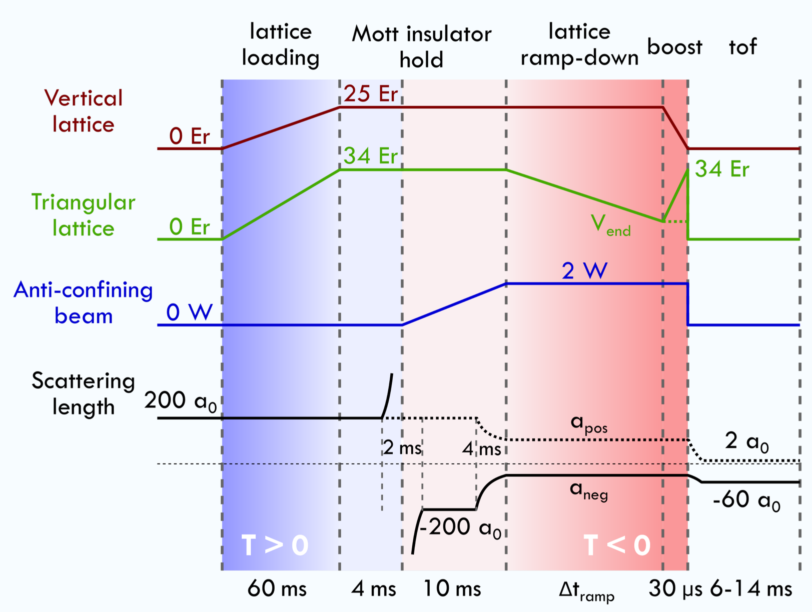
Band structure



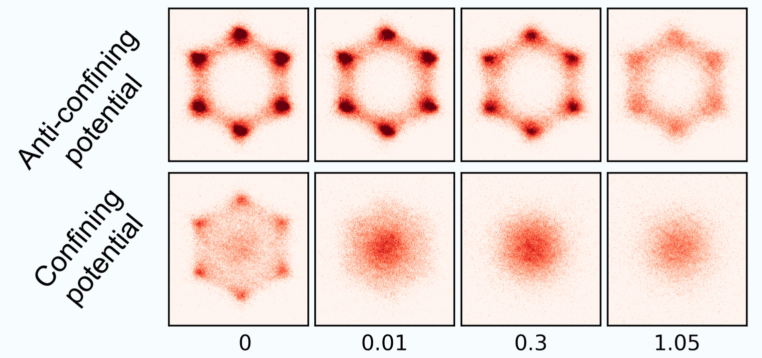
Preparation of negative-temperature state

- at $U, T > 0$, adiabatic ramp to deep $n = 1$ Mott insulator – eigenstate of both $U > 0$ and $U < 0$
- quench interaction to $U < 0$, which flips the energy spectrum, thus giving $T < 0$
- ramp up anti-confining harmonic potential
- adiabatic ramp to shallow lattice at $T < 0$





Negative temperature lifetime in triangular lattice

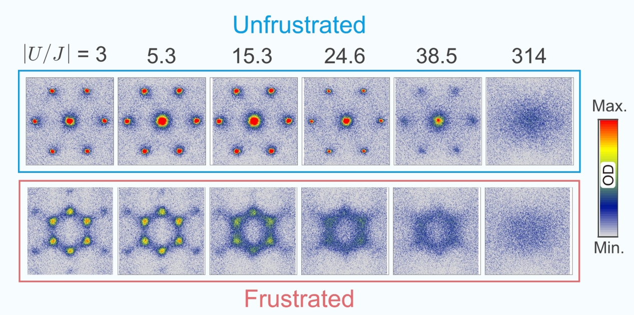


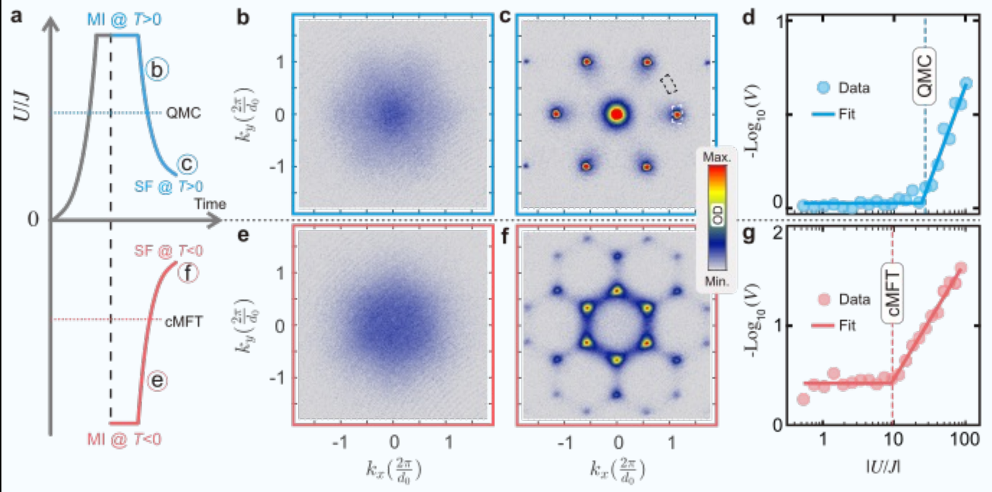
Hold time in negative temperature superfluid (s)

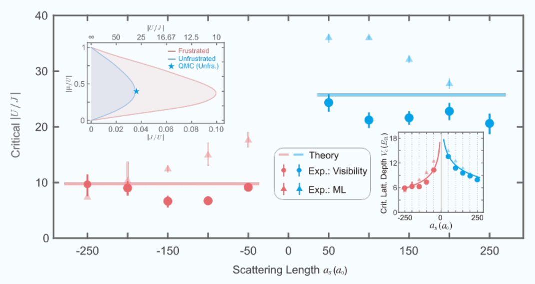
Mott insulator – superfluid transition

- start with deep MI, ramp down horizontal lattice at fixed scattering length
- maintain deep vertical lattice: 2D physics
- measure visibility of satellite peaks vs $|U/J|$

Time-of-flight images







$(U/J)_c$	Theory	Experiment
T > 0	25.5-26.0	21.9 ± 0.7
T < 0	9.5	8.2 ± 0.5

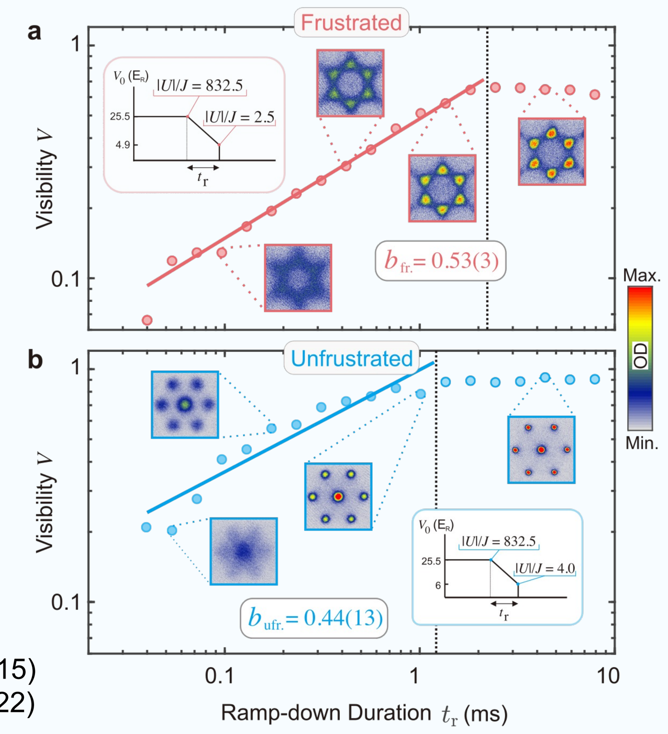
MI – SF at negative temperature

- superfluid is less stable: transition at lower $(U/J)_c$, suppressed by a factor of 2.7
- chiral superfluid (χ-SF) at K or K', breaks time reversal symmetry

Dynamics of phase transition

- χ -SF: break Z_2 as well as U(1)
- symmetries could break together (likely first order), or transition could occur via χ -MI (two continuous transitions), but theory inconclusive
- experimentally we observe similar behaviour for $T < 0$ as for $T > 0$, which suggests continuous transition(s)

M. Hasan et al., manuscript in preparation

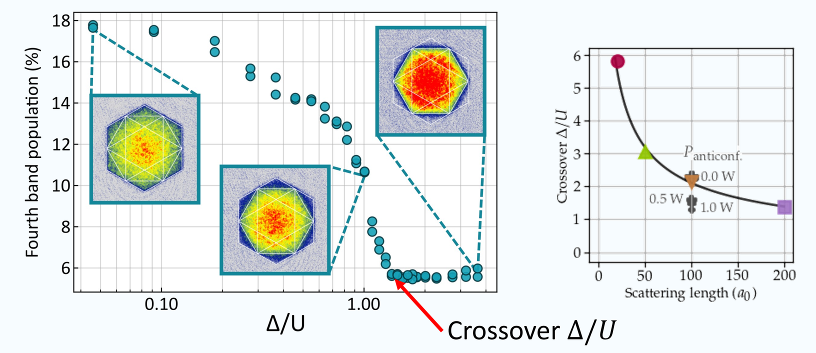


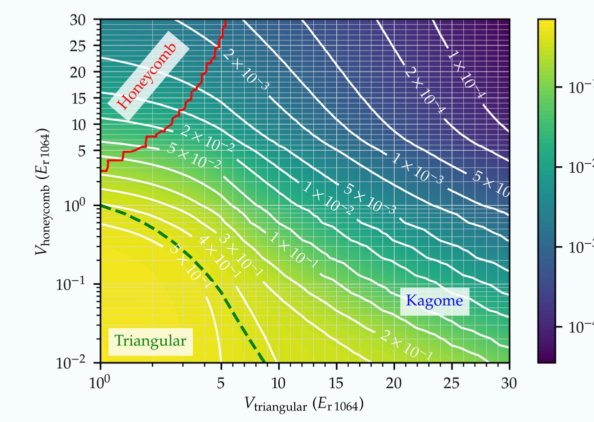
Yamamoto et al., Comms Phys 3:56 (2020)
Zaletel et al., PRB 89, 155142 (2014)
Romen et al., PRB 98, 054519 (2018)
Braun et al., PNAS 112, 3641 (2015)
Song et al., Nat Phys 18, 259 (2022)

Kagome lattice

- third band analytically flat only in tight binding limit
- crossover from triangular to kagome MI when fourth site energy offset, Δ, reaches the chemical potential

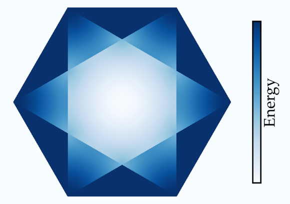
Crossover from triangular to kagome MI





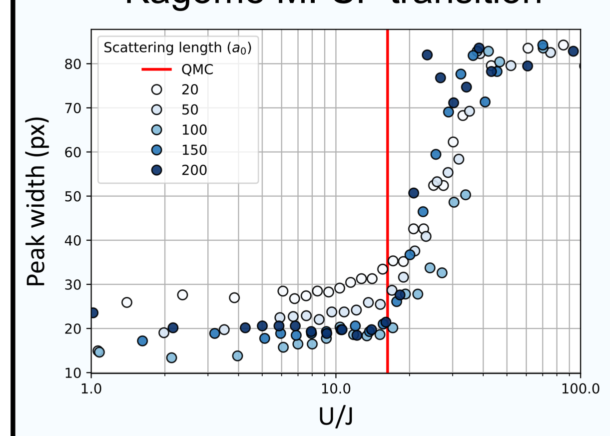
Imaging

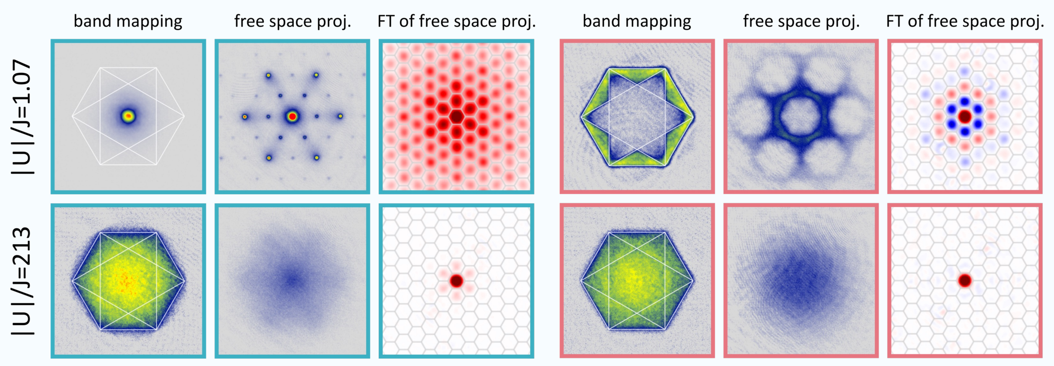
- optimized band mapping to measure quasimomentum distribution in extended BZ
- project to free space to measure momentum distribution - take FT to see real space correlation



Top fractional width of "flat band"
Left: kagome extended BZ

Kagome MI-SF transition





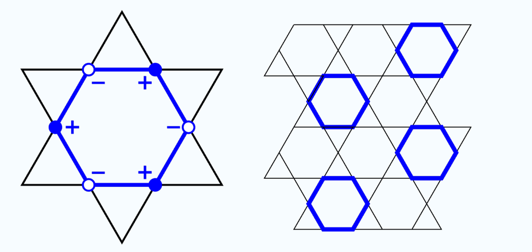
Positive temperature

- probe MI-SF transition at different scattering lengths
- preliminary: compatible with QMC prediction of $(U/J)_c$=16.26(2)

Negative temperature

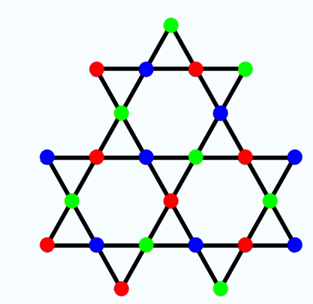
- bosonic ground state predicted to be SF at K point but $T_c \approx 10^{-3} J$
- in classical XY limit, at higher temperature, expect trion SF – equal mixture of "3-colour states" – state with long-range $\langle b^3\rangle \neq 0$ but $\langle b\rangle = 0$
- for $n < 1/9$, expect density wave of localised states in the flat band, supersolid at higher filling
- experimentally - increasing coherence with decreasing $|U/J|$ but no condensation

Localised state



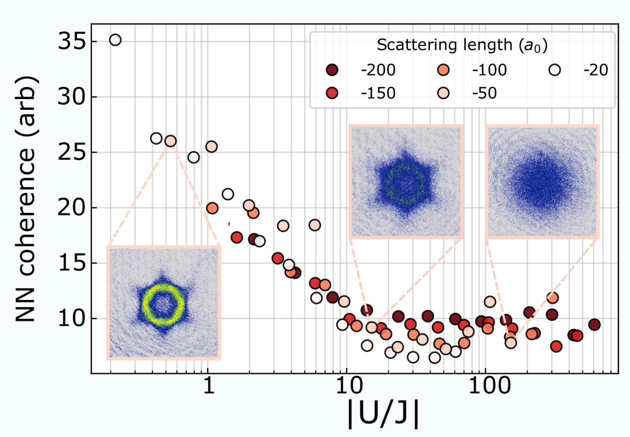
Huber et al, PRB 82, 184502 (2010)

3-colour state



You et al., PRL 109, 265302 (2012)

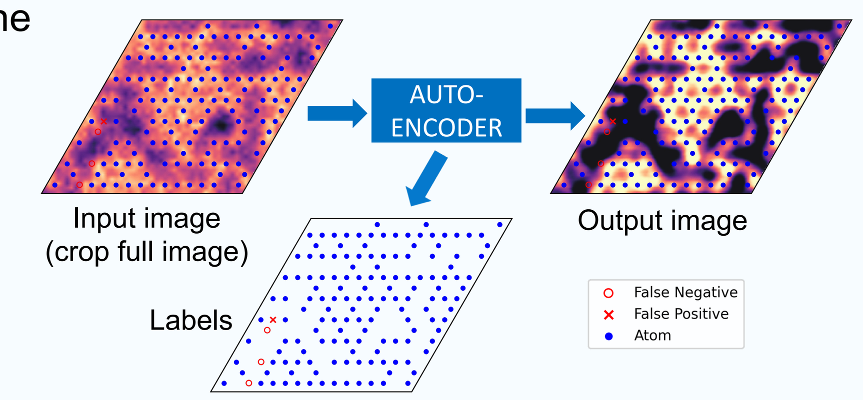
Melting MI into the flat band



Outlook

- Momentum-space experiments in the flat band
  - Many-body physics in the flat band
  - Topology via interferometry, Wilson line
- Quantum gas microscope
  - Single-layer selection
  - Raman sideband cooling
  - Image analysis with conv. neural network
- Homogeneous potentials with DMD
- Fermionic physics with ^{40}K

Microscope image analysis



Based on Impertro et al., arXiv:2212.11974 (2022)