

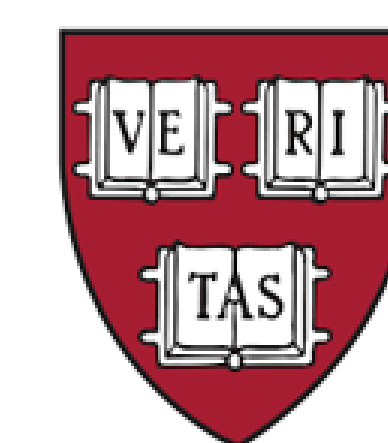


Greiner group

# Ferrimagnetism of ultracold fermions in a multi-band Hubbard system

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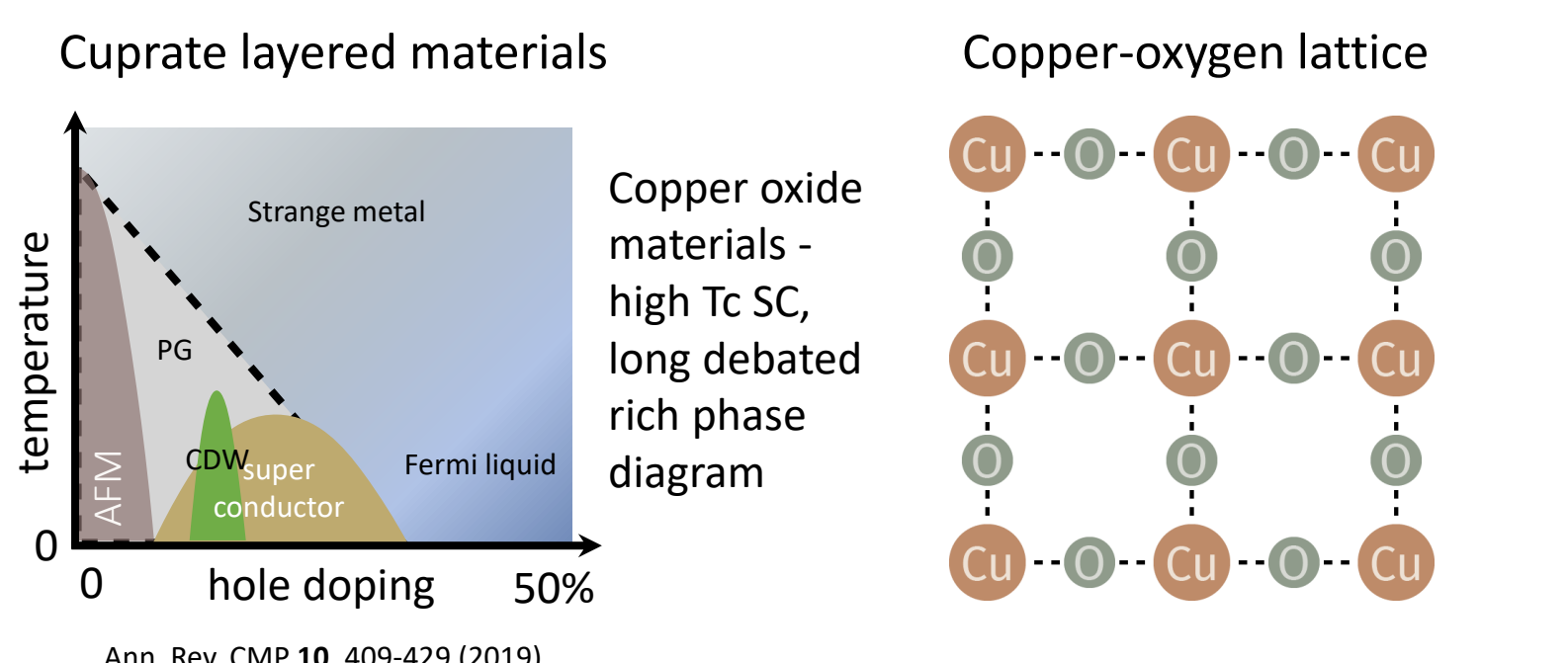
Preprint: arXiv 2404.17555



Harvard Physics

## Lieb lattice and ferrimagnetism

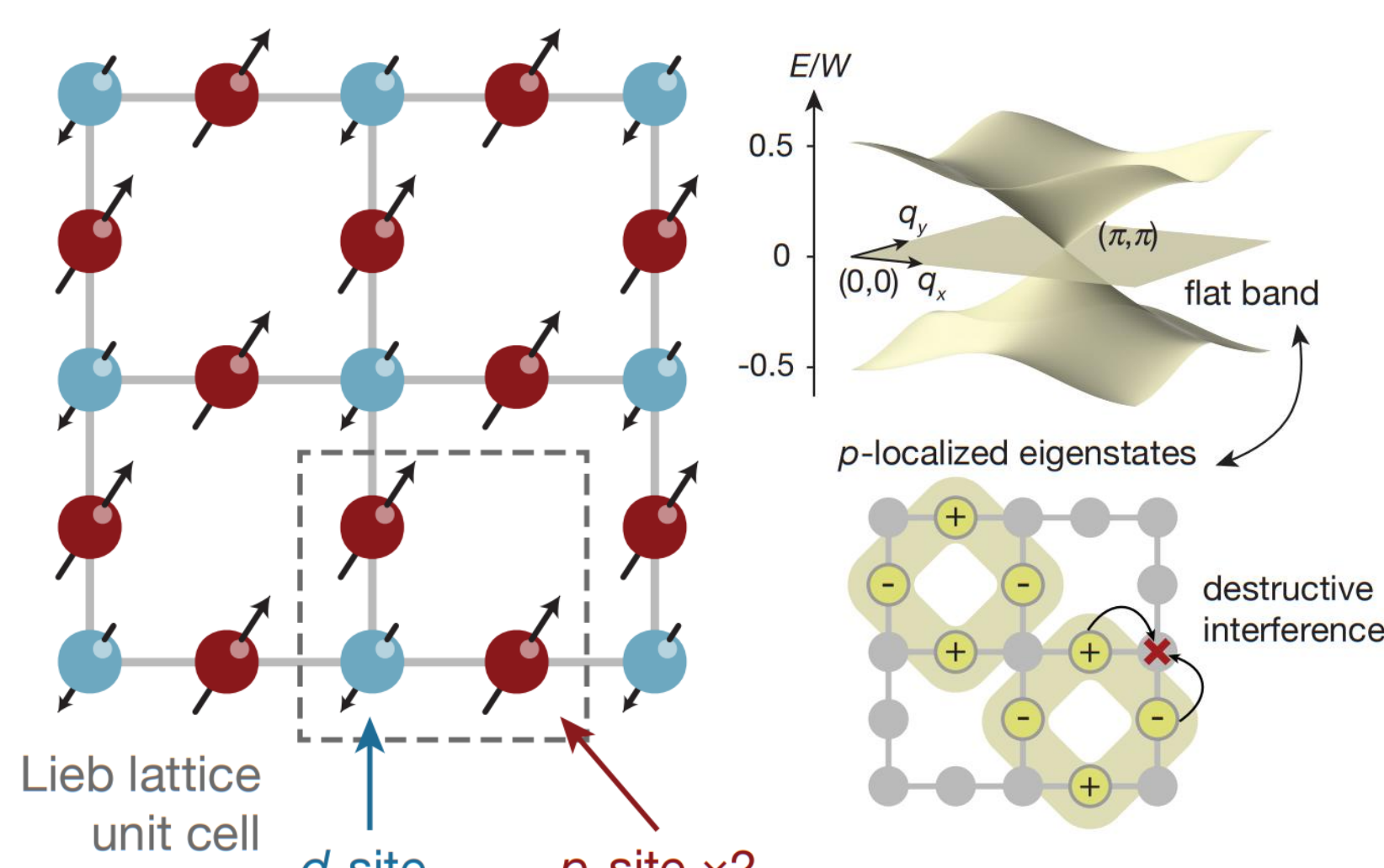
Long standing open question to understand microscopic mechanism leading to phases of strongly correlated systems



Cuprates have 2d planes of Copper and Oxygen atoms arranged in a Lieb lattice (with different interactions and offsets). Three band model is usually simplified into effective single band model on square lattice. However, recently debated if this is a valid simplification (downfolding problem)

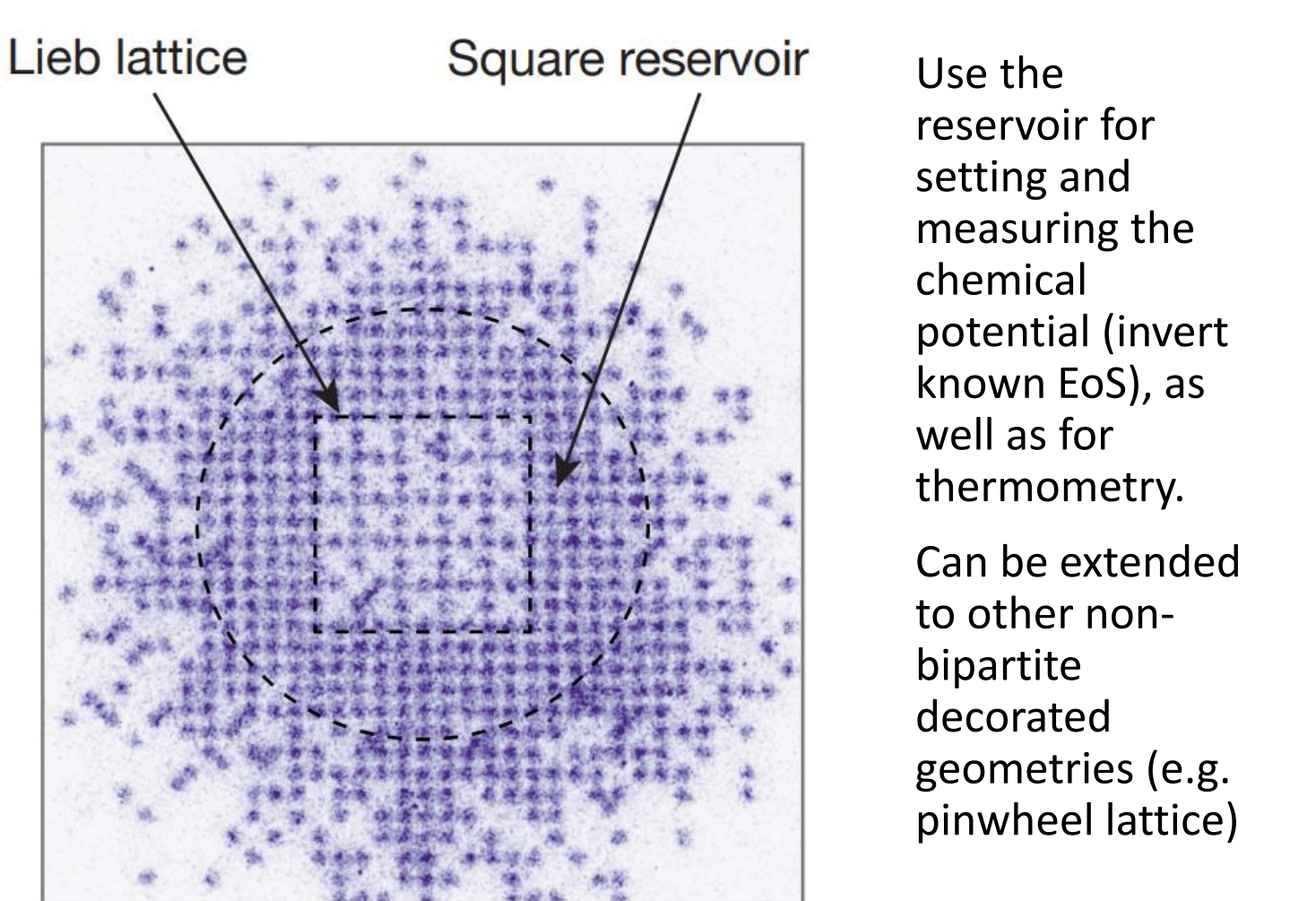
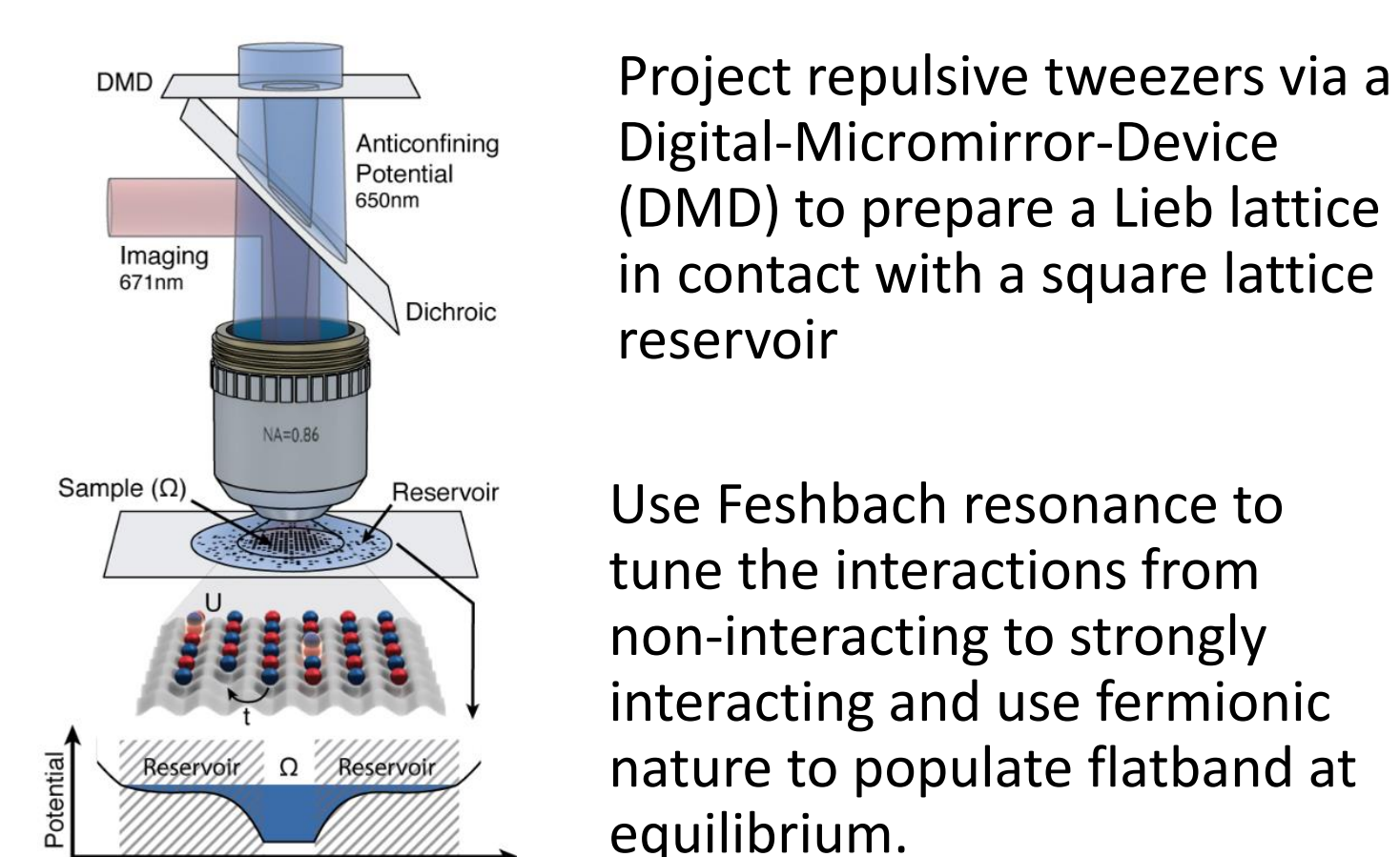
PRX 10, 031016 (2020), PNAS 118, e2106476118 (2021), PRB 108, L161111 (2023).

### Homogenous Lieb lattice



3-band lattice with a flat band in the middle – Flat energy band leads to localized states which live only on p-sites.

## Preparing a flatband lattice



See also: Takahashi group, Sci Adv. 1, e1500854 (2015) Bloch group, Phys. Rev. X 13, 021042 (2023)

Fermi-Hubbard model

$$H = -t \sum_{i,\sigma} (c_{i\sigma}^\dagger c_{j\sigma} + hc) + U \sum_i n_{i\uparrow} n_{i\downarrow} + \sum_i \epsilon_i n_i$$

Tunneling  $t$  and on-site interaction  $U$  lead to effective spin superexchange  $J$

$$J = \frac{4t^2}{U}$$

Single-site resolved imaging allows measurement of on-site observables and real-space correlation functions. Spin removal + density imaging via conditional Landau-Zener transfer of spin states

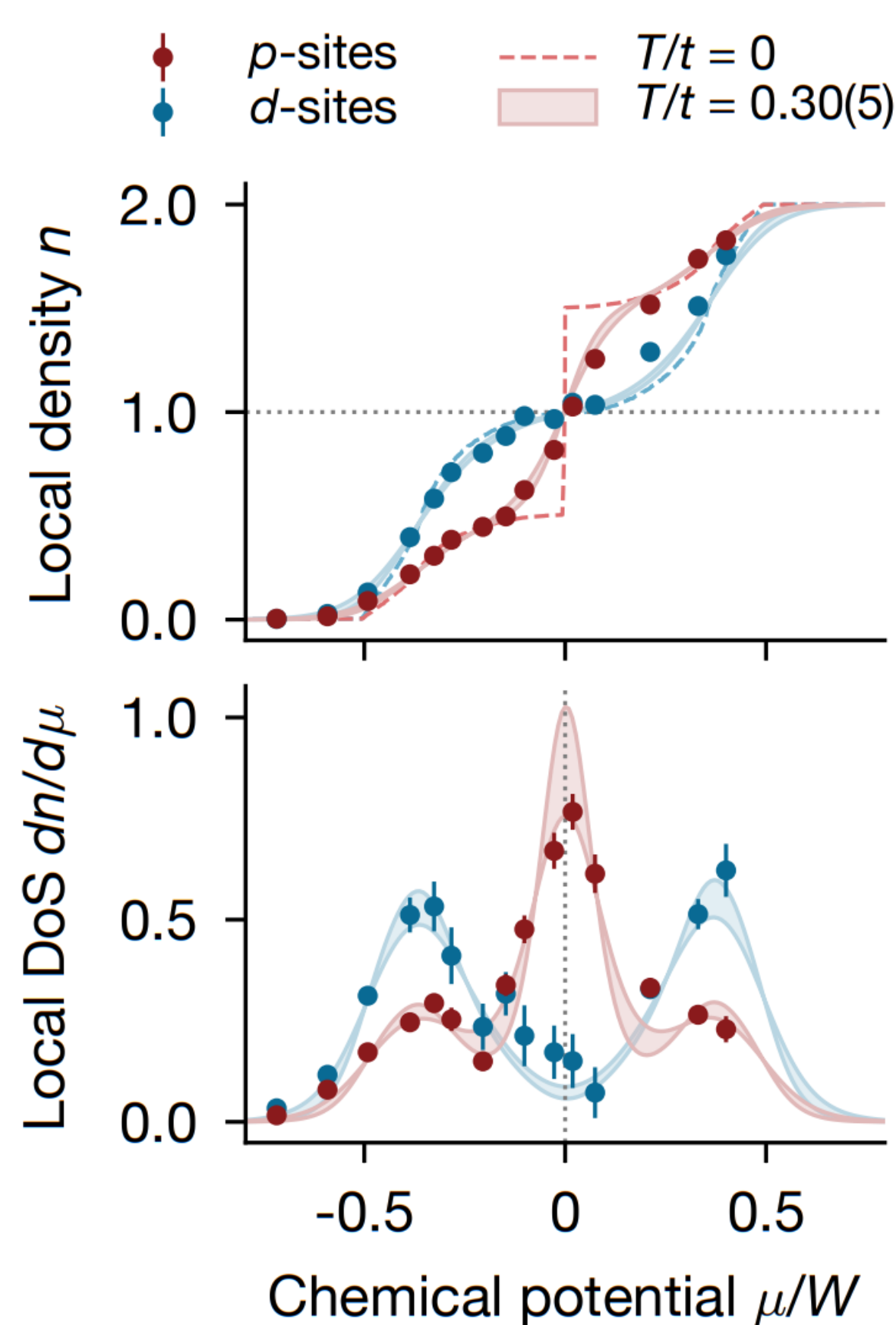
Lieb's theorem PRL 62, 1201 (1989)

Ground state in a bipartite lattice for any  $U > 0$  has total spin  $S_{tot} = \frac{N_A - N_B}{2}$ . For Lieb lattice  $S_{tot} = \frac{1}{2} \times$  (unit cells) -- **ferromagnet**

S. Shen et al PRL 72, 1280 (1994)

Lieb lattice has  $S(\pi, \pi) > S(0, 0) = O(N)$  for any  $U > 0$ , i.e. ground state is a long range **antiferromagnet**

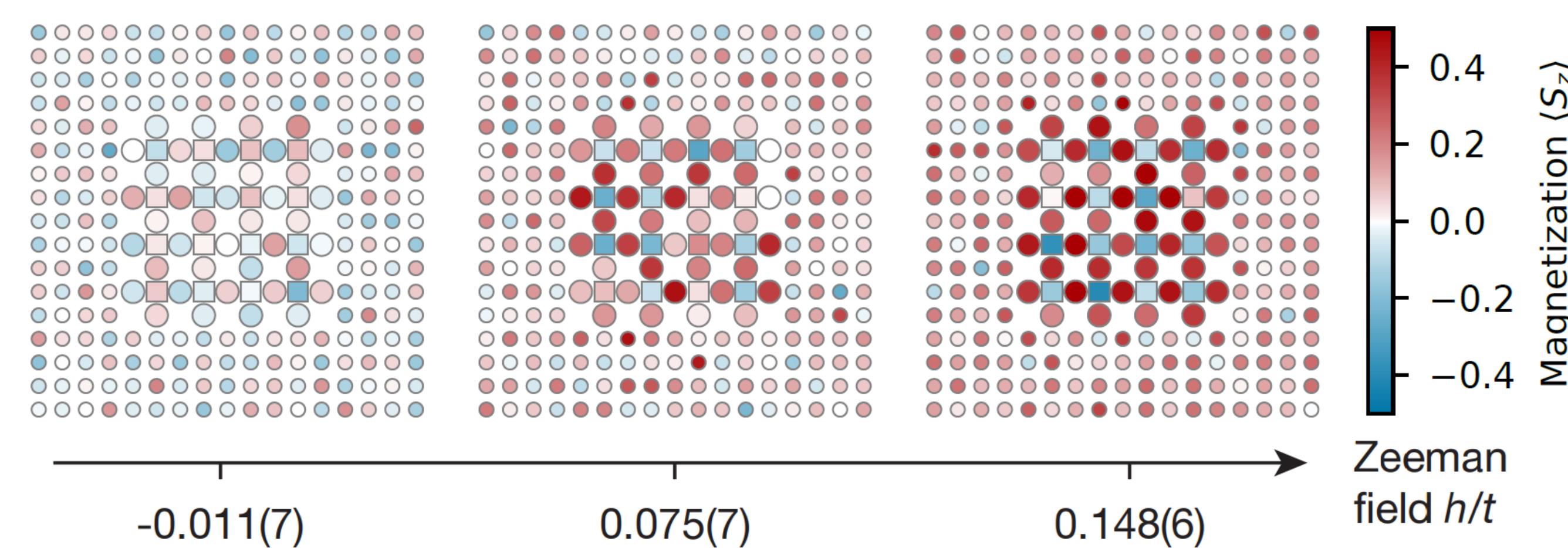
Together, ground state of half-filled Lieb lattice for any  $U > 0$  is **ferrimagnetic!**



Vary the atom number (hence chemical potential) to probe the band structure. Sharp rise in p-site density and peak in local compressibility at half-filling sign of flat band.

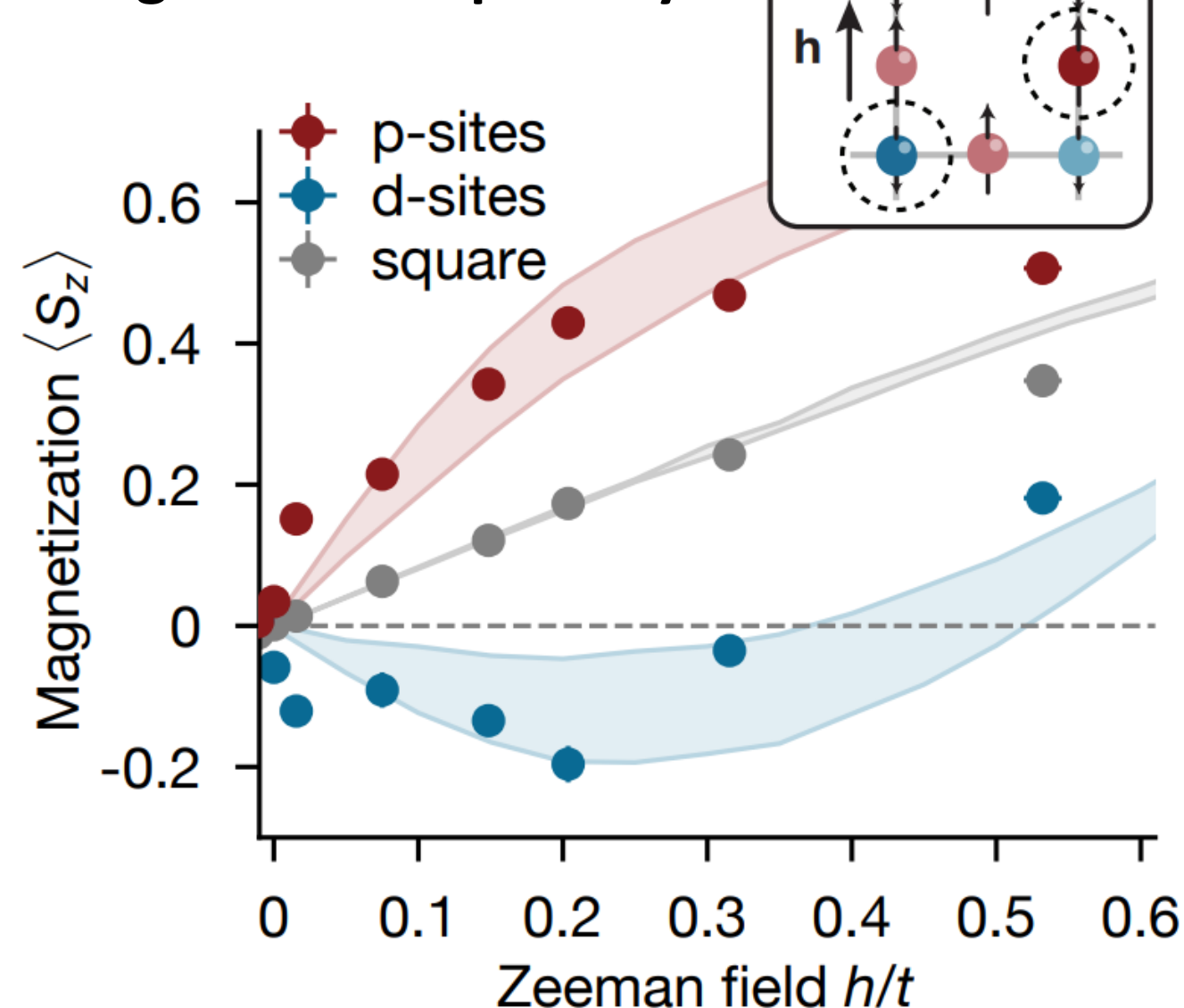
## Signatures of ferrimagnetism

With interaction strength  $U/t = 6.6(1)$ , measure **local magnetization**  $\langle S_z \rangle$  upon applying a global Zeeman field. Zeeman field is realized by preparing a spin imbalanced atomic cloud ( $N_\uparrow \neq N_\downarrow$ ) by evaporatively cooling in a magnetic field

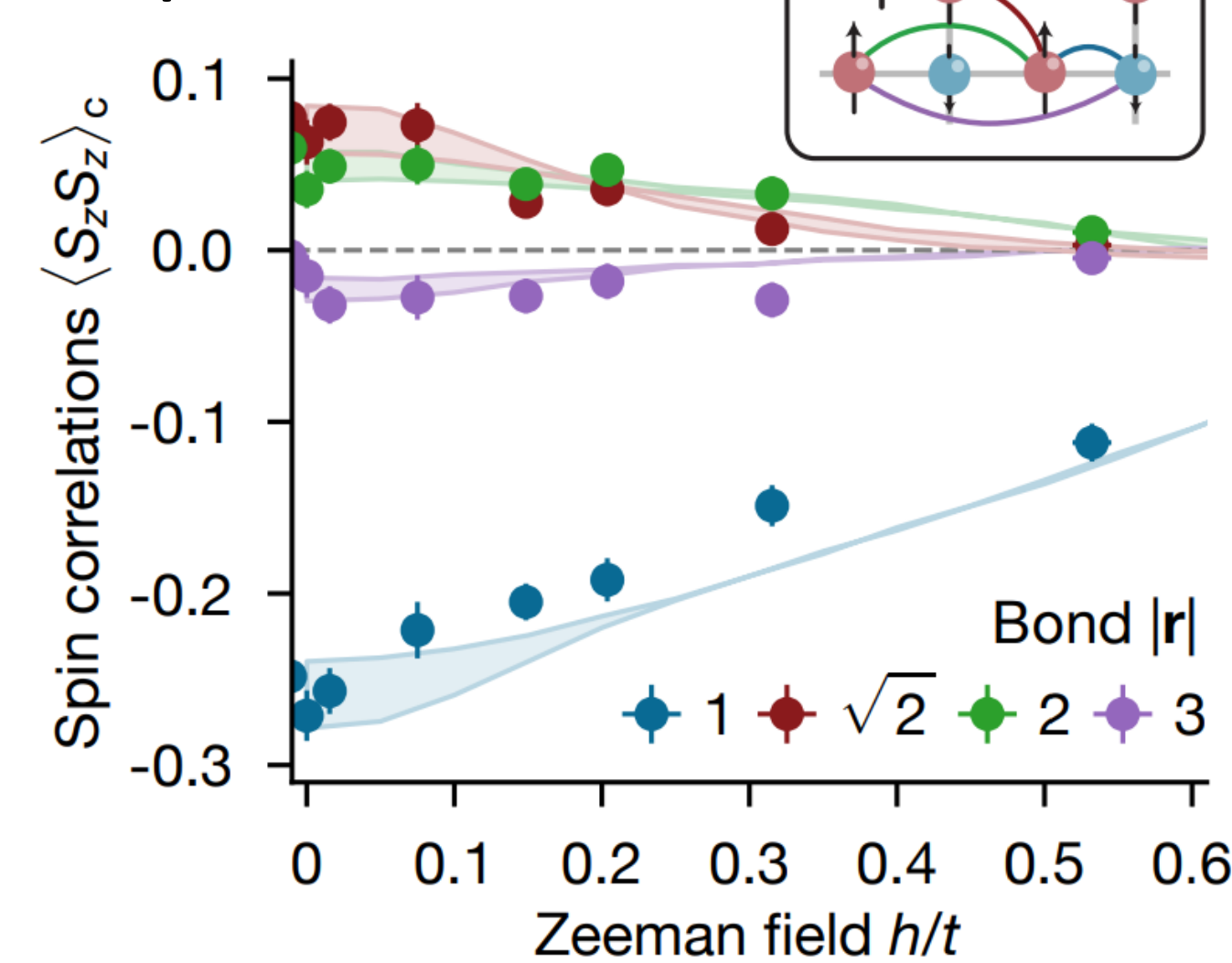


With increasing Zeeman field, a staggered magnetization appears parallel to the applied field in Lieb lattice. Magnetic moments on d-sites aligned opposite to applied field: negative local susceptibility!

### Magnetic susceptibility



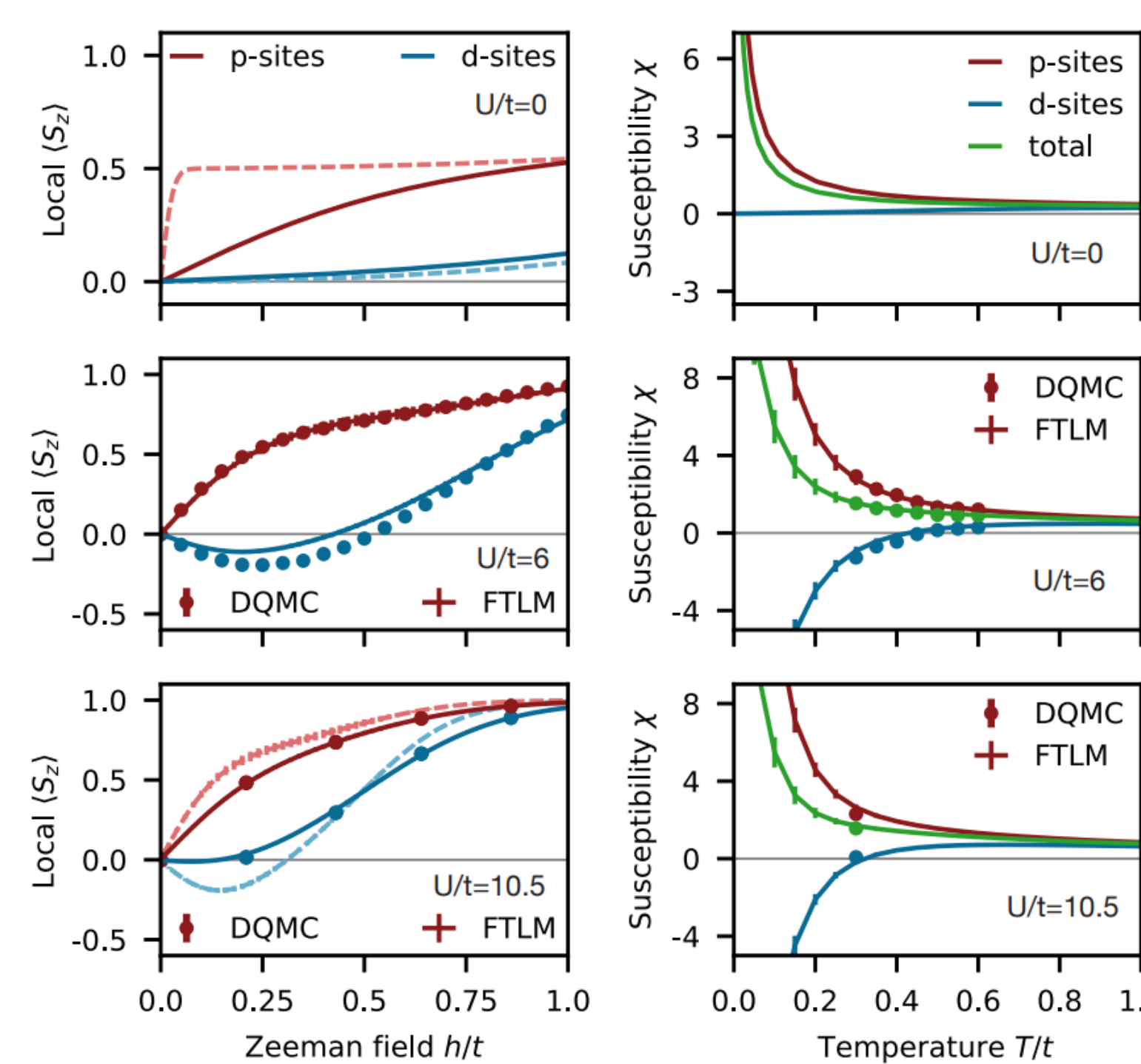
### Connected spin correlations



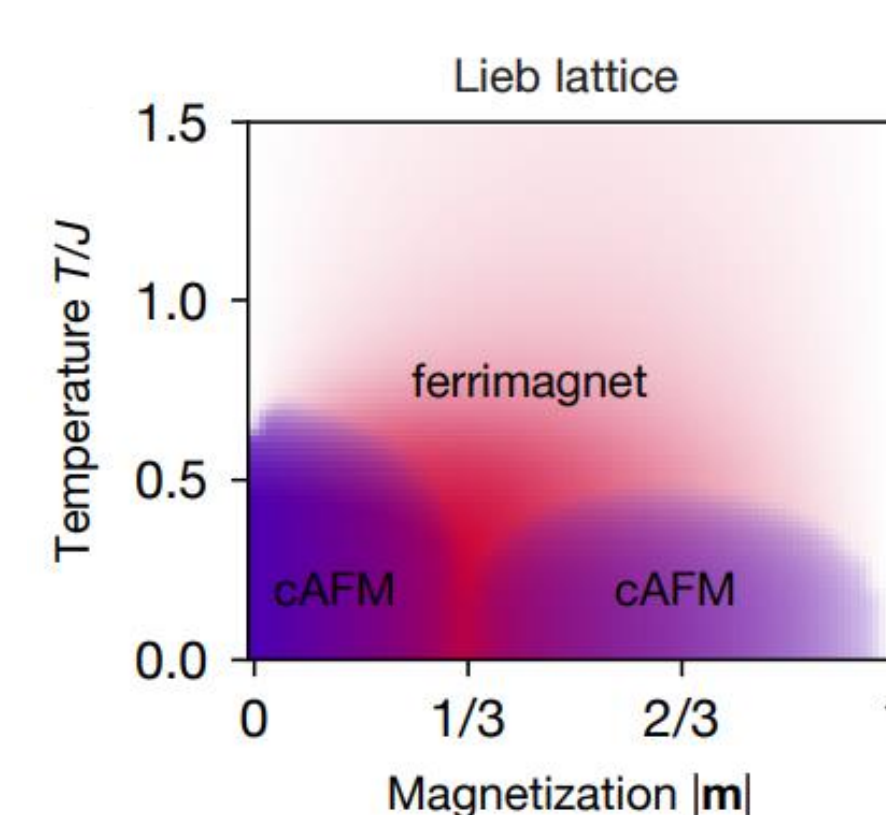
Non-monotonic behavior of d-site magnetization results from competition between Zeeman field and antiferromagnetic correlations. Connected spin correlators positive between same sublattice ( $|r| = \sqrt{2}, 2$ ) and negative between opposite sublattice ( $|r| = 1, 3$ )

## Numerical results

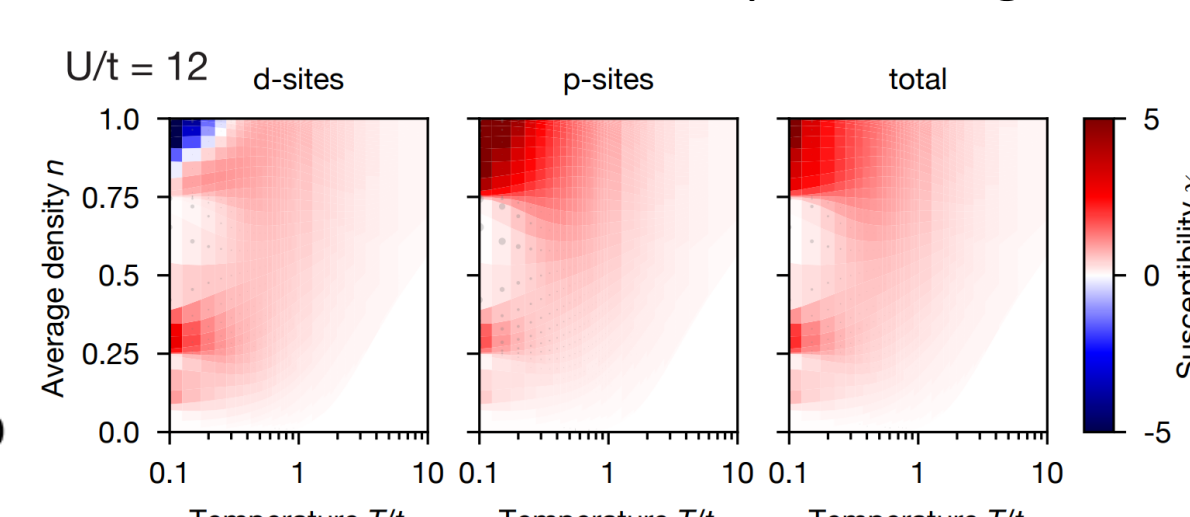
Use Determinant Quantum Monte Carlo (DQMC), Finite Temperature Lanczos Method (FTLM) and Curie-Weiss meanfield to numerically study the Lieb lattice Hubbard model



Numerically computed local magnetization and susceptibility



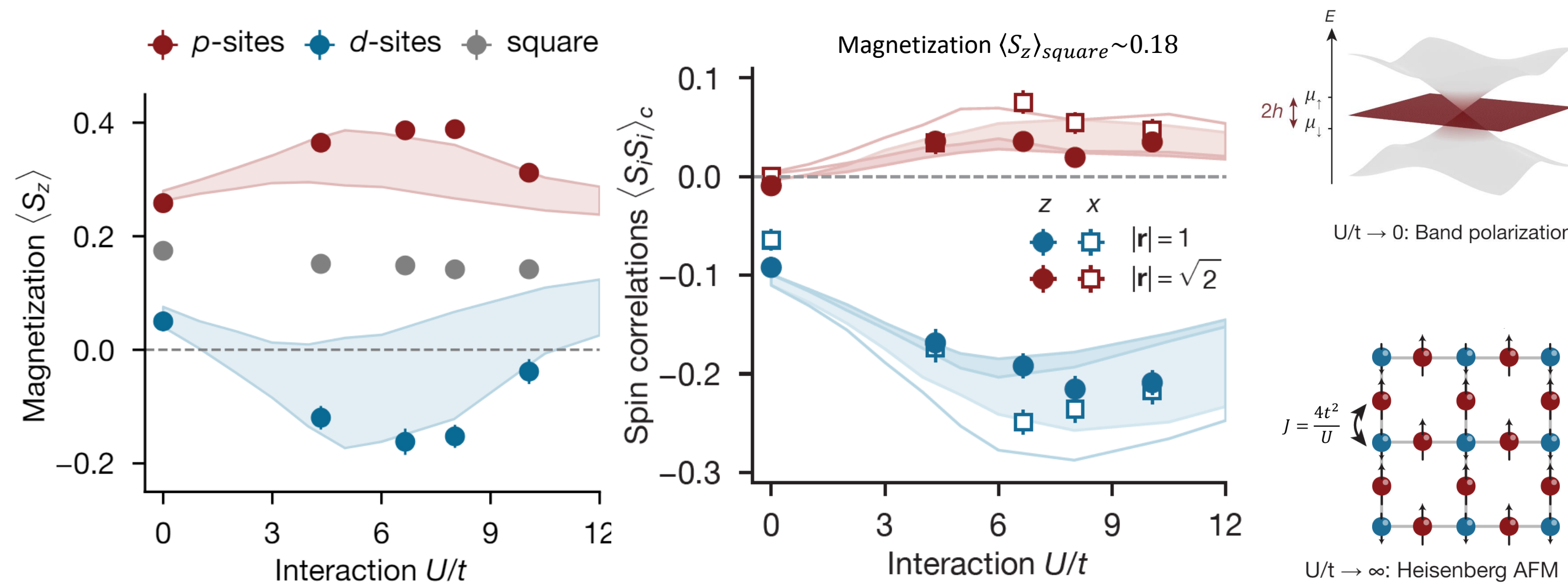
### Curie-Weiss mean-field phase diagram



Susceptibility below half-filling from FTLM

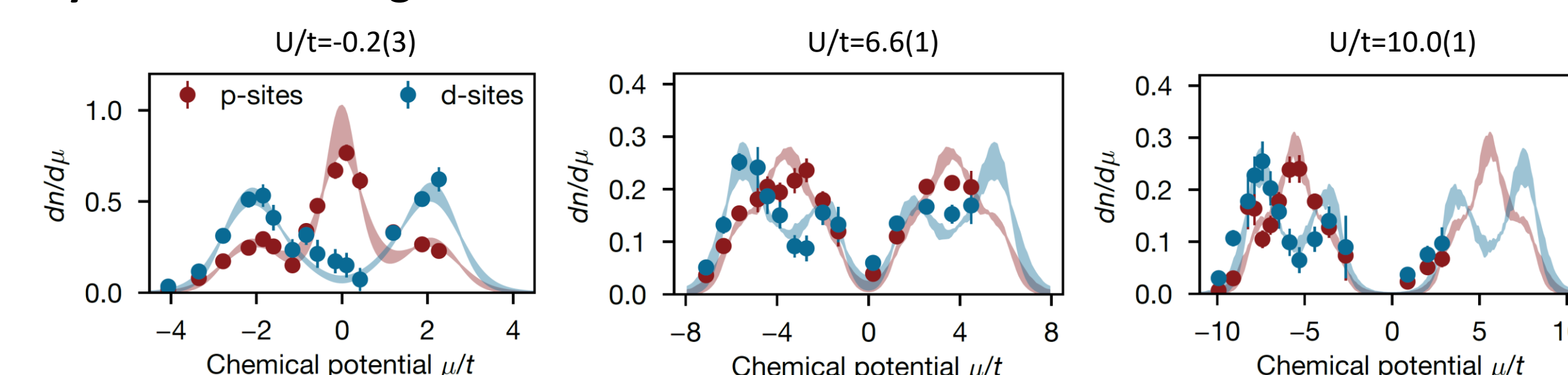
## Effect of interactions

Staggered magnetization seen across a broad range of interactions, along with robust AFM connected spin correlations.



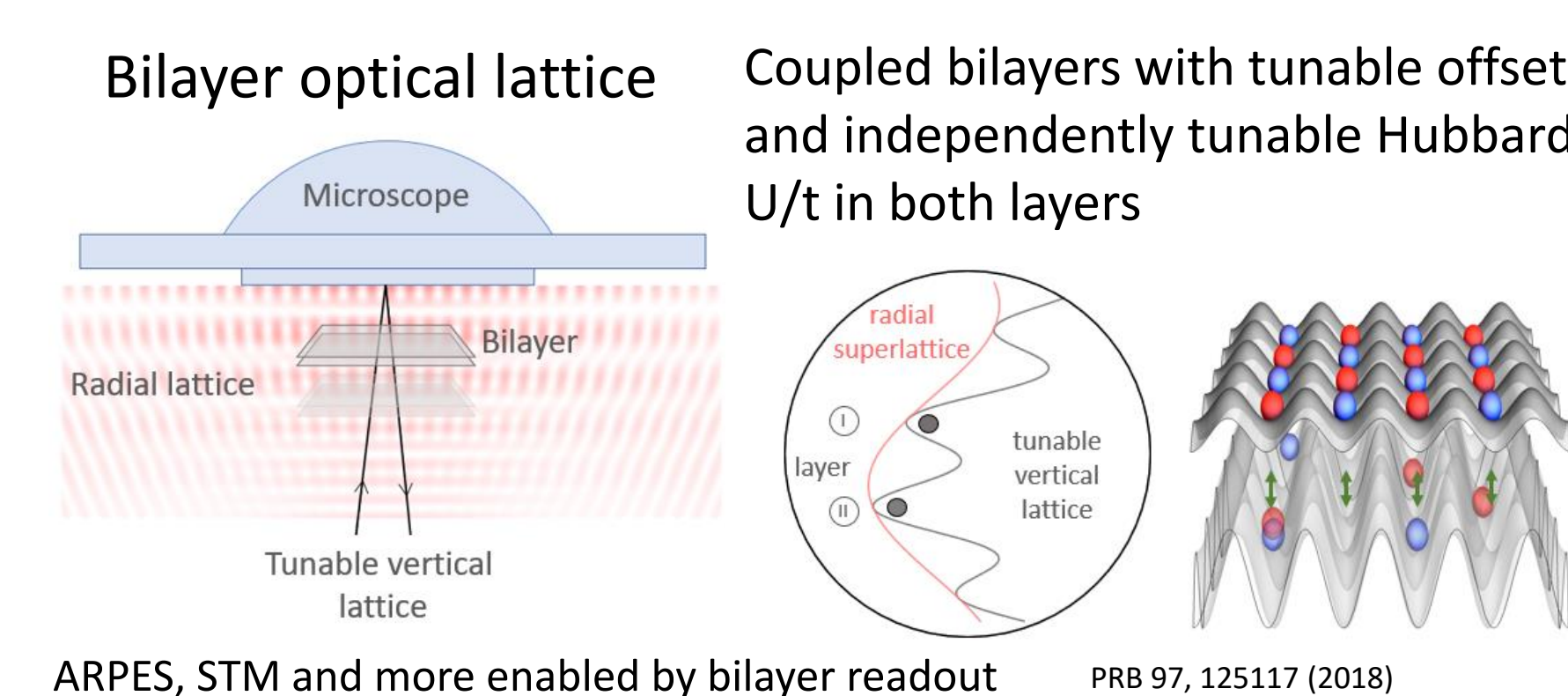
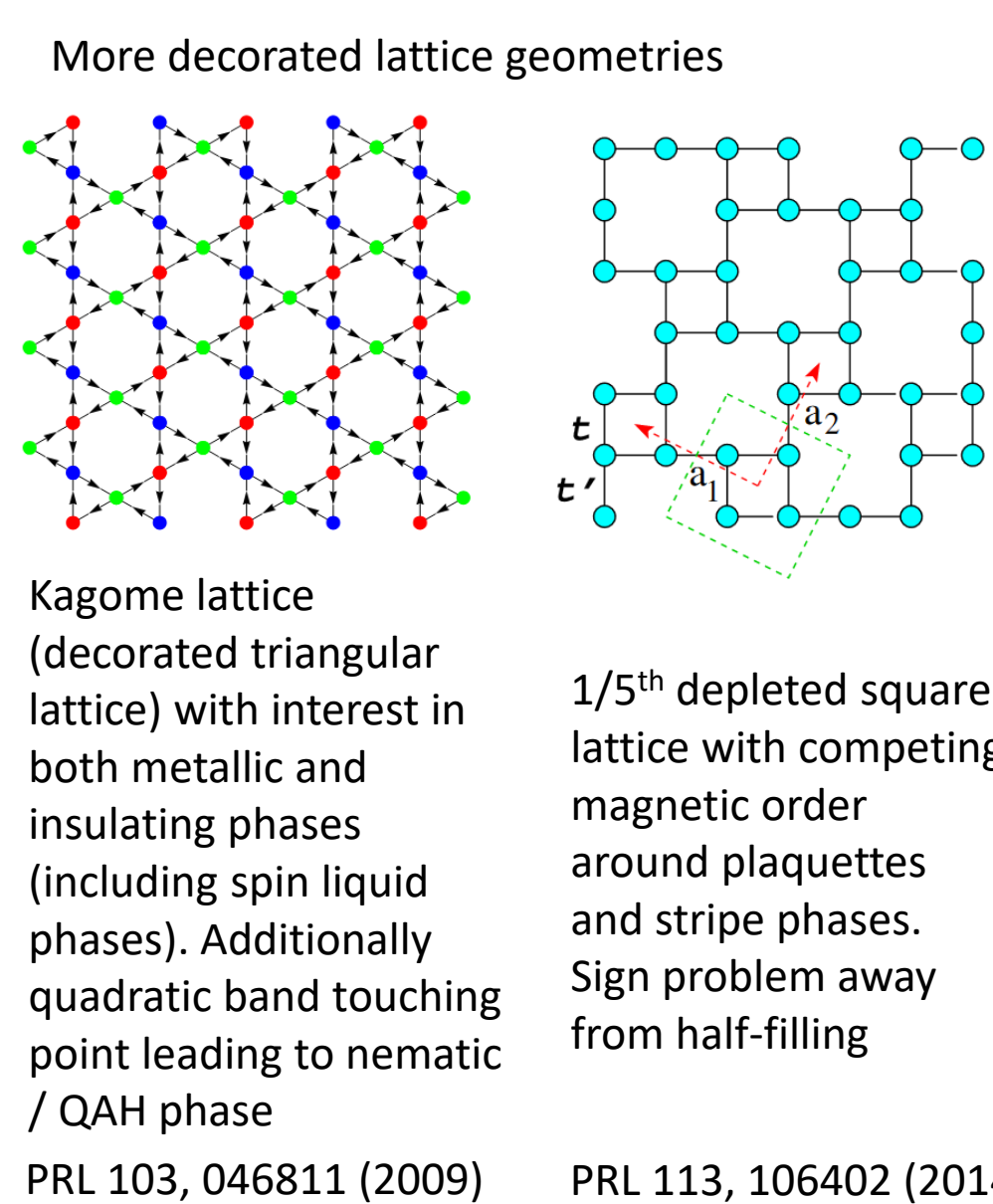
Ferrimagnetism can be understood in the two limiting cases of  $U/t \rightarrow 0$  (band polarization) and in the large  $U/t$  limit (Heisenberg AFM). Measuring spin correlations along (Z) and transverse (X) to the applied field reveal slightly larger fluctuations perpendicular to the Zeeman field.

### Away from half-filling:



Measured local compressibility reveals the evolution from flat band at  $U/t=0$  to Mott insulating gap at large interactions. Interestingly the local compressibility curve at large interactions shows a "band-structure doubling" compared to the  $U/t=0$  case, indicating a possible mapping to spinless fermions or ferromagnetism.

## Outlook



Improved entropy redistribution in bilayer to reach lower temperatures

Beyond "vanilla" square Hubbard

Next-nearest neighbor tunneling crucial to see SC in Hubbard model

Science 365, 1424-1428 (2019)

arXiv: 2303.08376

## Acknowledgements



AK and LHK acknowledge funding from NSF GRFP, AK and YG acknowledge Harvard Quantum Initiative (HQI), ML acknowledges the Swiss NSF and the Max Planck/Harvard Research Center for Quantum Optics.

