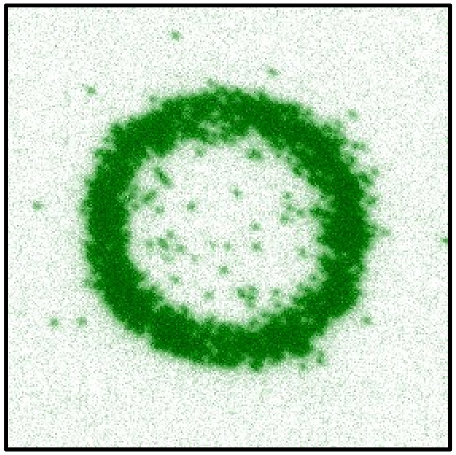
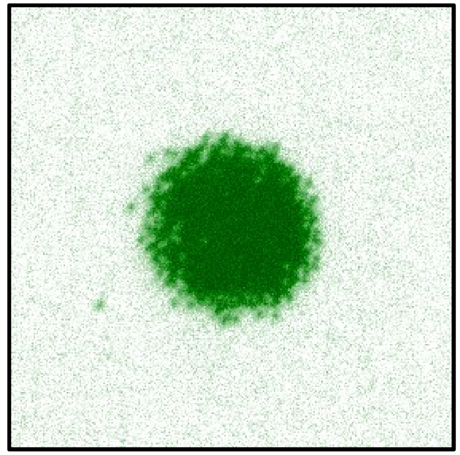
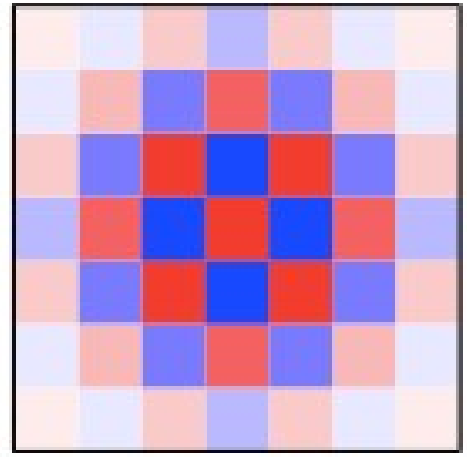
  

Quantum gas microscopy of the Fermi-Hubbard model in new regimes

Peter Schauss, Princeton University

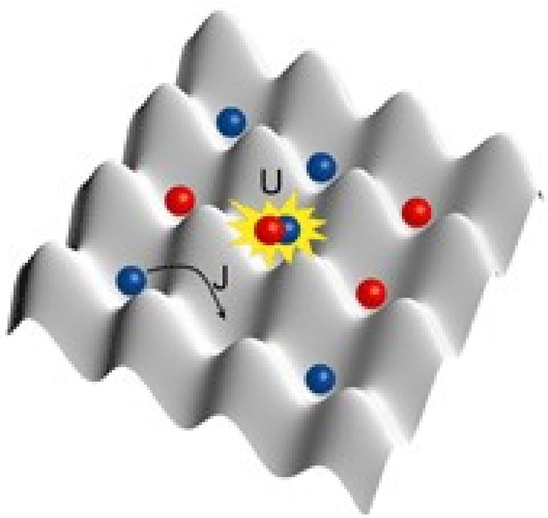
Debayan Mitra, Peter Brown, Elmer Guardado-Sanchez,

Stanimir Kondov, Trithep Devakul, David Huse, Waseem Bakr

Ehsan Khatami, Thereza Paiva, Nadini Trivedi

Trieste, November 2017

The Fermi-Hubbard model



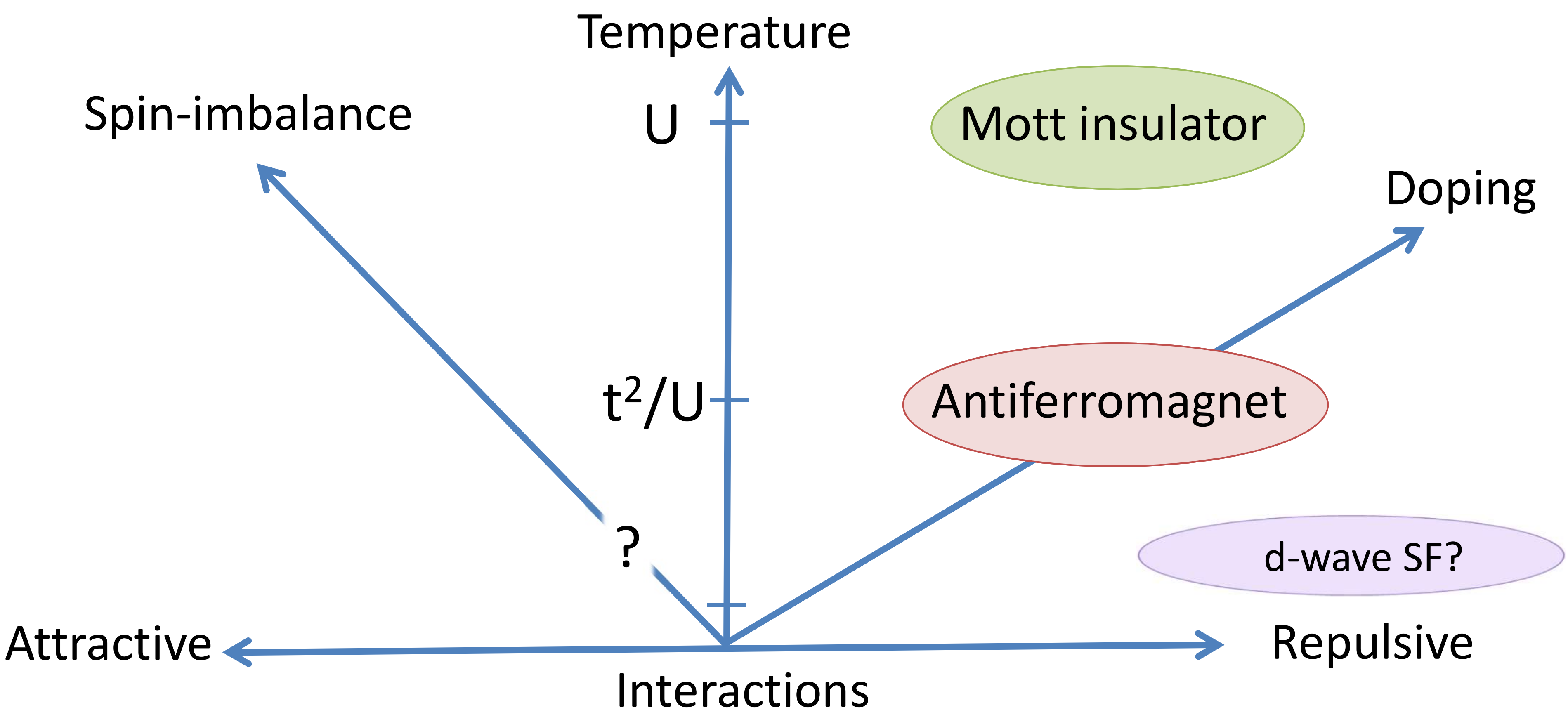
- Two species of fermions in a 2D lattice.
- Nearest neighbor tunneling *t*.
- Onsite interactions *U*.

$$\mathcal{H} = -t \sum_{\langle ij \rangle, \sigma} \left(c_{i,\sigma}^{\dagger} c_{j,\sigma} + c_{j,\sigma}^{\dagger} c_{i,\sigma} \right) + U \sum_{i} n_{i,\uparrow} n_{i,\downarrow}$$

- Realized naturally with cold atoms in optical lattices with fully tunable parameters.

Jaksch, PRL **81**, 3108 (1998)

The parameter space

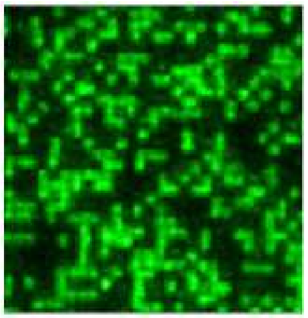


Mott insulator: Munich, ETH

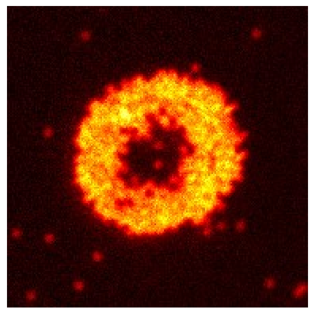
Antiferromagnet: ETH, Rice, Harvard, MIT, Munich, Bonn

Quantum gas microscopy

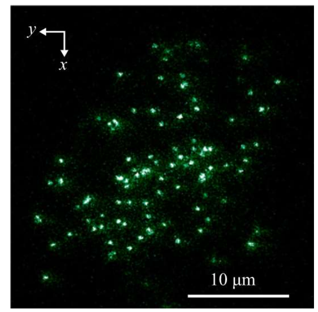
- Boson microscopes



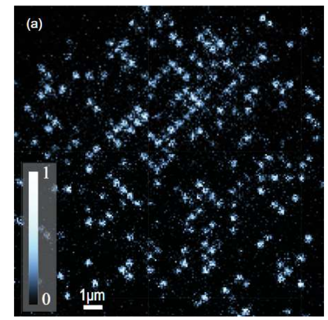
Harvard



MPQ

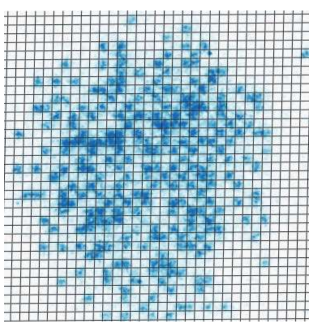


Kyoto

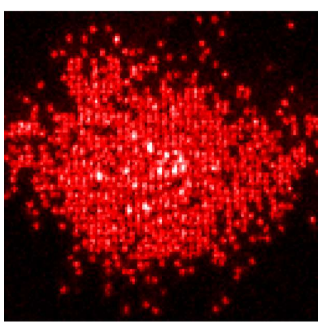


Tokyo

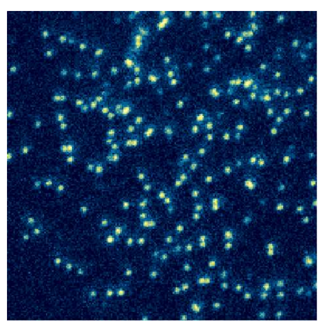
- Fermion microscopes



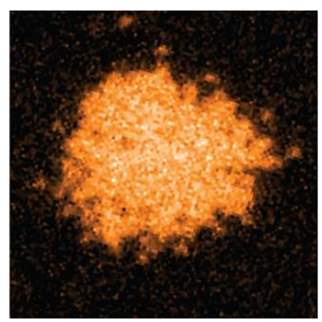
Harvard



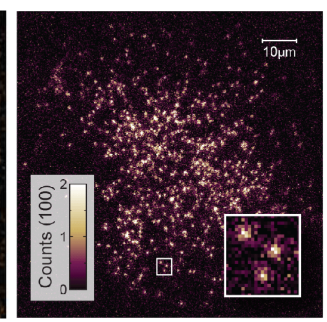
MPQ



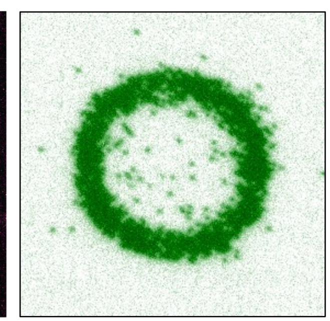
Strathclyde



MIT

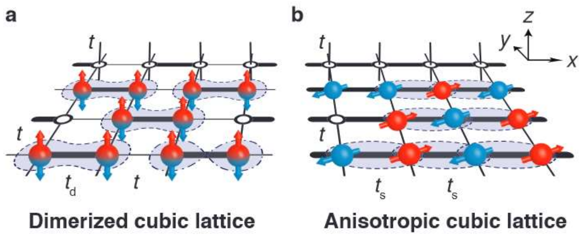


Toronto



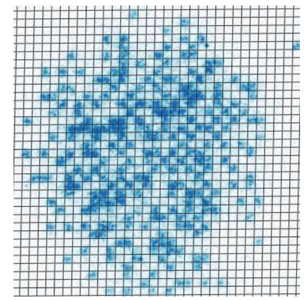
Princeton

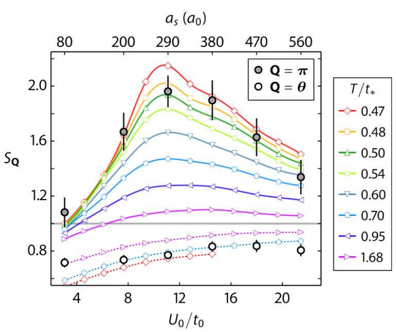
Antiferromagnetic correlations



Esslinger group
Science 340, 1307 (2013)

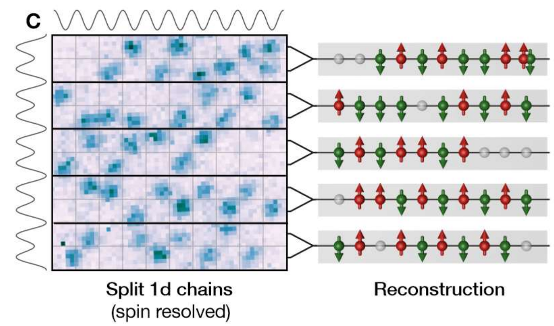
Greiner group
T/t = 0.45 (2D)
Science 353, 1253 (2016)

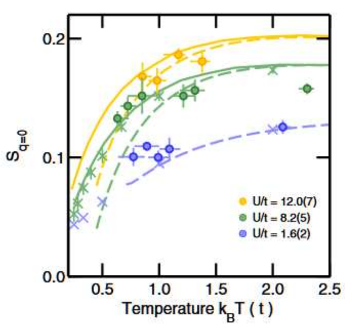




Hulet group
Nature 519, 211 (2015)

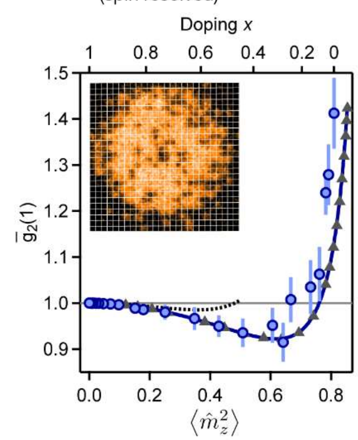
Bloch/Gross group
1D
Science 353, 1257 (2016)





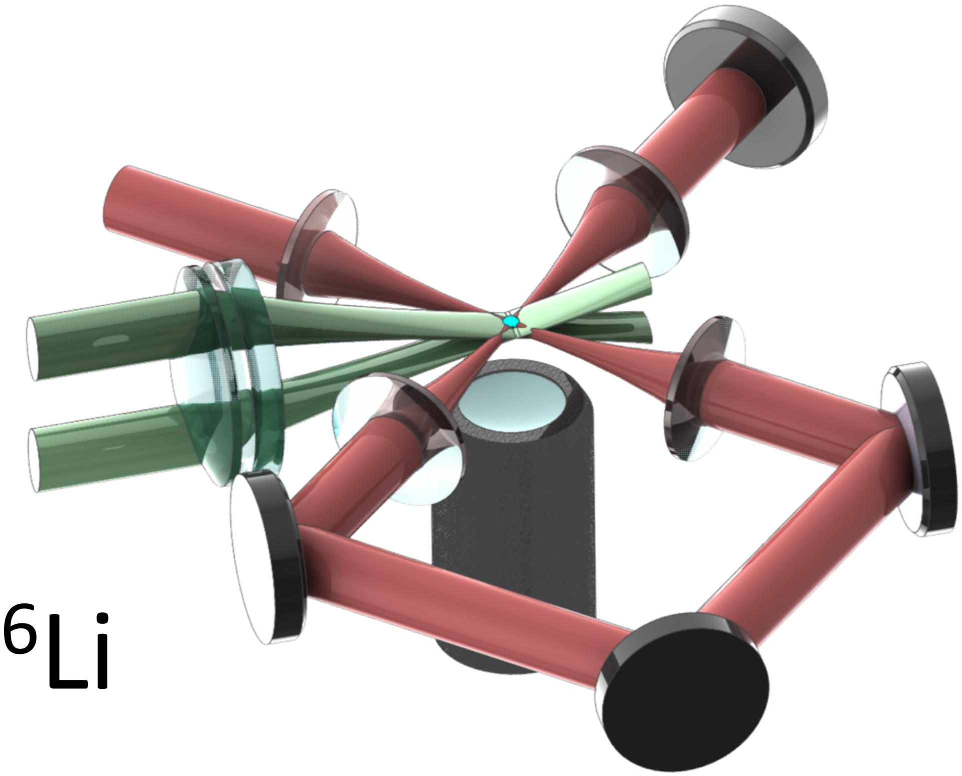
Köhl group (2D)
PRL 118, 170401 (2017)

Zwierlein group
T/t = 0.89 (2D)
Science 353, 1260 (2016)



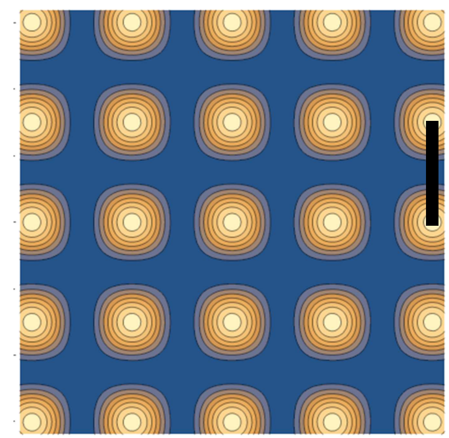
A simplified Fermi gas microscope

- Single beam optical lattice @ 1064 nm simplifies microscopy:
  4-fold interference enhances depth + larger lattice spacing.

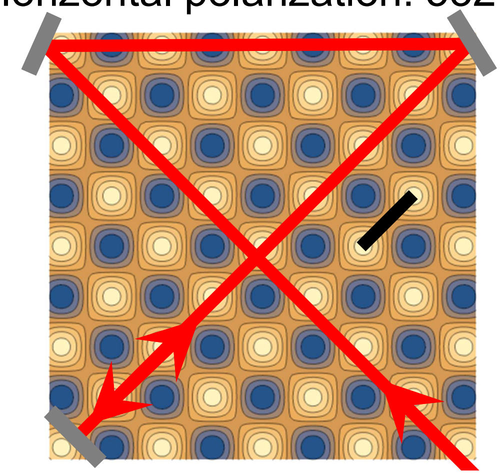


^6Li

Vertical polarization: 752 nm



Horizontal polarization: 532 nm

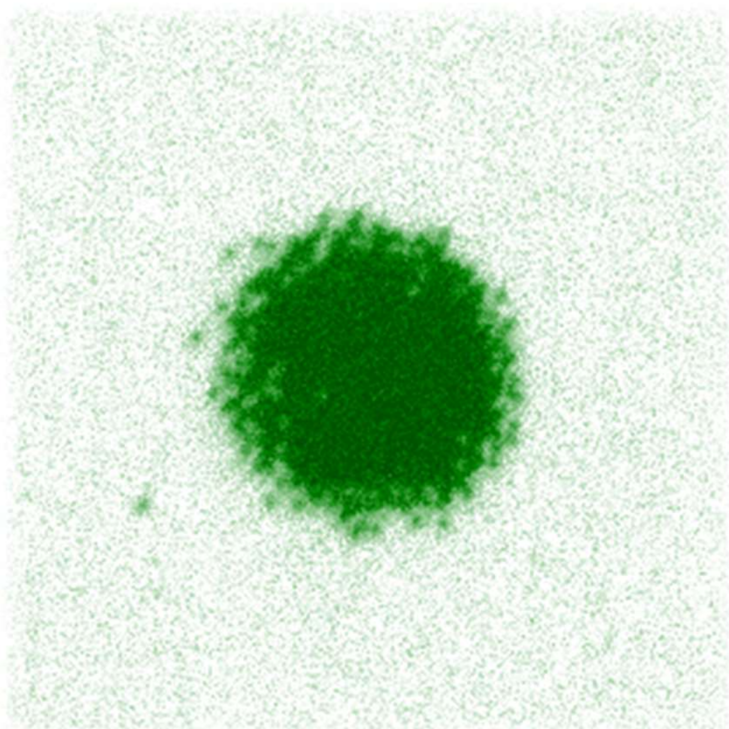


Lithium allows for large lattice spacing:

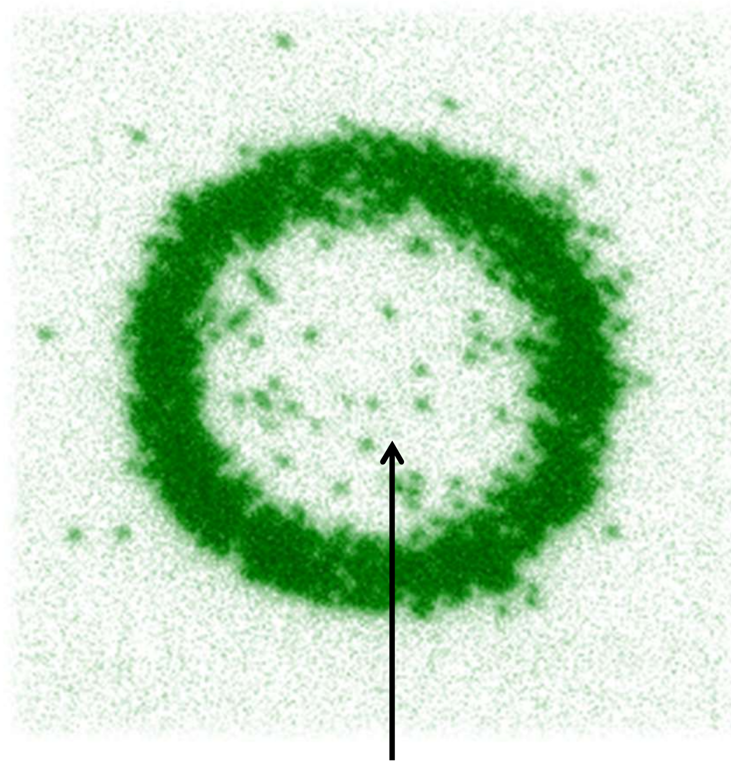
- Light
- “good” Feshbach resonances
- NA = 0.5 is sufficient for single-site

Repulsive Hubbard model: Mott insulators and band insulators

Detect 1000 photons/atom in 1.2s via Raman sideband cooling
Hopping: 0.4%, loss: 1.6%



Mott insulator



Band insulator
(in presence of light assisted collisions)

Brown et. al., Science 357, 1385 (2017)

Outline

1. Spin-imbalance in
   repulsive Hubbard model

2. Attractive Hubbard model

1. Spin-imbalance in a 2D Fermi-Hubbard system

Brown et. al., Science 357, 1385 (2017)

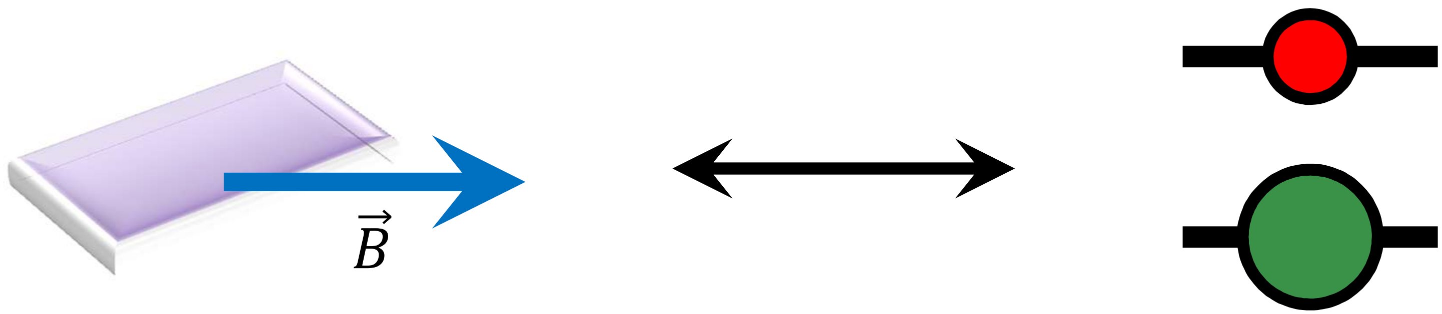
Spin imbalance

Condensed matter system:
Spin imbalance by applied magnetic field (Zeeman effect)

Cold atoms:

Spin-imbalance prepared before loading to lattice by evaporation in spin-dependent potential.

No spin-relaxation.



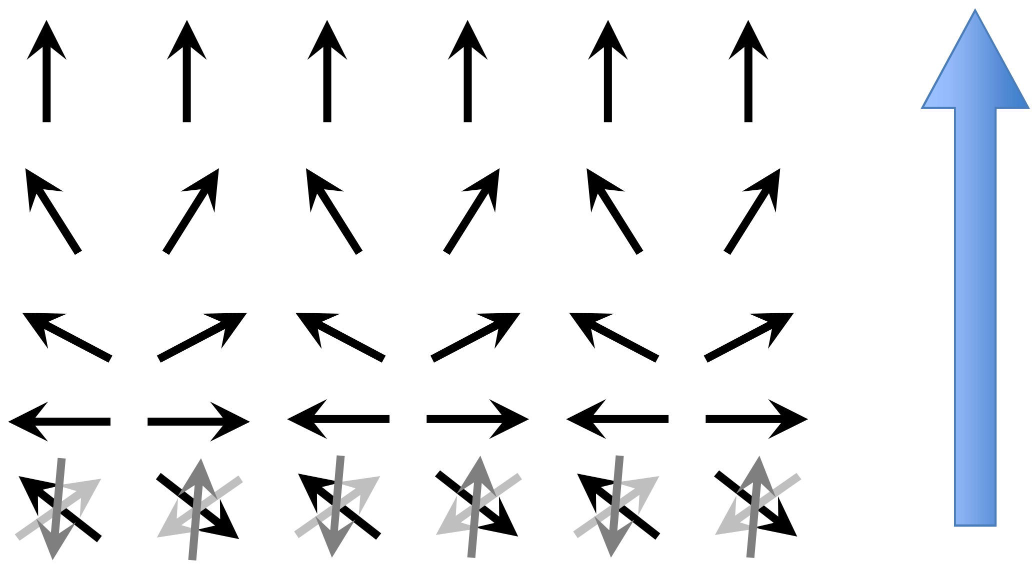
Zeeman field

Spin-polarization

Spin canting – classical model

Classical antiferromagnetic Heisenberg model

$$H = J \sum_{\langle i,j \rangle} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + h \sum_i \boldsymbol{S}_i^{\boldsymbol{z}}$$



Increasing
magnetic field
h

Polarization:

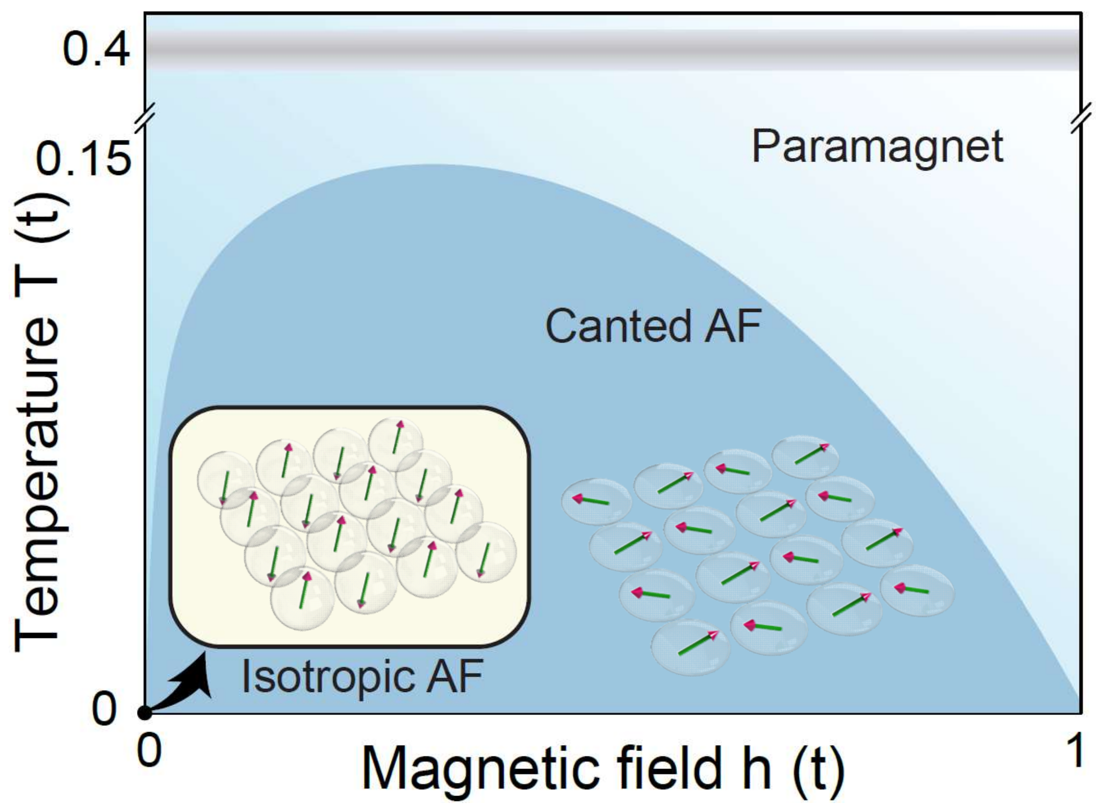
$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = 2\, S_z$$

$$C_j^{x,z} = \left\langle S_i^{x,z} S_{i+j}^{x,z} \right\rangle - \left\langle S_i^{x,z} \right\rangle \left\langle S_{i+j}^{x,z} \right\rangle$$

→ Main signature: Asymmetry in S^zS^z vs S^xS^x correlation

Spin Canting: 2D Hubbard Phase Diagram at half-filling

- Superexchange energy scale $J = 4t^2/U$, BKT phase transition
- Field breaks SU(2) symmetry
- AFM correlations build up preferably in XY plane

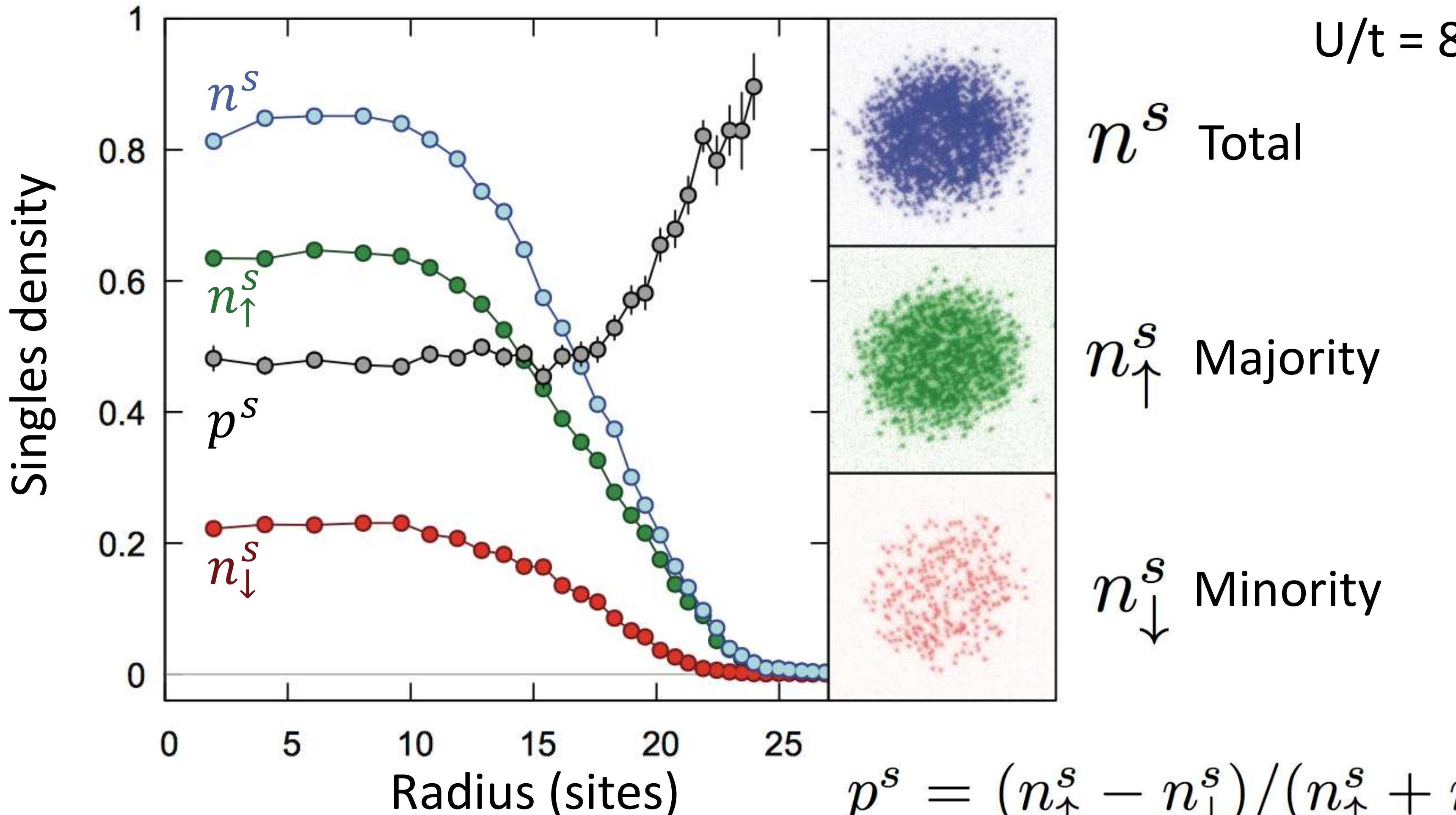


Isotropic AF with QGM:
Science **353**, 1253 (2016)
Science **353**, 1257 (2016)
Science **353**, 1260 (2016)

Phase Diagram:
PRB **69**, 184501 (2004)
PRA **81**, 023628 (2010)

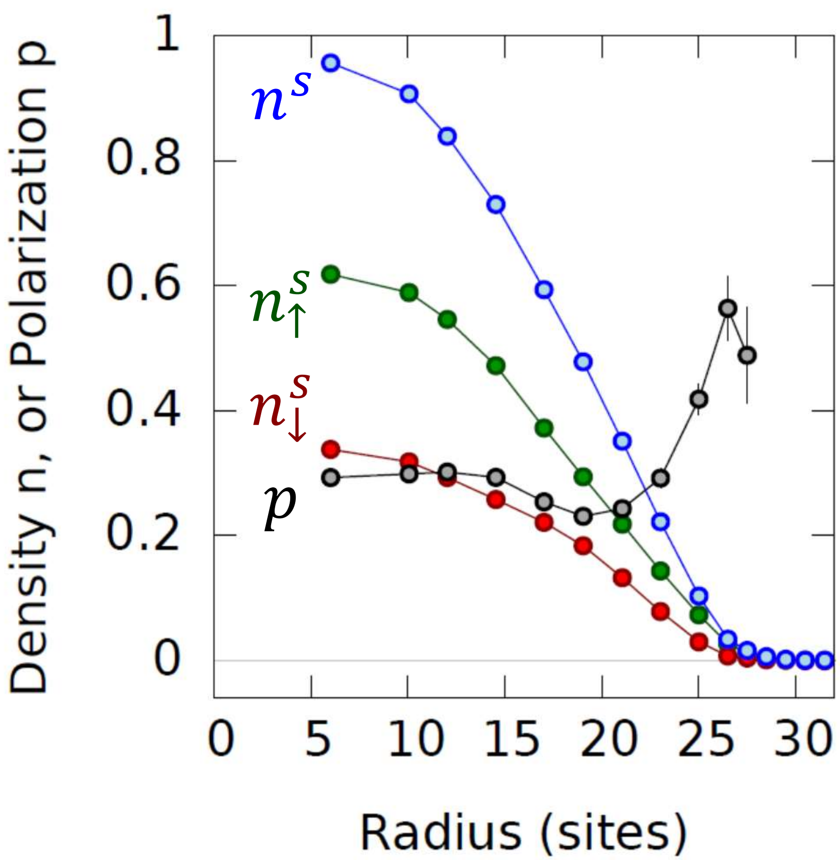
Spin-imbalanced Mott insulators

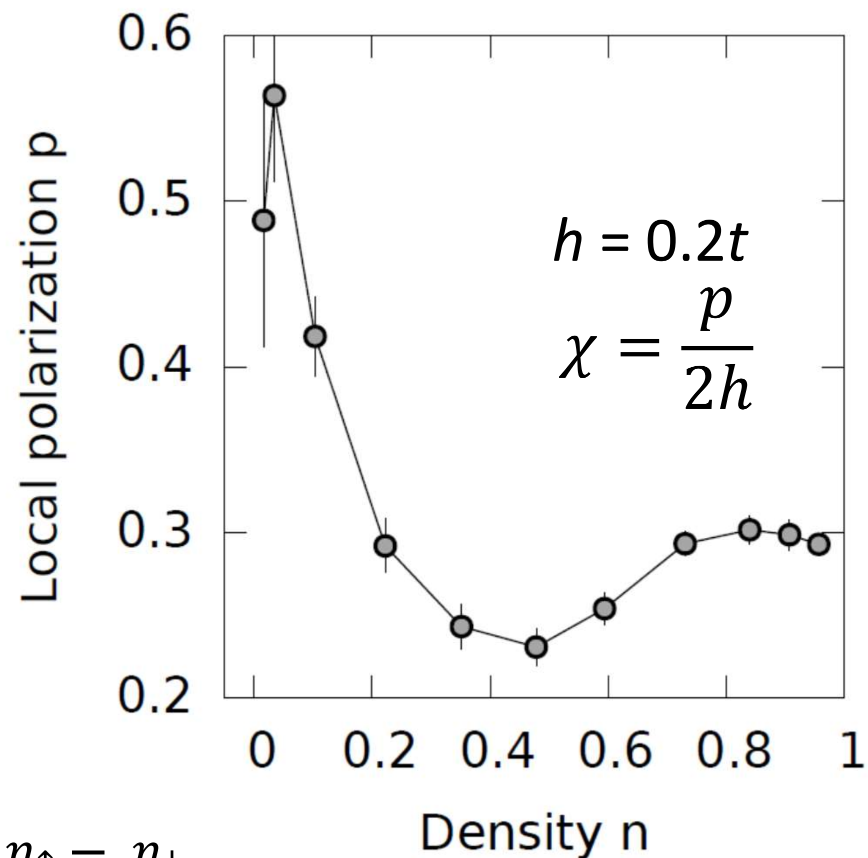
Mott physics is not affected by imbalance
Polarization is constant in Mott insulator region



$$p^s = (n^s_\uparrow - n^s_\downarrow)/(n^s_\uparrow + n^s_\downarrow)$$

Interesting interesting behavior in density at larger interaction (U/t = 15)



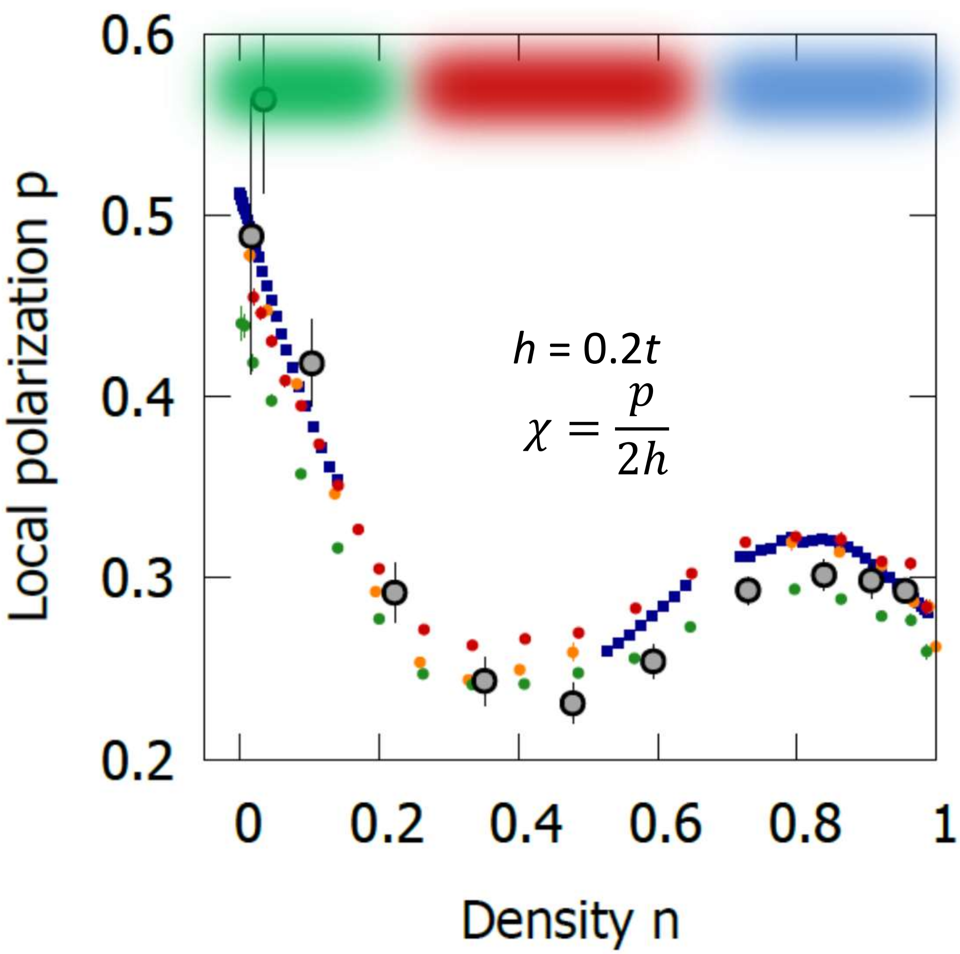


$$p = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow}$$

Spin-Susceptibility

non-degenerate gas   Metallic region   AF region

$\chi_m \propto 1/t \qquad \chi_{AF} \propto 1/J = U/4t^2$



$$\chi = \frac{1}{n}\frac{\partial\langle S^z\rangle}{\partial h}\bigg|_{\mu} = \frac{p}{2h} \text{ (linear regime)}$$

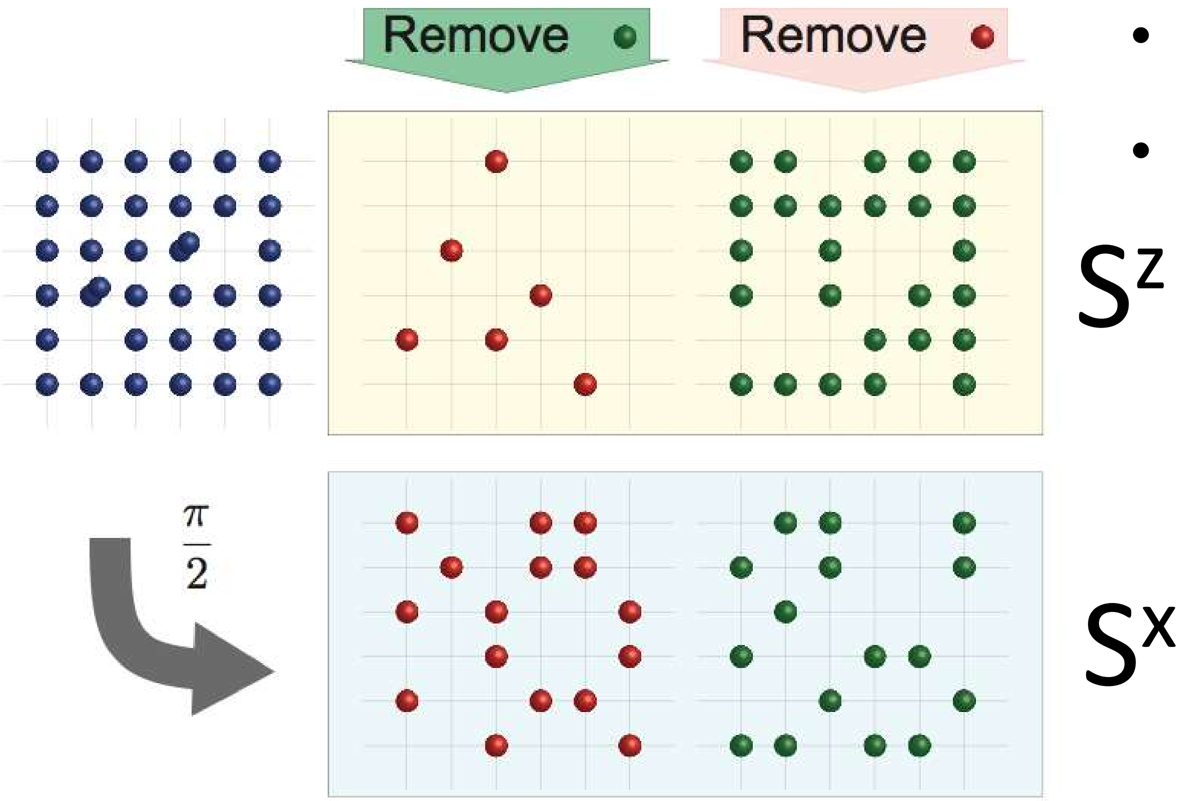
Hubbard reproduces peak in cuprate susceptibility at about 20% doping.

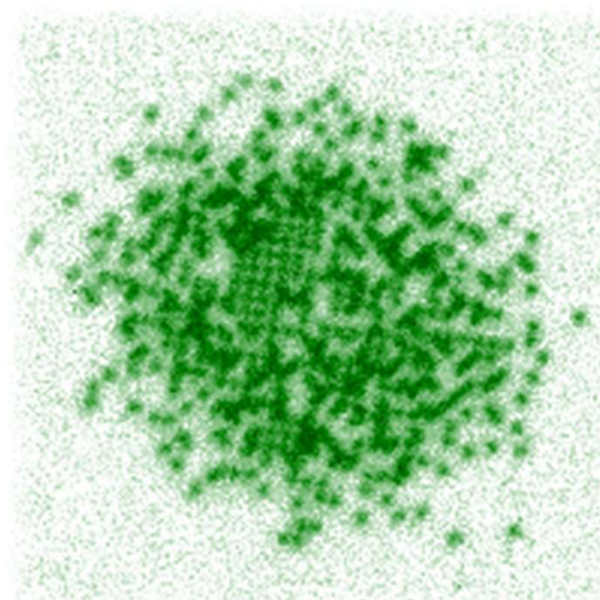
PRB **40**, 8872 (1989)
PRL **62**, 957 (1989)
PRB **40**, 2254 (1989)

Brown et. al. Science **357**, 1385 (2017)

Probing spin-imbalanced lattice gases

- 1-3 mixture of lithium
- Evaporate in gradient
- Load into lattice at U/t = 8





Vary: $p^s = (n^s_\uparrow - n^s_\downarrow)/(n^s_\uparrow + n^s_\downarrow)$

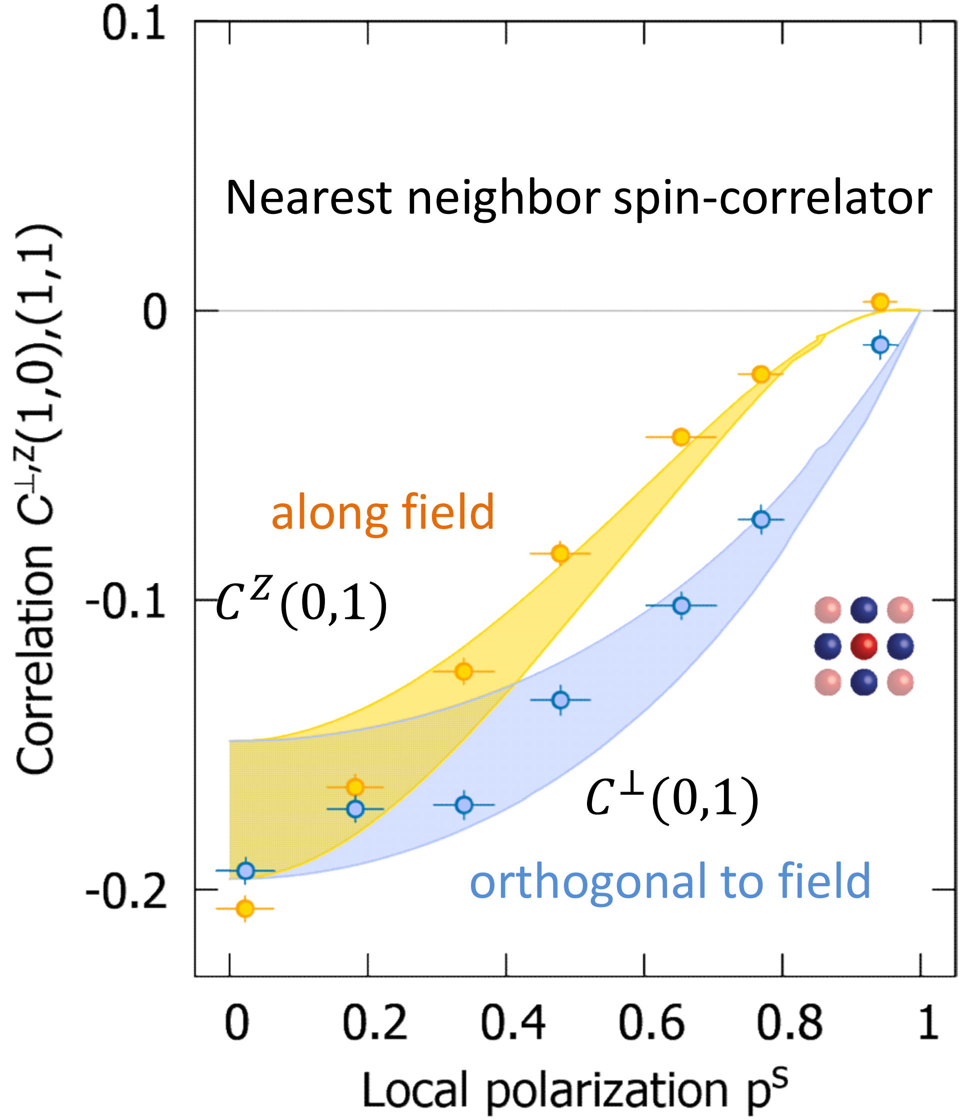
Brown et. al. Science **357**, 1385 (2017)

Spin Canting

- $p^s = \frac{n_\uparrow^s - n_\downarrow^s}{n_\uparrow^s + n_\downarrow^s}$
- Good agreement with NLCE & DQMC
- *T/t* increases from 0.40 to 0.57

DQMC by Thereza Paiva and Nandini Trivedi
NLCE by Ehsan Khatami

$$C^\alpha(\mathbf{d}) = 4\left(\left\langle S^\alpha_{\mathbf{i}} S^\alpha_{\mathbf{i+d}}\right\rangle - \left\langle S^\alpha_{\mathbf{i}}\right\rangle \left\langle S^\alpha_{\mathbf{i+d}}\right\rangle\right) \quad \alpha = z, \perp$$



Brown et. al. Science **357**, 1385 (2017)

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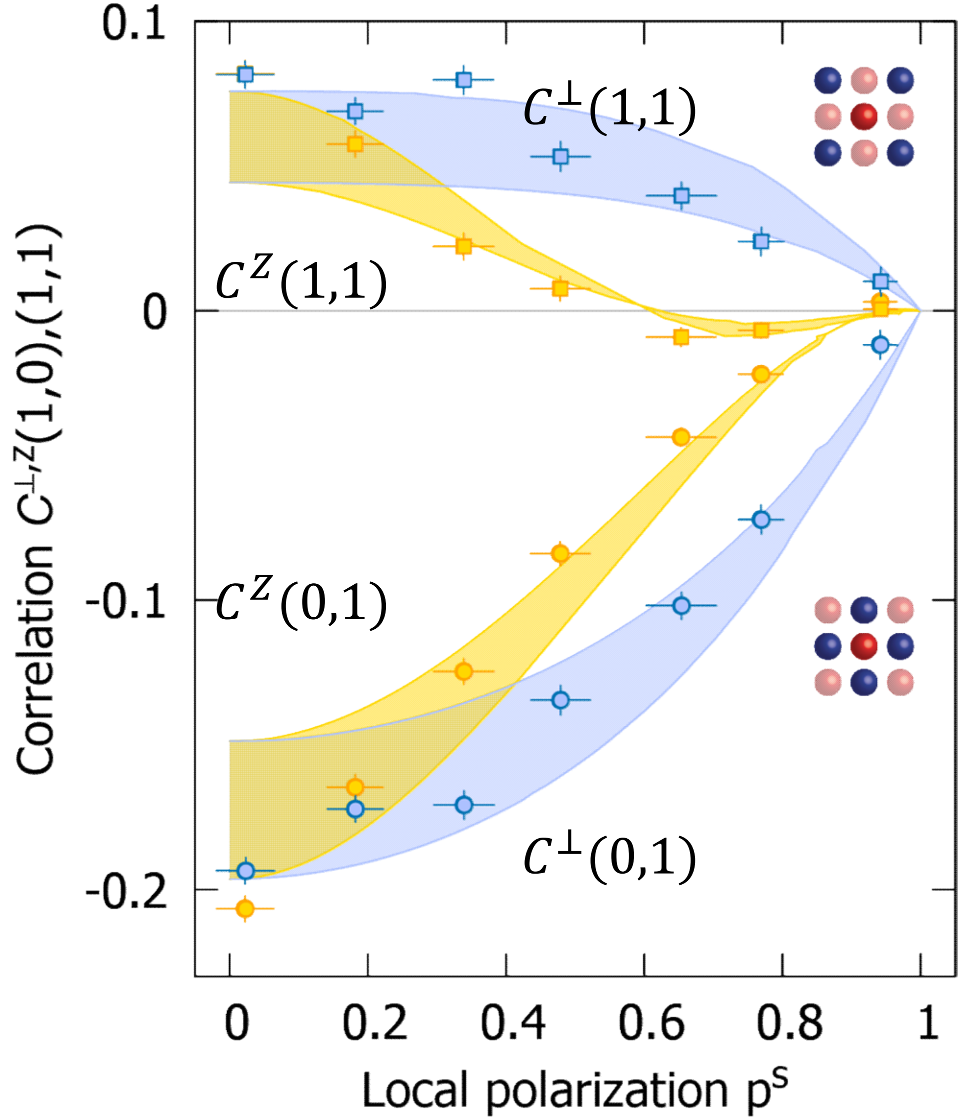

Brown et. al. Science **357**, 1385 (2017)

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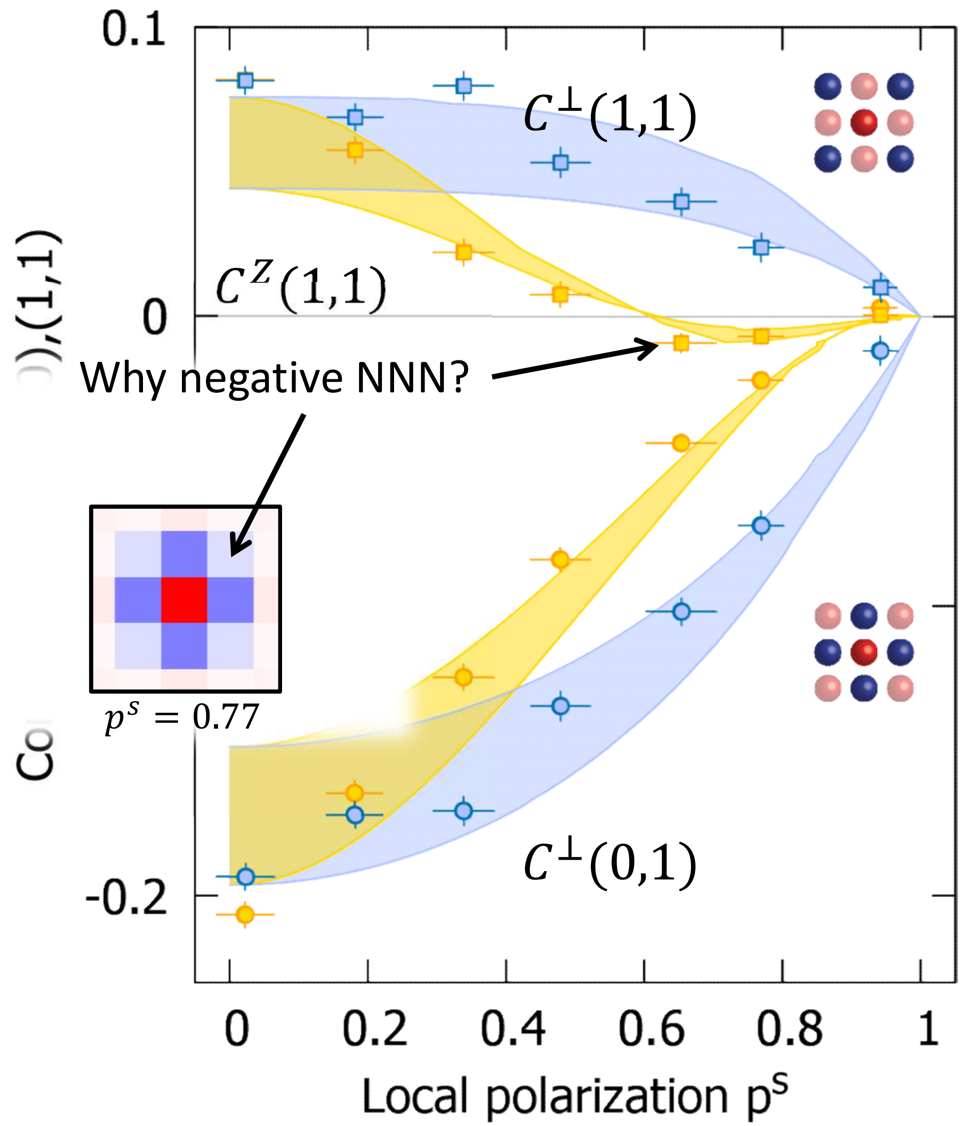
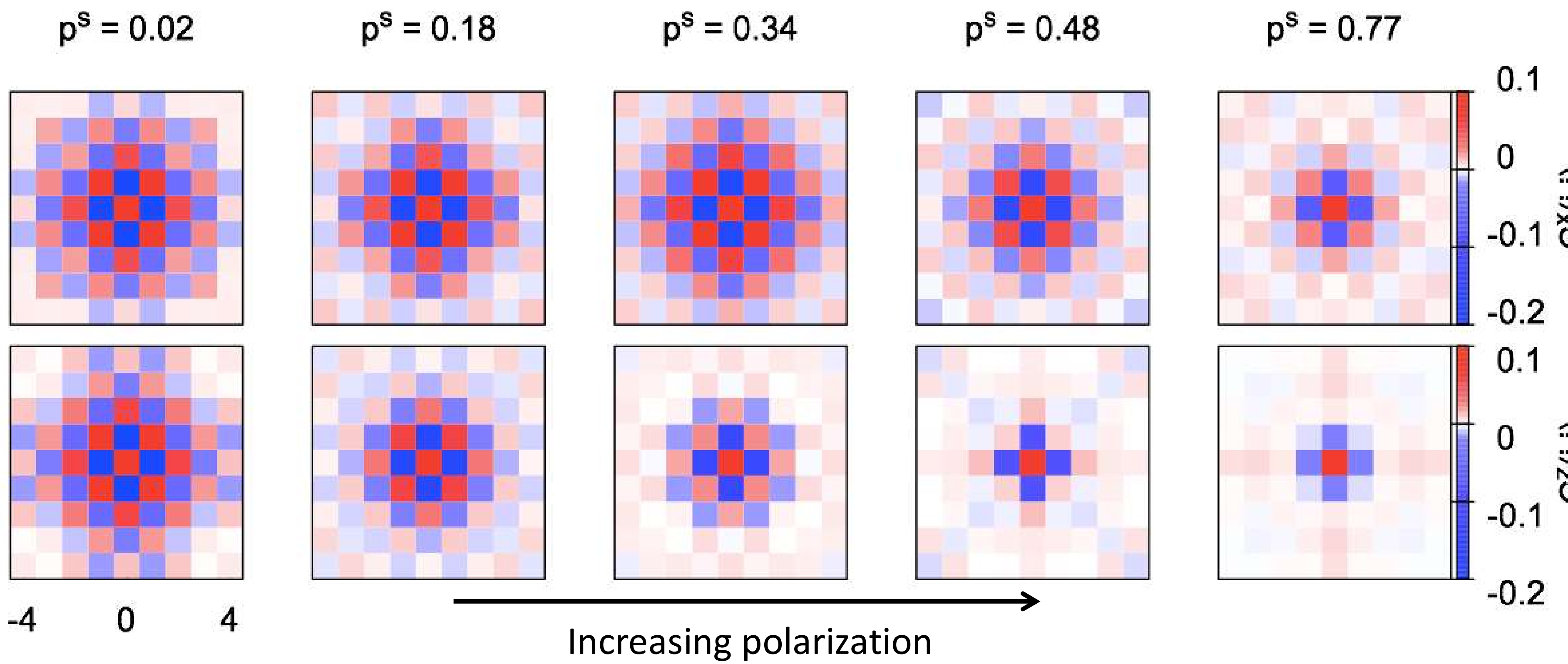


Brown et. al. Science **357**, 1385 (2017)

Correlations at larger distances

$$C^{\alpha}(\mathbf{d}) = 4\left(\langle S^{\alpha}_{\mathbf{i}} S^{\alpha}_{\mathbf{i+d}}\rangle - \langle S^{\alpha}_{\mathbf{i}}\rangle\langle S^{\alpha}_{\mathbf{i+d}}\rangle\right) \quad \alpha = z, \perp$$



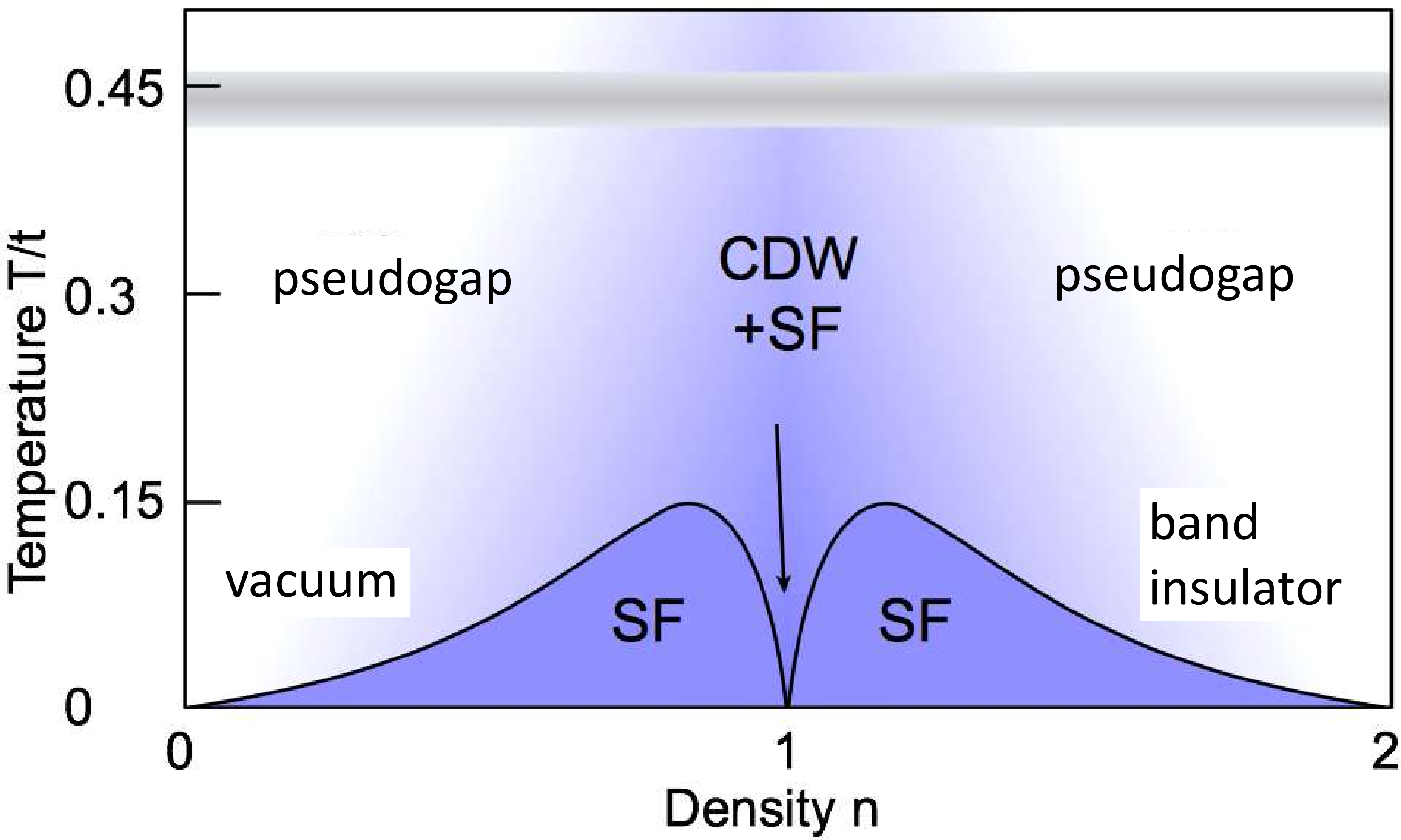
Unpolarized gas: isotropic spin correlations [SU(2) symmetry]

Polarized gas: AFM correlations preferred in the plane

2. Quantum gas microscopy of an attractive Fermi-Hubbard system

Mitra et. al, Nature Physics, 10.1038/nphys4297 (2017)

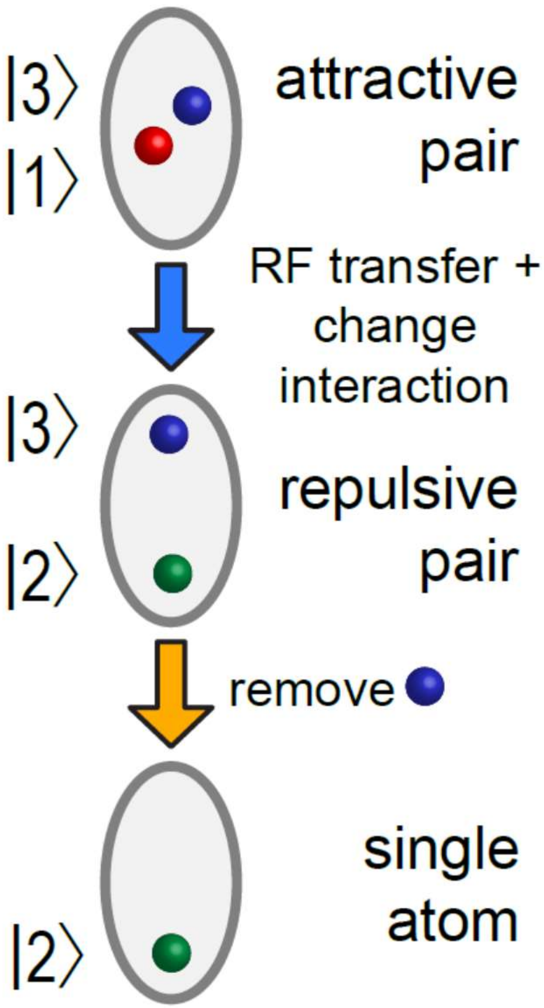
Spin-balanced attractive Hubbard model



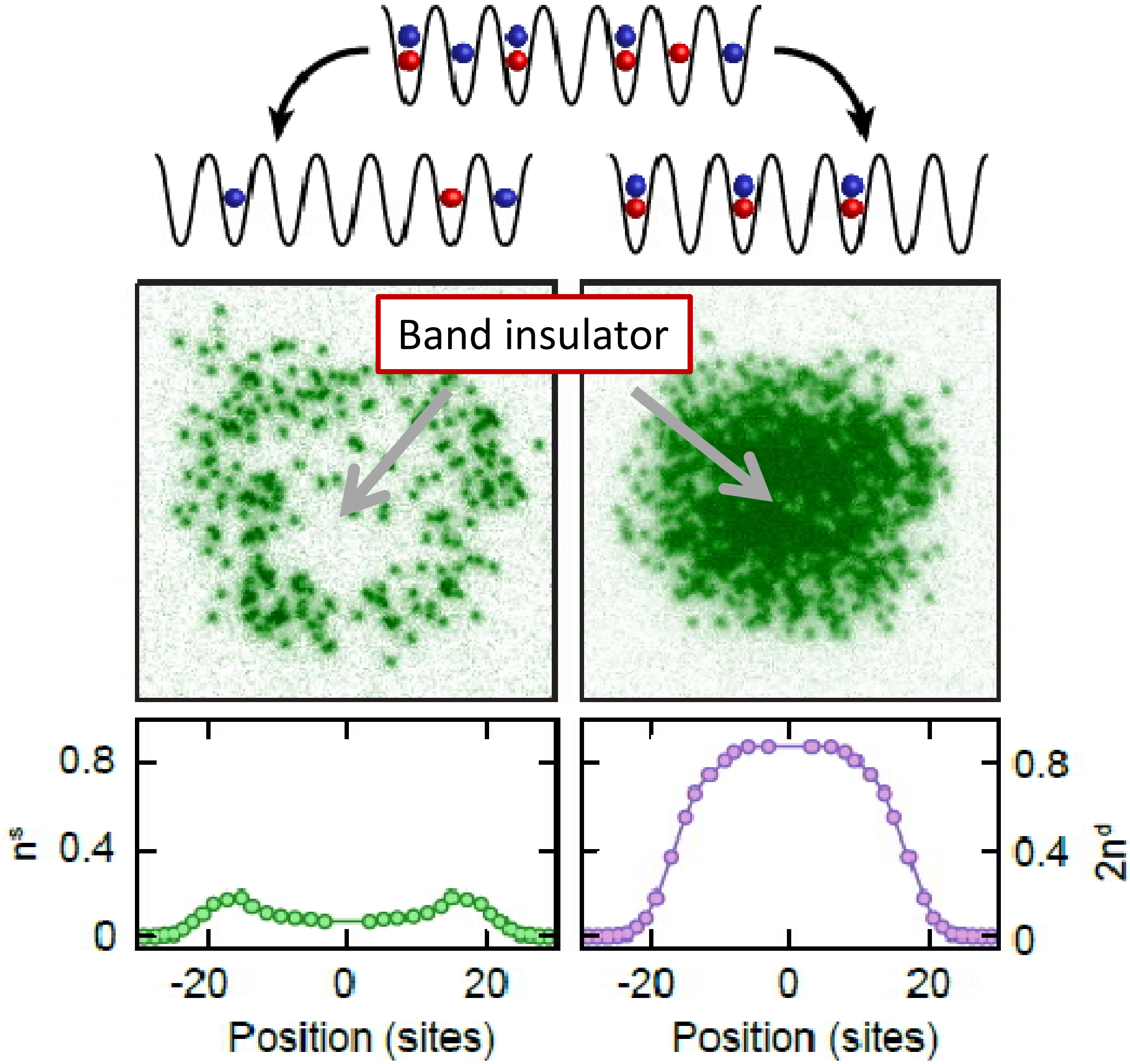
Preformed pairs: U

Superfluidity: $4t^2/U$ Mitra et. al, Nat. Phys., 10.1038/nphys4297 (2017)

Site-resolved doublon detection



90 % fidelity

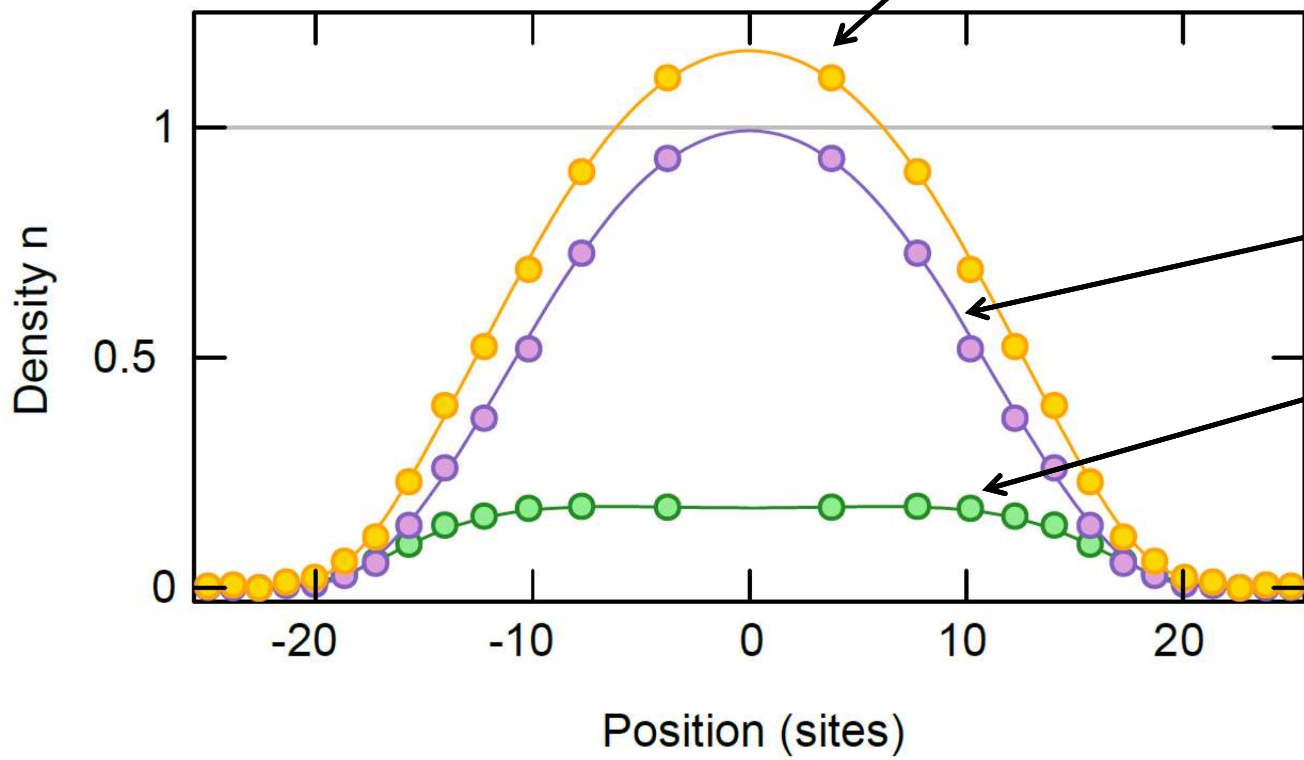


Mitra et. al, Nat. Phys., 10.1038/nphys4297 (2017)

Density profile of attractive lattice gas

Experimental data with DQMC fit
T/t = 0.45
U/t = -5.7

Total density



Expect s-wave pairing correlations near n = 1

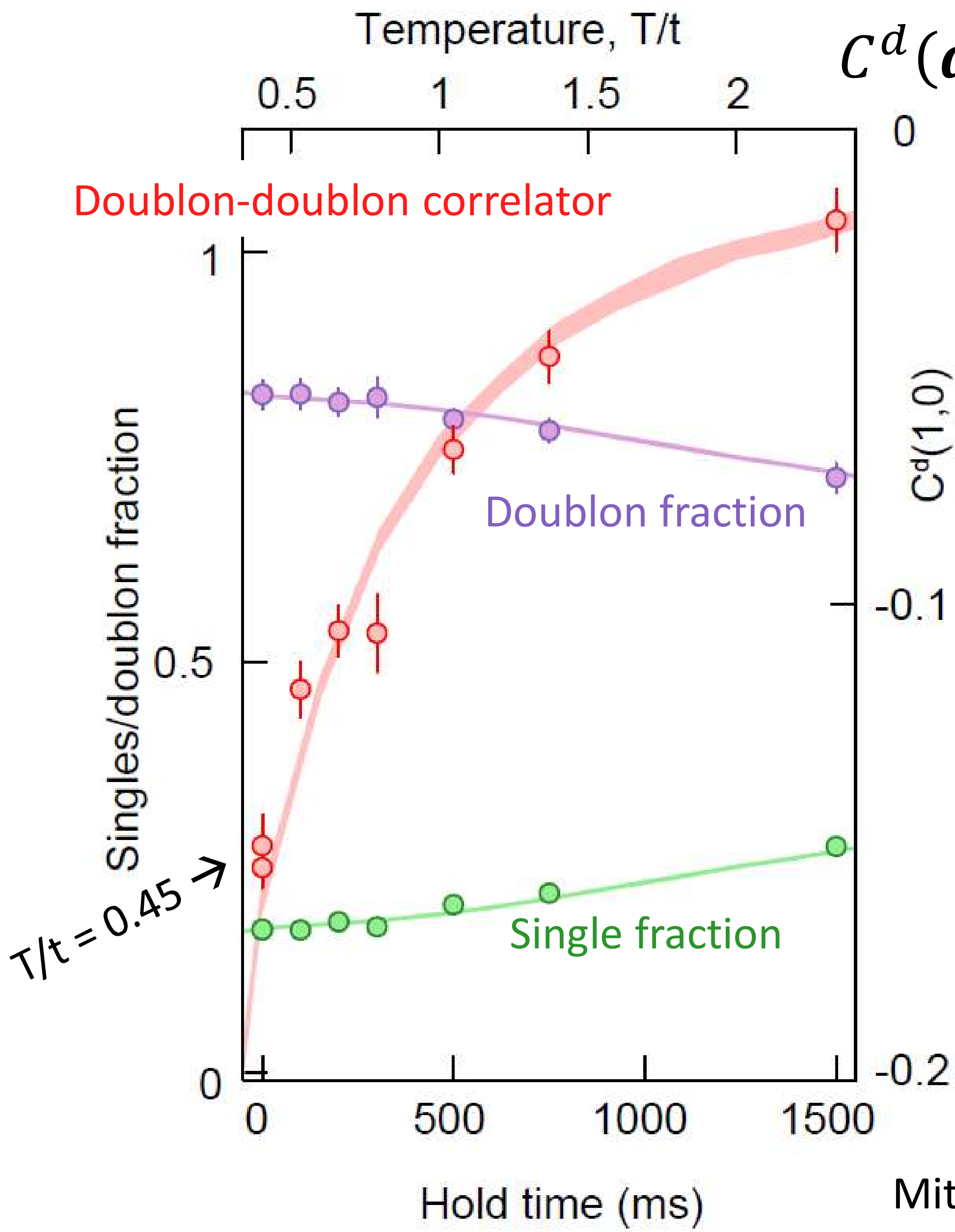
Density in doublons

Singles fraction suppressed at large |U|/t due to fermion pairing

Reasonably large region of cloud near half filling
At trap frequency $\omega = 2\pi$ 200 Hz

Mitra et. al, Nat. Phys., 10.1038/nphys4297 (2017)

Thermometry in attractive Hubbard system



$$C^d(\boldsymbol{a}) = 4\left(\langle n^d_{\boldsymbol{r}} n^d_{\boldsymbol{r}+\boldsymbol{a}}\rangle - \langle n^d_{\boldsymbol{r}}\rangle\langle n^d_{\boldsymbol{r}+\boldsymbol{a}}\rangle\right)$$

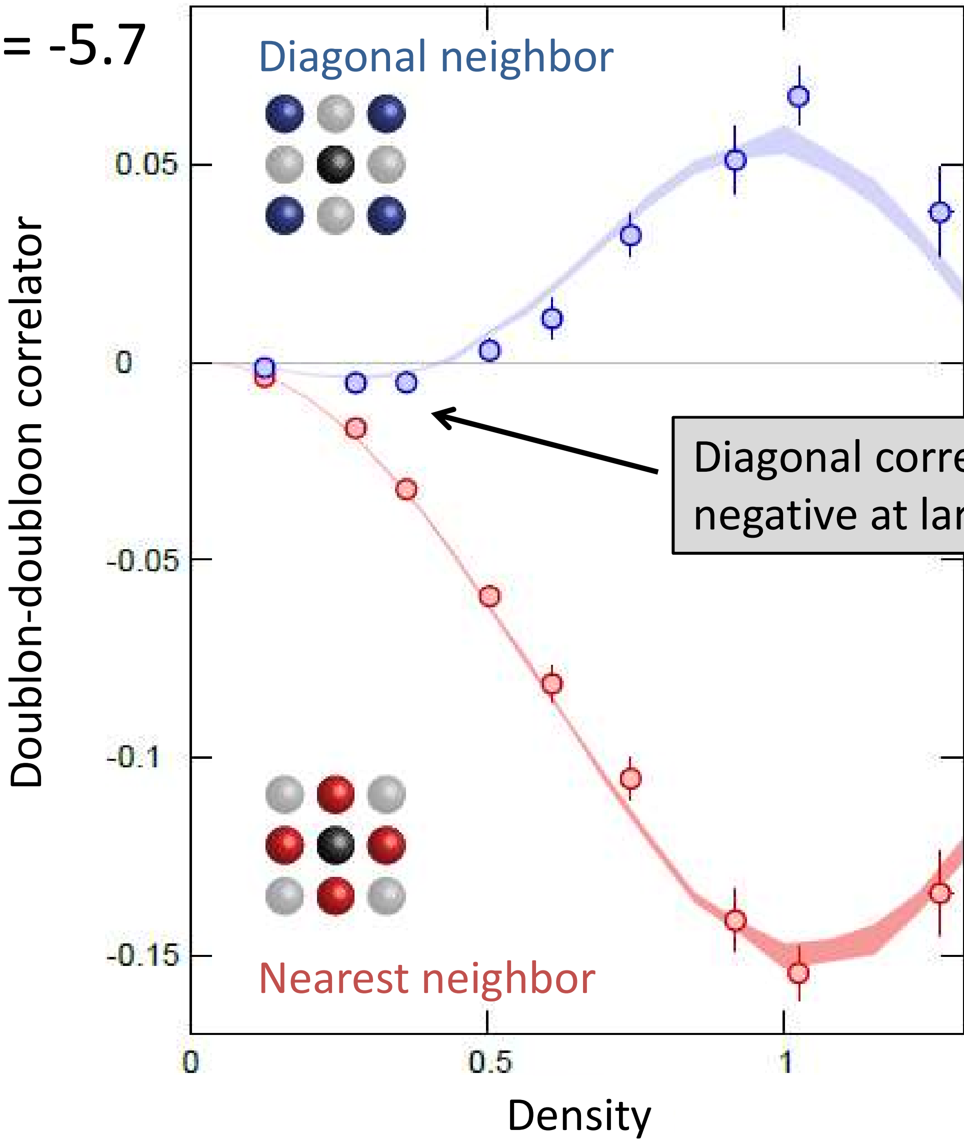
$$n^d = n_\uparrow n_\downarrow$$

- Singles fraction increases as gas heats up during hold time
- Singles fraction for thermometry only for T/t > 1
- Correlation thermometry at T/t < 1

Mitra et. al, Nat. Phys., 10.1038/nphys4297 (2017)

Doublon-doublon correlators

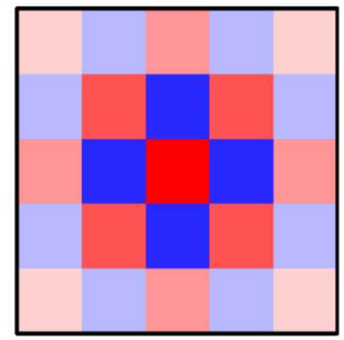
U/t = -5.7



Diagonal correlator goes negative at large doping?

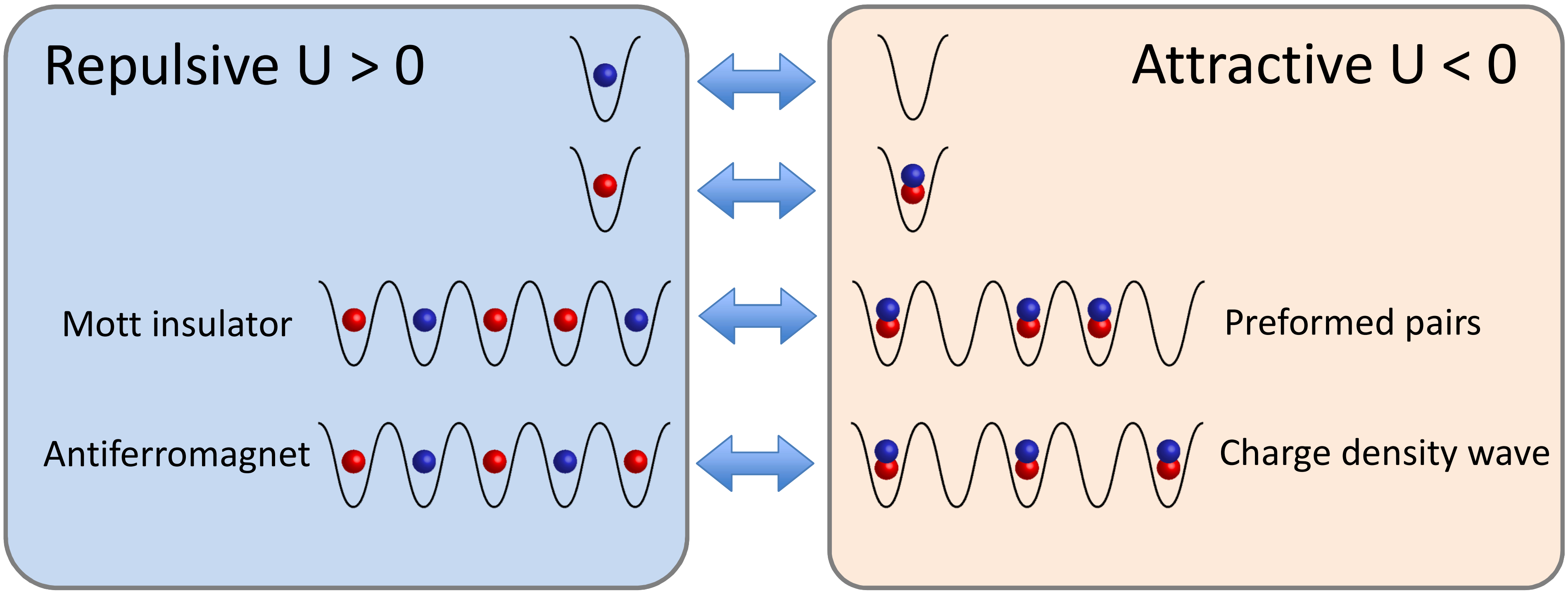
n = 1.0

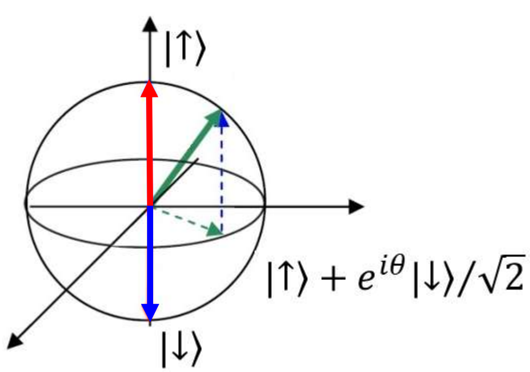
Correlations
Up to d = 2



Haven’t we heard this story before?

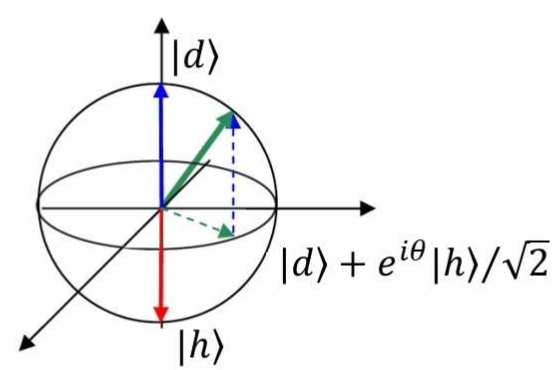
Mapping between the models





$$c_{i\downarrow} \leftrightarrow (-1)^{i_x+i_y} c_{i\downarrow}^{\dagger}$$

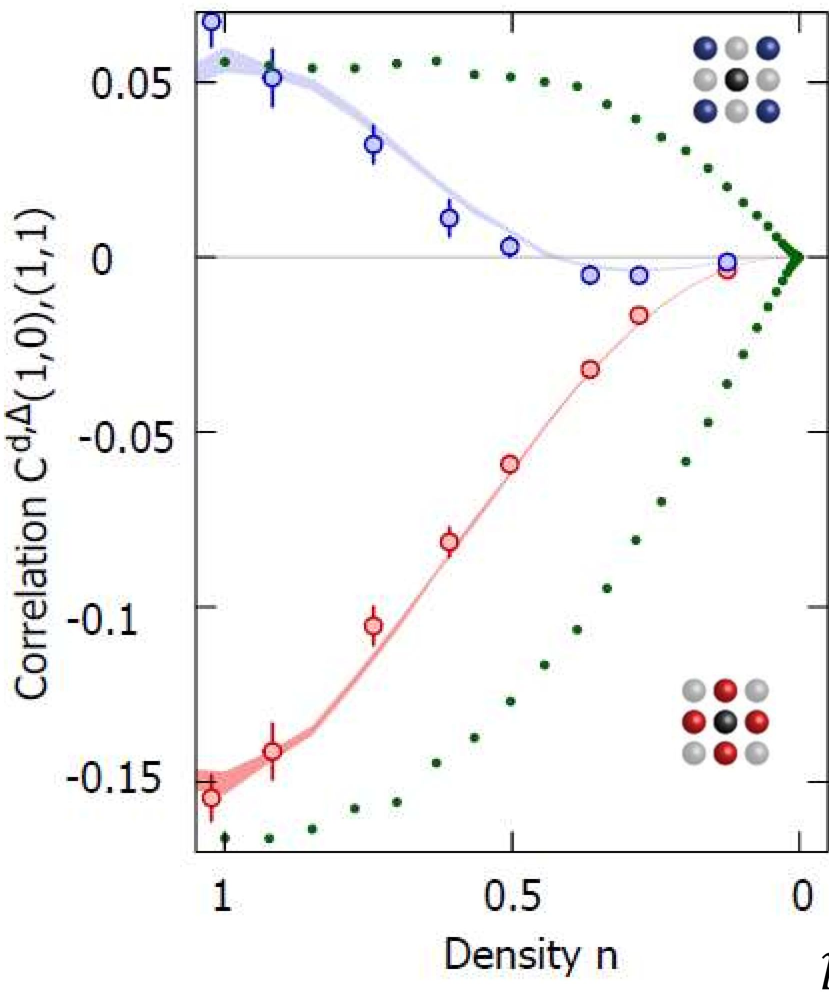
1. $U \leftrightarrow -U$
2. $\mu \leftrightarrow h$



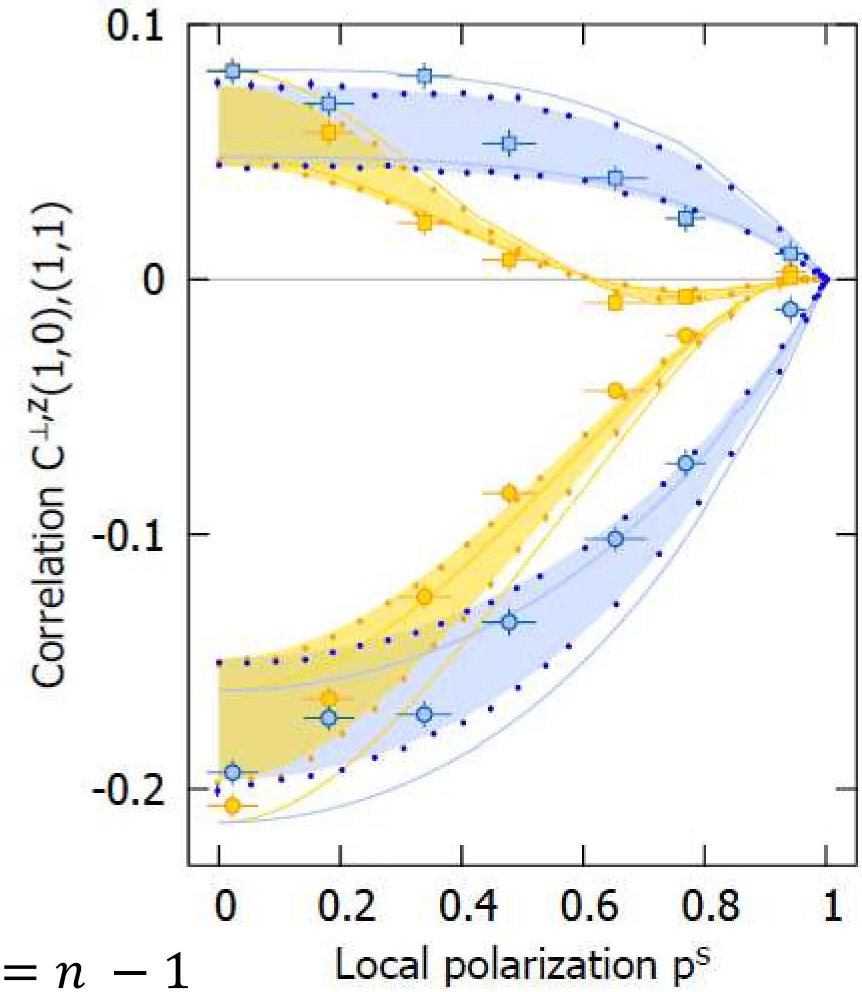
Phys. Rev. A **79**, 033620 (2009)

Correlator symmetry

Attractive Hubbard



Repulsive Hubbard

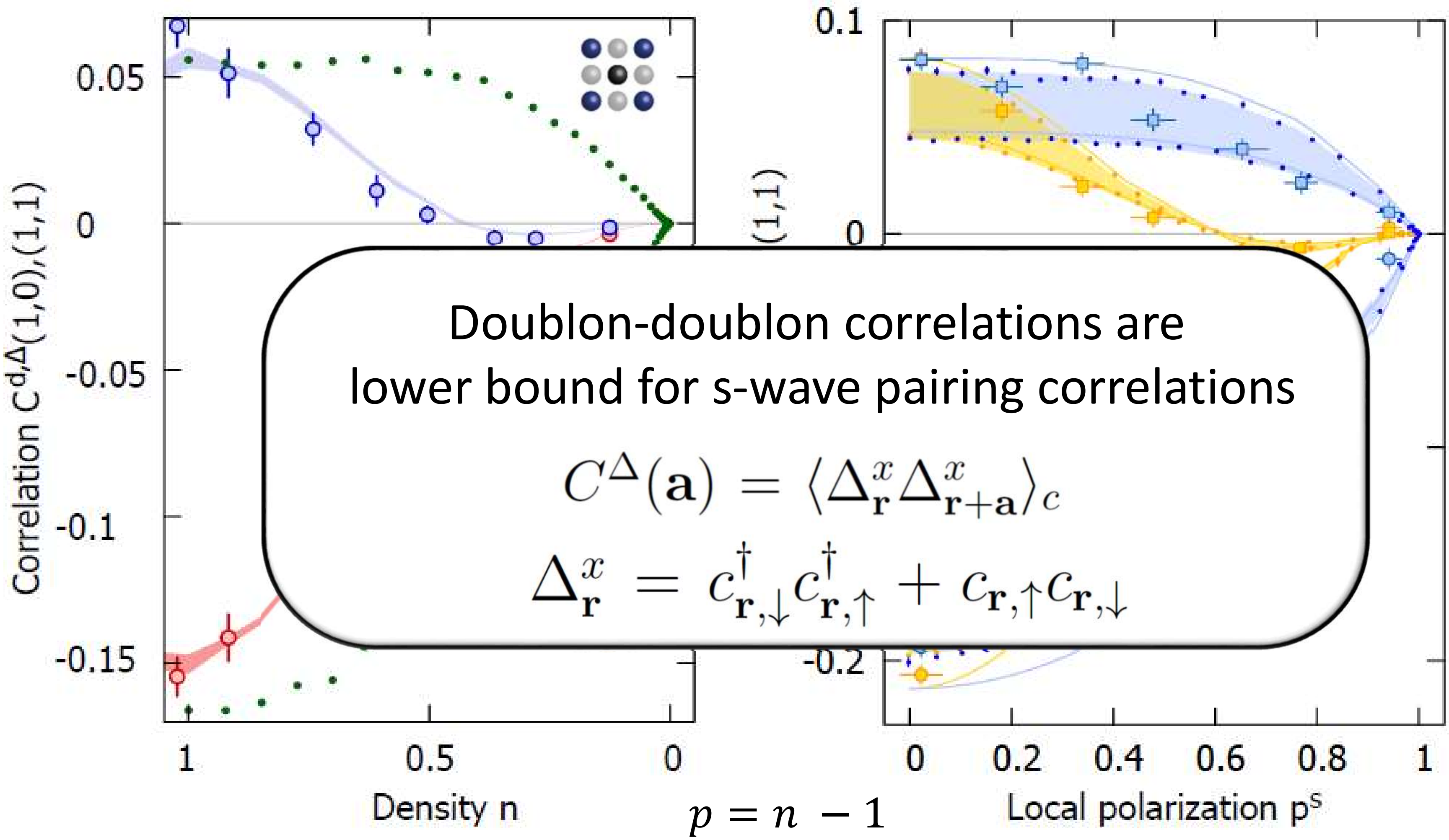


$p = n - 1$

Correlator symmetry

Attractive Hubbard

Repulsive Hubbard



Doublon-doublon correlations are lower bound for s-wave pairing correlations

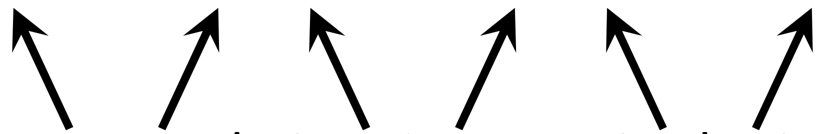
$$C^{\Delta}(\mathbf{a}) = \langle \Delta^x_{\mathbf{r}} \Delta^x_{\mathbf{r}+\mathbf{a}} \rangle_c$$

$$\Delta^x_{\mathbf{r}} = c^\dagger_{\mathbf{r},\downarrow} c^\dagger_{\mathbf{r},\uparrow} + c_{\mathbf{r},\uparrow} c_{\mathbf{r},\downarrow}$$

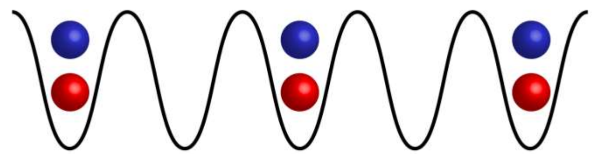
$p = n - 1$

Conclusions and outlook

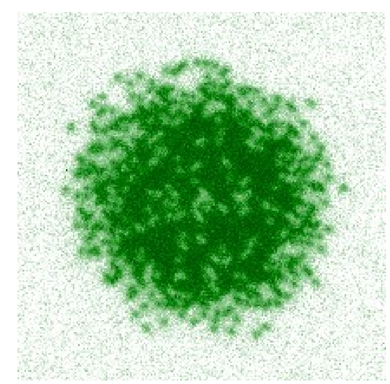
- Observation of canted antiferromagnetic correlations in spin-imbalanced repulsive gases.



- Observation of charge density wave correlations in attractive lattice gases.

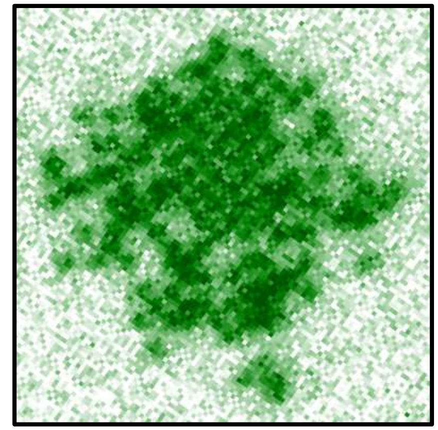


- Outlook:
  - Lower temperatures (e.g. entropy redistribution)
  - Beyond single band Hubbard on attractive branch
  - Spin-imbalanced attractive gases in 1D-2D crossover (FFLO)
  - Dynamics
  - LDOS measurements on topological defects
  - Dipolar interactions through Rydberg dressing

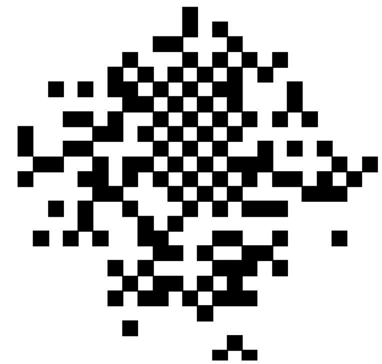


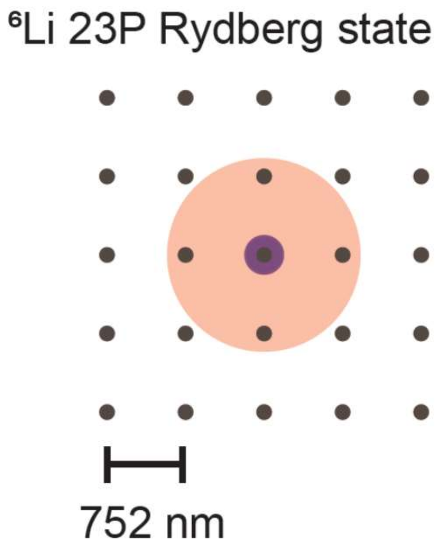
Lithium Rydberg excitation

Quench dynamics in an antiferromagnetic 2D Ising Hamiltonian

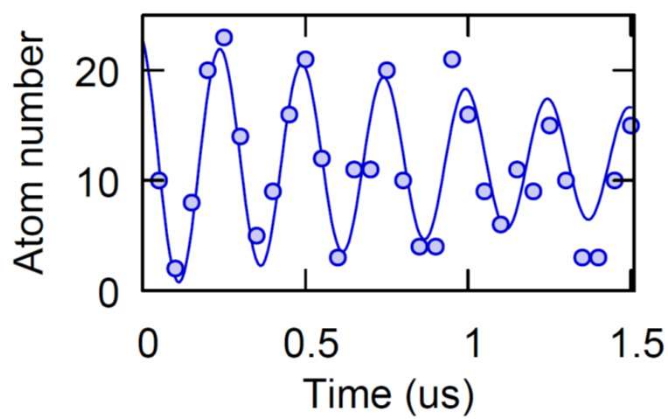


- Direct excitation at 230nm
- Detection via loss
- Rabi frequency: up to 6 MHz
- Towards Rydberg dressing of Fermions

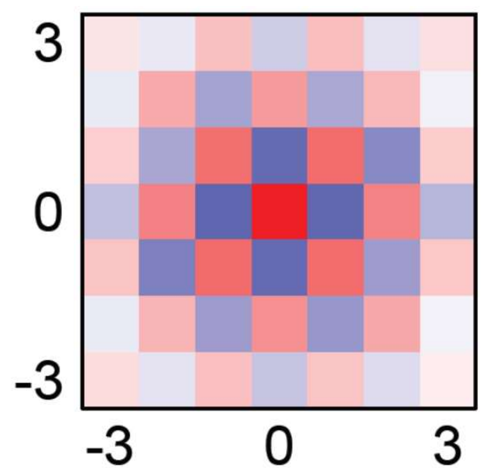




Rabi oscillation

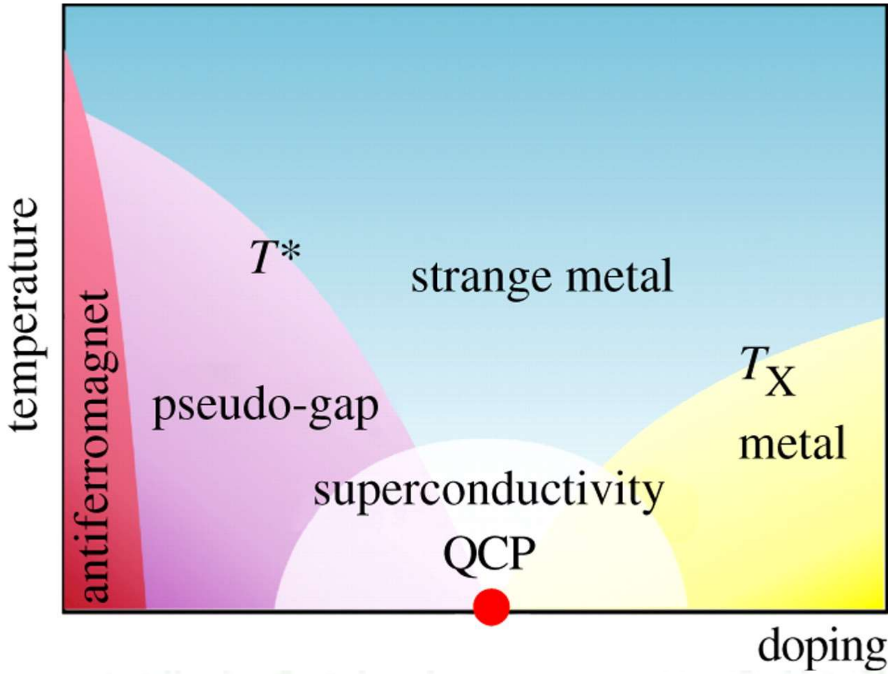


Pair correlation:



Guardado-Sanchez *et. al.* arXiv:1711.00887 (2017)

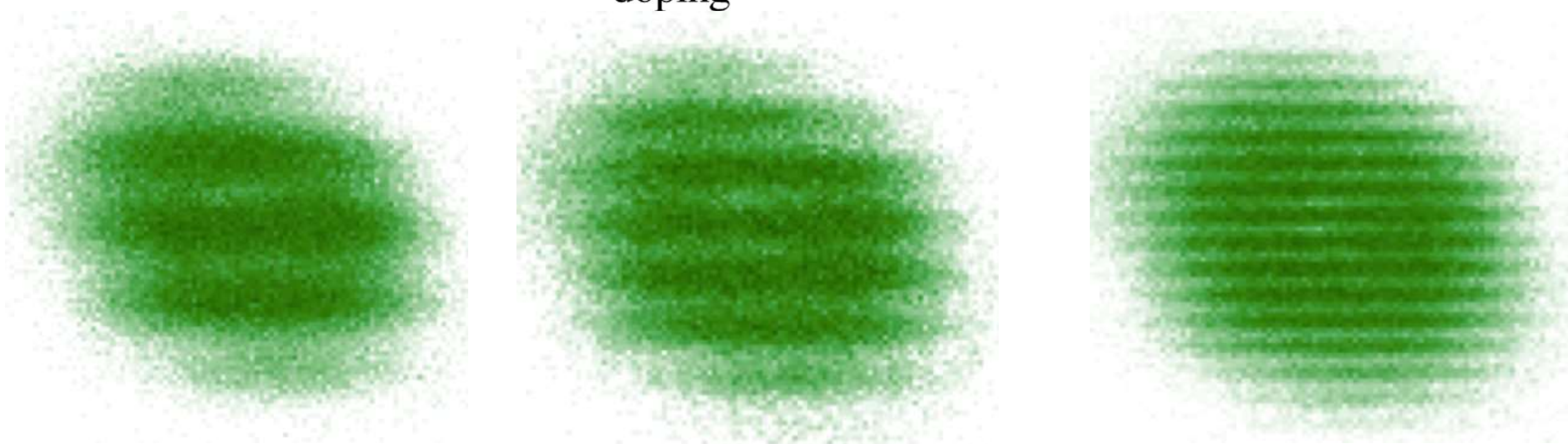
Outlook: Hubbard dynamics



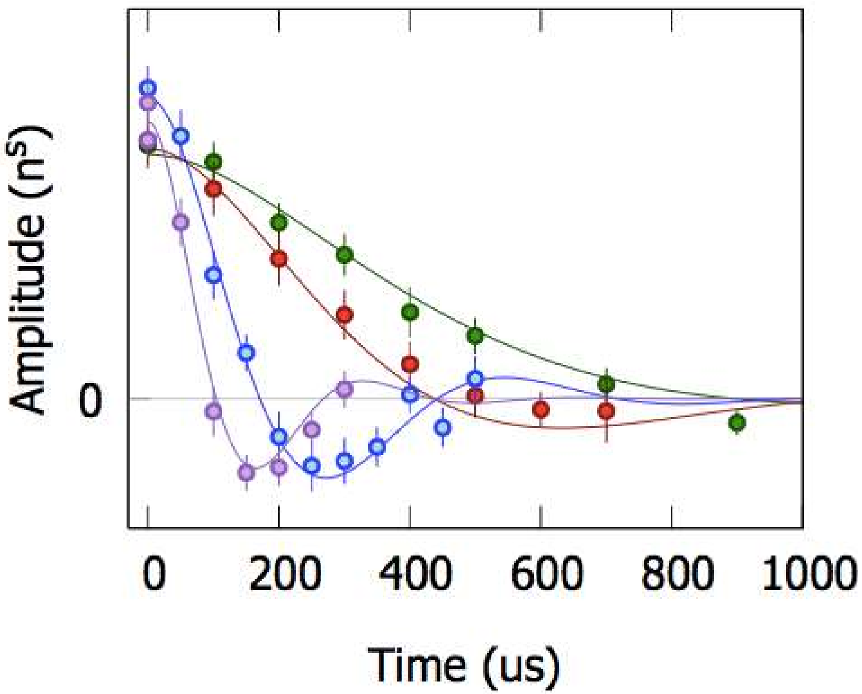
Strange metal phase is within reach of current Fermi-Hubbard experiments.

Defined by “strange” transport behavior (dynamics)

Ongoing: charge hydrodynamics (sound, diffusion in doped Hubbard model.



Outlook: Hubbard dynamics



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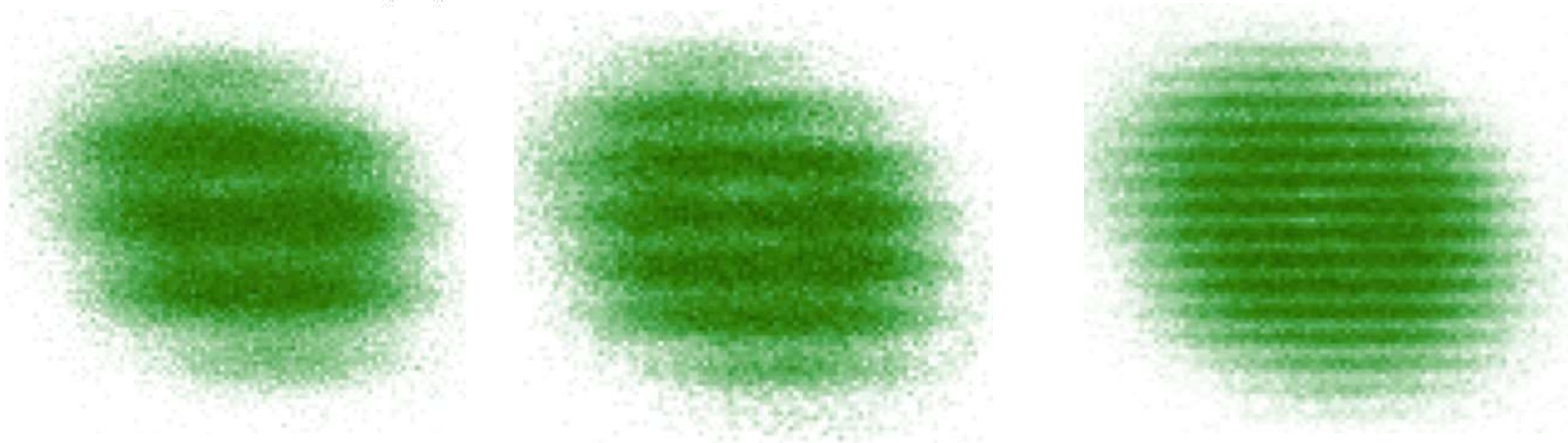

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Funding:

PRINCETON UNIVERSITY

NDSEG

NSF

the David & Lucile Packard FOUNDATION

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Alfred P. Sloan FOUNDATION