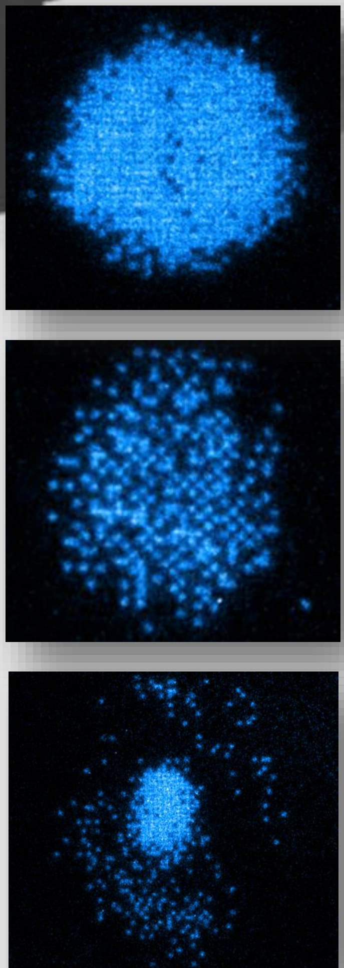
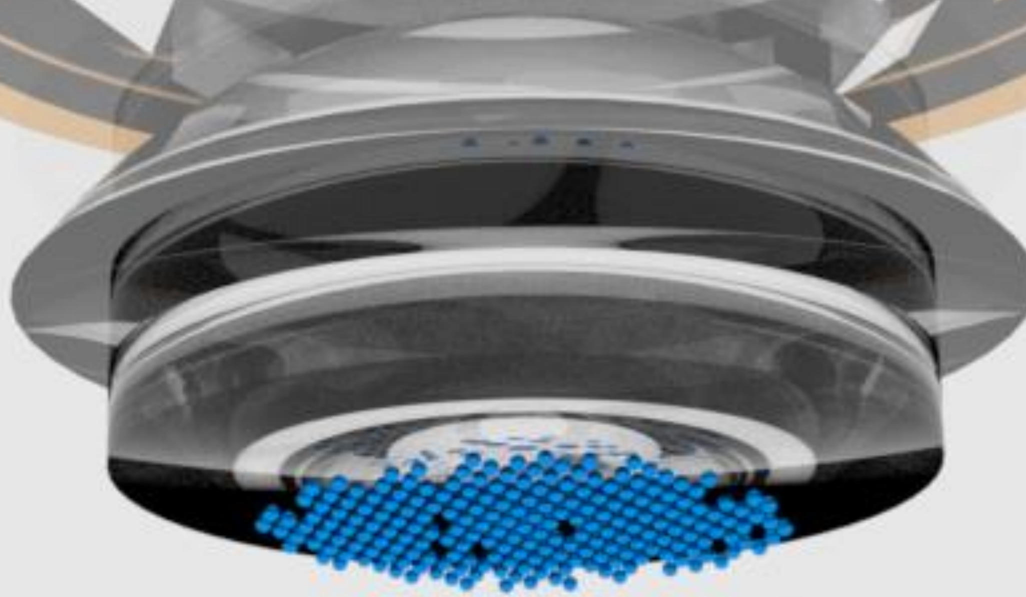




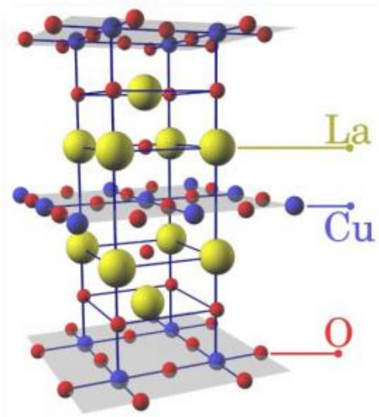
Antiferromagnetic long-range order in the Fermi-Hubbard model with ultracold atoms

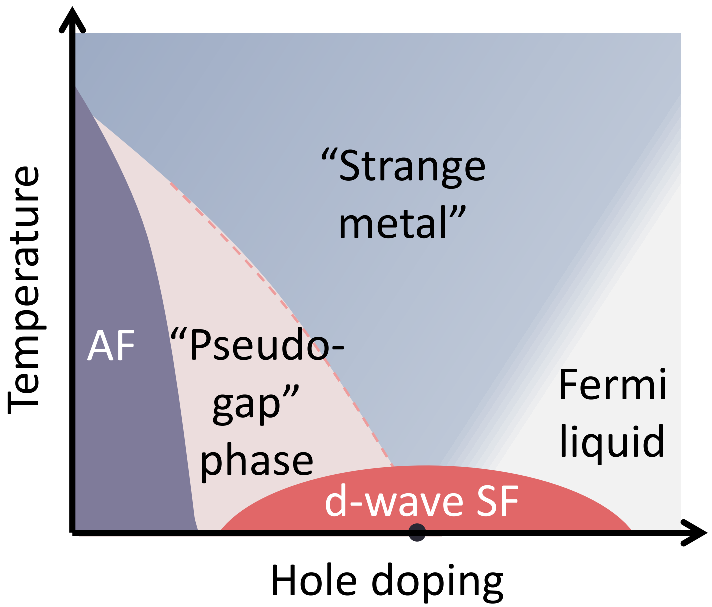
Christie Chiu

Markus Greiner, Harvard University

Fermions in optical lattices

High T_C superconductivity

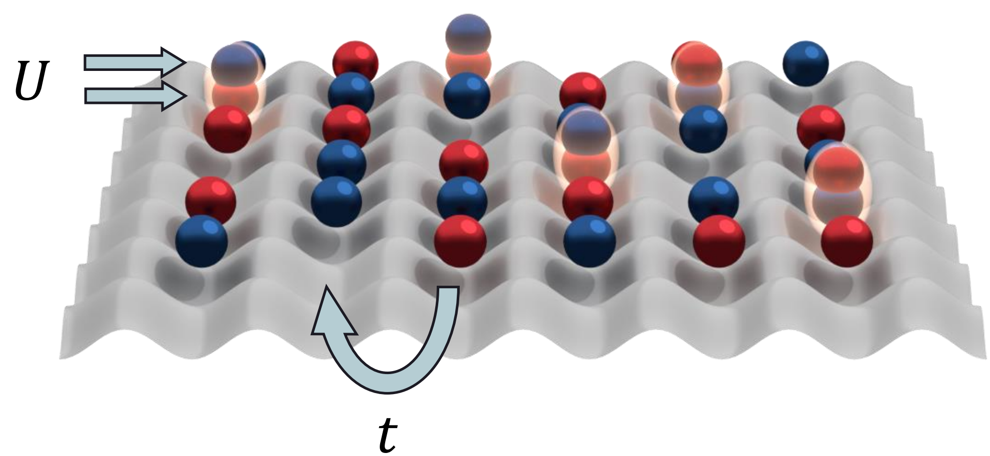




Fermi-Hubbard model

P.W. Anderson:
minimal model for cuprate superconductors

$$\hat{H} = \underbrace{-t \sum_{\langle i,j \rangle, \sigma} \left(c^{\dagger}_{i,\sigma} c_{j,\sigma} + \mathrm{H.c.} \right)}_{\text{tunneling}} + \underbrace{U \sum_{i} \hat{n}_{i\uparrow} \hat{n}_{i\downarrow}}_{\text{On-site interaction}}$$

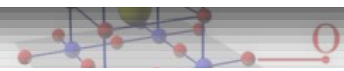


Fermions in optical lattices

High T_C superconductivity

Cold atom proposal: 2002

W. Hofstetter, J. I. Cirac, P. Zoller, E. Demler, and M. D. Lukin PRL 89, 220407



Fermi-Hubbard with cold atoms: 2008
Esslinger, Bloch, Hulet, Takahashi, …

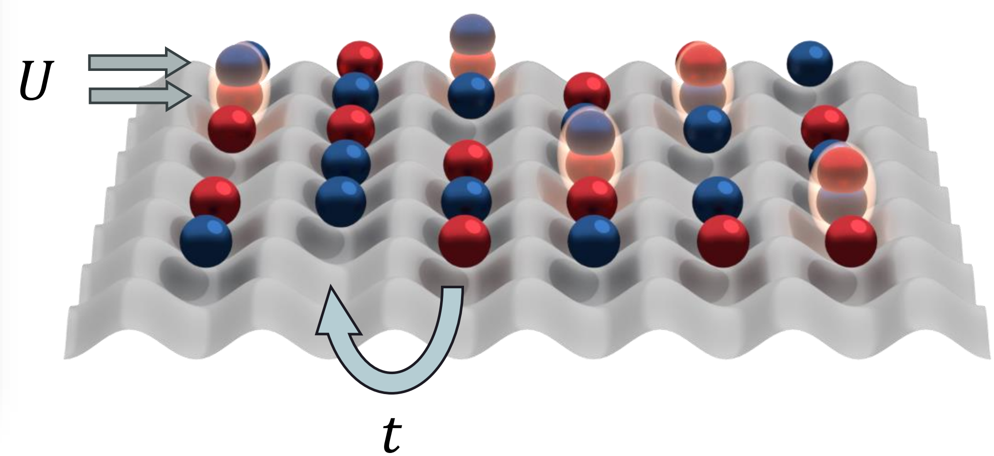
R. Jördens, et.al., Nature 455, 204 (2008)
U. Schneider, et al., Science 322, 1520 (2008)
S. Taie, et al., Nature Physics 8, 825 (2012)
T. Uehlinger, et al., PRL 111, 185307 (2013)
M. Messer, et al., PRL 115, 115303 (2015)
P. M. Duarte, et al., PRL 114, 070403 (2015)
C. Hofrichter, et al., PRX 6 021030 (2016)
....

Hole doping

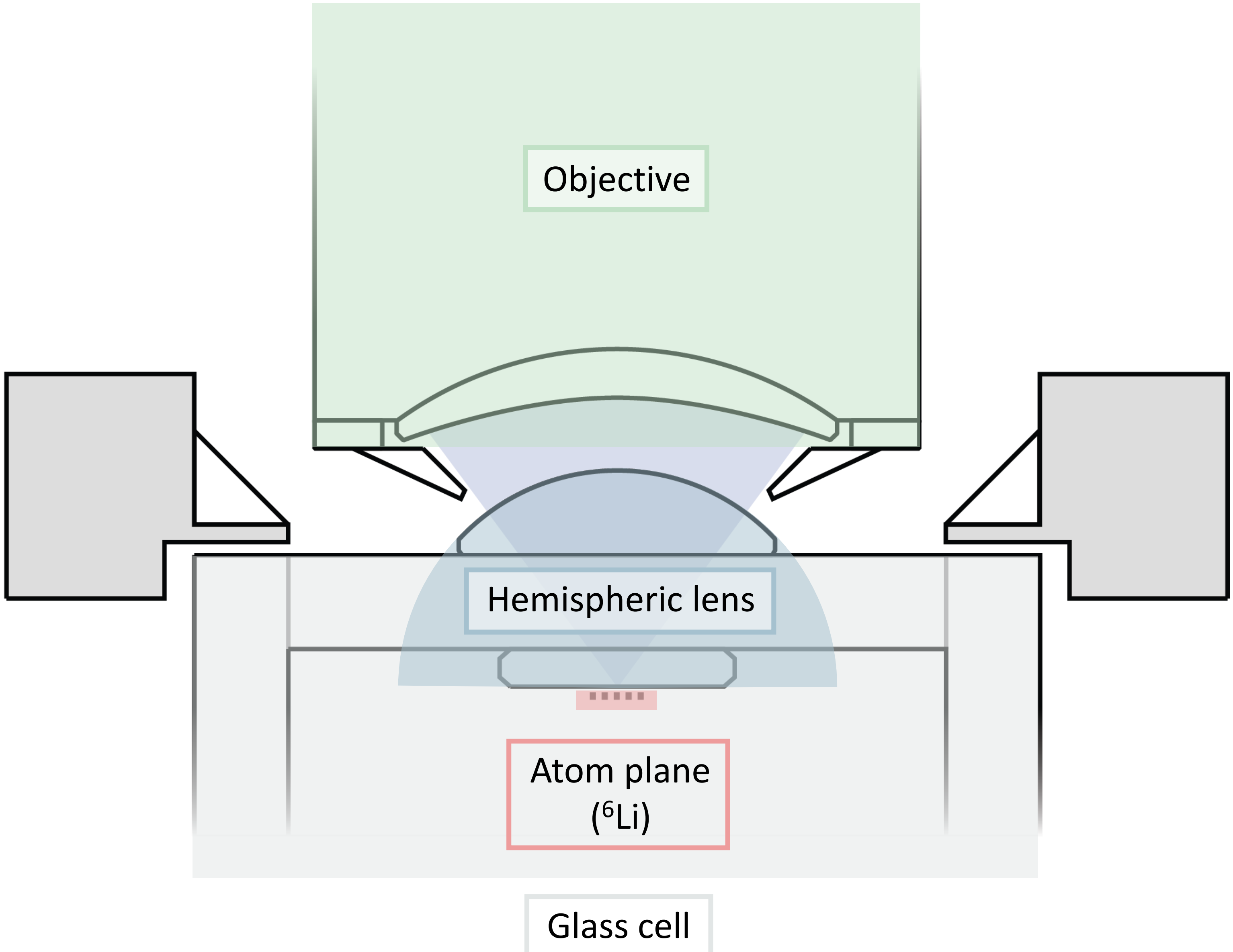
Fermi-Hubbard model

P.W. Anderson:
minimal model for cuprate superconductors

$$\hat{H} = \underbrace{-t \sum_{\langle i,j \rangle,\sigma} \left(c^{\dagger}_{i,\sigma} c_{j,\sigma} + \mathrm{H.c.} \right)}_{\text{tunneling}} + \underbrace{U \sum_{i} \hat{n}_{i\uparrow} \hat{n}_{i\downarrow}}_{\text{On-site interaction}}$$

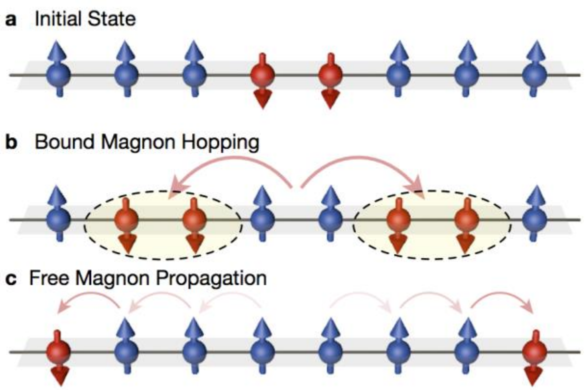


Quantum gas microscopy



Quantum gas microscopy

Detection



Novel probing tools

Local observables

Spin/Density correlator

Full information

M. Endres*, et al., Nature 487*, 454 (2012)
R. Islam, *et al., Nature* 528, 77 (2015)
P. Preiss*, et al., PRA 91*, 041602 (2015)
T. Fukuhara*, et al., PRL 115,* 035302 (2015)
…

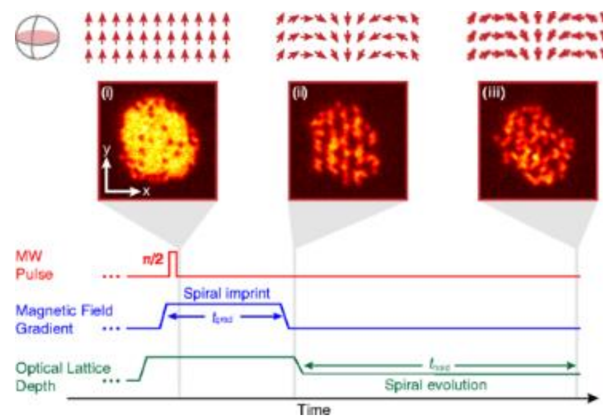
Out of equilibrium

Hole propagation

Correlation propagation

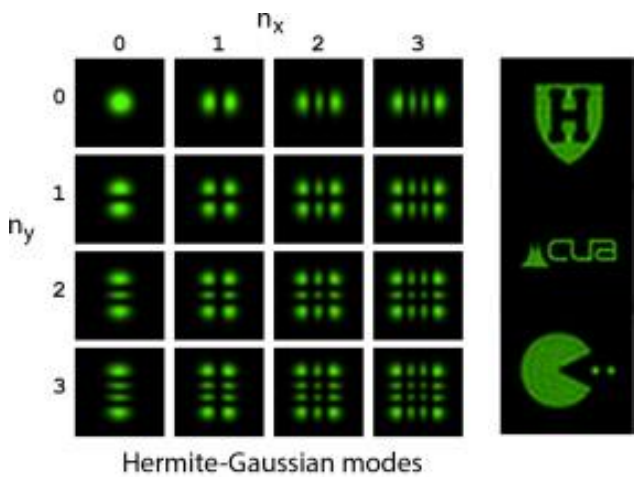
Spin waves

M. Cheneau*, et al., Nature 481*, 484 (2012)
T. Fukuhara*, et al., Nature Phys. 9*, 235 (2013)
T. Fukuhara*, et al., Nature 502*, 76 (2013)
S. Hild*, et al., PRL 113,* 147205 (2014)
P. Preiss*, et al., Science 347*, 1229 (2015)
A. Kaufman*, et al., Science 353*, 794 (2016)
…



Quantum gas microscopy

Control



Arbitrary Potentials

Digital Micromirror Device (DMD)

Boxes/ Edges

Site addressing

C. Weitenberg, et al., Nature 471, 319 (2011)
P. Zupancic et al., Opt. Express 24, 13881 (2016)
…

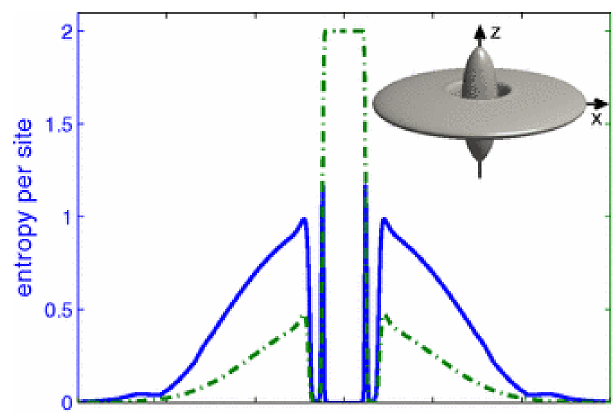
Lower temperatures

Lattice loading

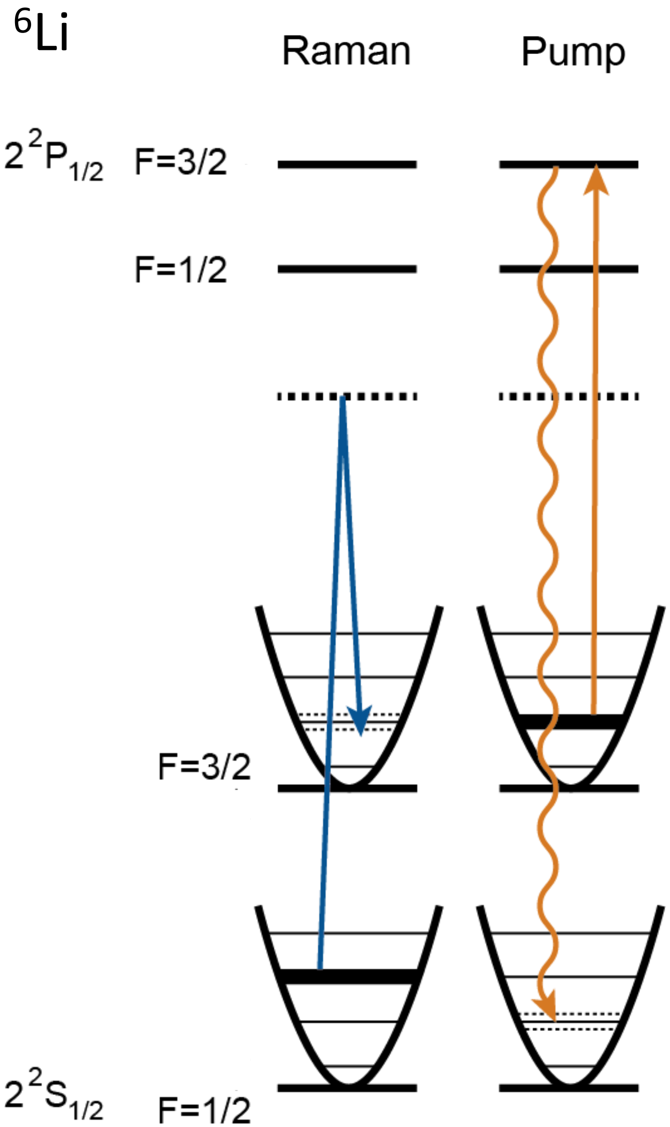
Equilibrium

Entropy redistribution

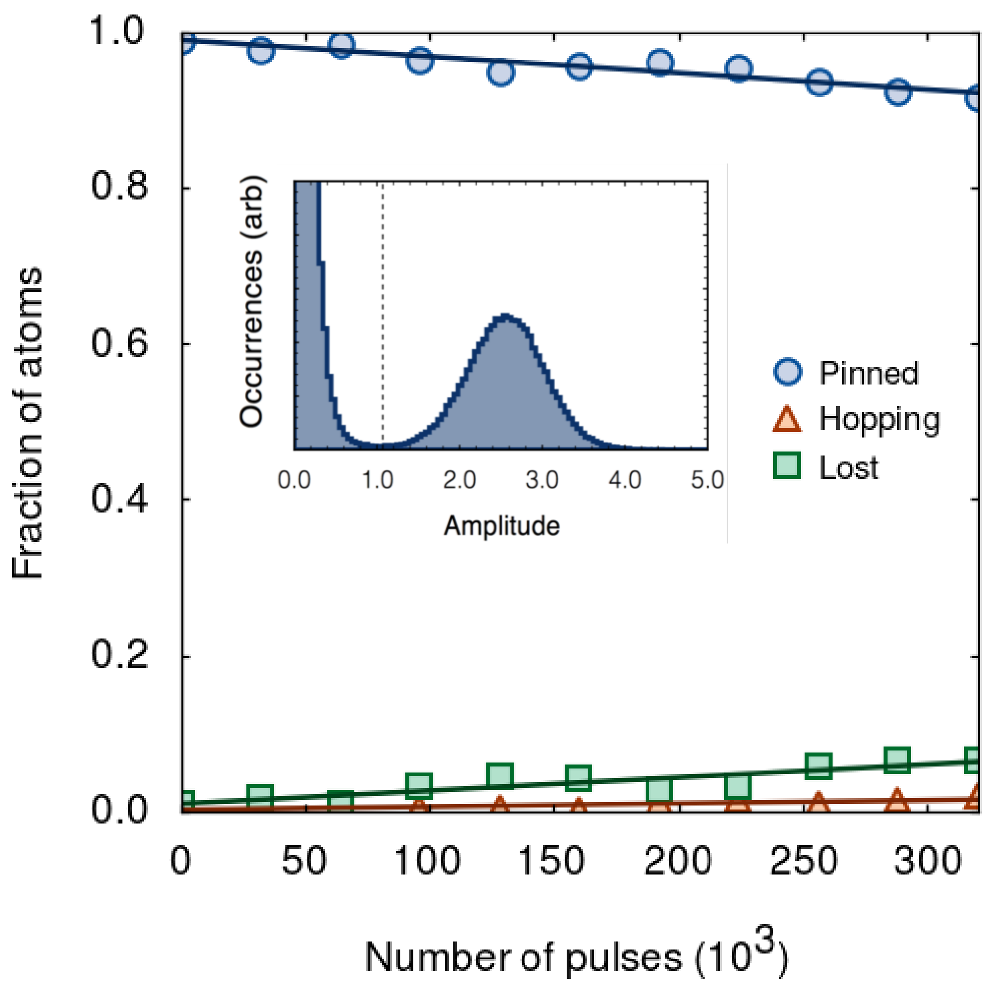
T.-L. Ho*, et al., PNAS 106,* 6916 (2009)
J.-S. Bernier, *et al., PRA 79,* 061601 (2009)
W. Bakr *et al., Nature 480*, 500 (2011)
…



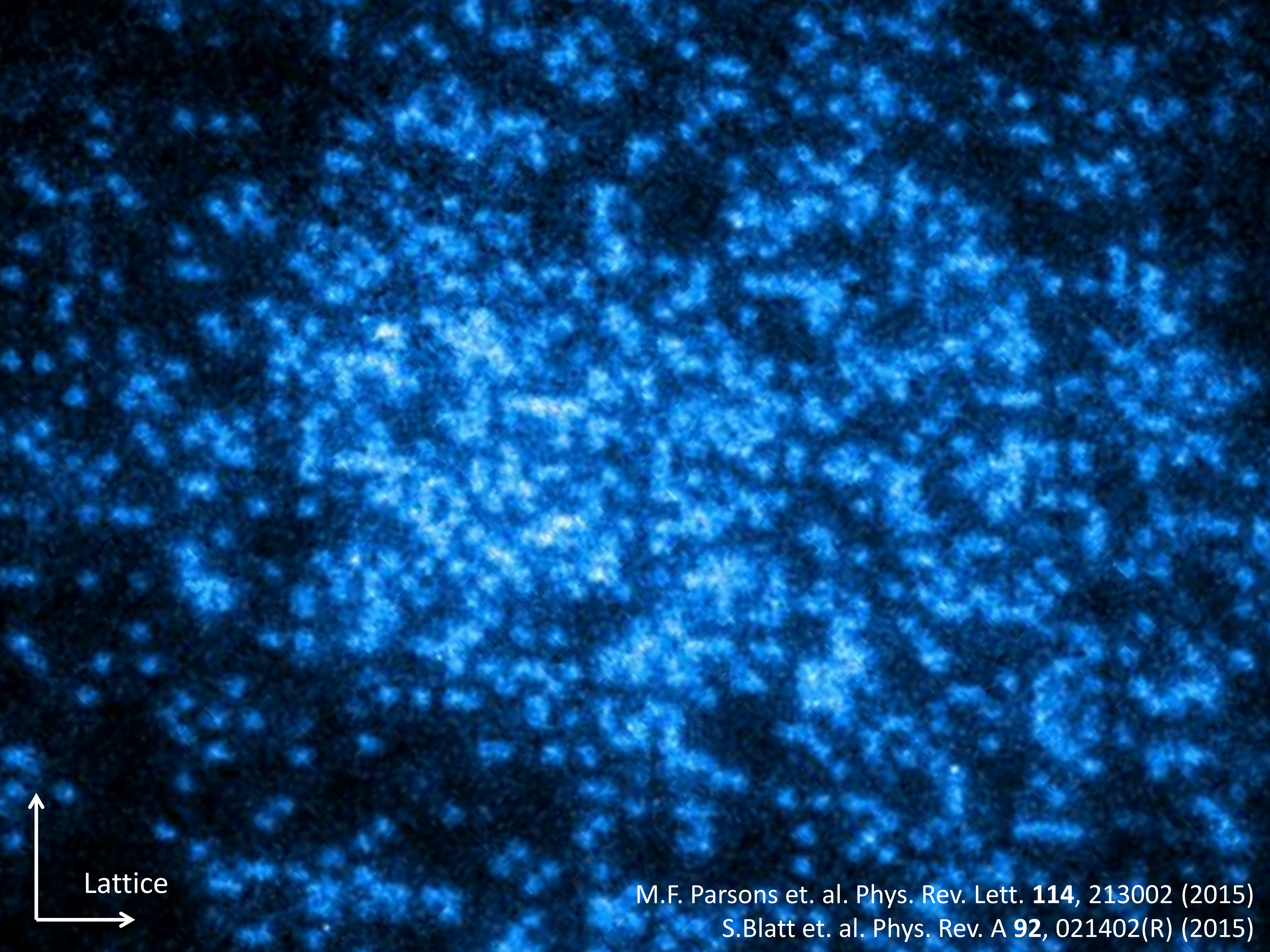
Raman sideband imaging



99.5% of atoms pinned in one image

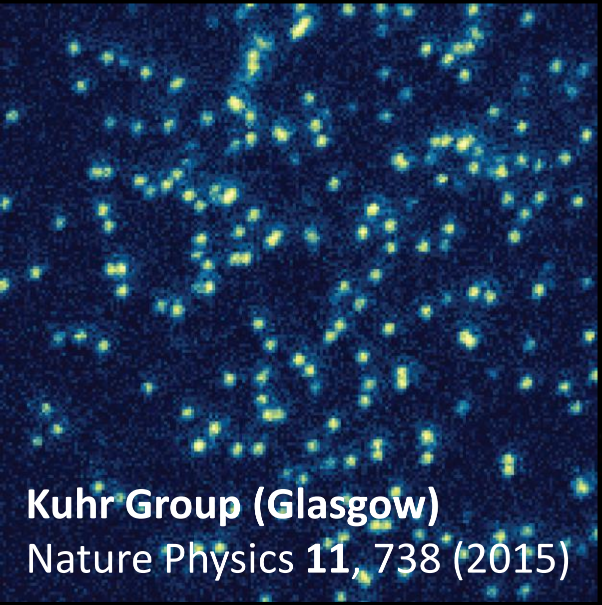


M.F. Parsons et. al. Phys. Rev. Lett. **114**, 213002 (2015)
S.Blatt et. al. Phys. Rev. A **92**, 021402(R) (2015)

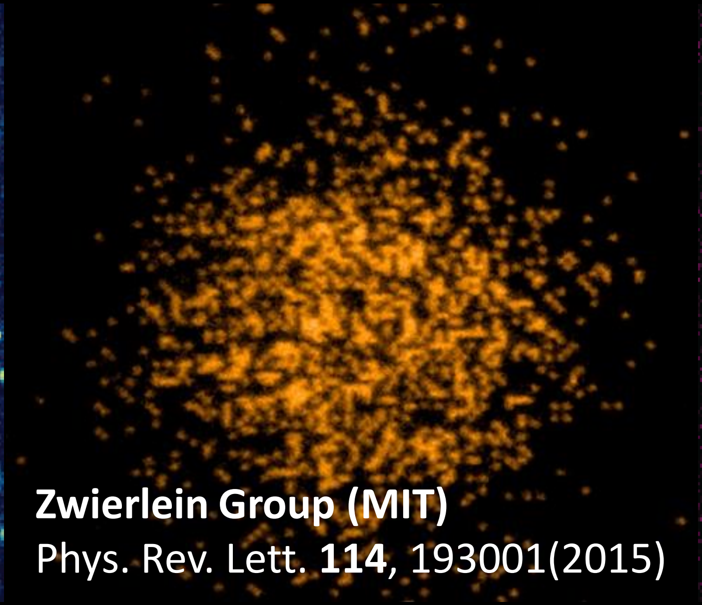


M.F. Parsons et. al. Phys. Rev. Lett. **114**, 213002 (2015)
S.Blatt et. al. Phys. Rev. A **92**, 021402(R) (2015)

2015 in Fermi Gas Microscopy



Kuhr Group (Glasgow)
Nature Physics **11**, 738 (2015)



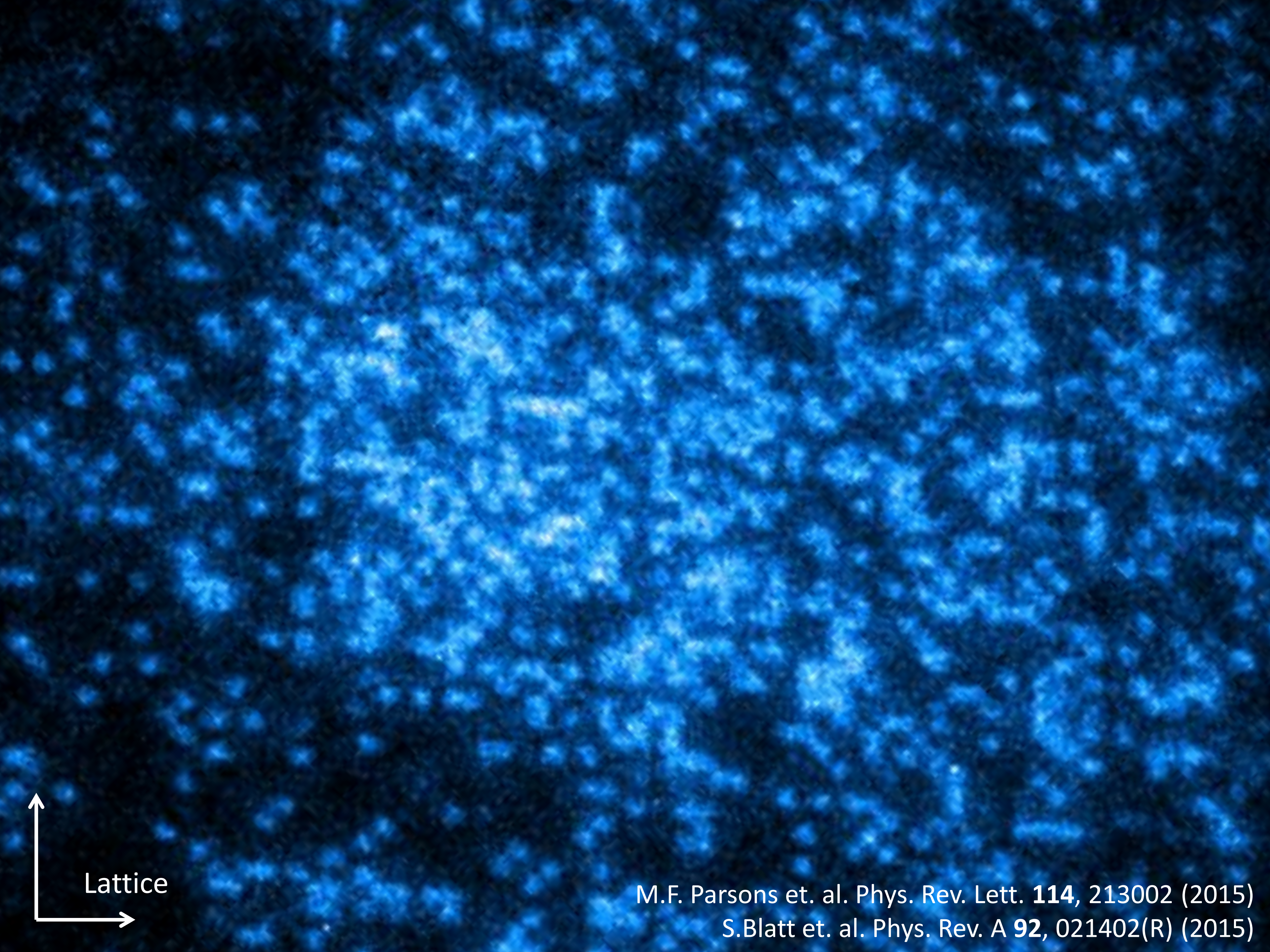
Zwierlein Group (MIT)
Phys. Rev. Lett. **114**, 193001(2015)

Thywissen Group (Toronto)
Phys. Rev. A **92**, 063406 (2015)

Gross/Bloch Group (Munich)
Spin Polarized Band Insulator
Phys. Rev. Lett. **115**, 263001 (2015)

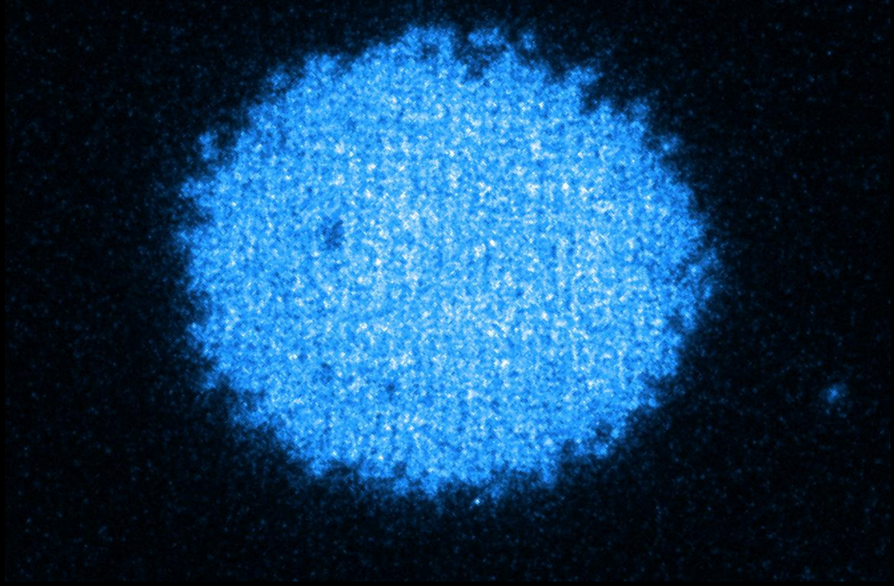
Greiner Group (Harvard)
Phys. Rev. Lett. **114**, 213002 (2015)

Also:
Bakr group (Princeton) and many more (10+)



M.F. Parsons et. al. Phys. Rev. Lett. **114**, 213002 (2015)
S.Blatt et. al. Phys. Rev. A **92**, 021402(R) (2015)

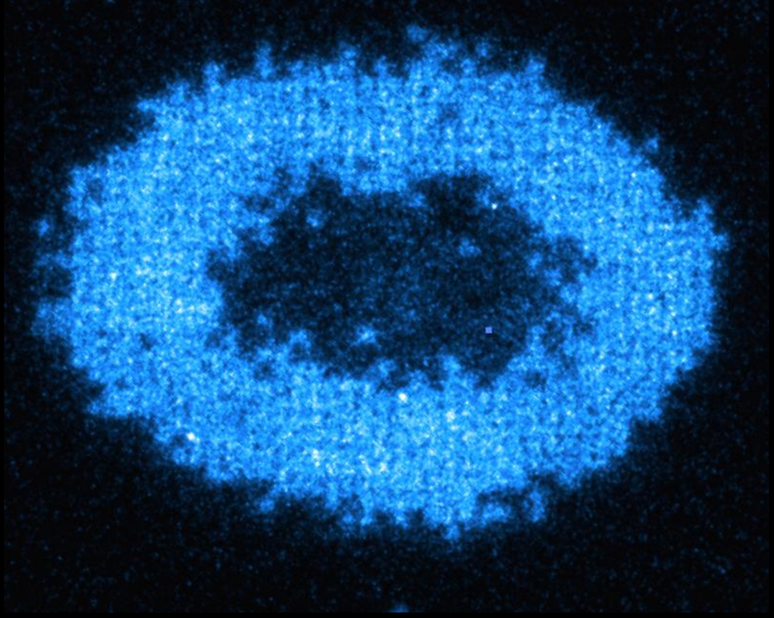
Mott Insulator



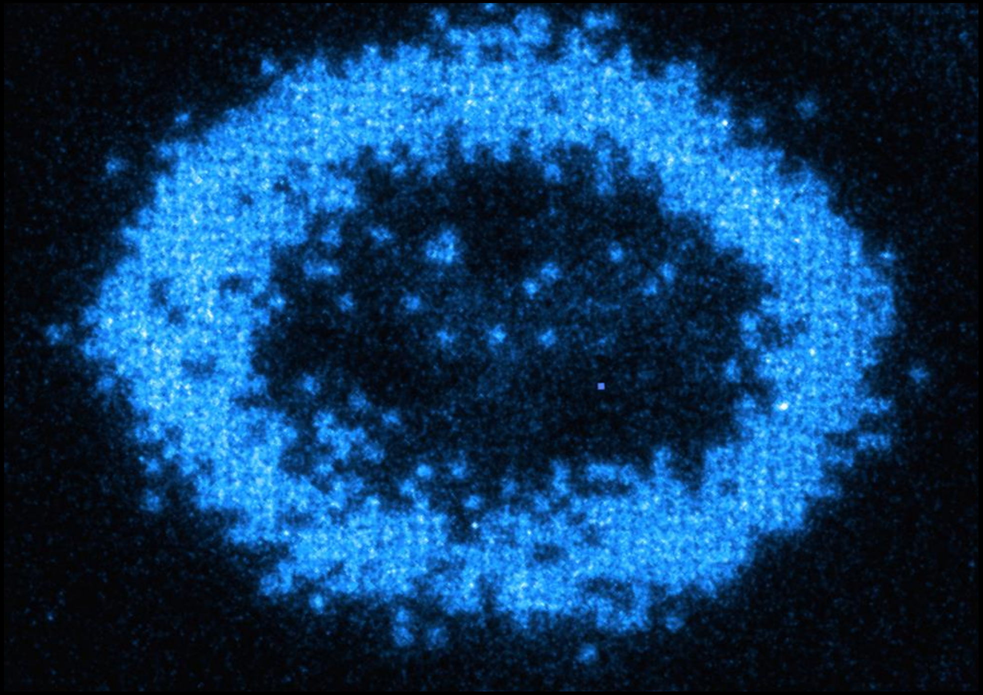
Experimental Parameters

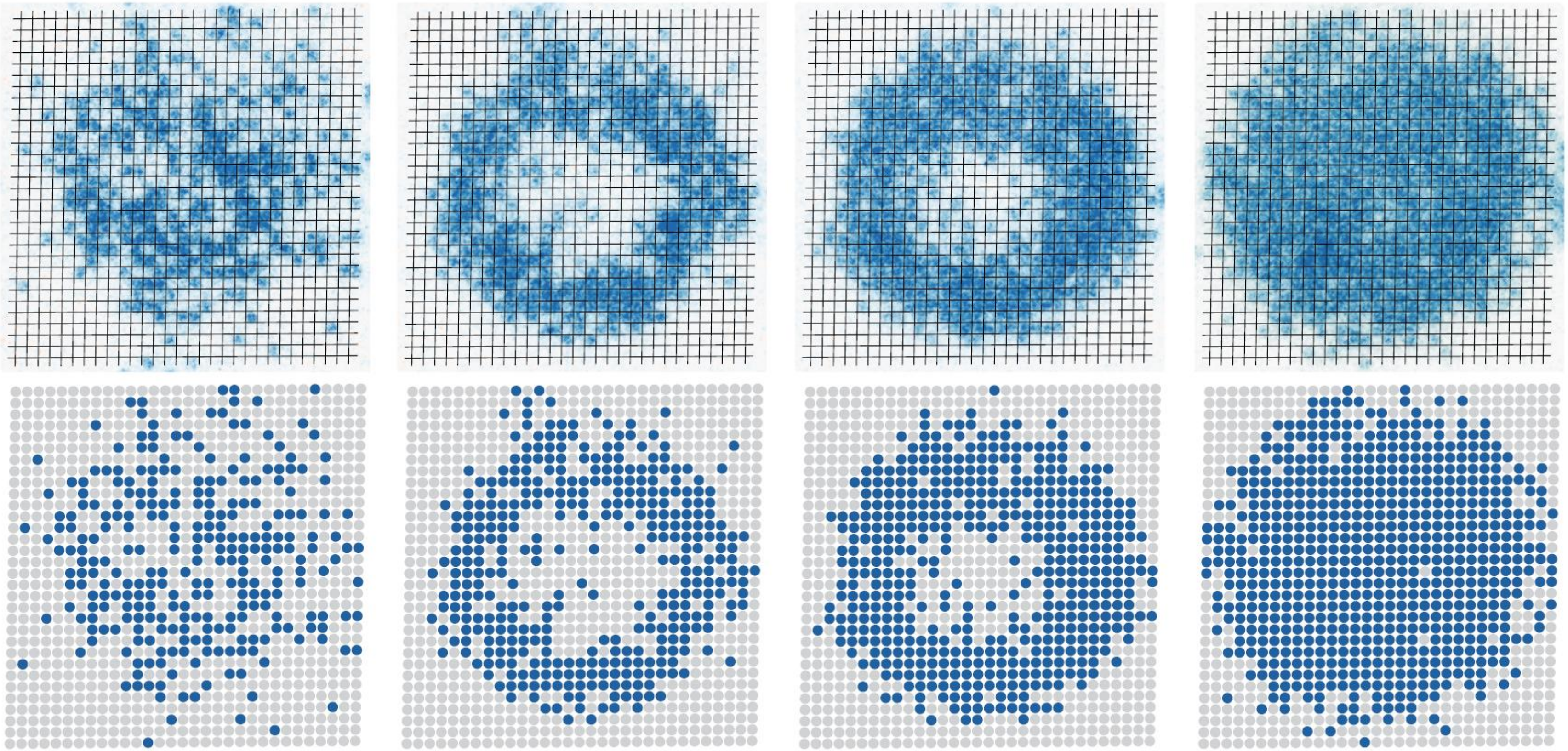
- Balanced two-component spin mix of Li-6 in hyperfine |1> and |2> states
- Atom numbers: N = 100-1000
- Repulsive interactions: $a = 37\text{-}515\ a_0$
- 1064nm optical lattice
- Lattice depth: 7– 16 E_R

Doublon Band Insulator



Large Doublon Band Insulator





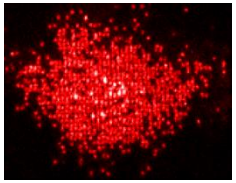
Increasing Interactions U/t

Metal

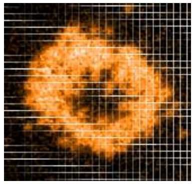
Band Insulator

Mott Insulator

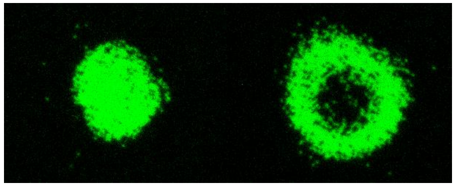
Gross/Bloch group (Munich)
Non-int. Band insulator:
A. Ohmran et al.,
PRL 115, 263001 (2015)



Zwierlein group (MIT)
L. Cheuk et al.,
PRL 116, 235301 (2016)

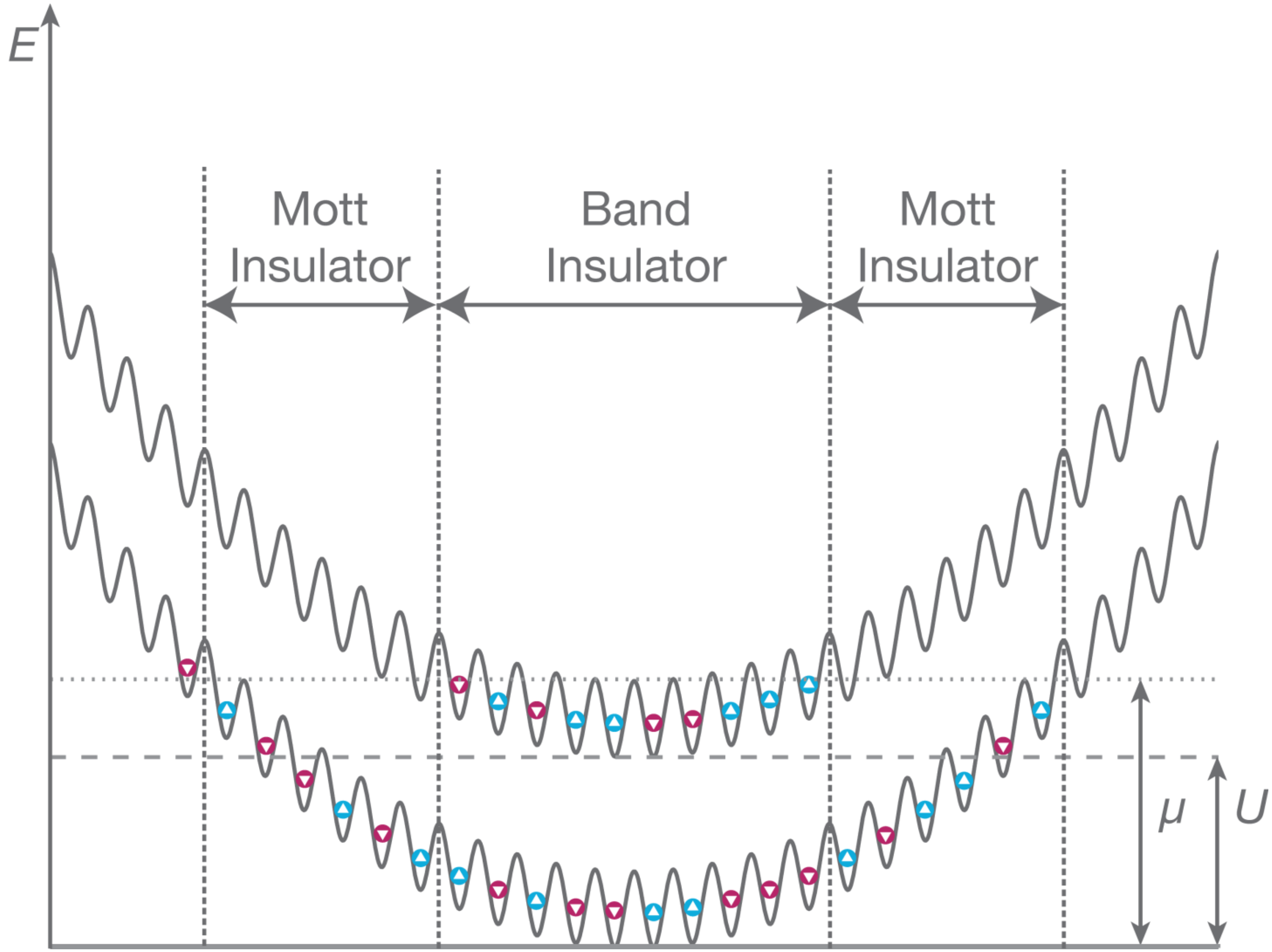


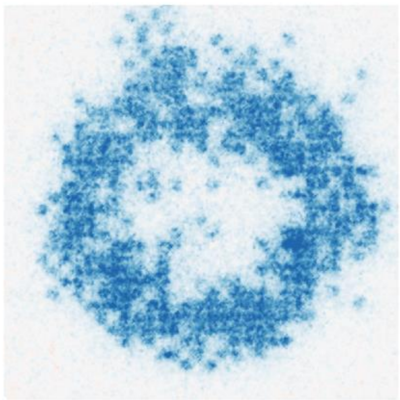
Bakr group (Princeton)
W. Bakr et al.:
unpublished



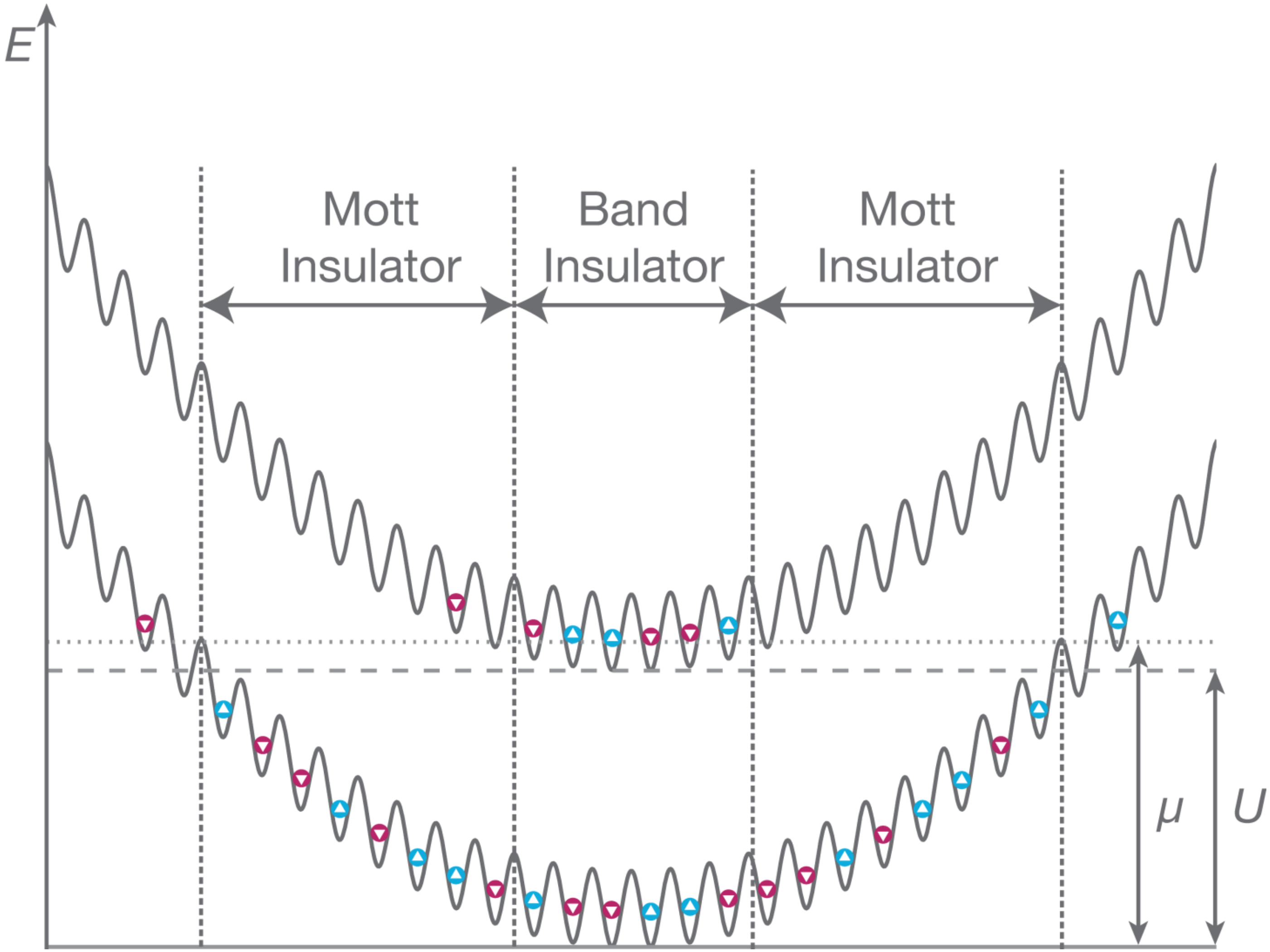
D. Greif et al., Science 351, 953 (2016)

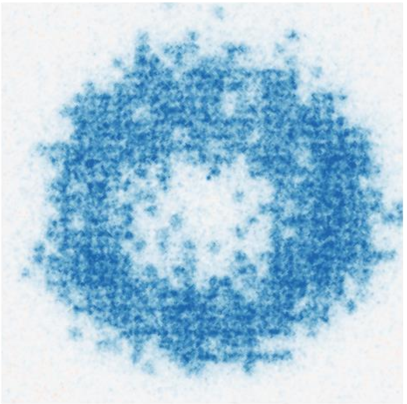
From metals to Mott insulators



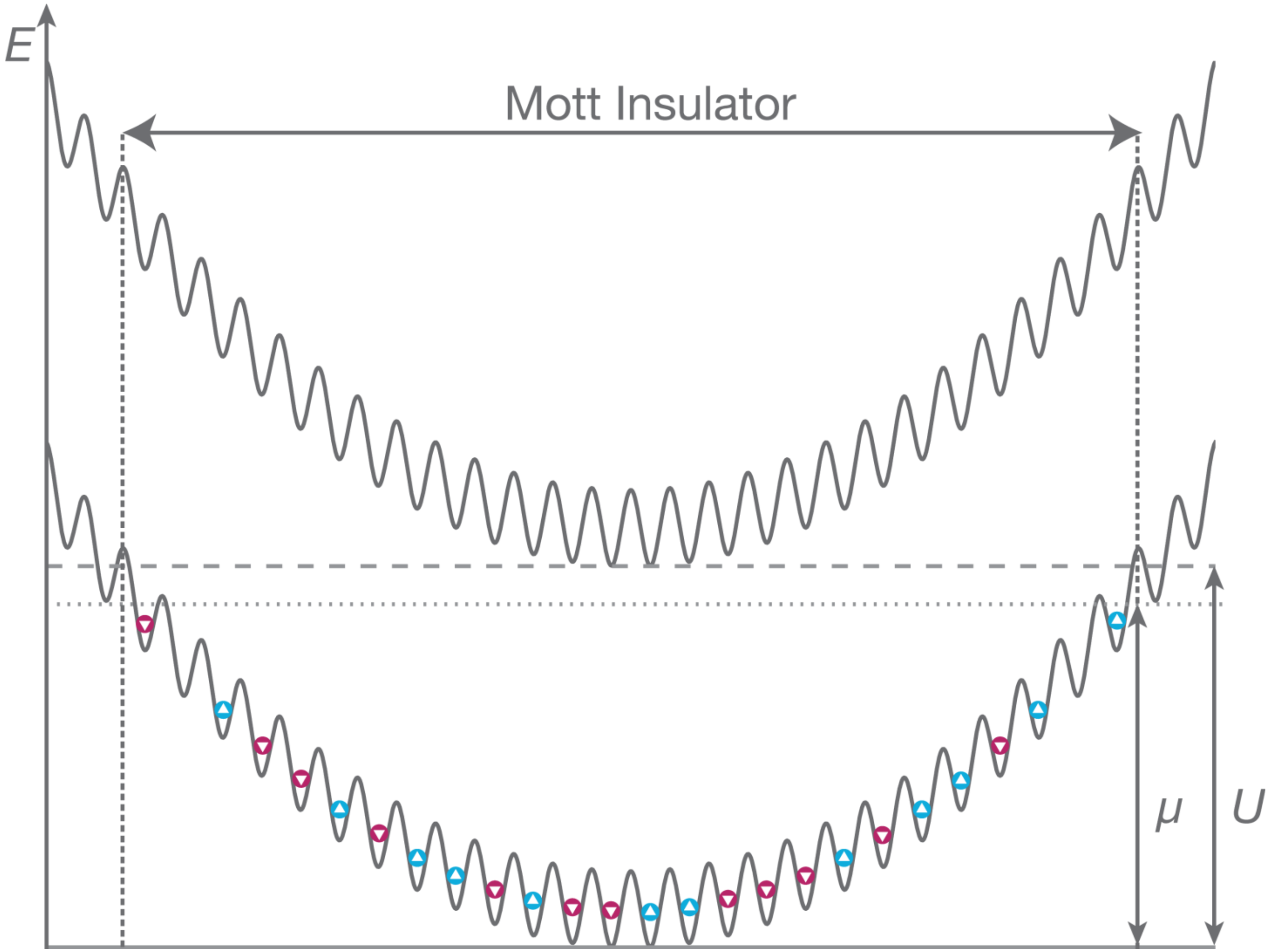


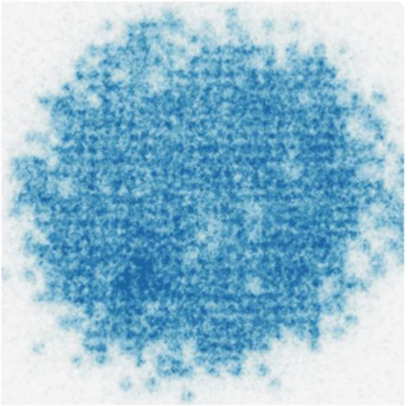
From metals to Mott insulators



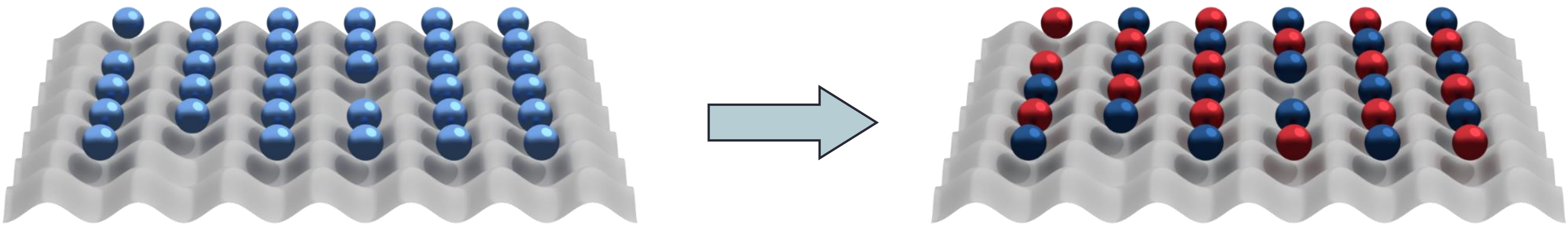


From metals to Mott insulators





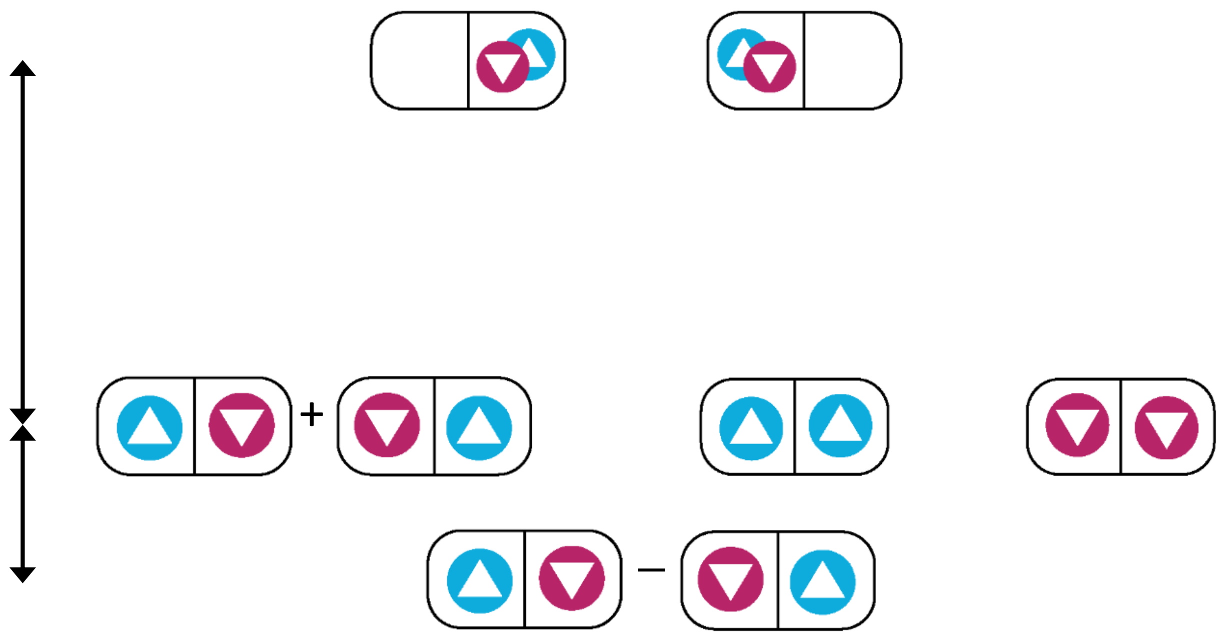
Antiferromagnetism in the Fermi-Hubbard model



$U \gg t$

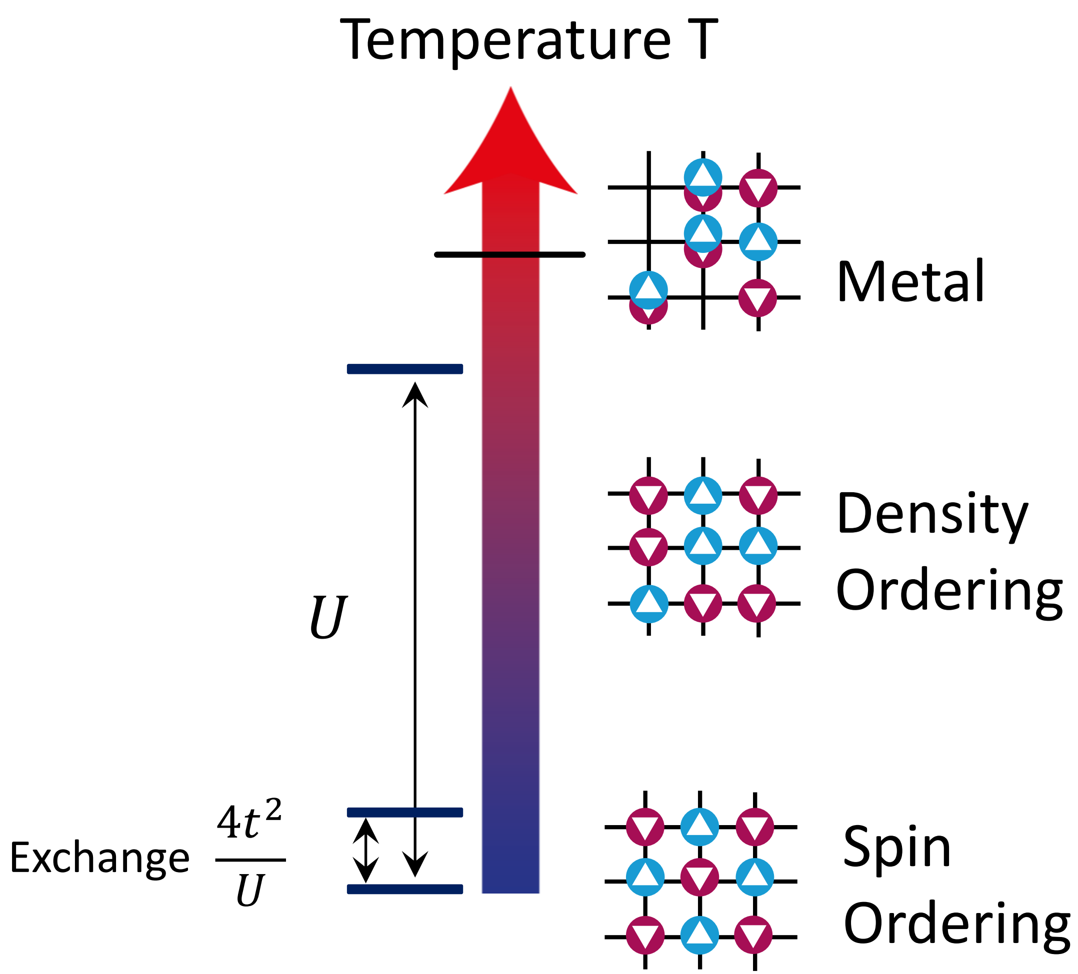
U

Exchange $\frac{4t^2}{U}$



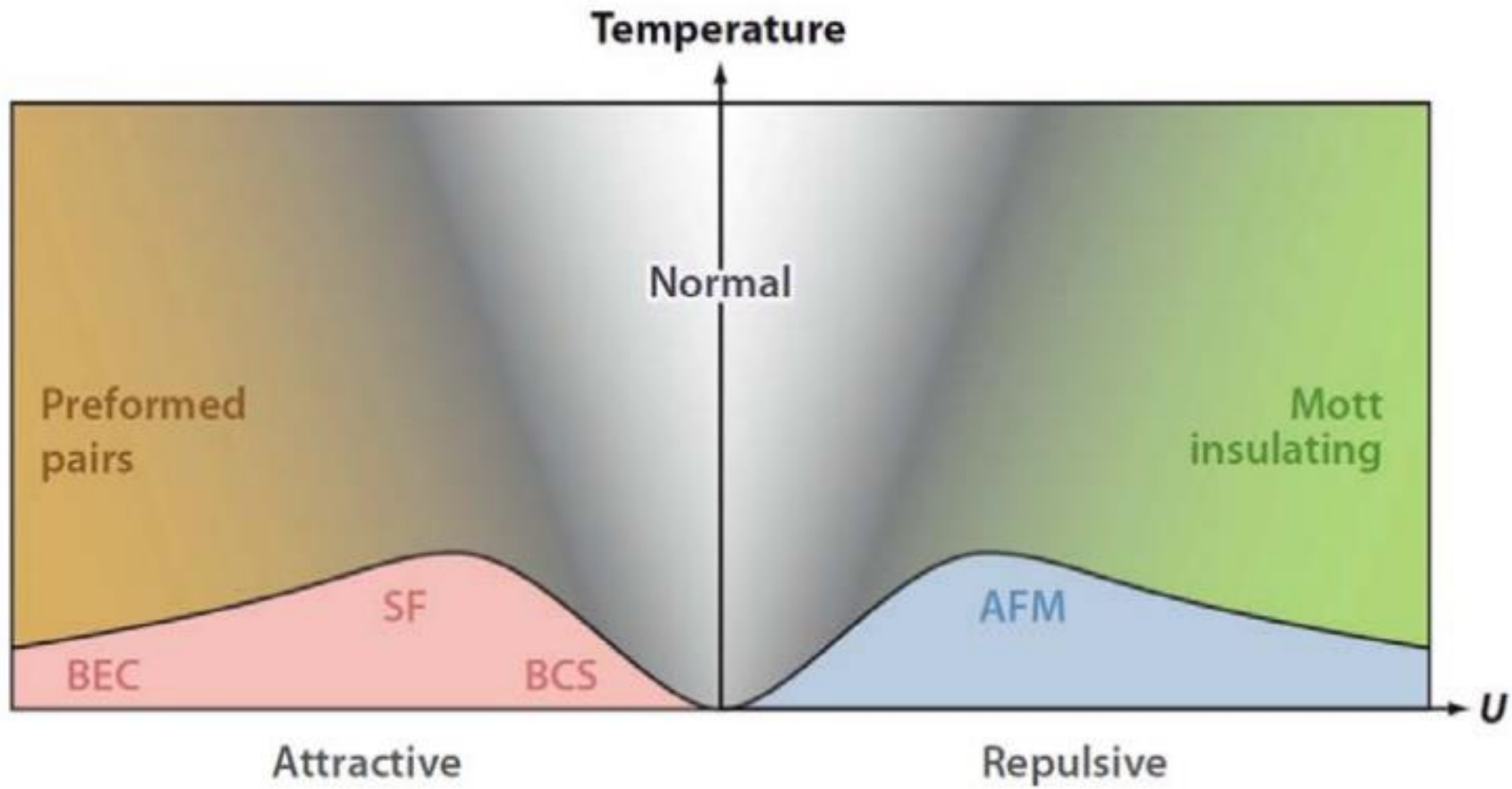
Antiferromagnetism in the Fermi-Hubbard model

$U \gg t$



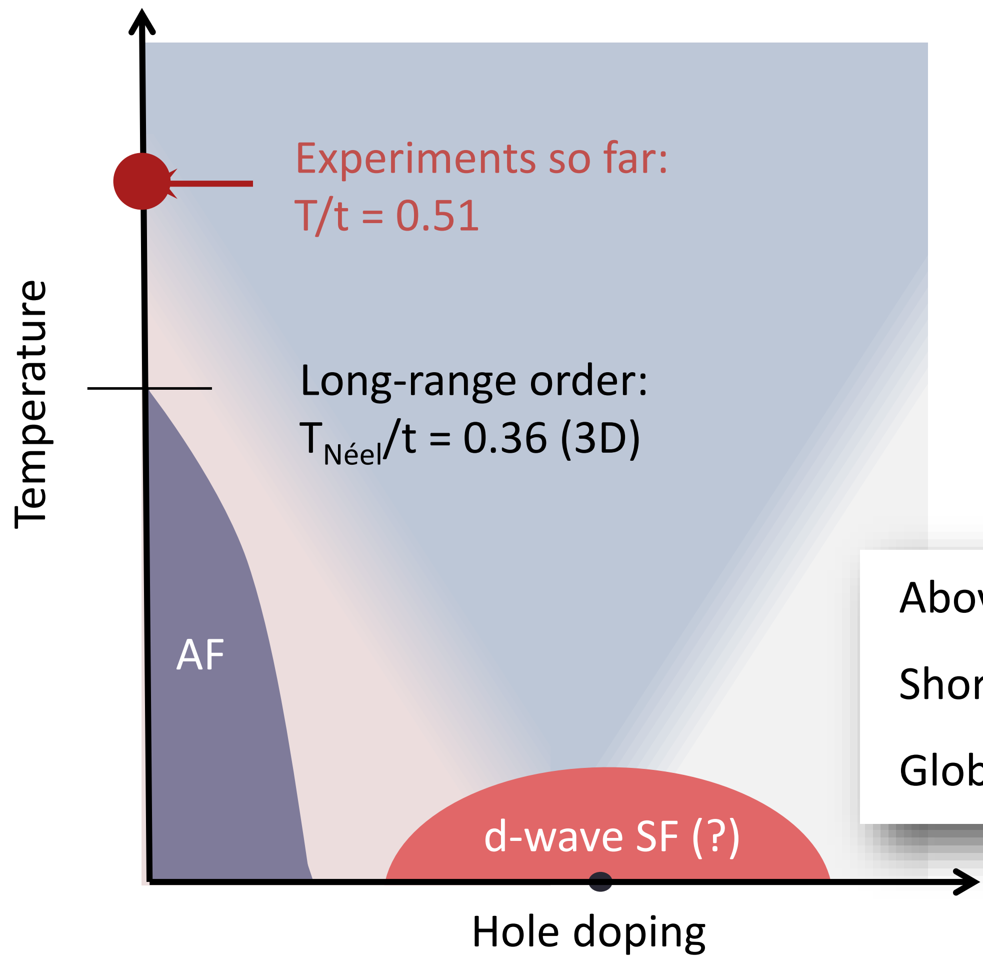
Antiferromagnetism in the Fermi-Hubbard model

3D Fermi-Hubbard model



Antiferromagnetism in the Fermi-Hubbard model

3D Fermi-Hubbard model



Theory:

- Lee et al., Rev. Mod. Phys. 78, 17 (2006)
- Varma et al., Nature 468, 184 (2010)
- Paiva et al., PRL 107, 086401 (2011)
- Kozik et al., PRB 87, 205102 (2013)

Detection via local singlets: Zurich
D. Greif, et al. Science, 340, 1307 (2013)

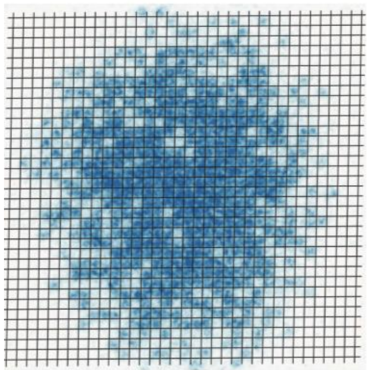
Detection via Bragg scattering: Rice
R. Hart, et al. Nature, 519, 211 (2015)

Above long-range ordering temperature $T_{Néel}$

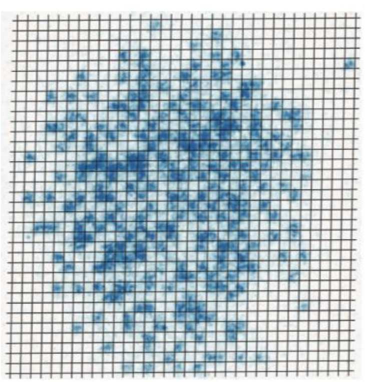
Short-range antiferromagnetic correlations

Globally averaged observables

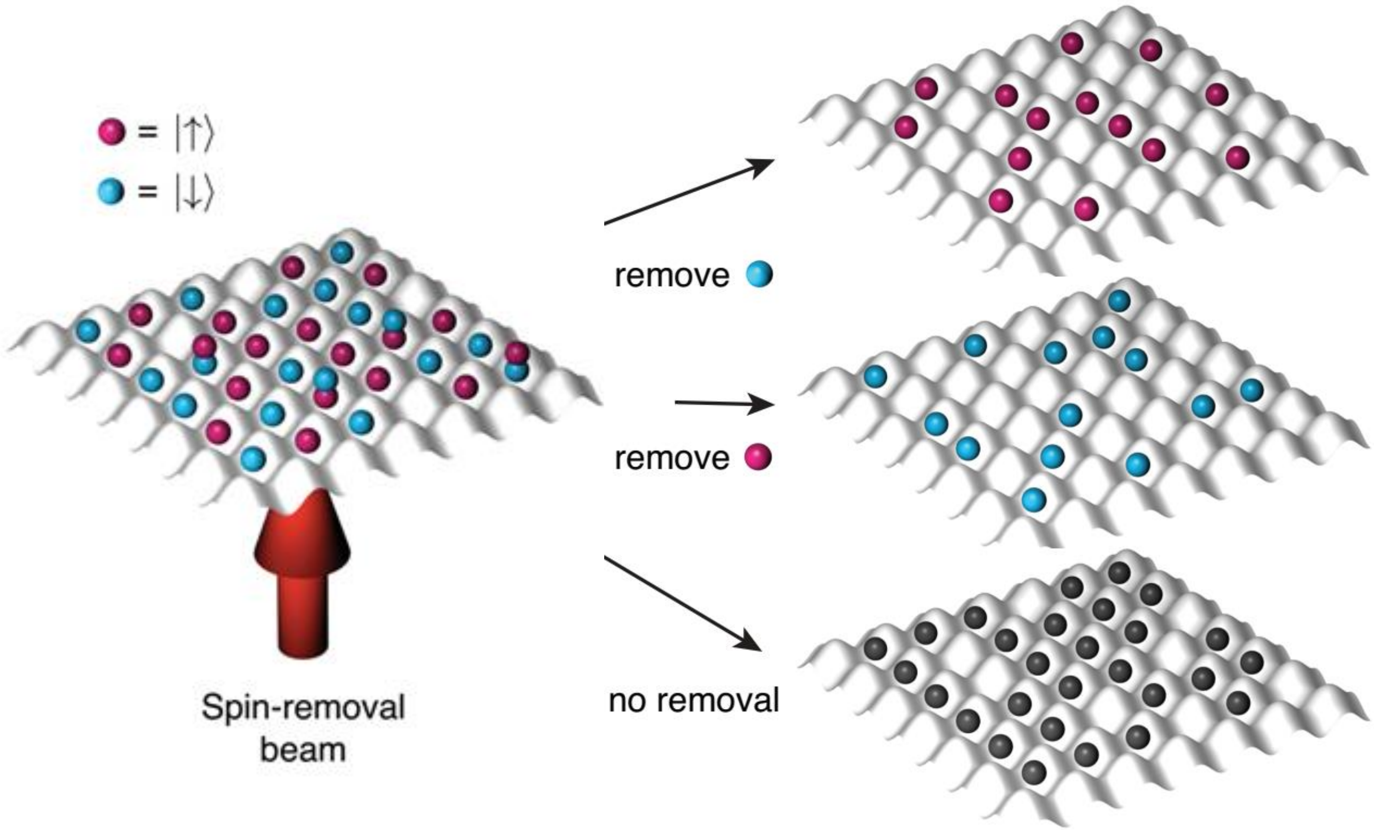
Measuring the spin correlator

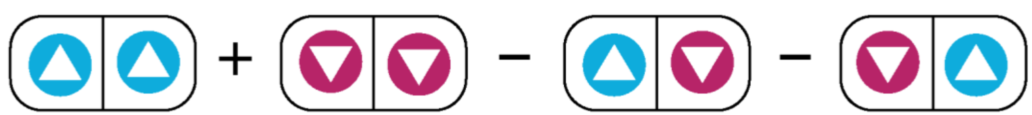


$|\uparrow\rangle + |\downarrow\rangle$

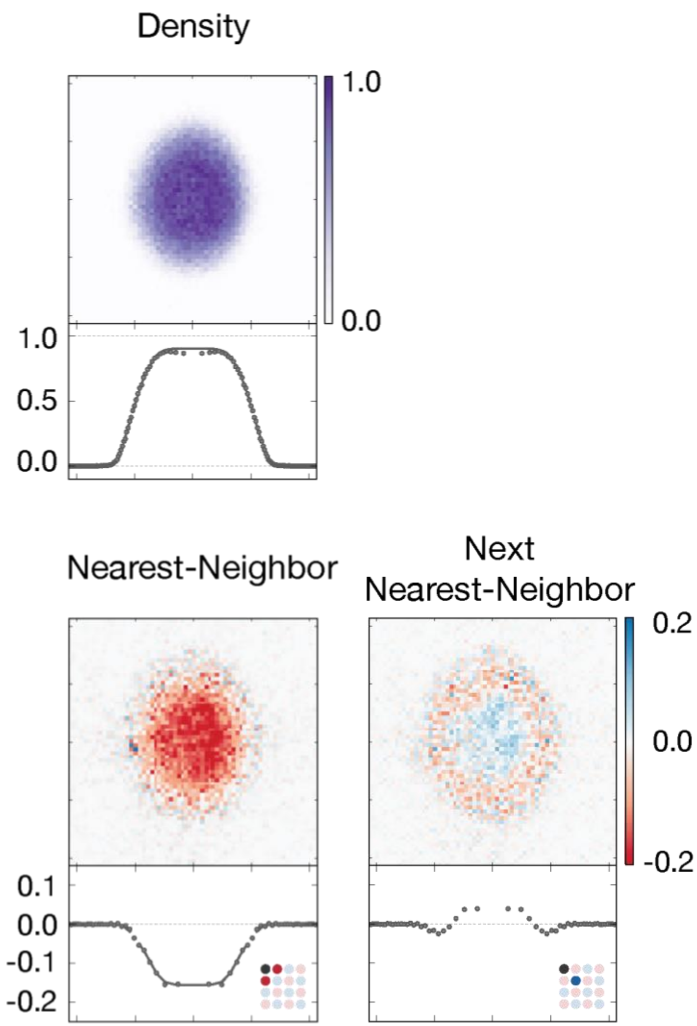


$|\uparrow\rangle$ only



$\langle S_i^z S_{i+d}^z \rangle =$ 

Antiferromagnetic correlations



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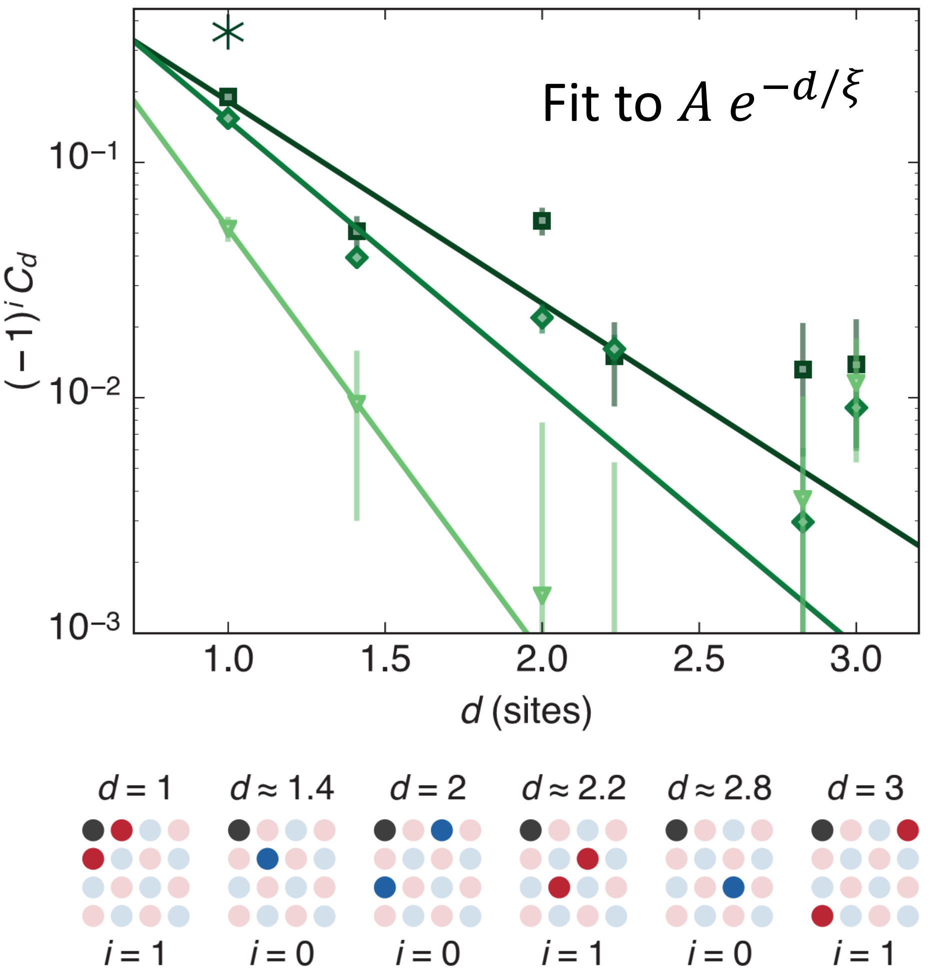
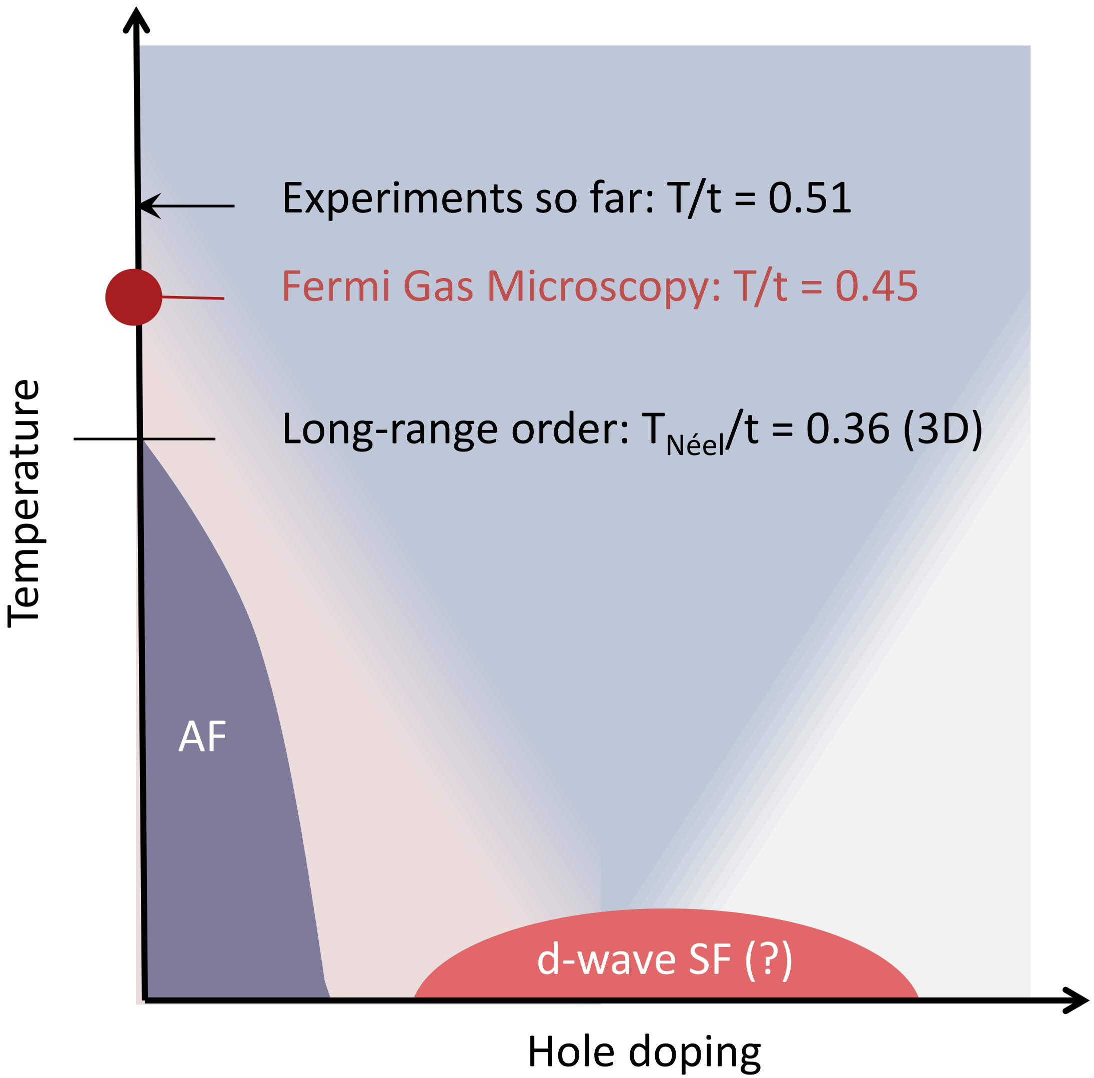
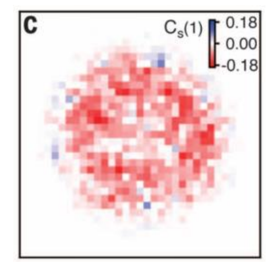


M. Parsons et al., Science 353, 1253 (2016)

Towards long-range order



Gross/Bloch group (Munich)
1D AFM chains
M. Boll et al.,
Science 353, 1257 (2016)



Zwierlein group (MIT)
Charge & spin correlations
L. Cheuk et al.,
Science 353, 1257 (2016)

Theory:
Maier et al., PRL 95, 237001 (2005)
Gull et al., PRL 110, 216405 (2013)

M. Parsons et al., Science 353, 1253 (2016)

Entropy engineering

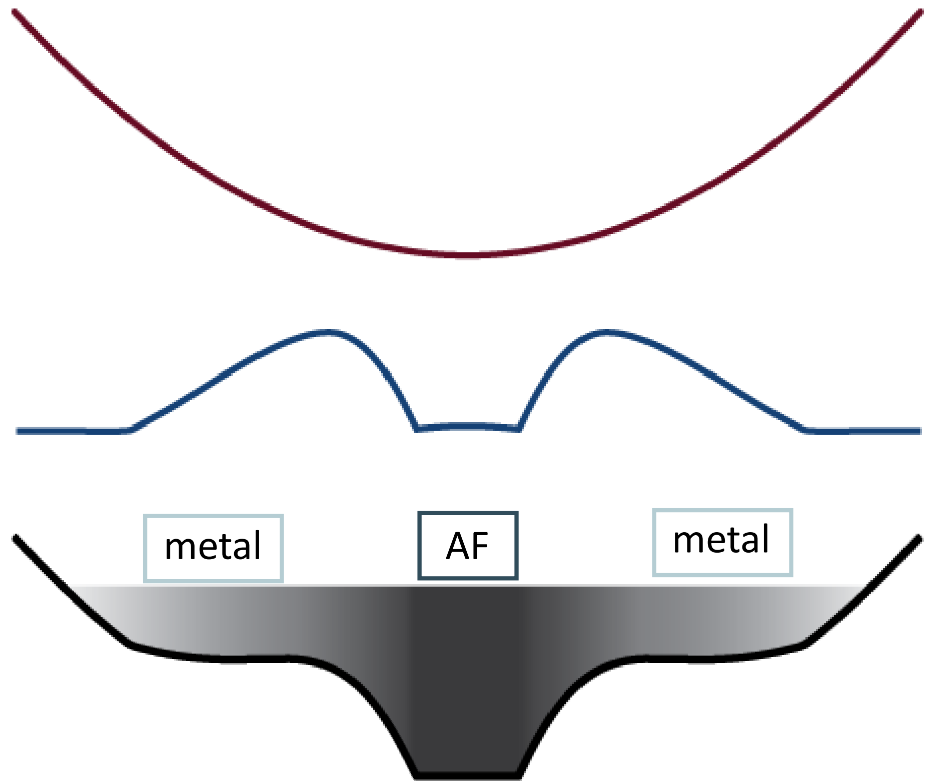
Harmonic potential
(lattices)

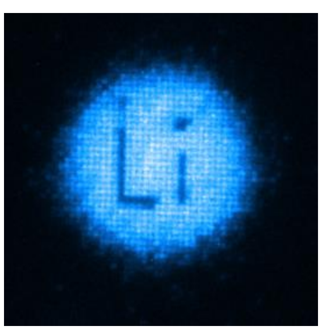
+

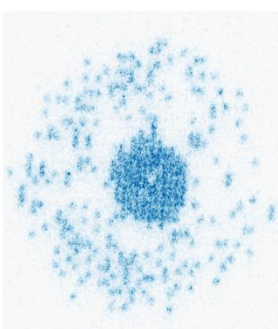
DMD potential

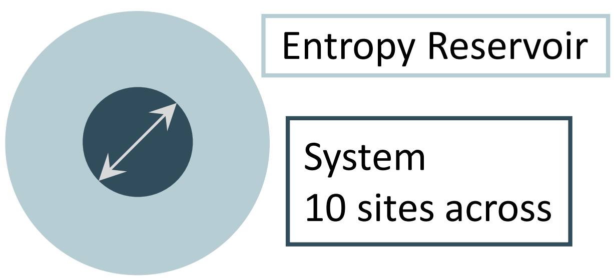
=

Total potential

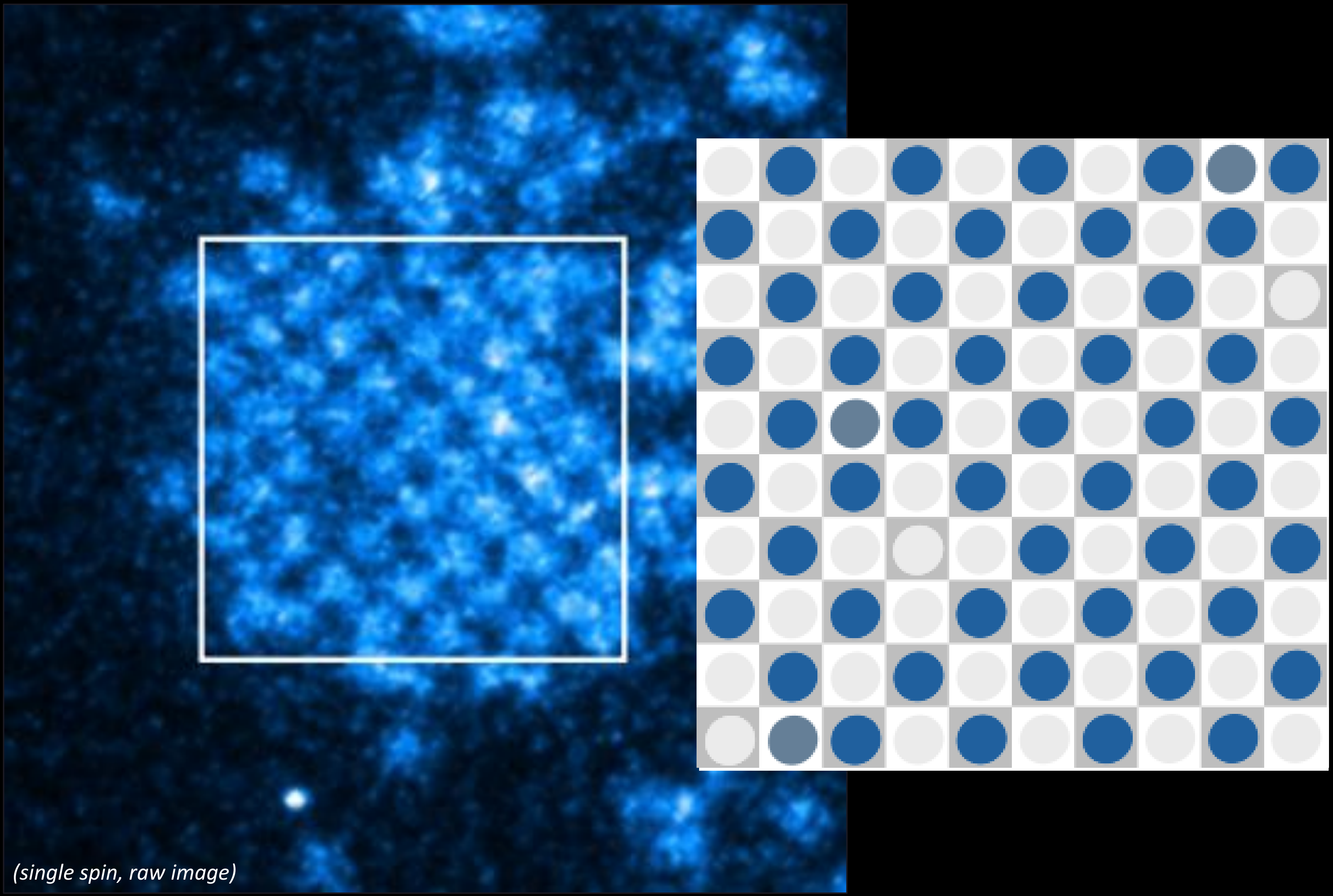




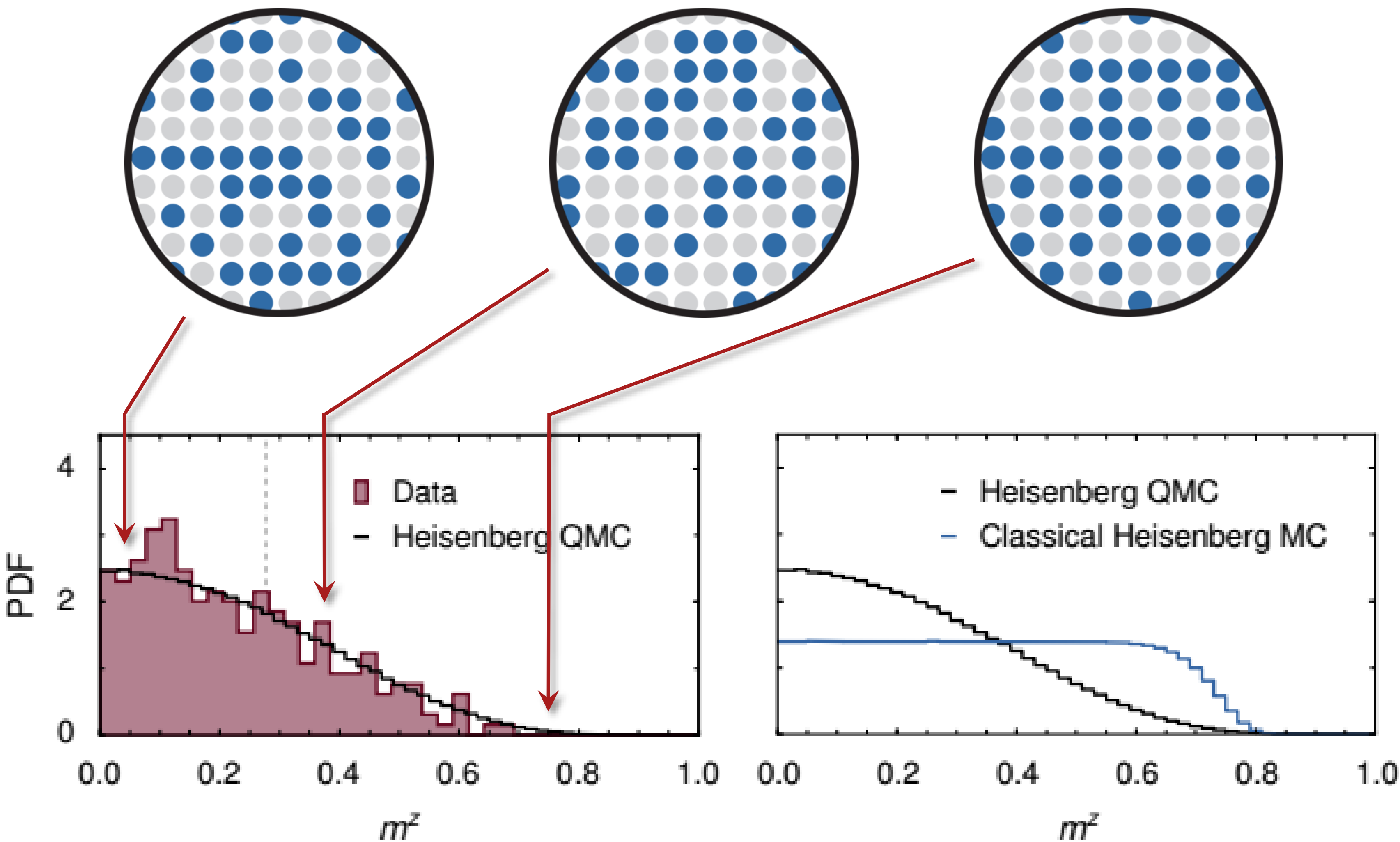




2D Antiferromagnetic order



2D Antiferromagnetic order

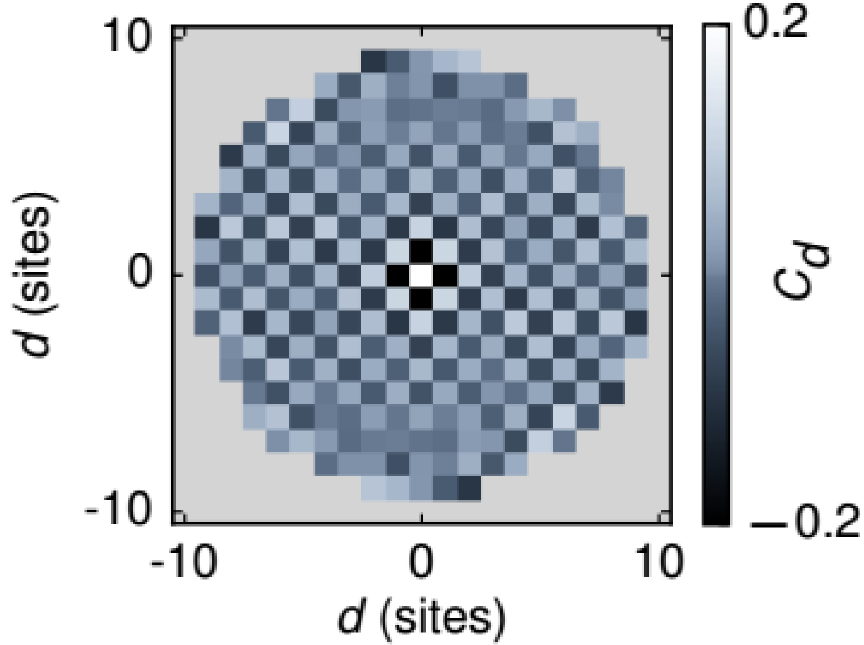


(preliminary)

In collaboration with Márton Kanász-Nagy, Richard Schmidt, Fabian Grusdt, and Eugene Demler

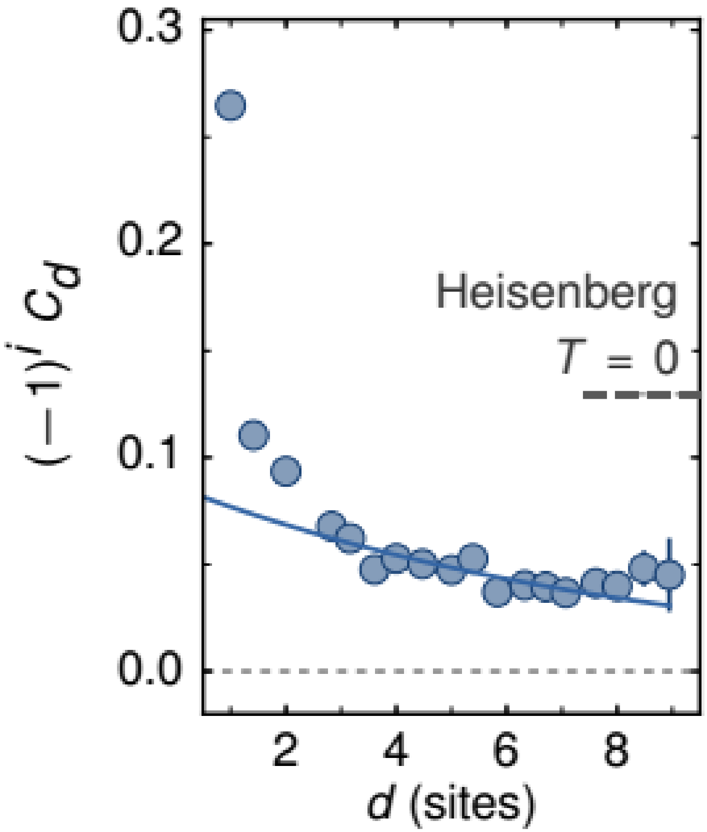
2D Antiferromagnetic order

Spin correlator



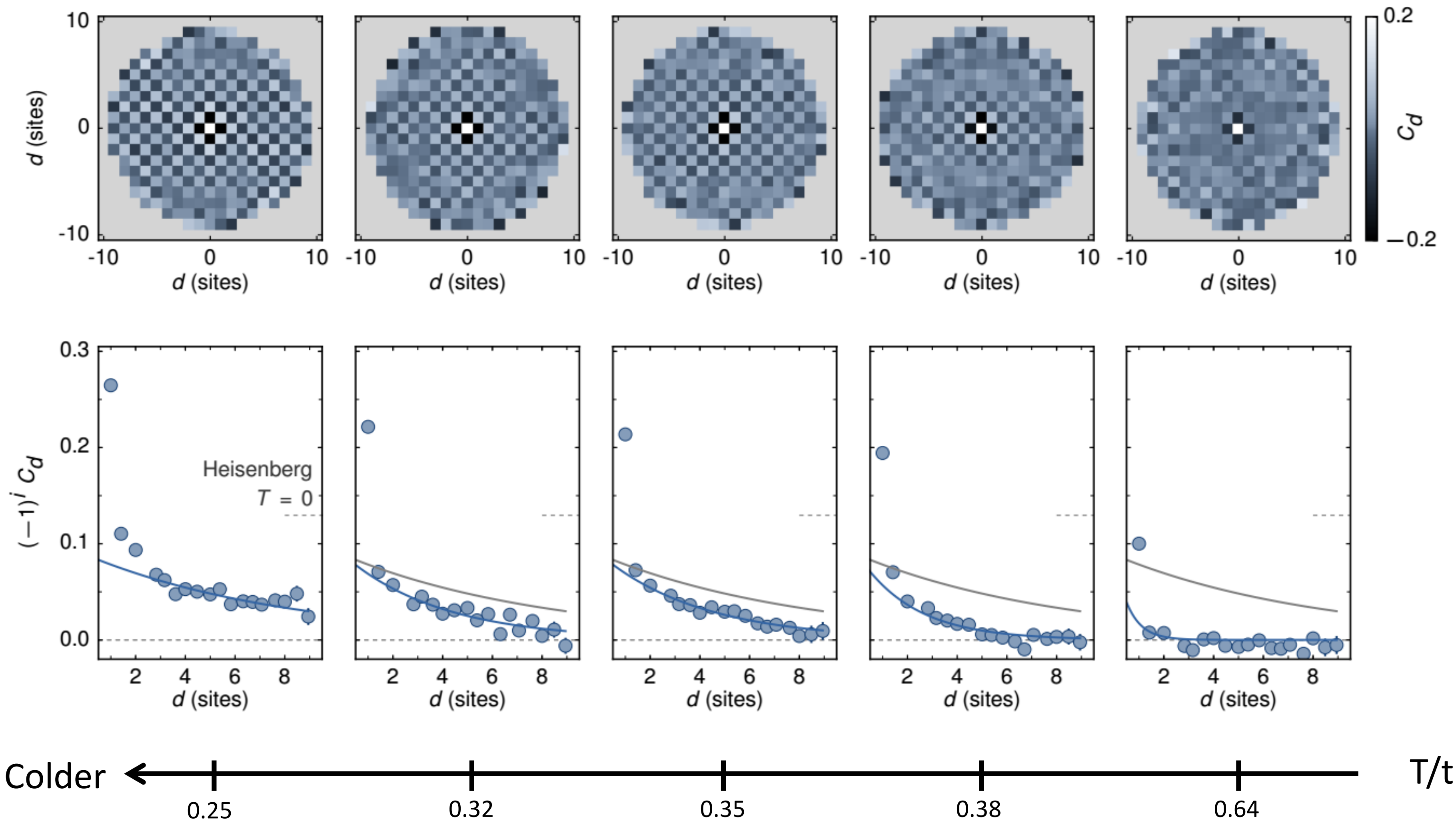
Azimuthal average

Spin correlation function



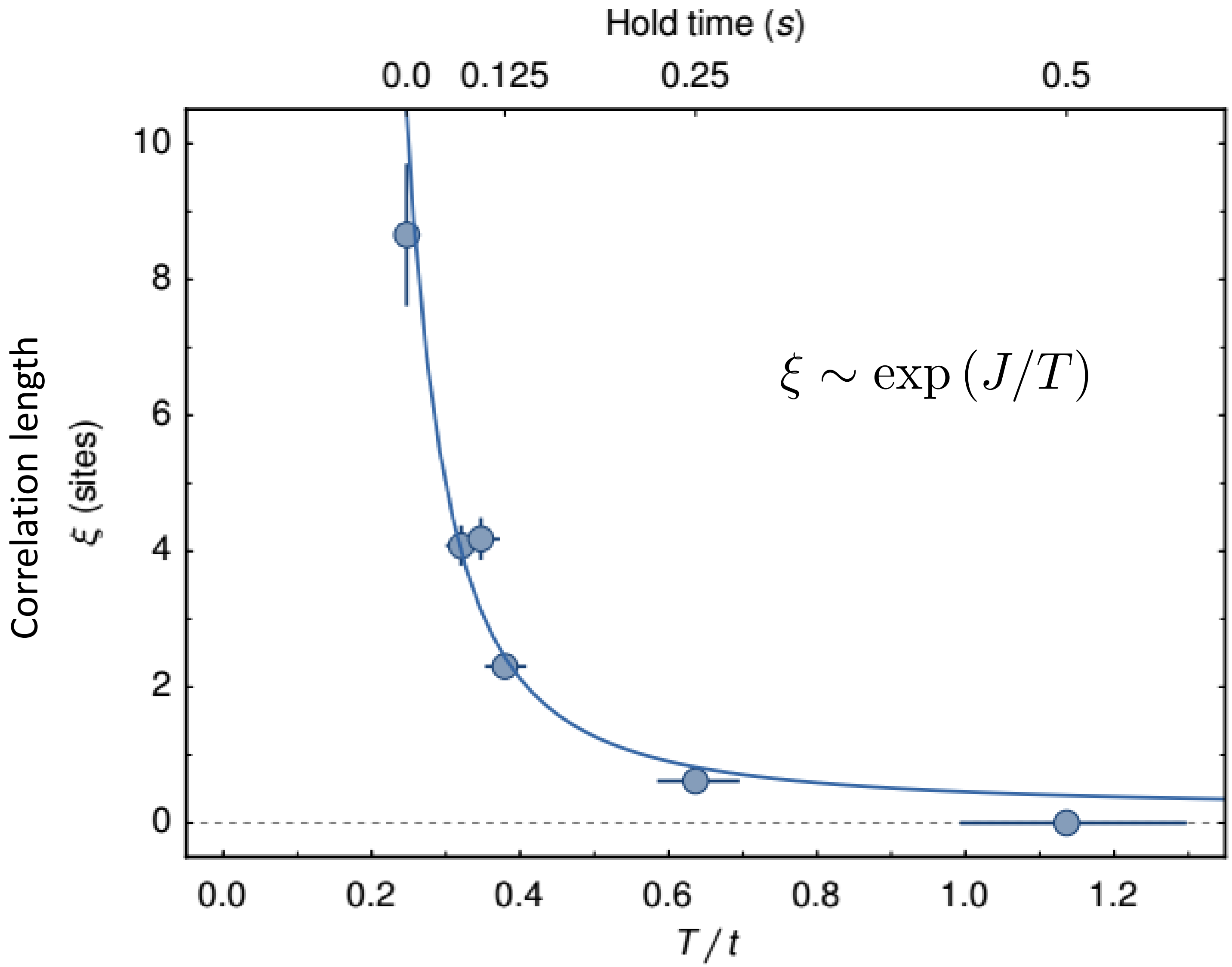
(preliminary)

2D Antiferromagnetic order



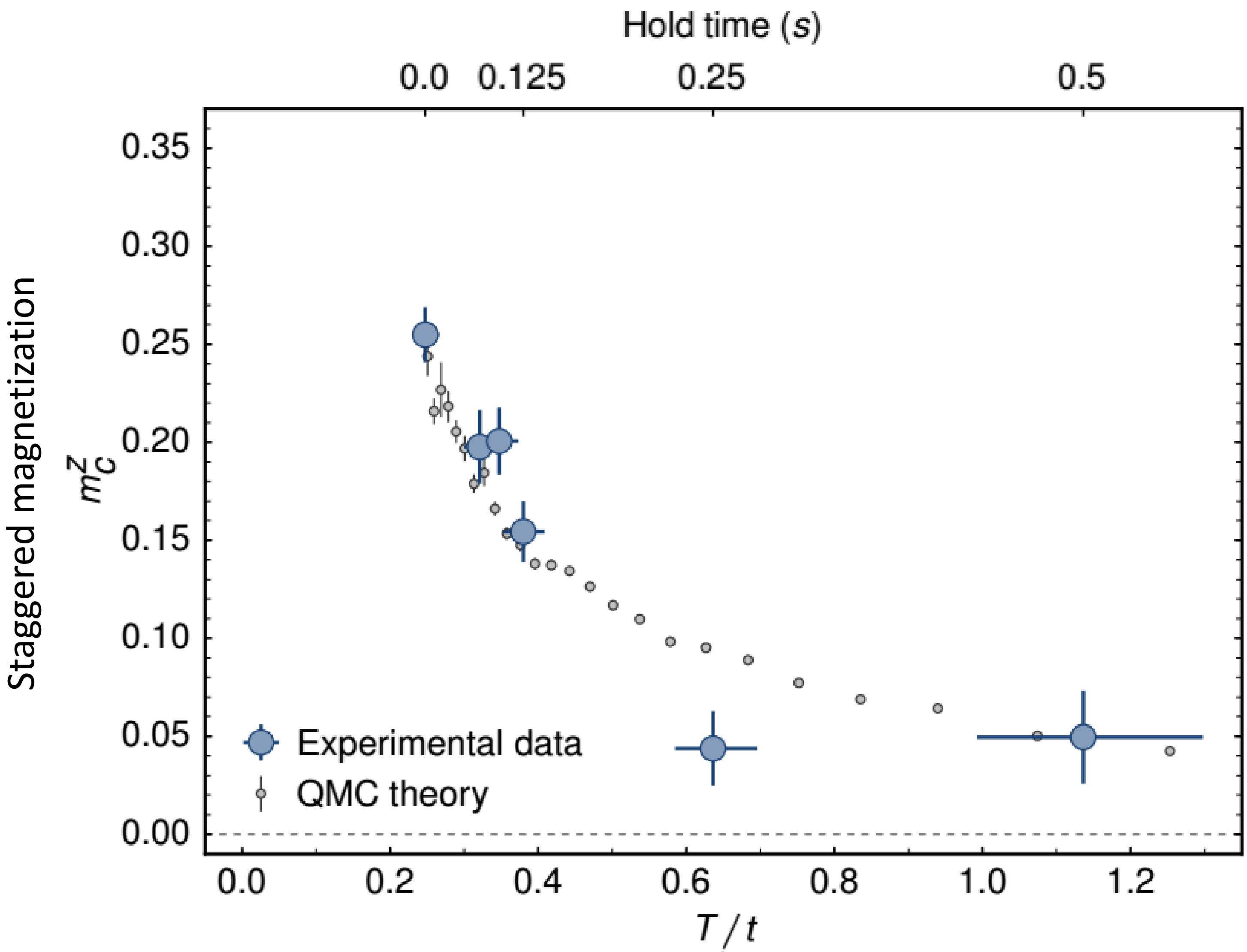
(preliminary)

2D Antiferromagnetic order



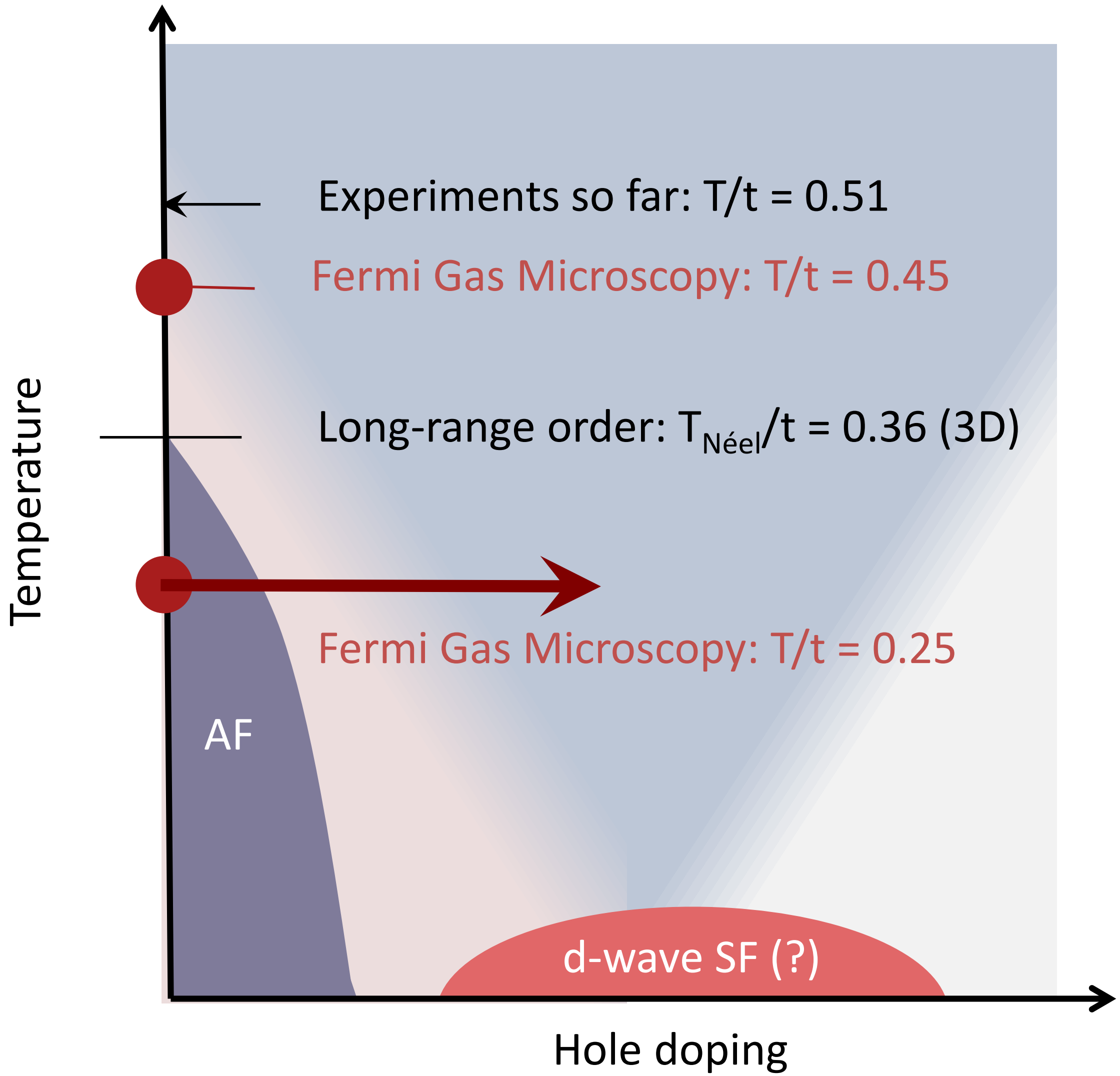
(preliminary)

2D Antiferromagnetic order

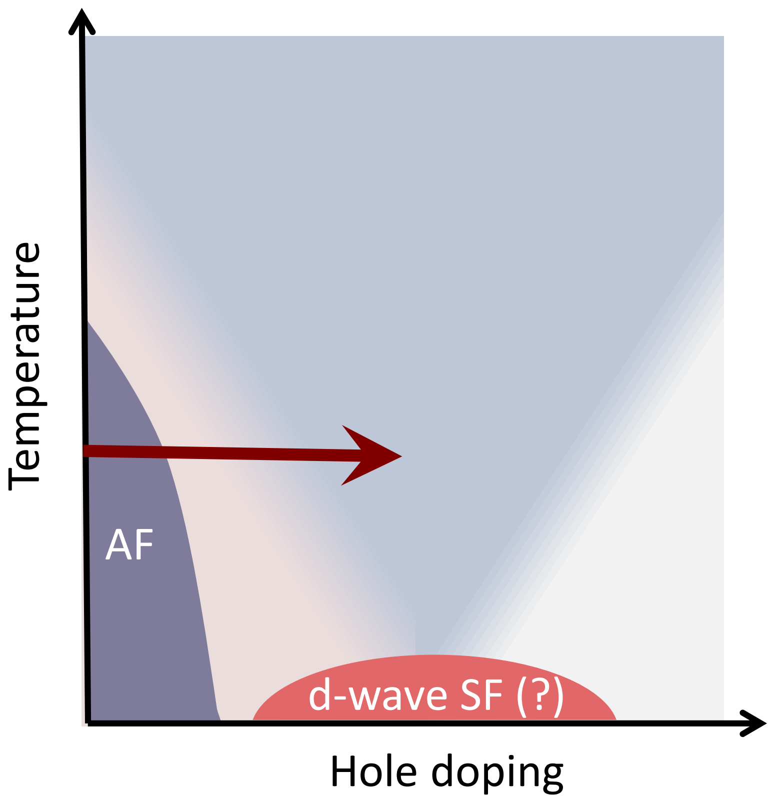


(preliminary)

2D Antiferromagnetic order



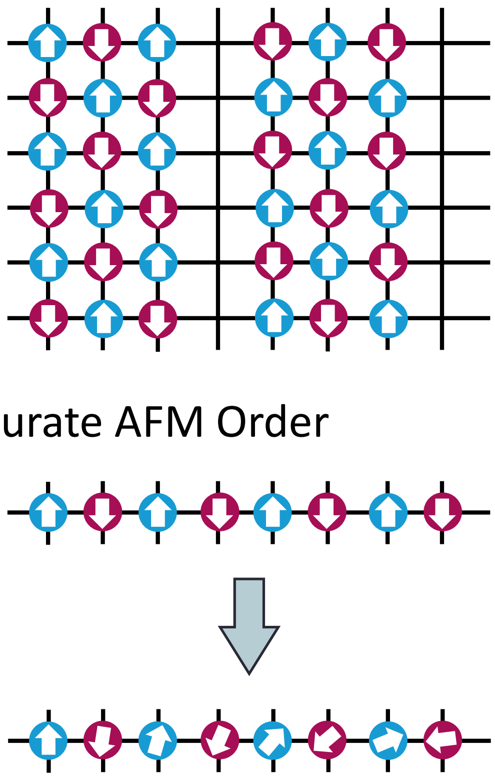
Doping in the Hubbard model



Candidates:

Stripe Order

Incommensurate AFM Order

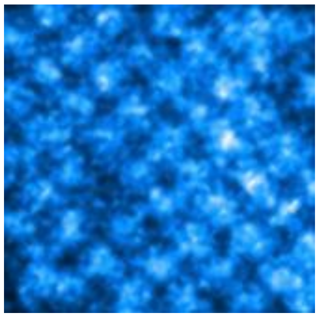


Pseudo-gap states
Spin liquid
...

(preliminary)

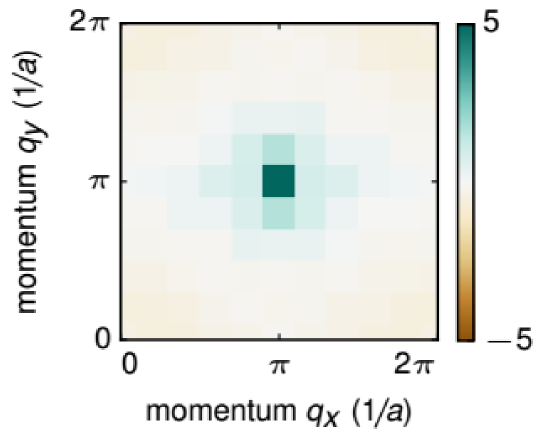
Doping in the Hubbard model

$|\uparrow\rangle$ only

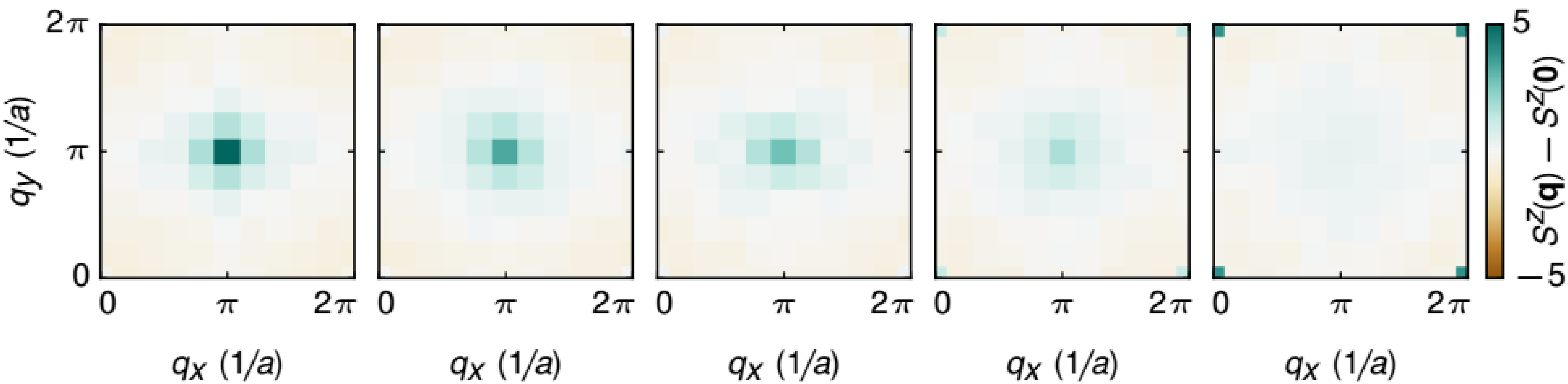


Average FFT

Spin structure factor



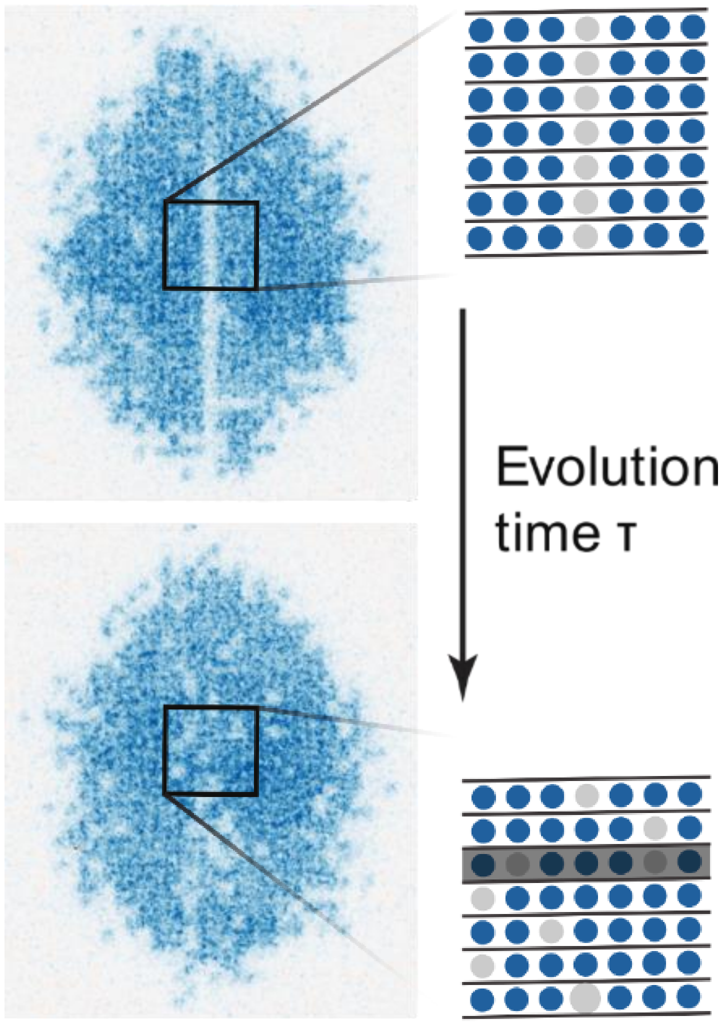
Doping 0.0% 2.3% 14.5% 19.9% 27.1%

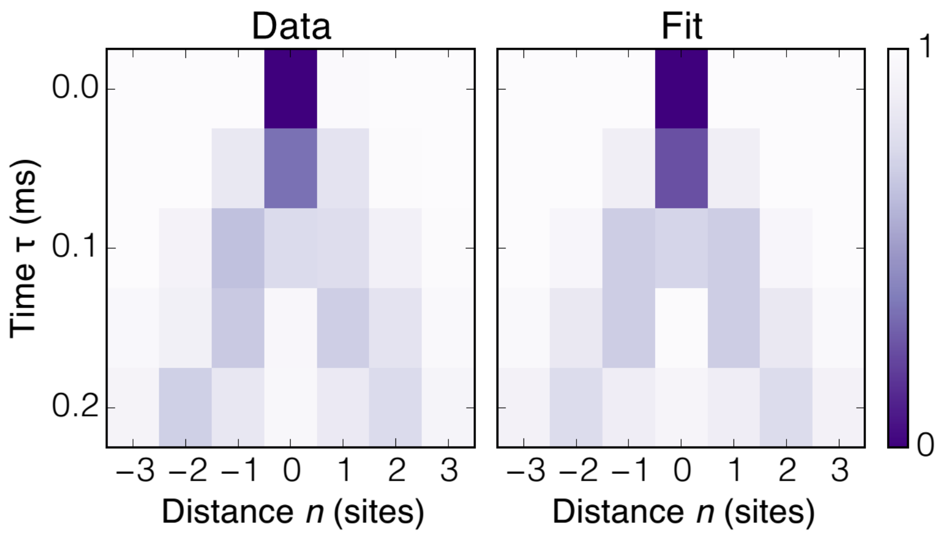


(preliminary)

Outlook: hole dynamics

Single Hole in 1D



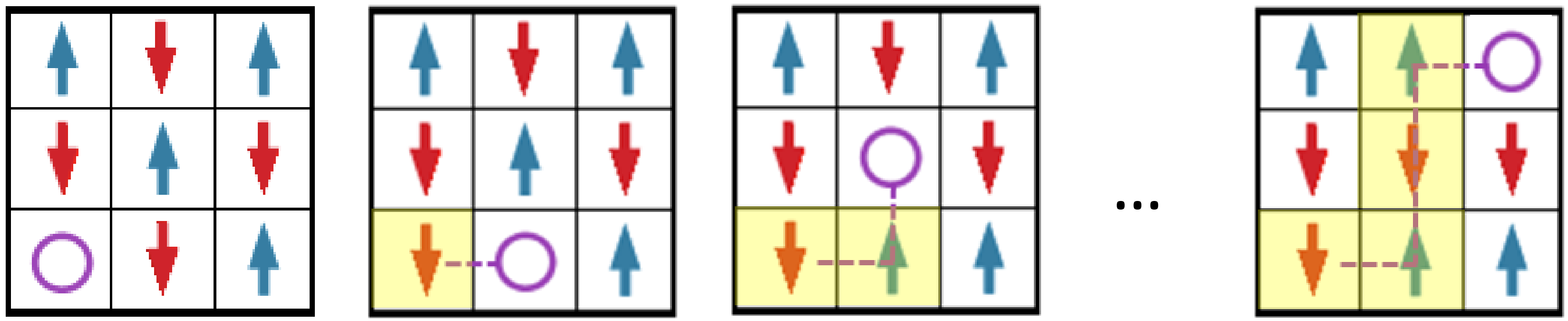


Theory collaboration with Eugene Demler, Fabian Grusdt, Annabelle Bohrdt, Marton Kanasz-Nagy, Michael Knap

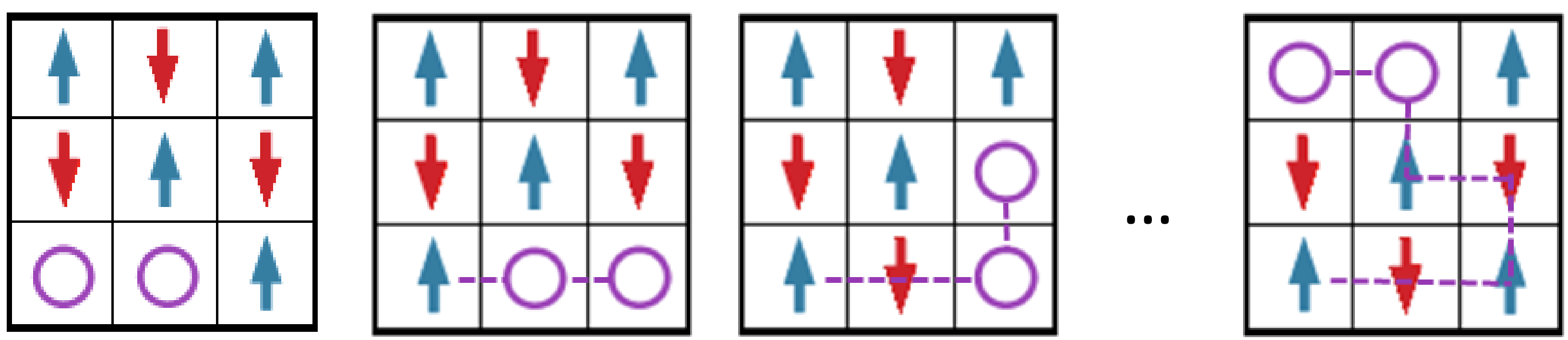
Theory: Carlström et. al. PRL **116**, 247202 (2016)

Outlook: hole dynamics

Single Hole in 2D, AFM background



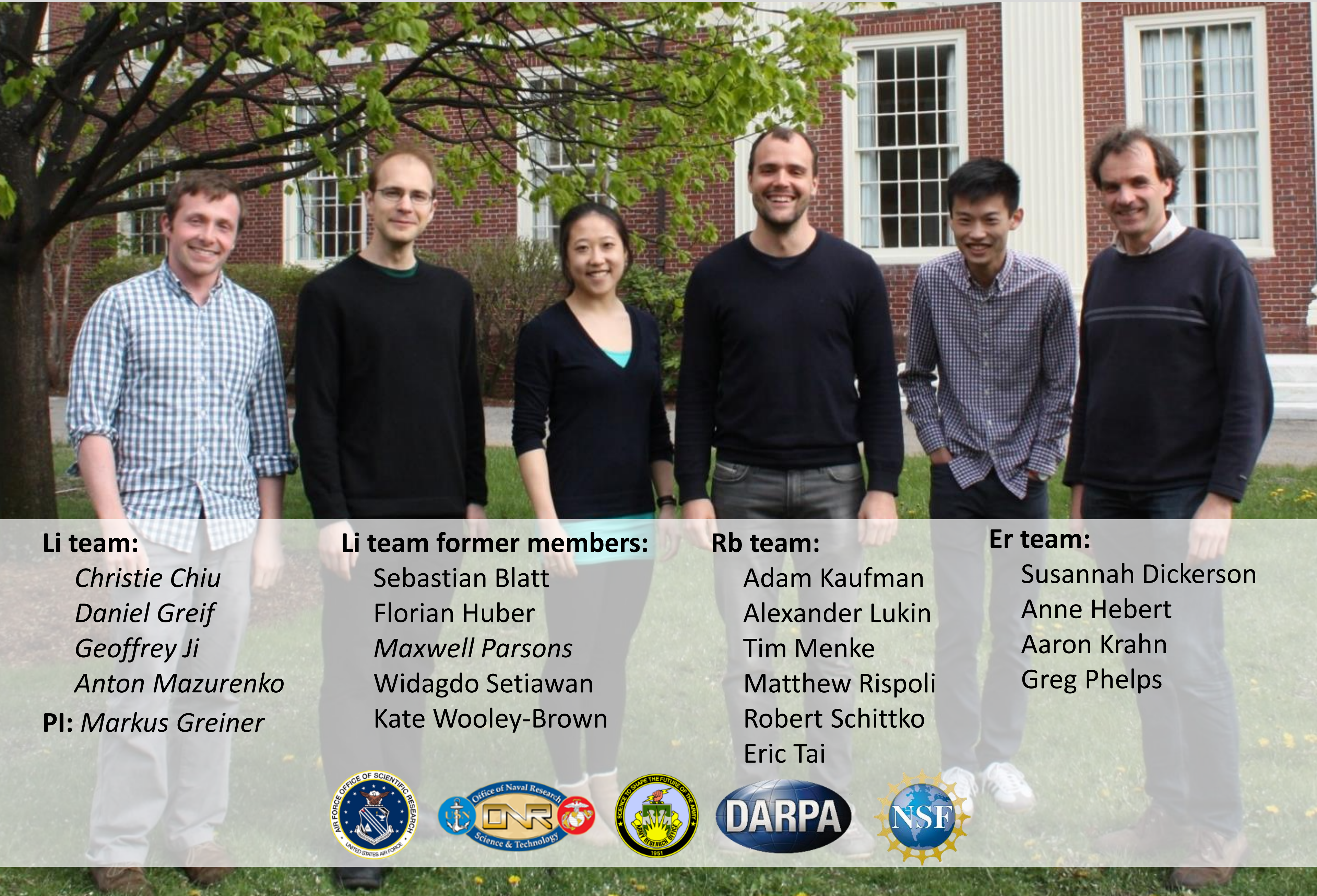
Two Holes in 2D, AFM background



Theory collaboration with Eugene Demler, Fabian Grusdt,
Annabelle Bohrdt, Marton Kanasz-Nagy, Michael Knap

Theory: Carlström et. al. PRL **116**, 247202 (2016)

Thank you



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