Quantum gas microscopy of atomic Fermi-Hubbard systems

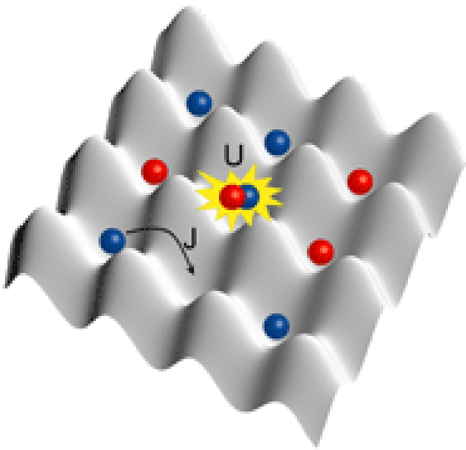
Waseem Bakr

ECT workshop*

June 2018

PRINCETON UNIVERSITY

The Fermi-Hubbard model

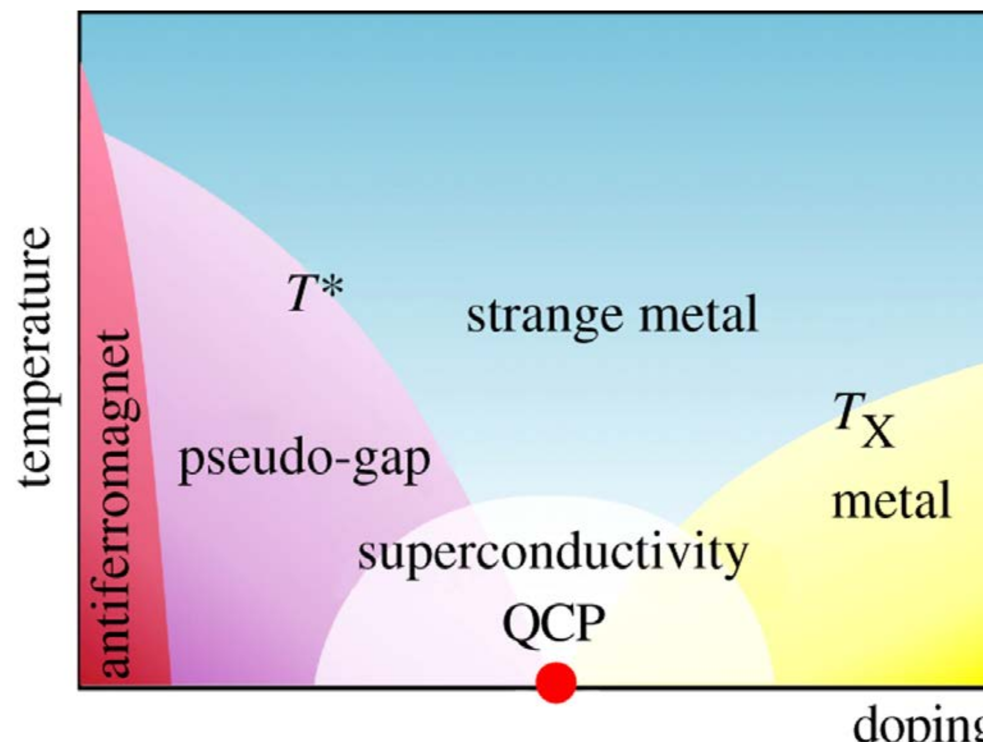


$$\mathcal{H} = -t \sum_{\langle ij \rangle, \sigma} \left(c_{i,\sigma}^{\dagger} c_{j,\sigma} + c_{j,\sigma}^{\dagger} c_{i,\sigma} \right) + U \sum_{i} n_{i,\uparrow} n_{i,\downarrow}$$

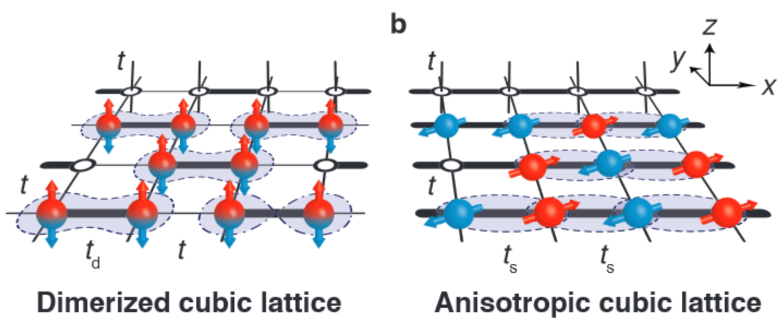
Realized naturally with cold atoms in optical lattices with fully tunable parameters.

Potentially rich phase diagram:

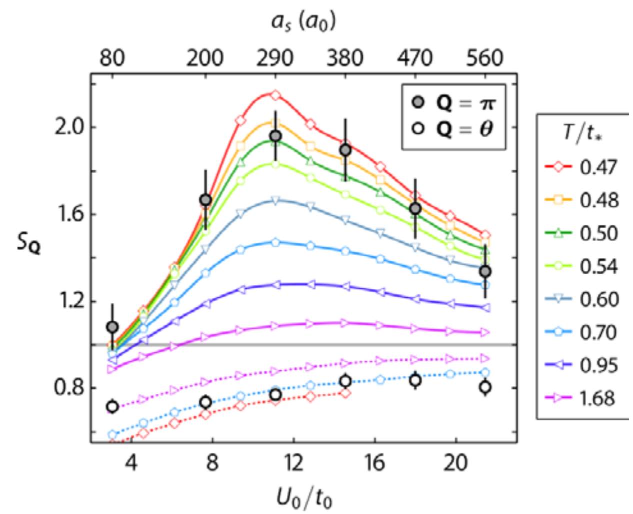
commensurate/incommensurate AFM, pseudogap, strange metal, d-wave superconductivity…



Antiferromagnetic correlations

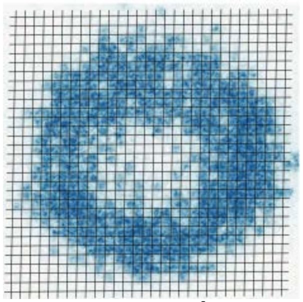


Esslinger
Science 340, 1307 (2013)

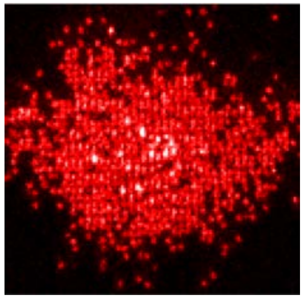


Hulet
Nature 519, 211 (2015)

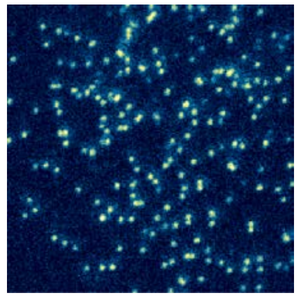
Fermion microscopes



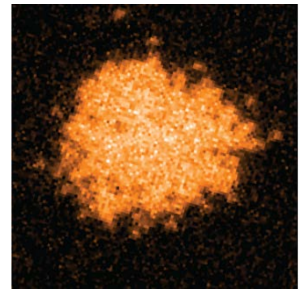
Harvard



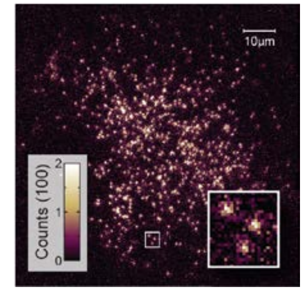
MIT



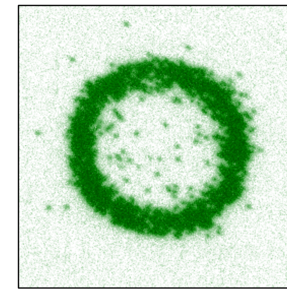
Strathclyde



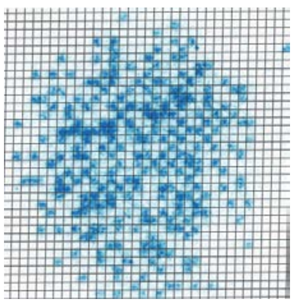
MIT



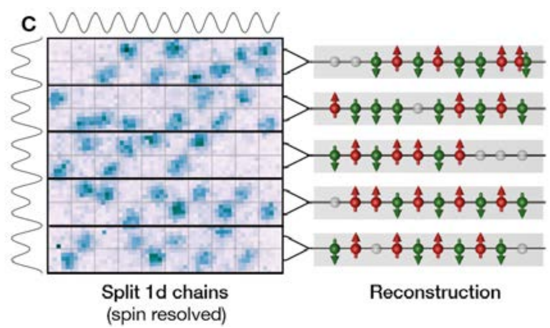
Toronto



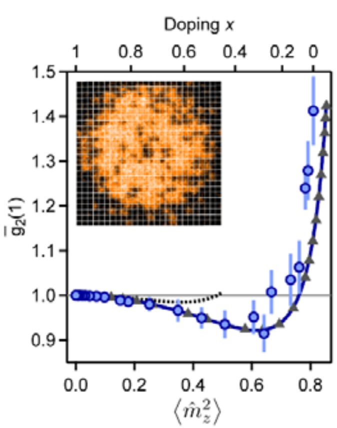
Princeton



Greiner (2D)
Science 353, 1253
(2016)



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

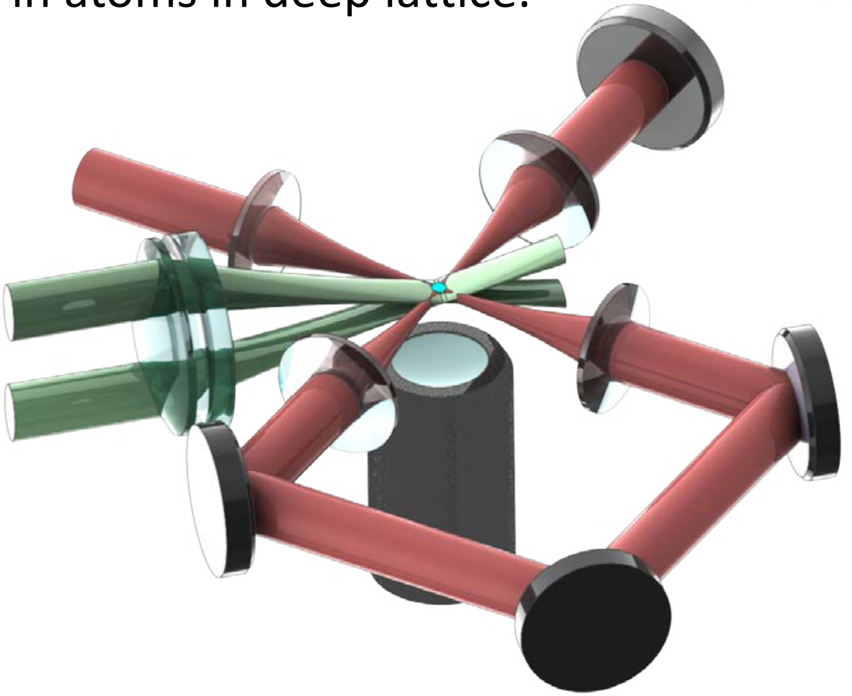


Zwierlein (2D)
Science 353, 1260 (2016)

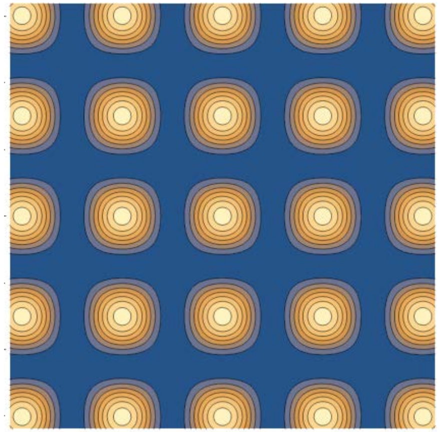
AFM correlations without site-resolved microscopy:
Köhl (2D)
PRL 118, 170401 (2017)

Princeton Fermi gas microscope

- Prepare a single layer 2D Fermi gas of lithium-6.
- Adiabatically load into 2D square lattice.
- Pin in atoms in deep lattice.



Lattice spacing: 752 nm



Relatively “low” NA objective (NA = 0.5)

Lithium helps: light, good Feshbach resonances

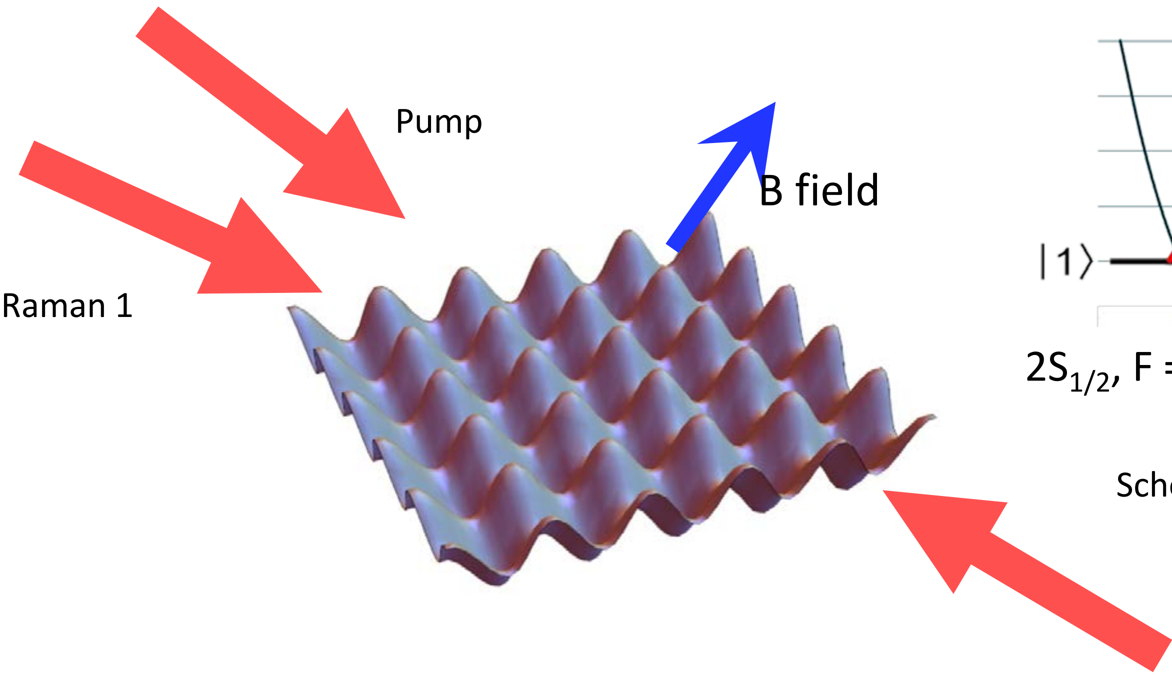
-> large lattice spacings okay.

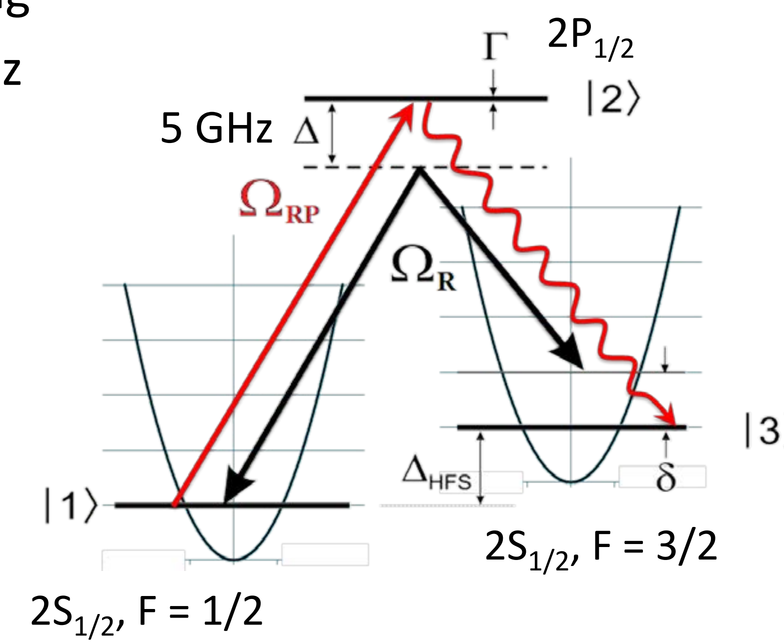
Princeton Fermi gas microscope

- Raman cooling for fluorescence imaging

  In-plane lattice frequency: 1.5 MHz

  Axial confinement: 0.1 MHz





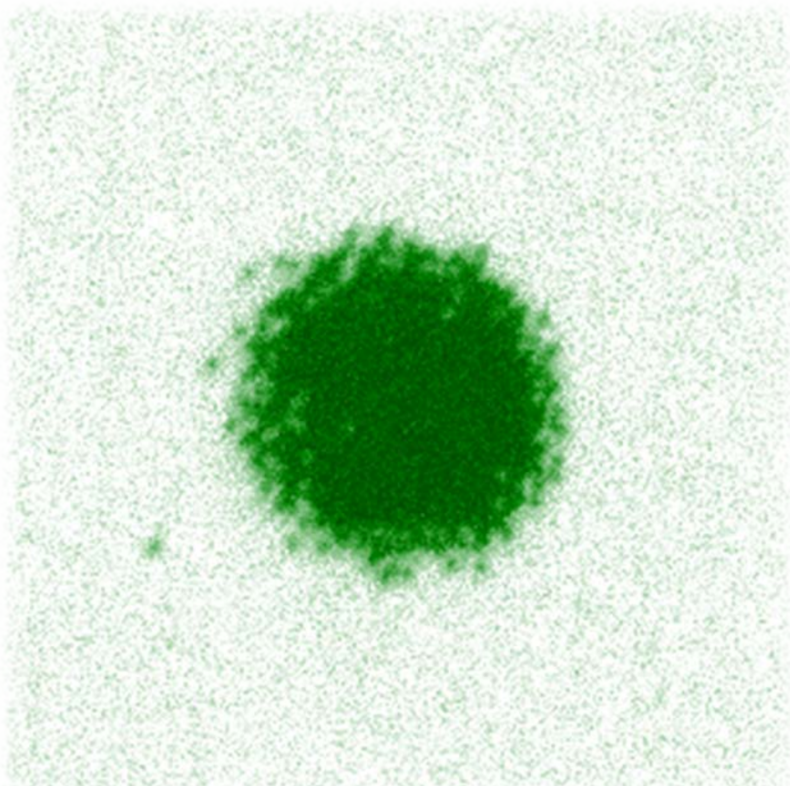
Scheme very similar to:

Parsons et *al.*, Science **353**, 1253 (2016)
Boll et *al.*, Science **353**, 1257 (2016)

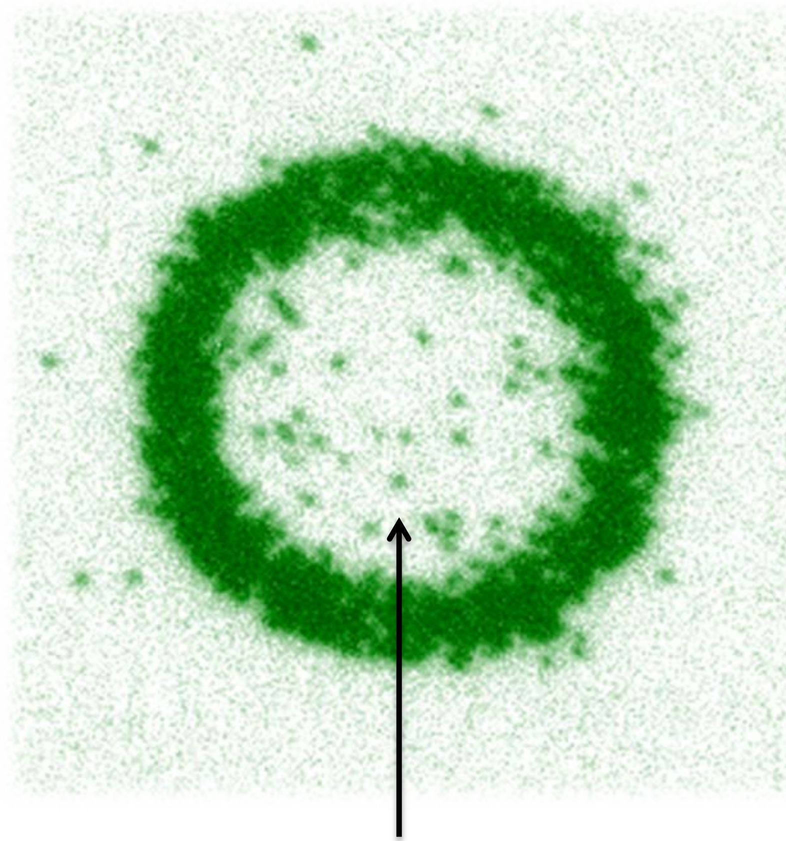
Detect 1000 photons/atom in 1.2s
Hopping: 0.4%, loss: 1.6%

Raman 2

Repulsive Hubbard model: Mott insulators and band insulators



Mott insulator



Band insulator
(in presence of light assisted collisions)

Spin-imbalance in a 2D Fermi-Hubbard system

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

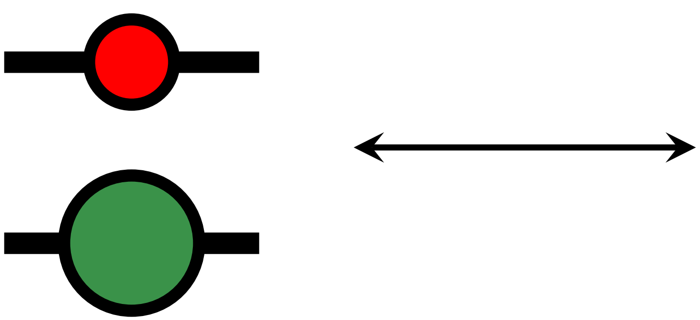
Spin imbalance

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

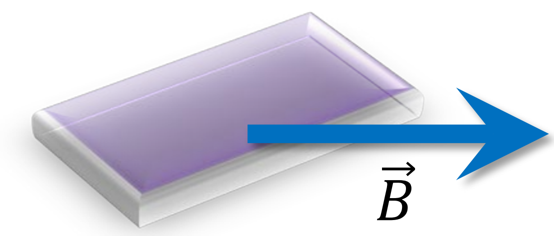
Cold atoms:

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

No spin-relaxation.



Spin-polarization



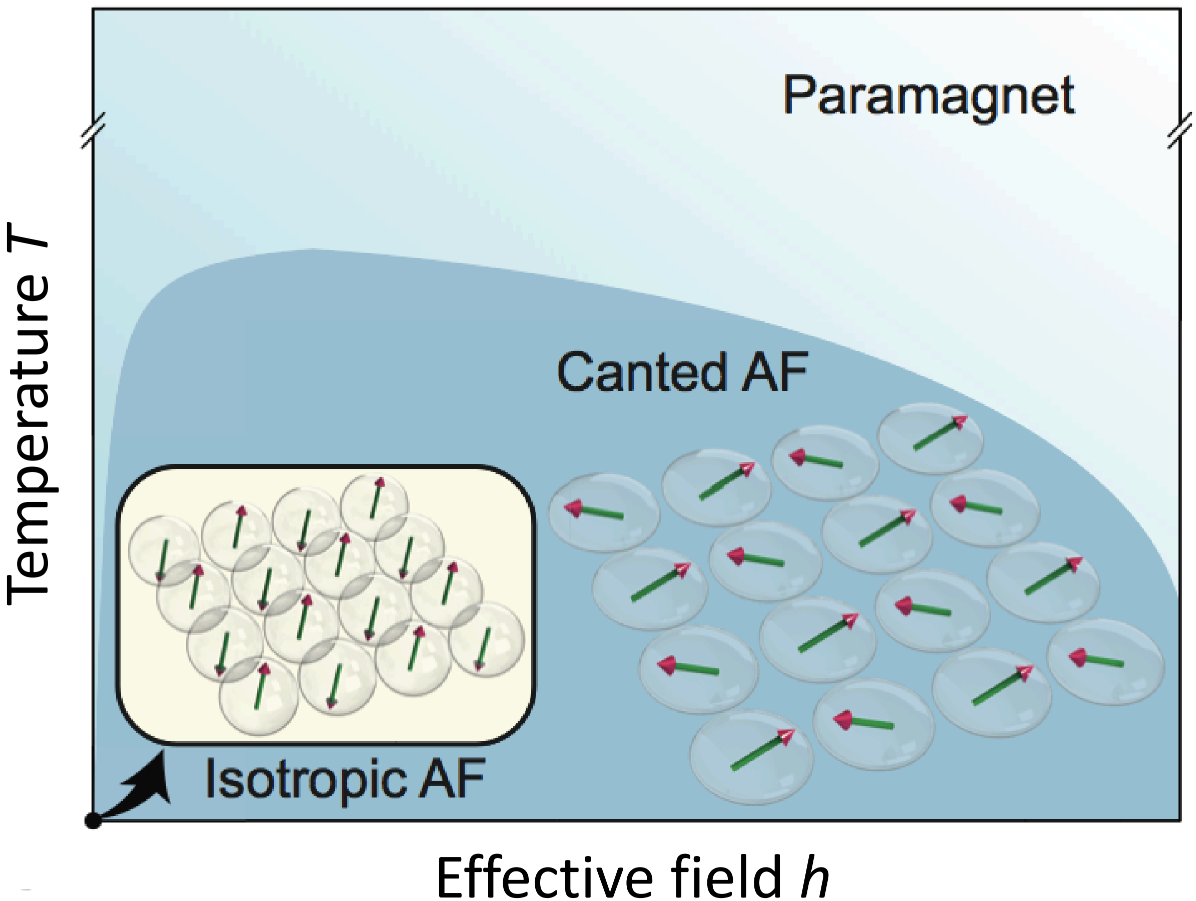
Zeeman field

Spin-imbalance at half-filling

Heisenberg model in an effective field

$$\mathcal{H} = J \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j - 2h \sum_i S_i^z$$

$$h = (\mu_\uparrow - \mu_\downarrow)/2$$

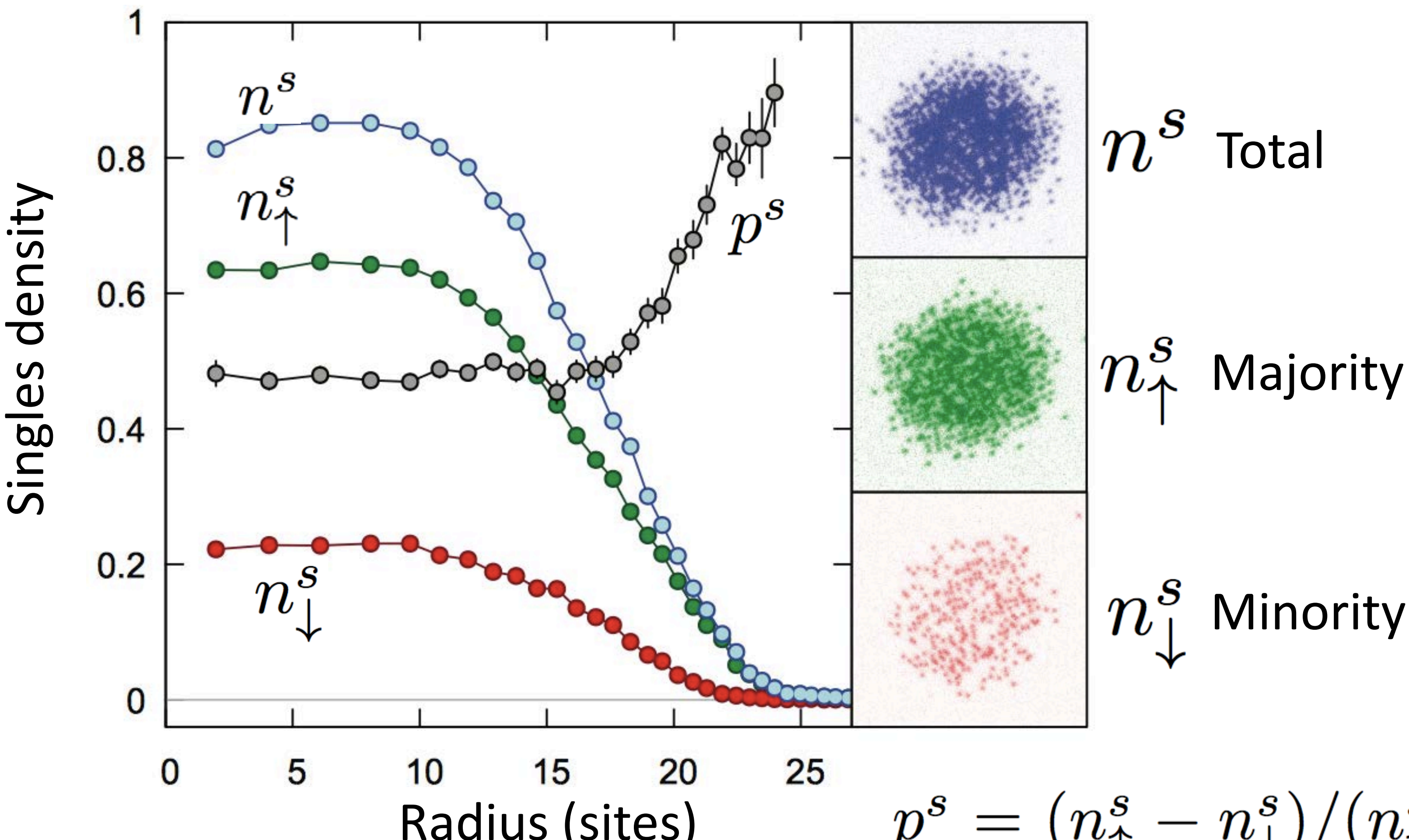


$h = 0$:
SU(2) symmetric AFM
Exponentially decaying correlations, diverging correlation length at $T = 0$

$|h| > 0$:
BKT-transition to canted AFM

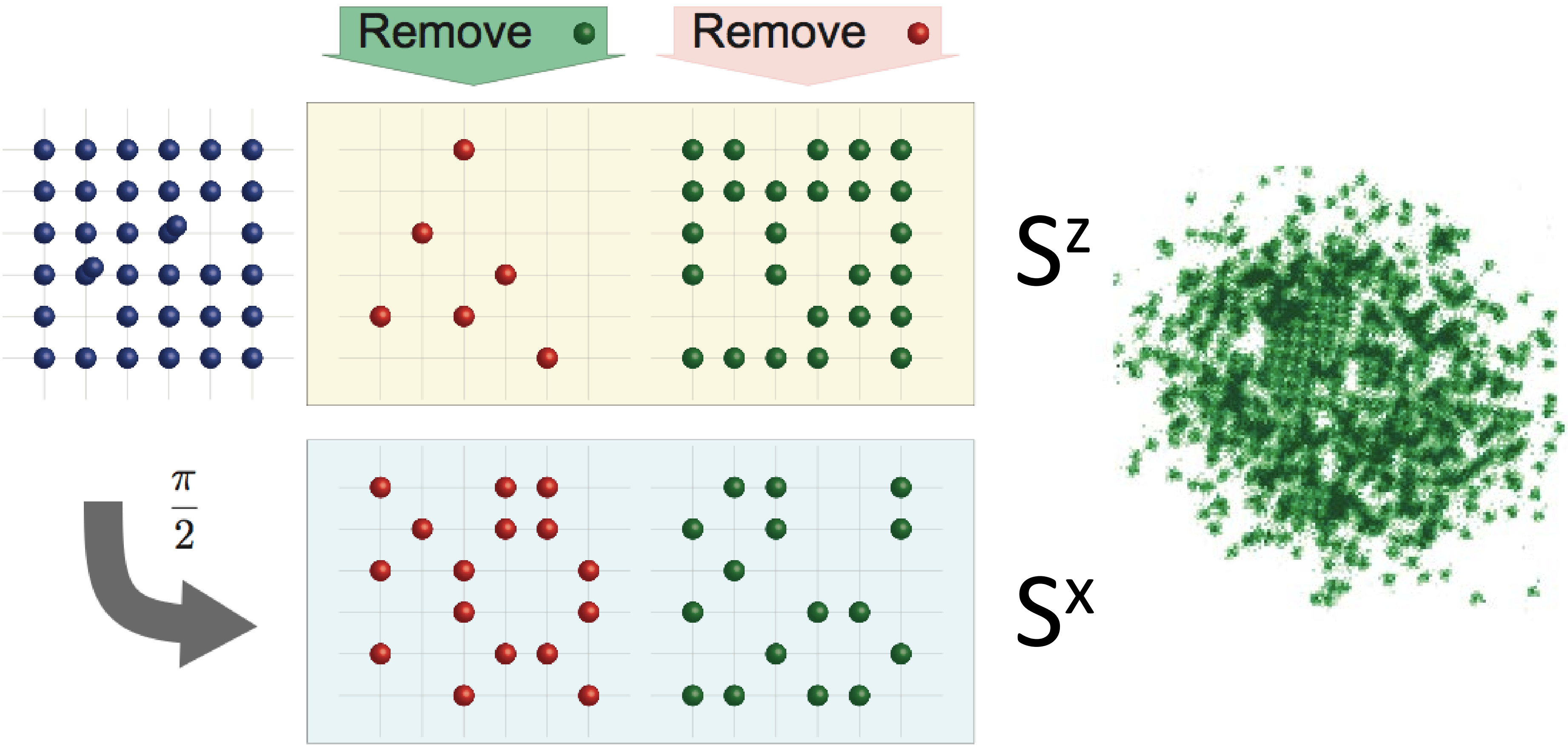
AFM correlations build up preferably in XY plane.

Spin-imbalanced Mott insulators

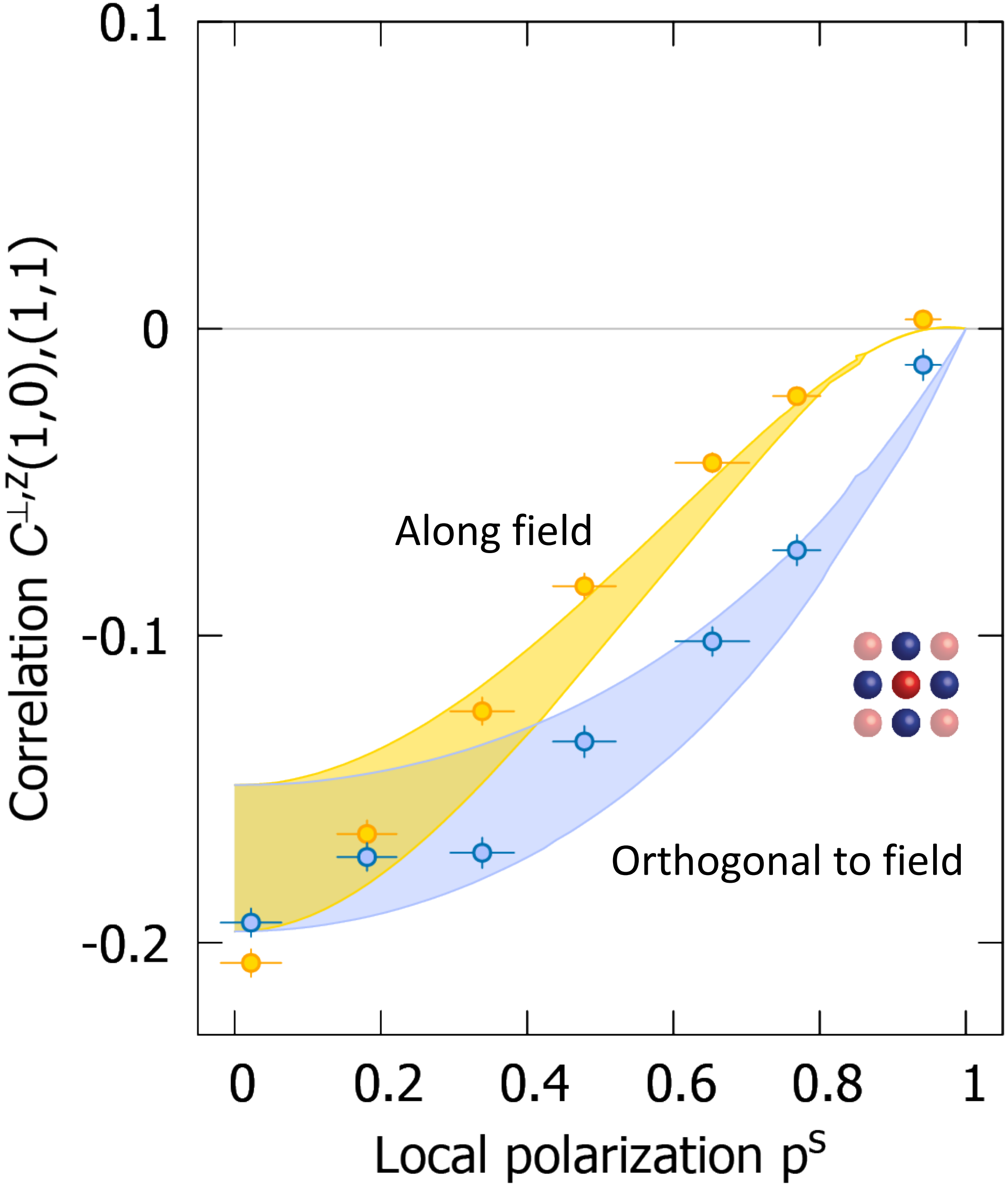


$$p^s = (n^s_\uparrow - n^s_\downarrow)/(n^s_\uparrow + n^s_\downarrow)$$

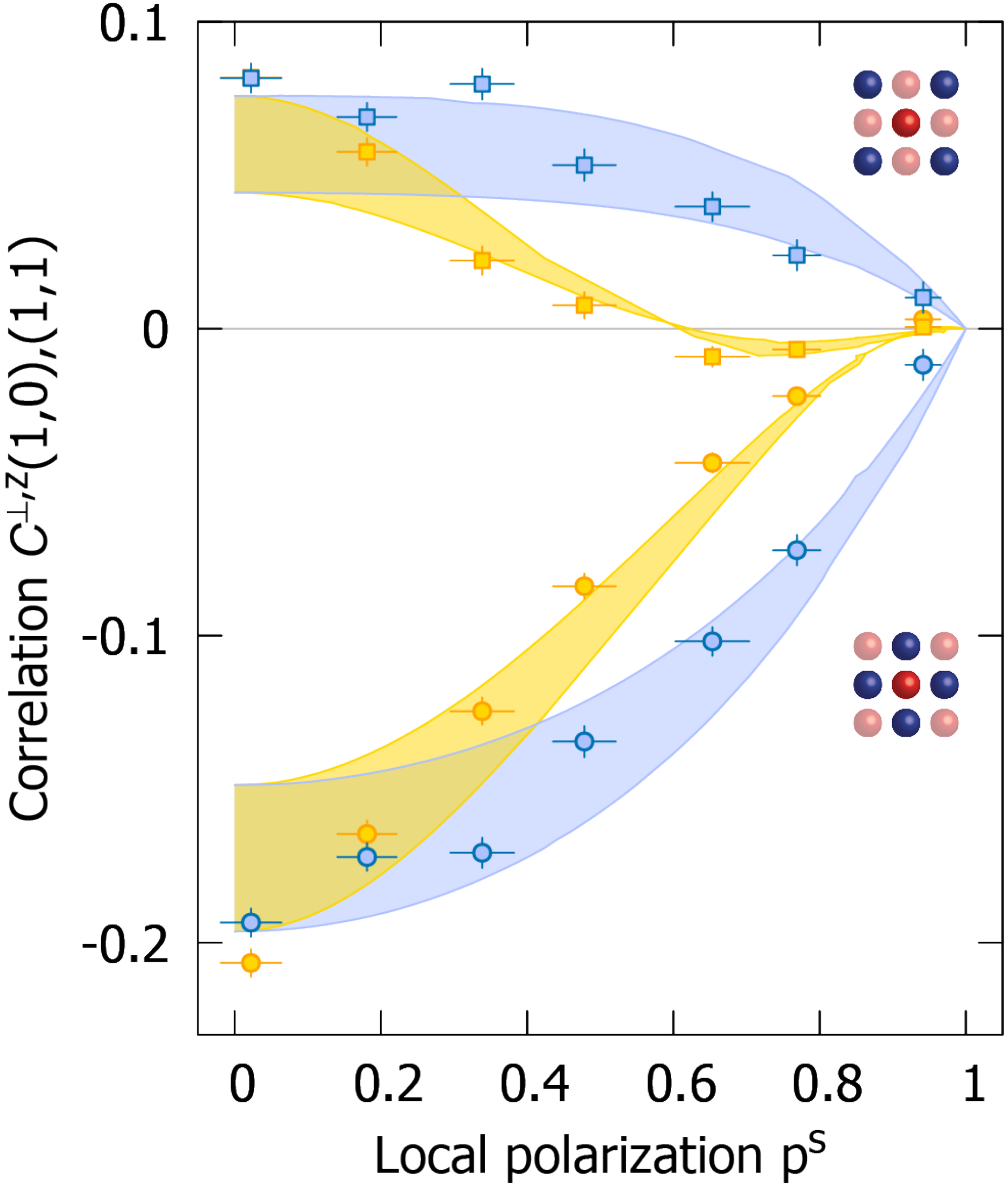
Probing spin-imbalanced lattice gases



Nearest-neighbor spin correlations



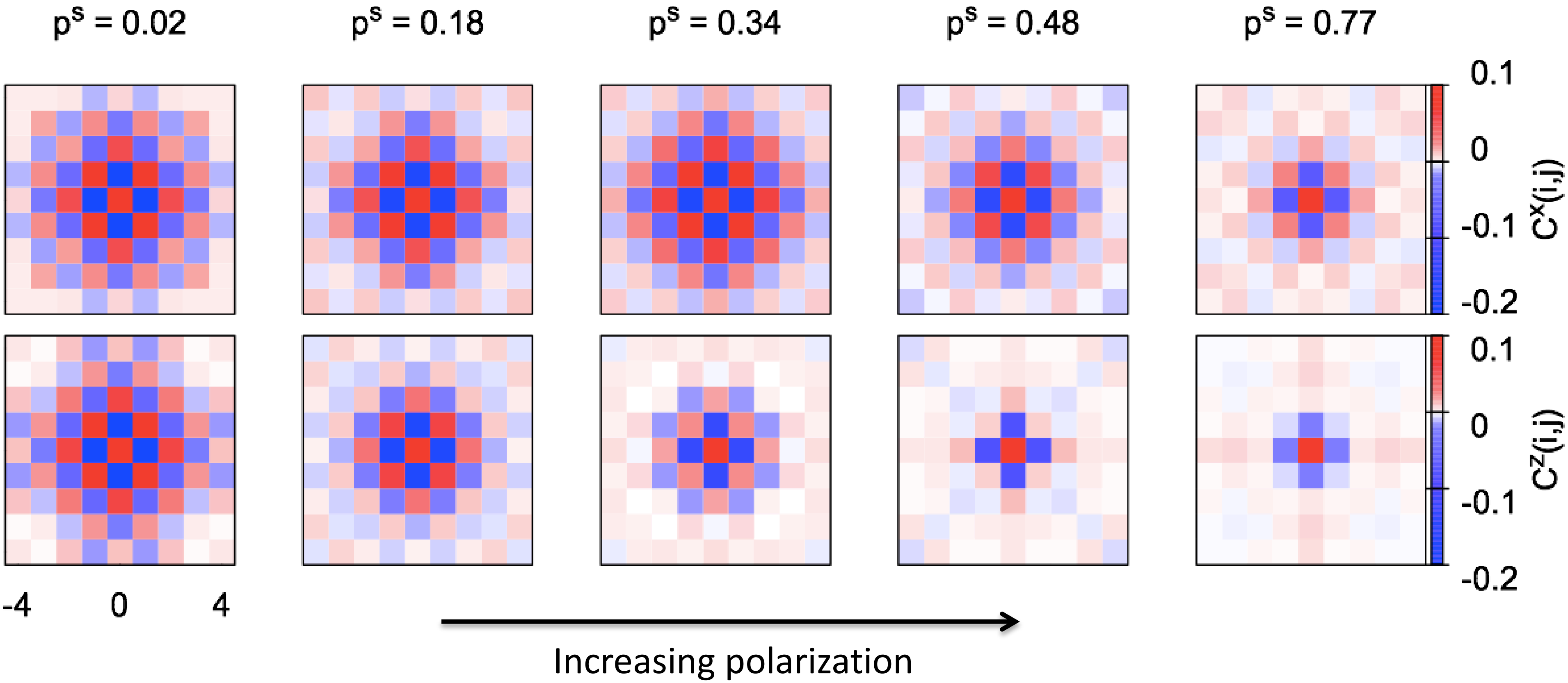
Next-nearest neighbor spin correlations



QMC & NLC comparison:

T/t increases from 0.4 to 0.57.

Correlations at larger distances



Unpolarized gas: isotropic spin correlations

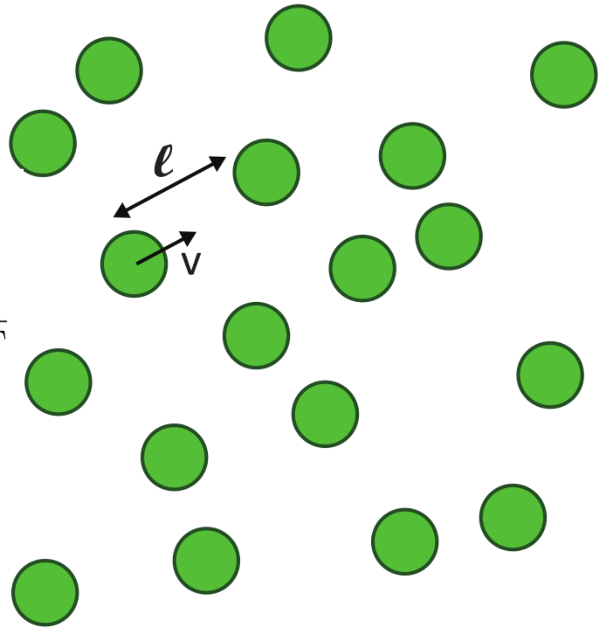
Polarized gas: AFM correlations preferred in the plane

Bad metallic transport in a cold atom Fermi-Hubbard system

Transport

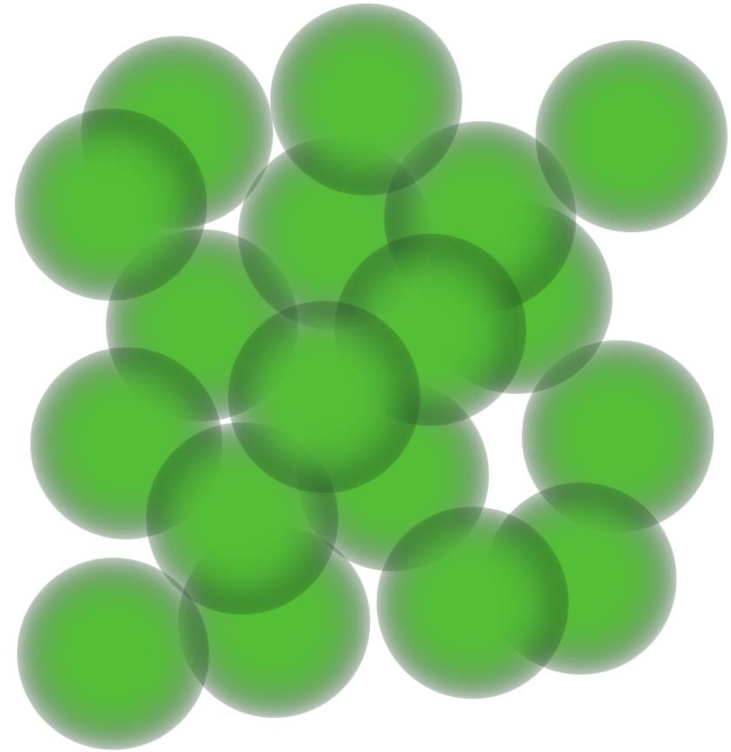
Conventional
(weakly interacting)

$$\Gamma = \frac{\langle v \rangle}{l}$$
$$\frac{1}{\rho} = \frac{ne^2}{m^*\Gamma}$$



- Charge, spin, energy transported by quasiparticles.
- Mean free path must be larger than lattice spacing
  Mott-Ioffe-Regel limit (MIR)
- Fermi liquid prediction $\rho \propto T^2$

Unconventional
(strongly correlated)



- Strong enough interactions destroy quasiparticles.
- Momentum relaxation no longer gives resistivity.
- “Bad metals” violate MIR limit and commonly exhibit $\rho \propto T$

Previous Work

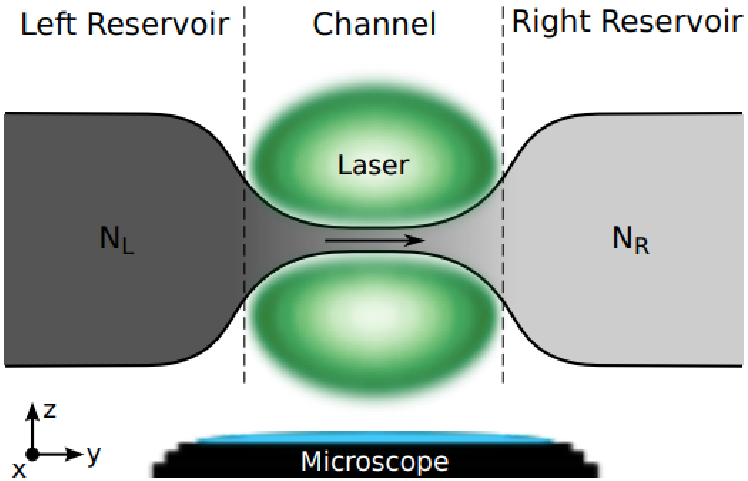
Mass transport experiments with Fermions

Mesoscopic systems:

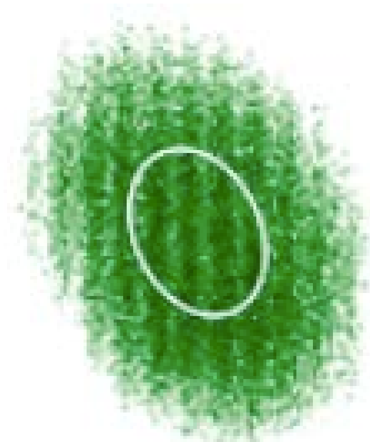
Brantut *et al.* Science **337**, 1069 (2012) (ETH Zurich)
...
Lebrat *et al.* PRX **8**, 011053 (2018) (ETH Zurich)
Valtolina *et al.* Science **350**, 1505 (2015) (Florence)

Bulk systems:

Ott *et al.* PRL **92**, 160601 (2004) (Florence)
Strohmaier *et al.* PRL **99**, 220601 (2007) (ETH Zurich)
Schnedier *et al.* Nat. Phys **8**, 213 (2012) (Munich)
Xu *et al.* arXiv:1606.06669 (2016) (UIUC)
Anderson *et al.* arXiv:1712.09965 (2017) (Toronto)



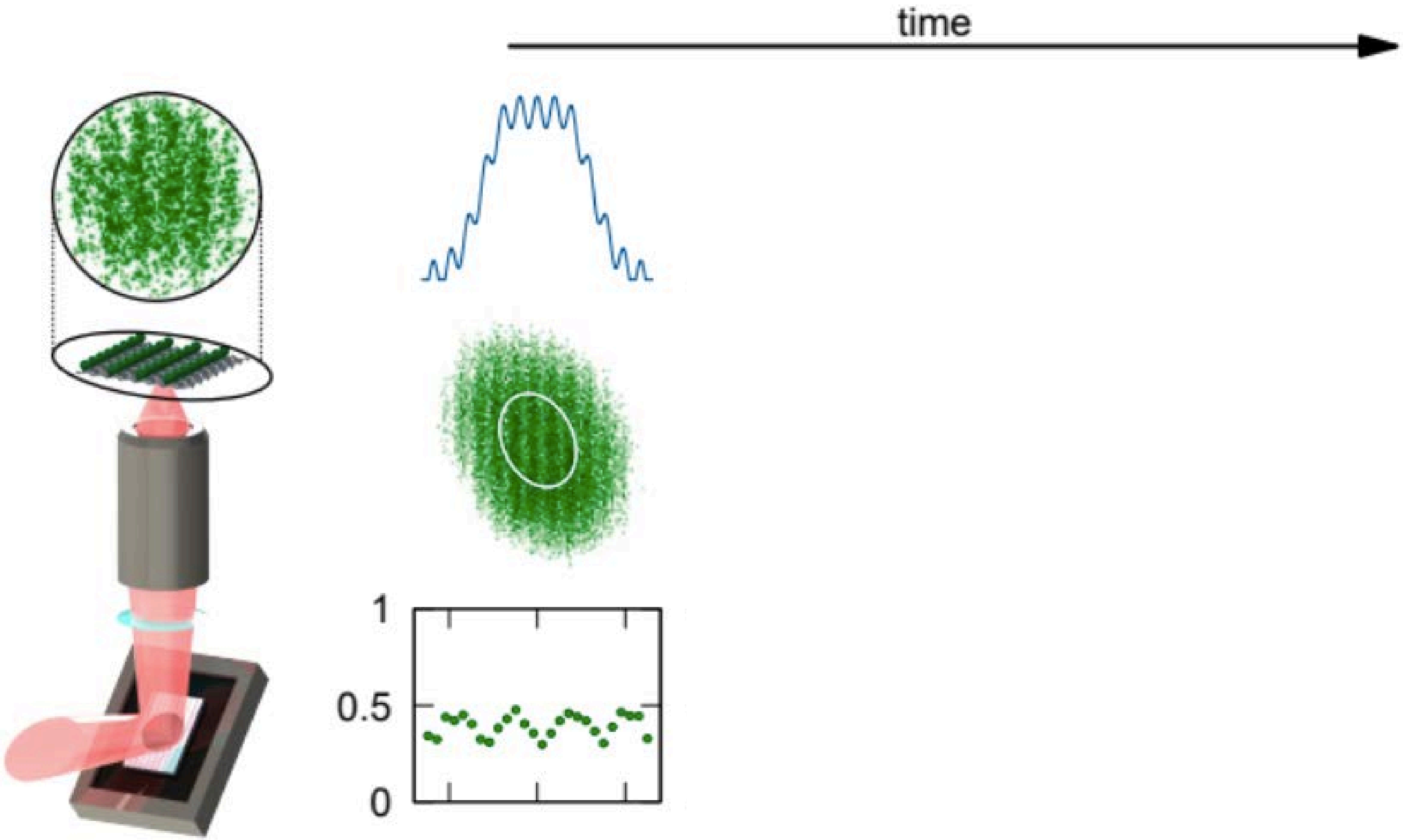
Esslinger group
e.g. Science 337, 1069 (2012)



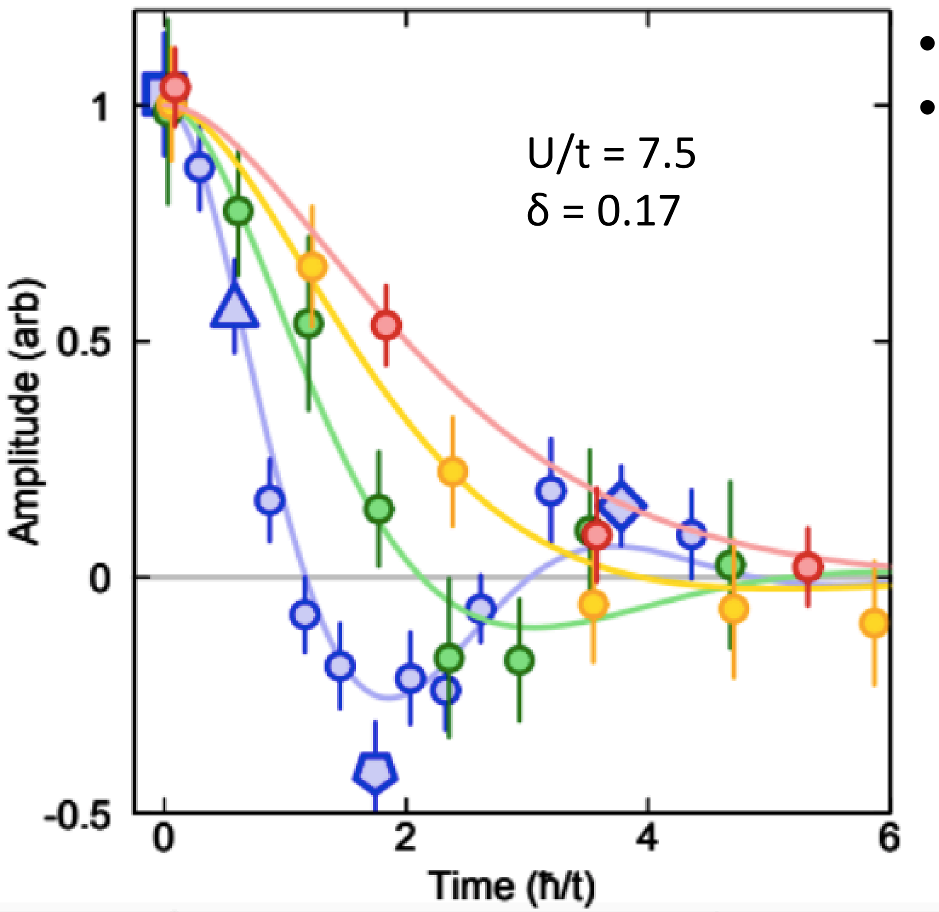
Extract diffusion constant *D* from decay of initial density modulation.

Nernst-Einstein relation: $\sigma = \chi_c D$

Measuring charge transport



Hydrodynamic model for charge transport



- Underdamped sound at short wavelengths.
- Exponential diffusive decay at long wavelengths.

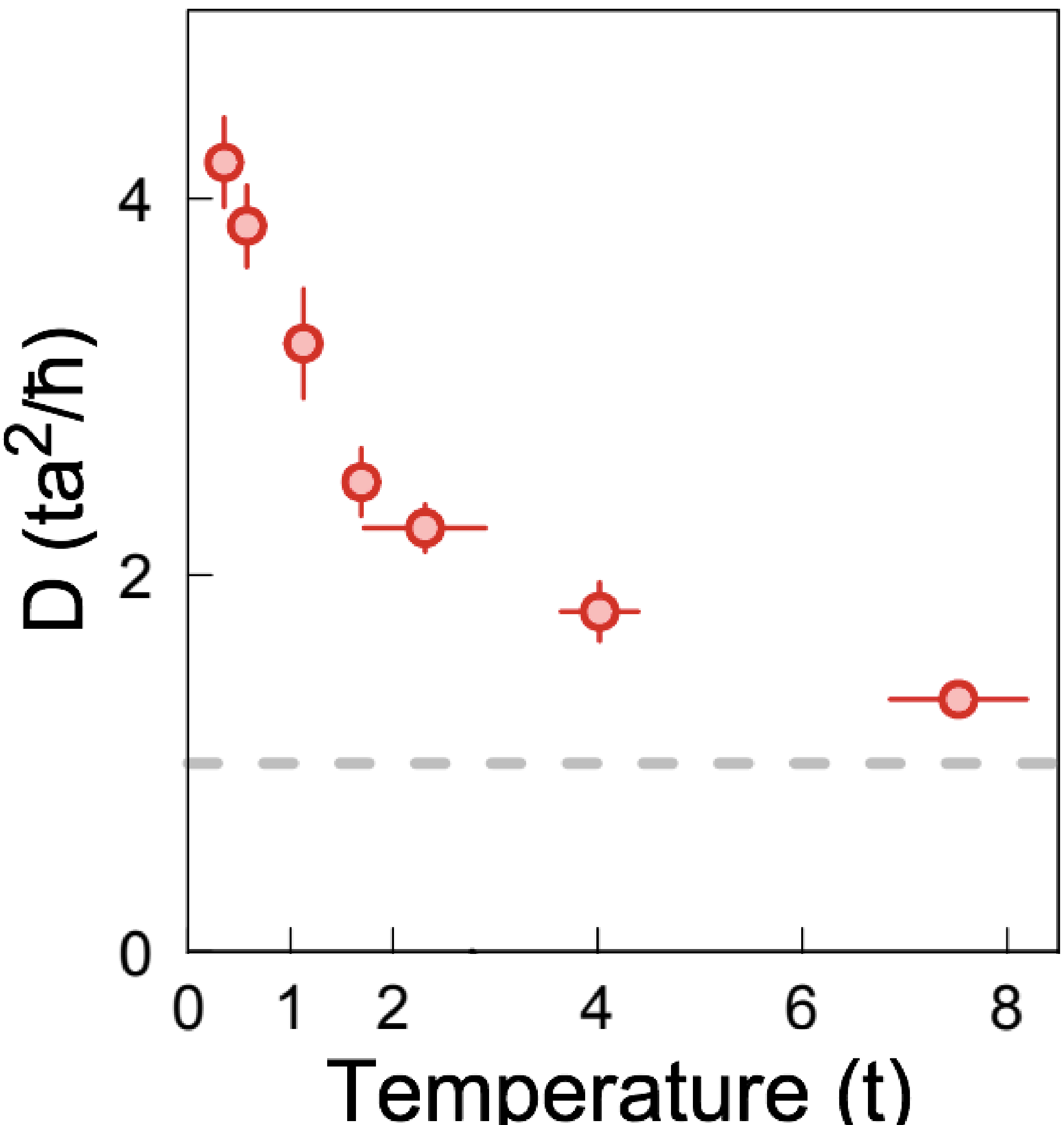
Charge conservation:

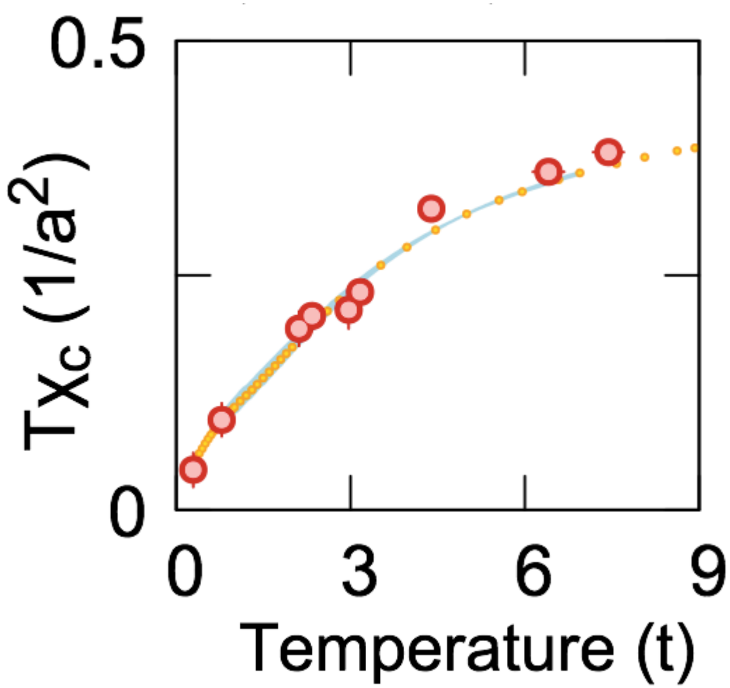
$$\partial_t n(\mathbf{r},t) + \nabla \cdot \mathbf{J}(\mathbf{r},t) = 0$$

Current relaxation (e.g. due to umklapp):

$$\partial_t \mathbf{J}(\mathbf{r},t) = -\Gamma\left(D\nabla n(\mathbf{r},t) + \mathbf{J}(\mathbf{r},t)\right)$$

Temperature dependence

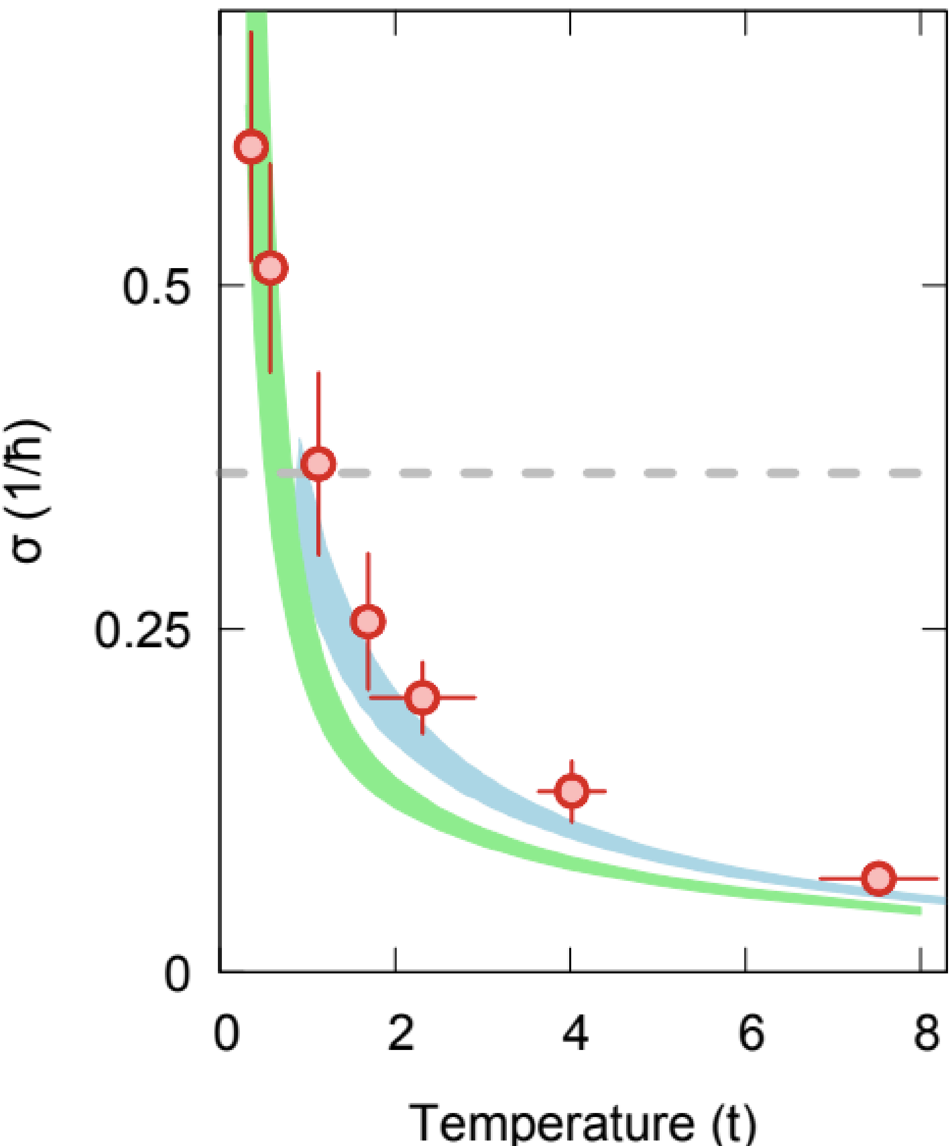


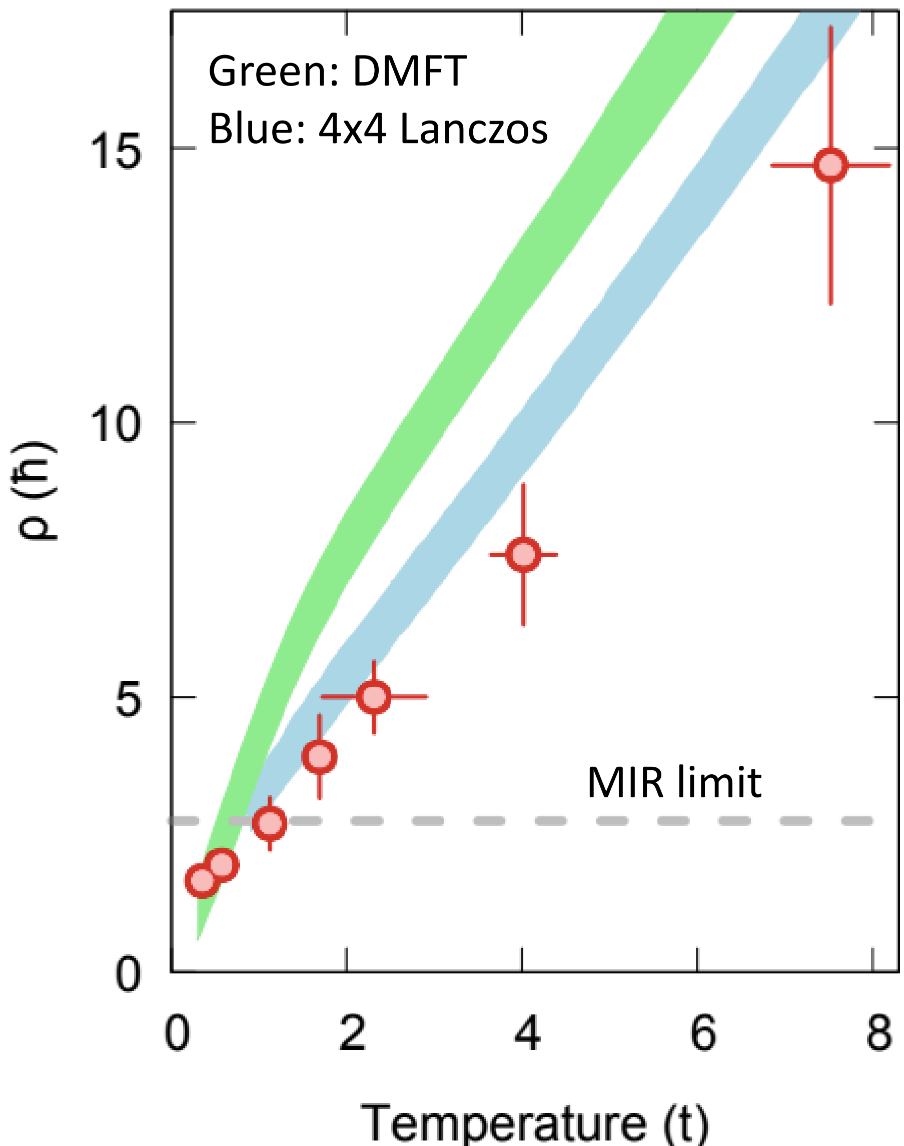


Both D and χ_c depend on temperature over accessible range of T.

χ_c is not in high temperature regime where it should go like $1/T$.

Bad metallic behavior





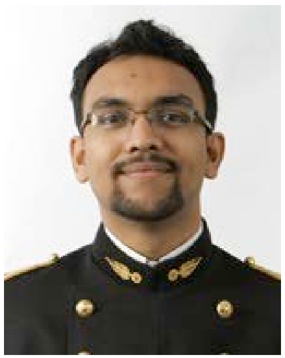
Conclusion: Equilibrium vs. dynamics

Exact numerical techniques well-developed for equilibrium systems: QMC, NLCE, etc.

State of the art Fermi-Hubbard experiments at $T/t = 0.25$-0.30 are just beyond reach of exact numerics.

Dynamics is much harder: Cold atom experiments can provide benchmarks for testing approximate techniques like DMFT.

Thanks



Debayan Mitra

Peter Brown

Stanimir Kondov (➔Columbia)

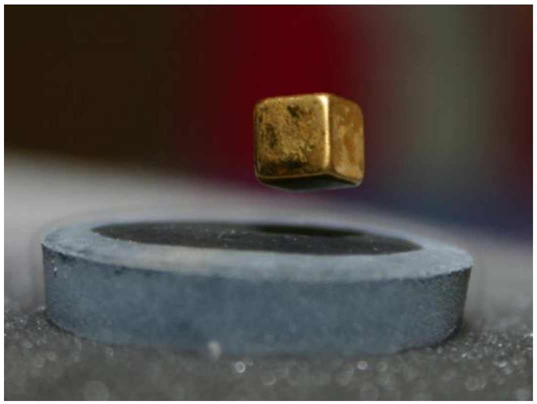
Peter Schauss

Elmer Guardado-Sanchez

Theory:

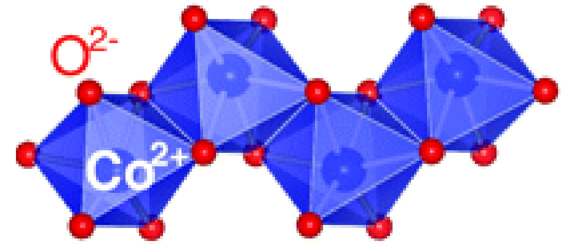
David Huse and Trithep Devakul, Princeton University
Nandini Trivedi, Ohio State University
Thereza Paiva, Universidade Federal do Rio de Janeiro
Ehsan Khatami, San José State University
Jure Kokalj, University of Ljubljana
Andre-Marie Tremblay, University of Sherbrooke

What kind of materials would we like to understand?

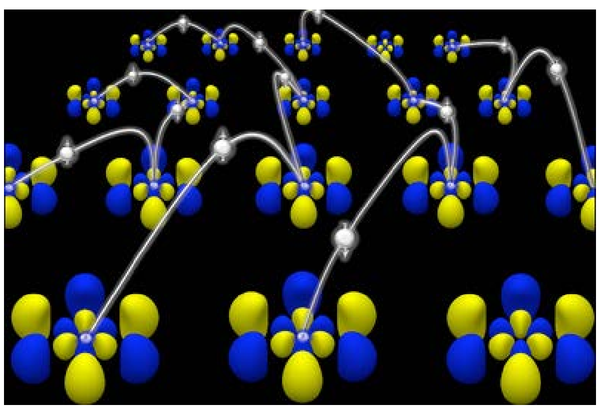


High T_c superconductors

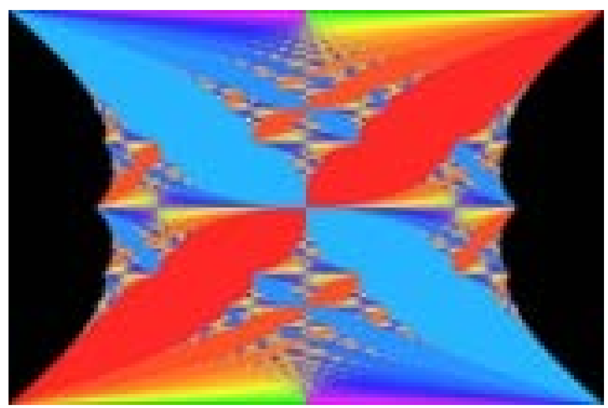
Strongly correlated materials



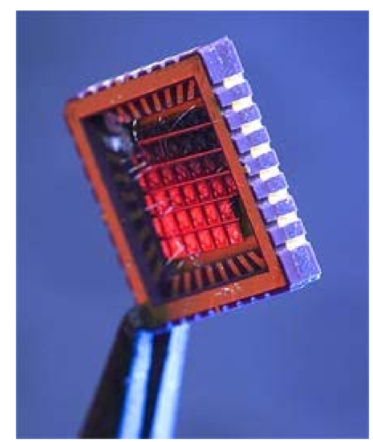
Quantum magnets



Heavy fermion metals

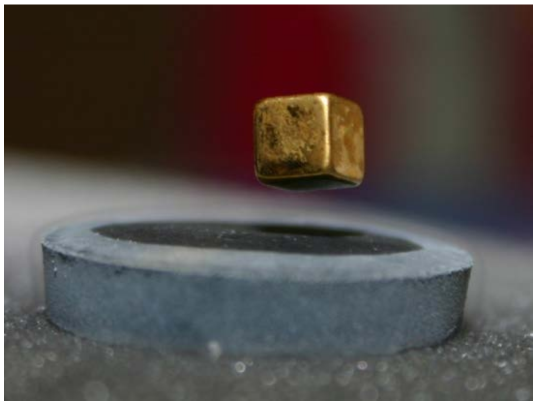


Topological phases



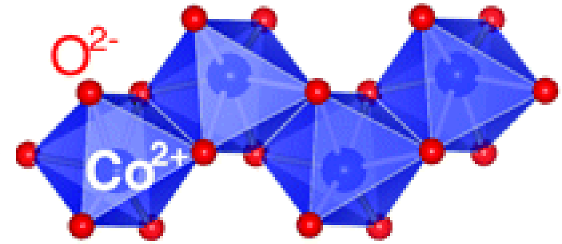
Spintronic materials

What kind of materials would we like to understand?



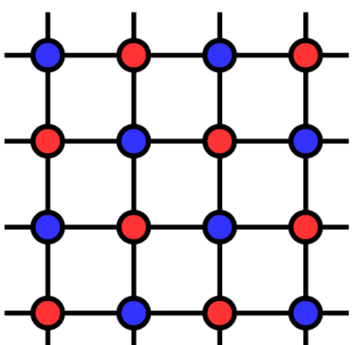
High T_c superconductors

Strongly correlated materials



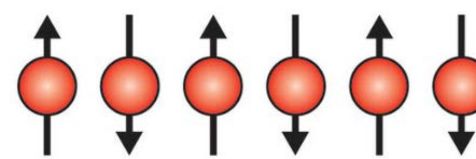
Quantum magnets

Hubbard model

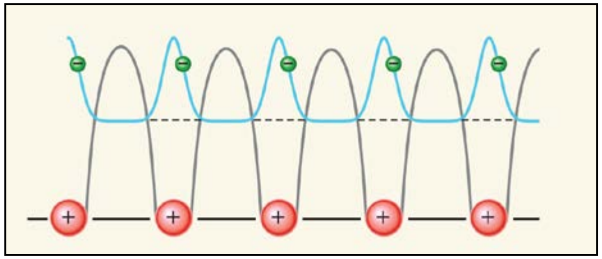


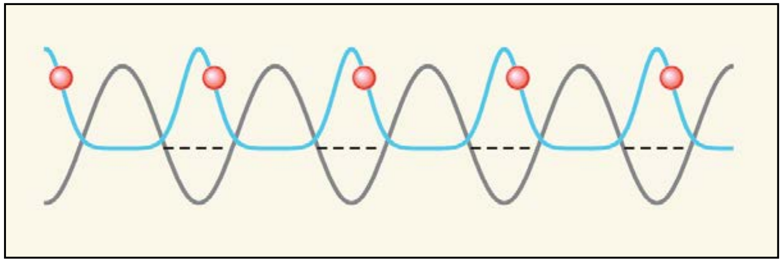
Condensed matter models

Quantum spin models (e.g. transverse Ising)



Interacting systems of ultracold atoms – enlarged model for condensed matter physics





Why ultracold atoms?

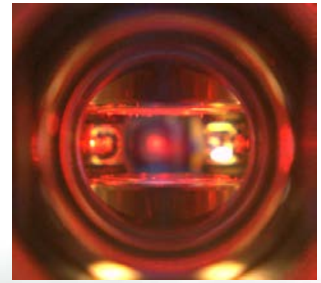
- Complete control of microscopic parameters
- Clean systems, no impurities
- Dynamics on observable timescales
- Understood from first principles
- Large interparticle spacing makes optical imaging/manipulation possible

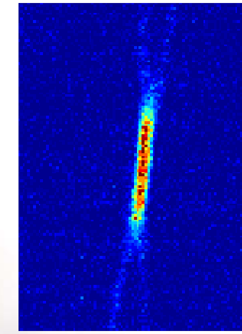
Theory comparison

$$\sigma_{\mathrm{reg}}(\omega) = \frac{e^2(1-\mathrm{e}^{-\beta\omega})}{N\omega}\mathrm{Re}\int_0^\infty dt\mathrm{e}^{i\omega t}\langle j_\alpha(t) j_\alpha(0)\rangle$$

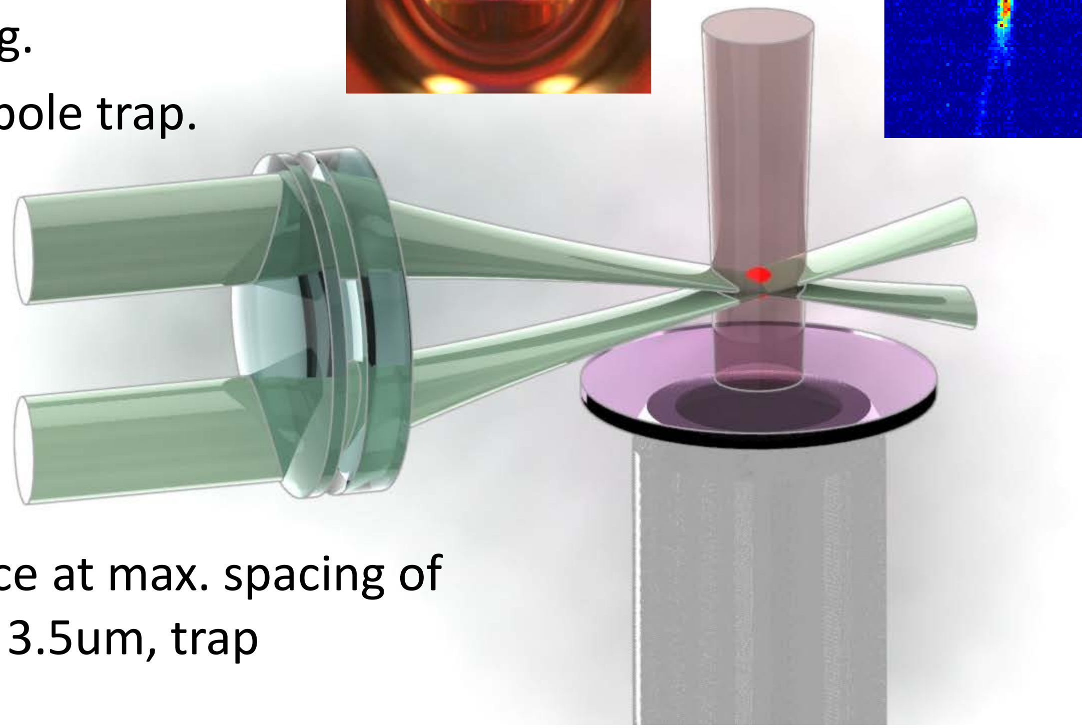
- Agrees well with finite-temperature Lanczos on 16 sites down to *T* = *t* where finite size effects start to matter (1 month runtime!)
- Reasonable agreement with single-site DMFT, but some discrepancies.

Princeton Fermi gas microscope

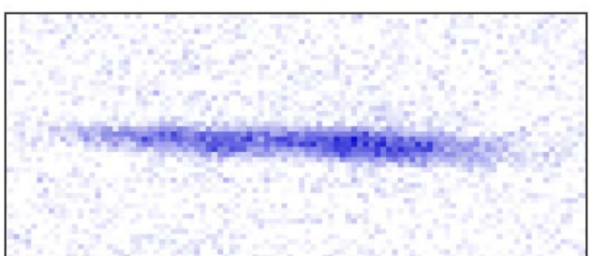


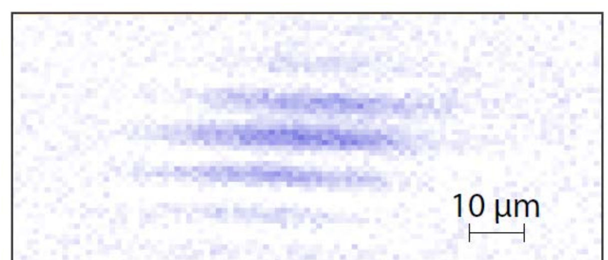


- ^{6}Li Oven + Zeeman slower
- Magneto-optical trapping.
- Evaporation in optical dipole trap.

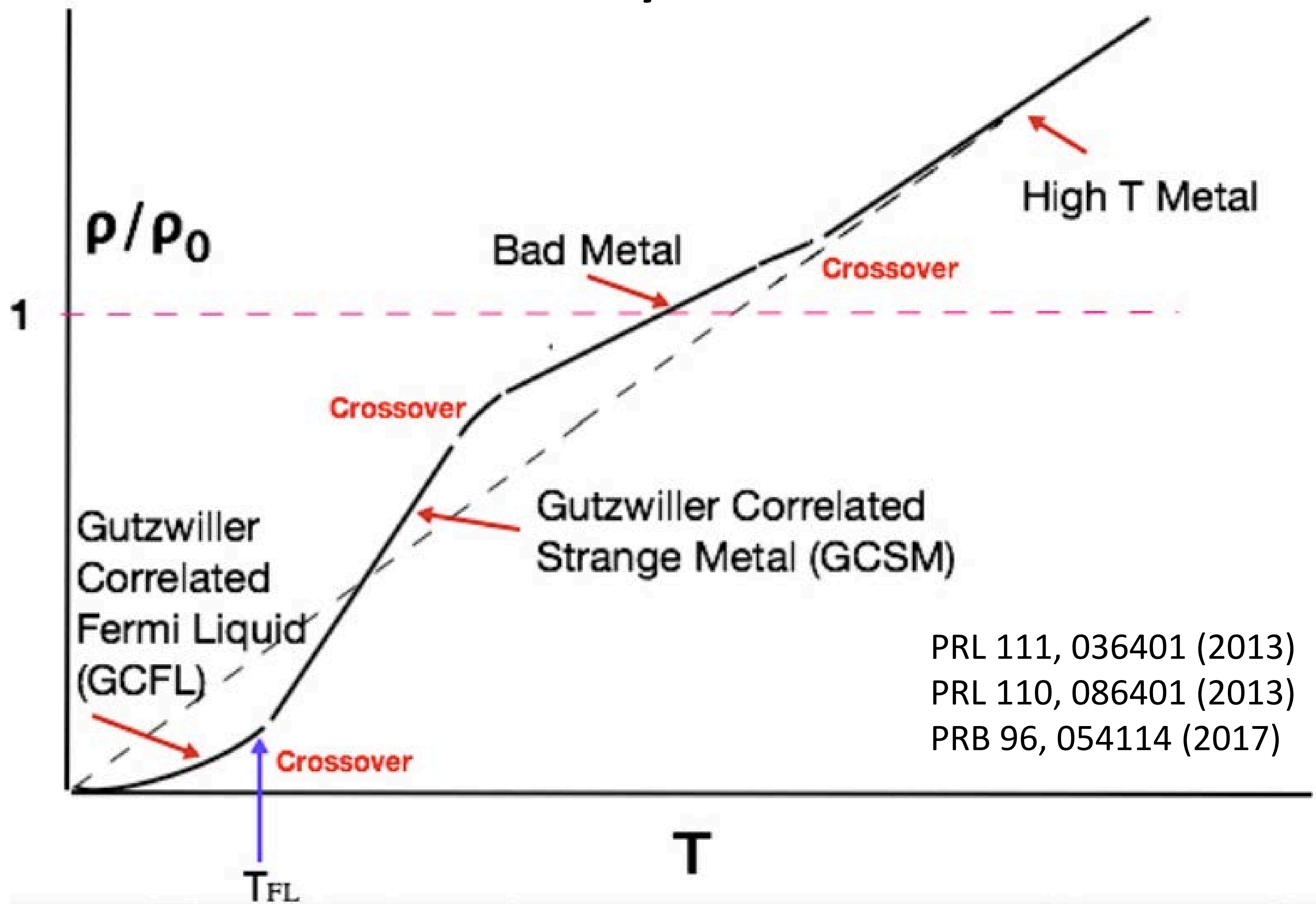


- Load into light sheet.
- Load into accordion lattice at max. spacing of 12um, then compress to 3.5um, trap frequency 20 kHz.





The DMFT picture from previous theory work

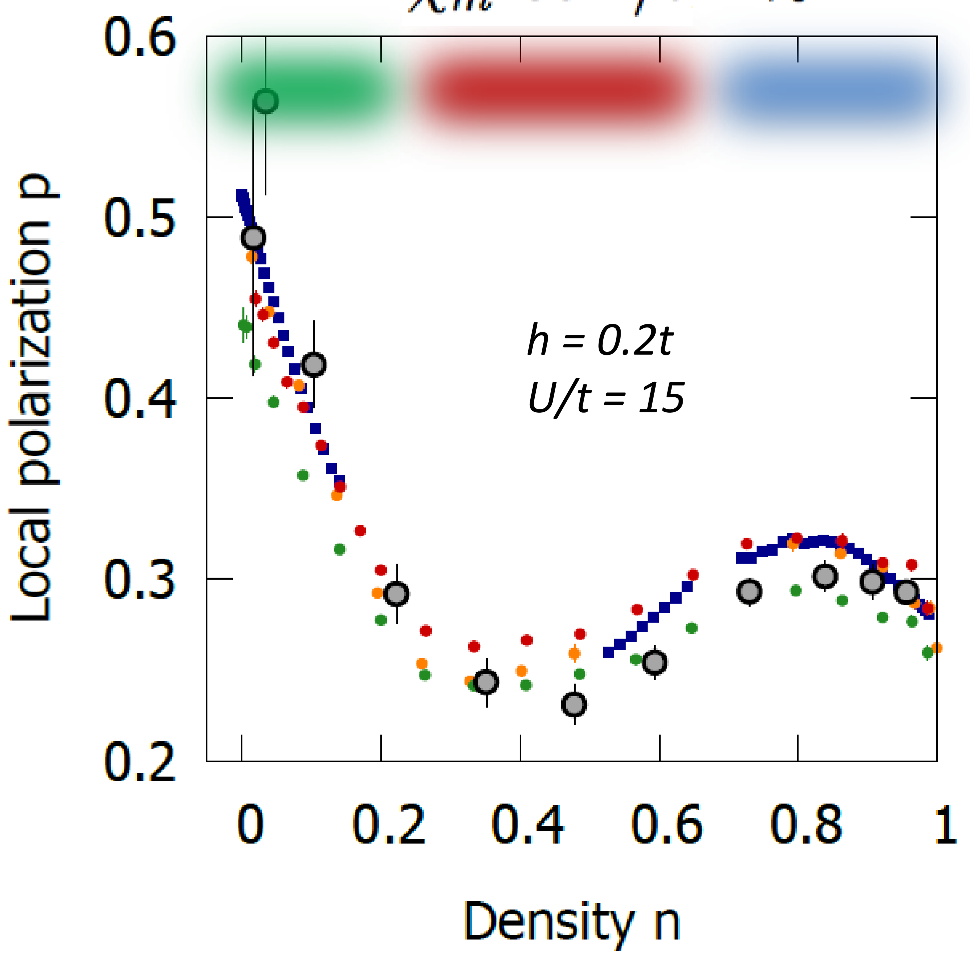


PRL 111, 036401 (2013)
PRL 110, 086401 (2013)
PRB 96, 054114 (2017)

Polarization profiles

non-degenerate gas | metallic region | AFM region

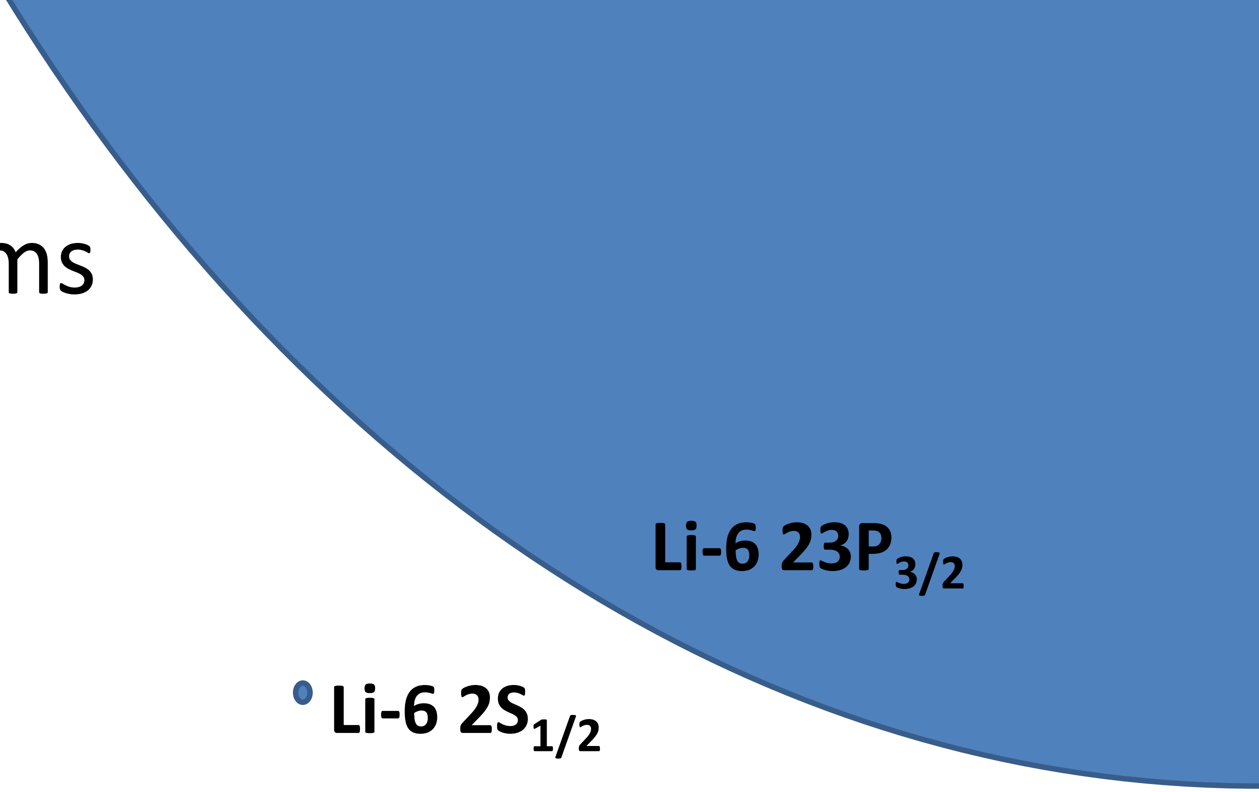
$\chi_m \propto 1/t$ $\quad$ $\chi_{AF} \propto 1/J = U/4t^2$



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

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

Rydberg atoms



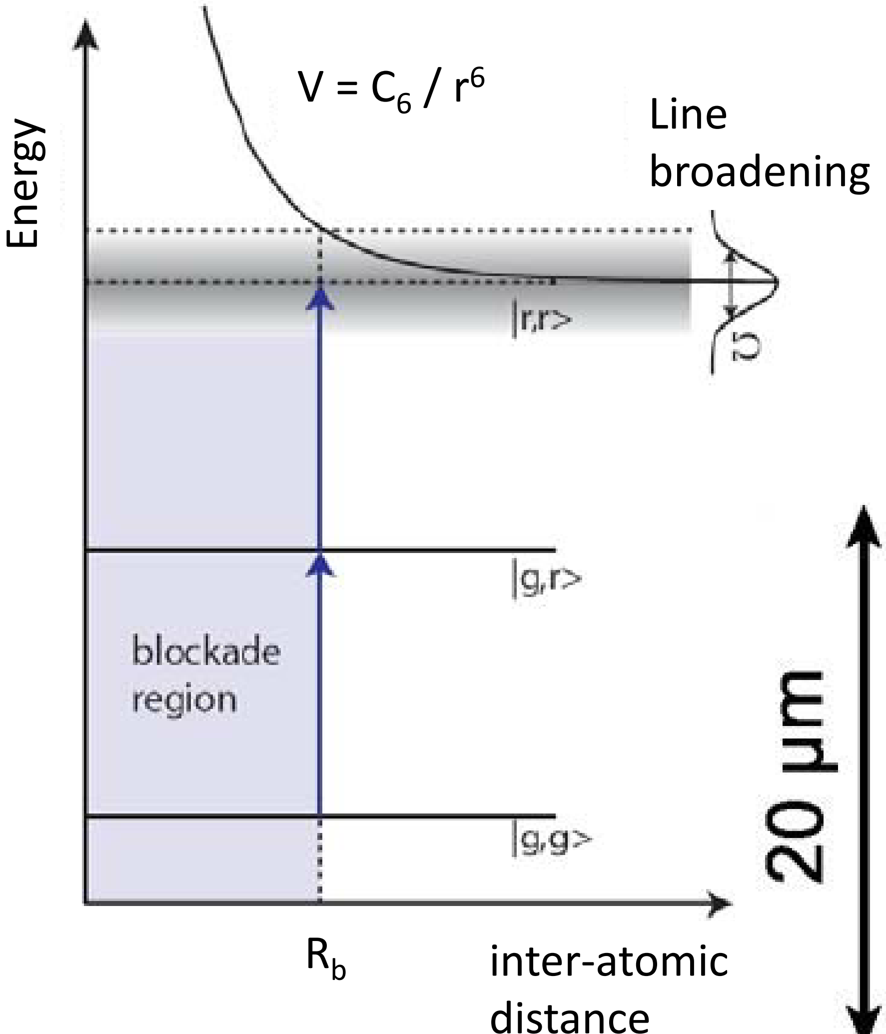
Hydrogen-like atoms with electron in a high n-state.

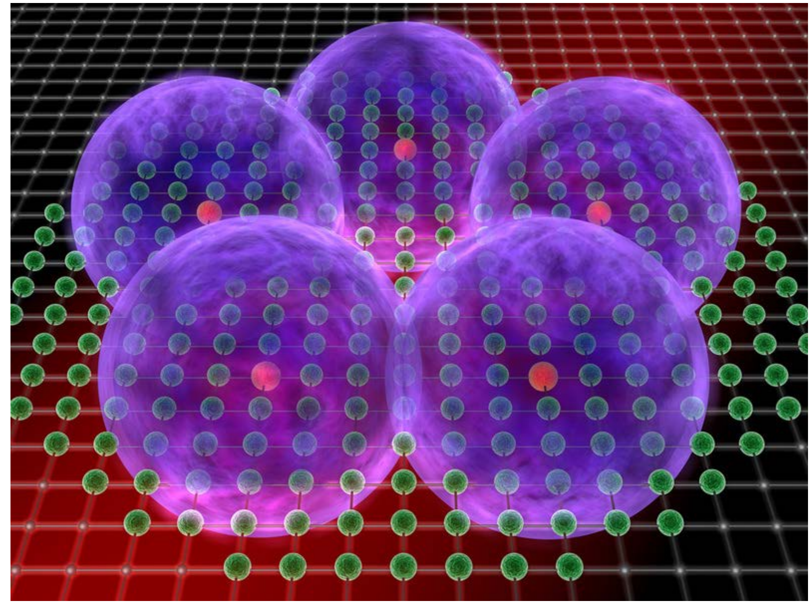
Very strong van der Waals interactions ($1/r^6$)

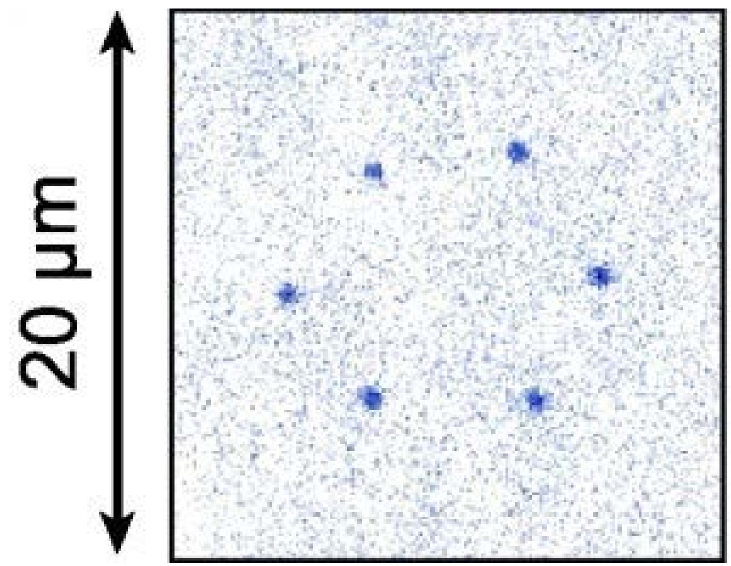
Property	Scaling	Li-6 $23P_{3/2}$
Lifetime	$(n^*)^2$	20 us
Radius	$(n^*)^2$	40 nm
Van der Waals (C_6)	$(n^*)^{11}$	2 MHz/um^6
Blockade Radius	$(n^*)^2$	850 nm

Saffman, Walker, & Mølmer Rev. Mod. Phys. (2010)

Rydberg crystals





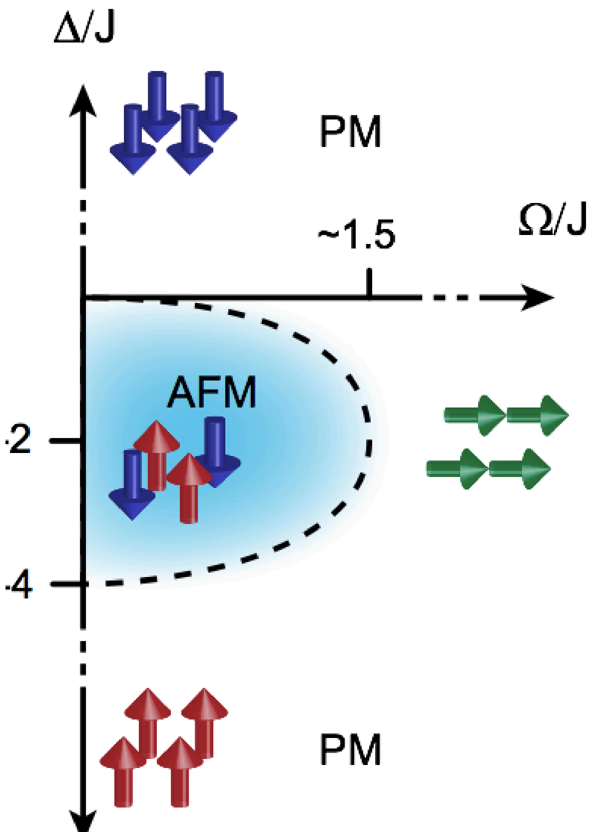


Bloch
Science 347, 1455 (2015)

$R_b >> a_l$

Rydberg antiferromagnets

$$H = \underbrace{\Omega \sum_i \hat{S}_i^x}_{\text{Transverse field}} + \underbrace{\sum_i (\mathcal{I}_i - \Delta)\hat{S}_i^z}_{\text{Longitudinal field}} + \underbrace{\sum_{i \neq j} \frac{V_{ij}}{2} \hat{S}_i^z \hat{S}_j^z}_{\text{Ising interaction}}$$



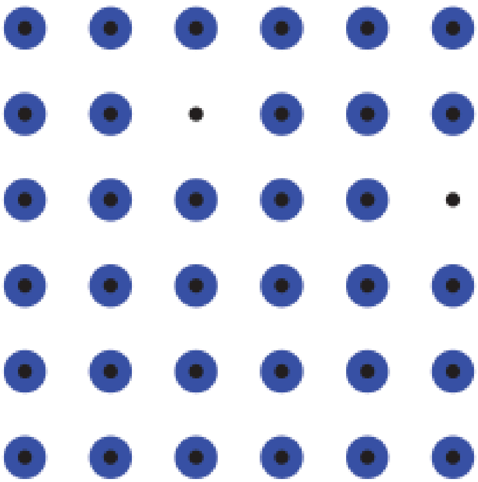
Phase diagram for $R_b \approx a_l$ has one AFM phase

Quench dynamics studied in 1D chains (Lukin) and rings of atoms (Browaeys)

In 1D, dynamics can be captured with Matrix Product States.

Experimental protocol

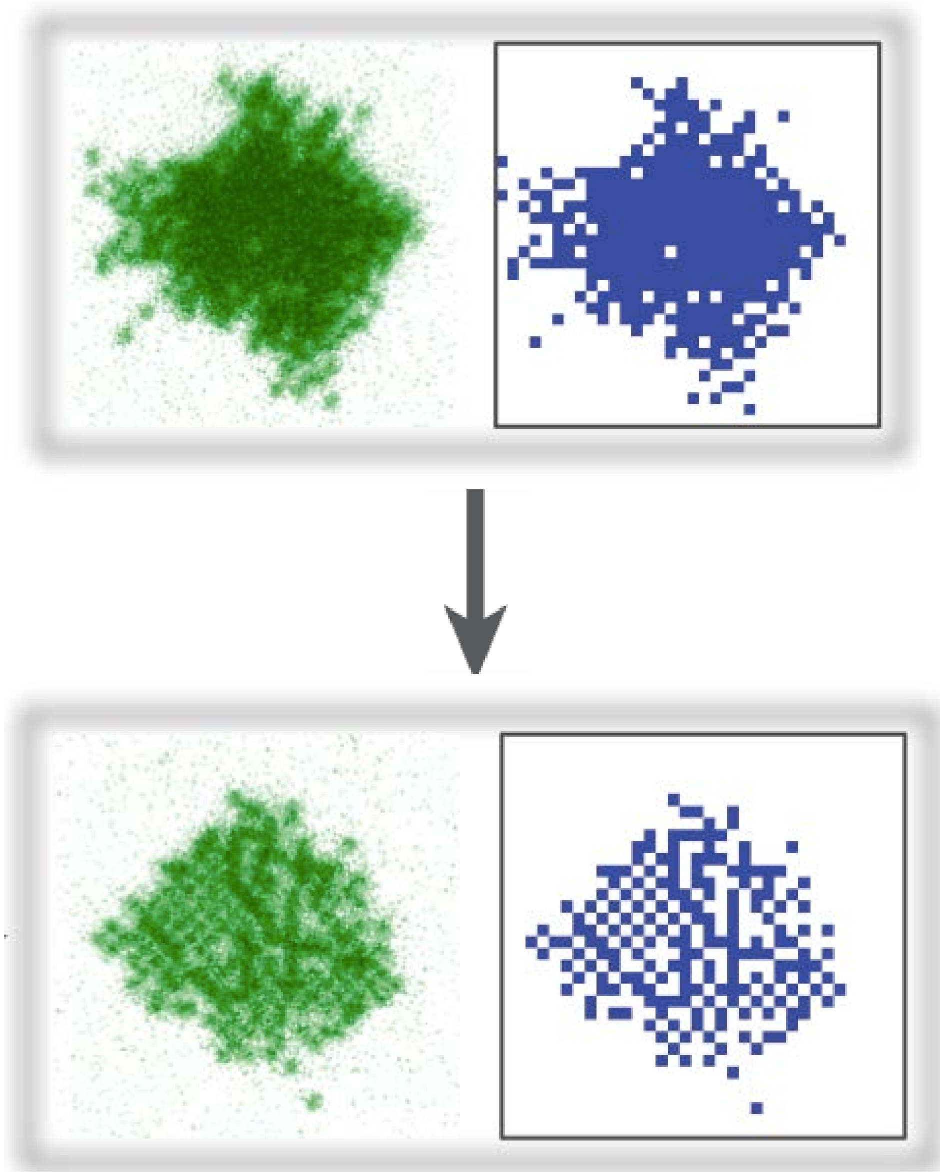
Initial preparation

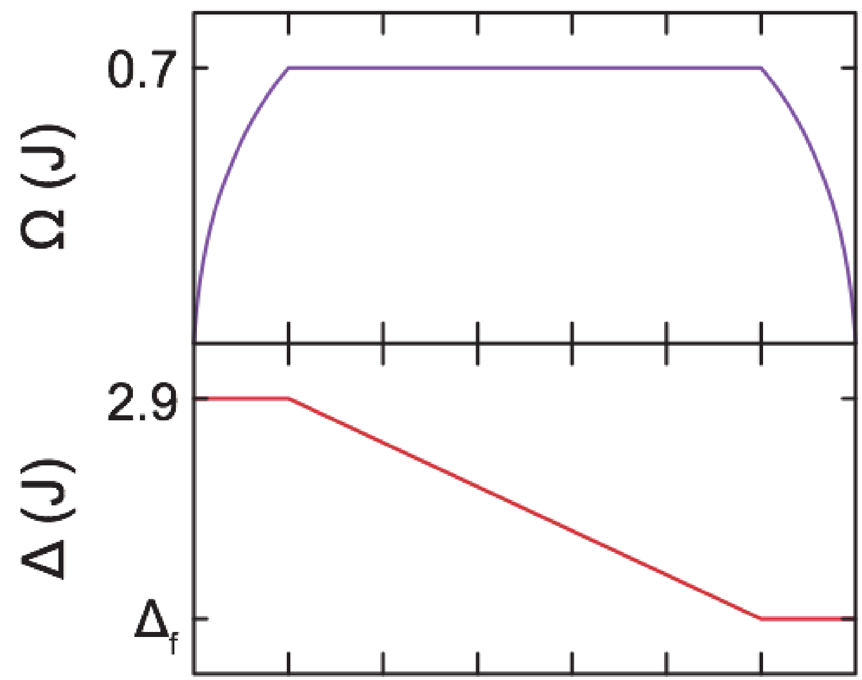


Spin-polarized band insulator of Li-6 in optical lattice with a_l = 750 nm

96% filling

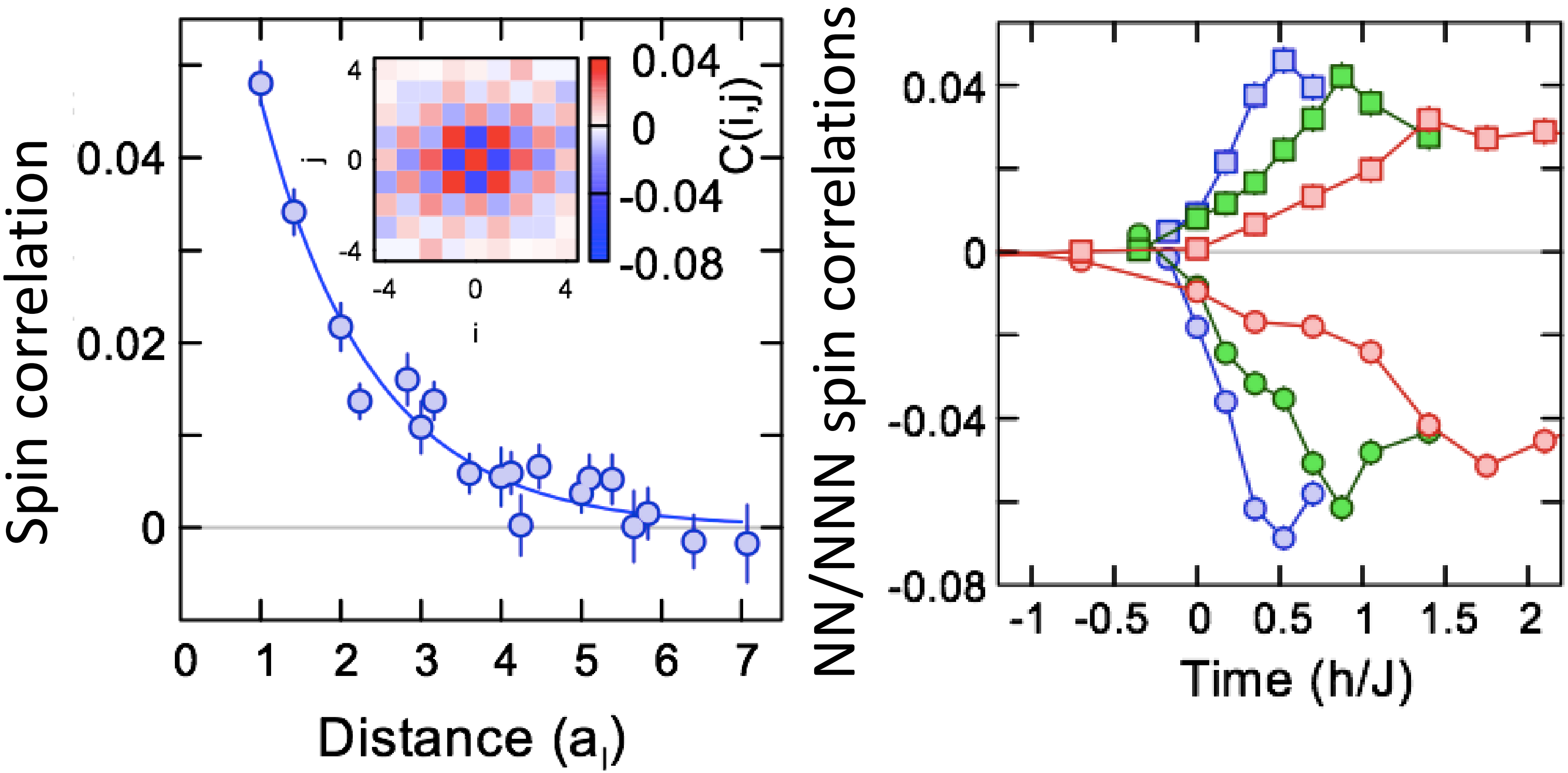
Preparation of Rydberg antiferromagnets





Ramp longitudinal field to quench across quantum phase transition from paramagnet to AFM.

Quench dynamics across phase transition



Obtain real-time evolution of spin correlations as quantum phase transition is crossed at different rates.

Conclusion: Equilibrium vs. dynamics

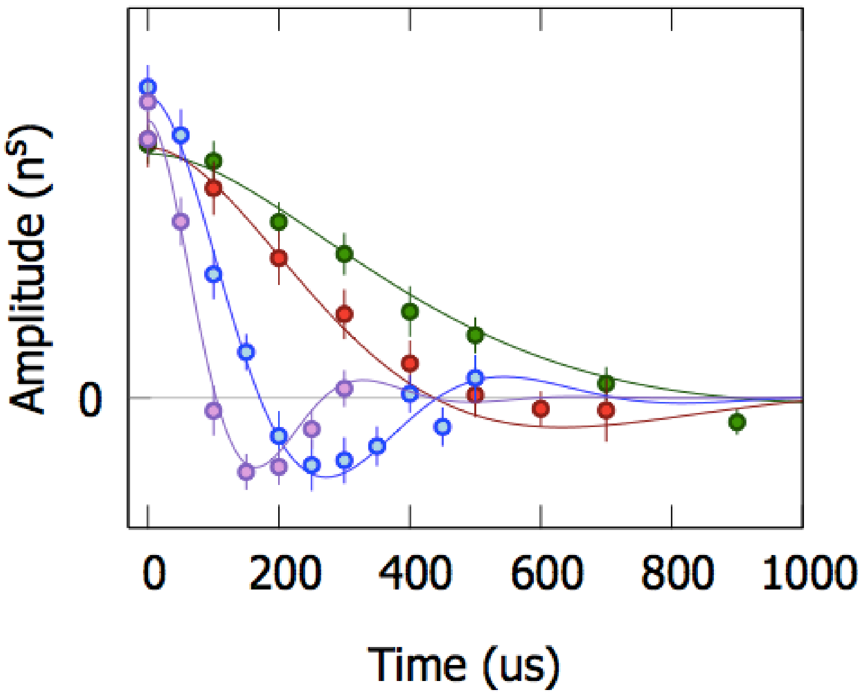
Exact numerical techniques well-developed for equilibrium systems: QMC, NLCE, DMRG, etc.

State of the art Fermi-Hubbard experiments at $T/t = 0.25$-0.30 are just beyond reach of exact numerics.

Dynamics is much harder, especially for more than one dimension.

- Generalization of MPS to higher dimensions (PEPS) is still in infancy.
- Cold atom experiments can provide benchmarks for testing algorithms.

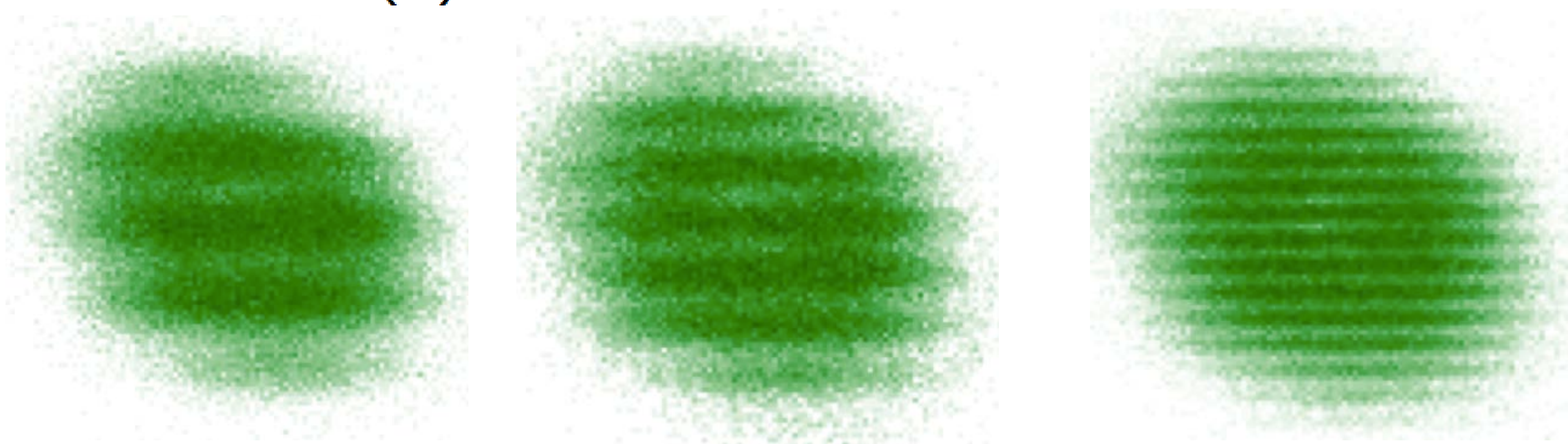
Outlook: Hubbard dynamics



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.



Thanks

Debayan
Mitra

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Kondov
(→Columbia)

Peter
Schauss

Elmer
Guardado-Sanchez

Theory:

David Huse and Trithep Devakul, Princeton University
Nandini Trivedi, Ohio State University
Thereza Paiva, Universidade Federal do Rio de Janeiro
Ehsan Khatami, San José State University

Sign change of spin z-correlations at high polarizations

At high polarizations, think of:

Fully polarized state as vacuum, minority spins as dilute gas of magnons.

$$\beta_{\mathbf{i}}^{\dagger} = S_{\mathbf{i}}^{+} \qquad \beta_{\mathbf{i}} = S_{\mathbf{i}}^{-} \qquad S_{\mathbf{i}}^{z} = \beta_{\mathbf{i}}^{\dagger}\beta_{\mathbf{i}} - 1/2$$

Heisenberg Hamiltonian as hard-core bosons:

$$\mathcal{H} = \frac{J}{2}\sum_{\langle \mathbf{i},\mathbf{j}\rangle}\left(\beta_{\mathbf{i}}^{\dagger}\beta_{\mathbf{j}} + \beta_{\mathbf{j}}^{\dagger}\beta_{\mathbf{i}}\right) + \sum_{i}(h-4J)\,\beta_{\mathbf{i}}^{\dagger}\beta_{\mathbf{i}} + J\sum_{\langle \mathbf{i},\mathbf{j}\rangle}\beta_{\mathbf{i}}^{\dagger}\beta_{\mathbf{j}}^{\dagger}\beta_{\mathbf{i}}\beta_{\mathbf{j}}$$

Positive tunneling   Chemical potential   NN repulsion

- Positive tunneling → BEC at **q** = (π, π). Maps to long-range antiferromagnetic correlations in plane
- Density correlations of liquid of repulsive bosons maps to z-correlations. These are negative at less than interparticle spacing.

Mapping between the attractive and repulsive Hubbard models

$$H = -t \sum_{\langle ij \rangle\ \sigma} c_{i\sigma}^{\dagger} c_{j\sigma} + U \sum_{i} (n_{i\uparrow} - \frac{1}{2})(n_{i\downarrow} - \frac{1}{2}) + H_{\text{ext}}$$

$$H_{\text{ext}} = \sum_{i} (\epsilon_i - \mu)(n_{i\uparrow} + n_{i\downarrow} - 1) - \sum_{i} h_i \,(n_{i\uparrow} - n_{i\downarrow})$$

Use the particle hole transformation:

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

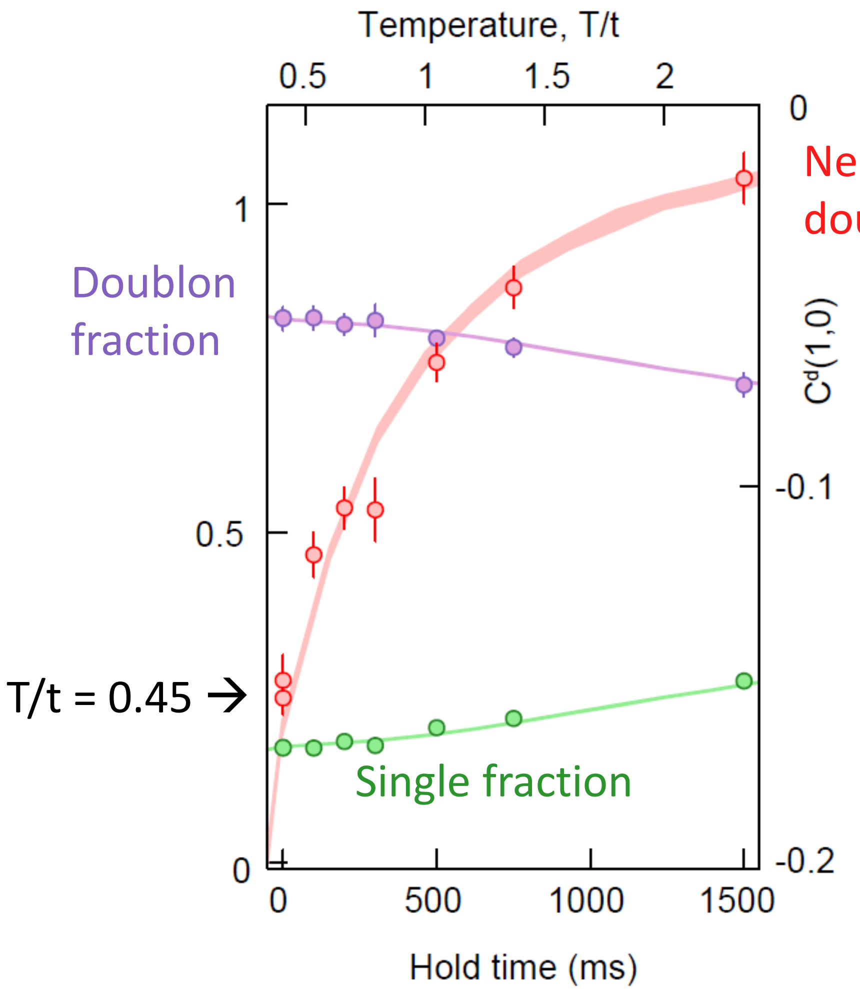
$$c_{i\uparrow} \longleftrightarrow c_{i\uparrow}.$$

Phase diagrams of attractive and repulsive Hubbard models are the same!

Hamiltonian takes the same form but:

1. Interaction flips sign.
2. Chemical potential and effective field swap roles.

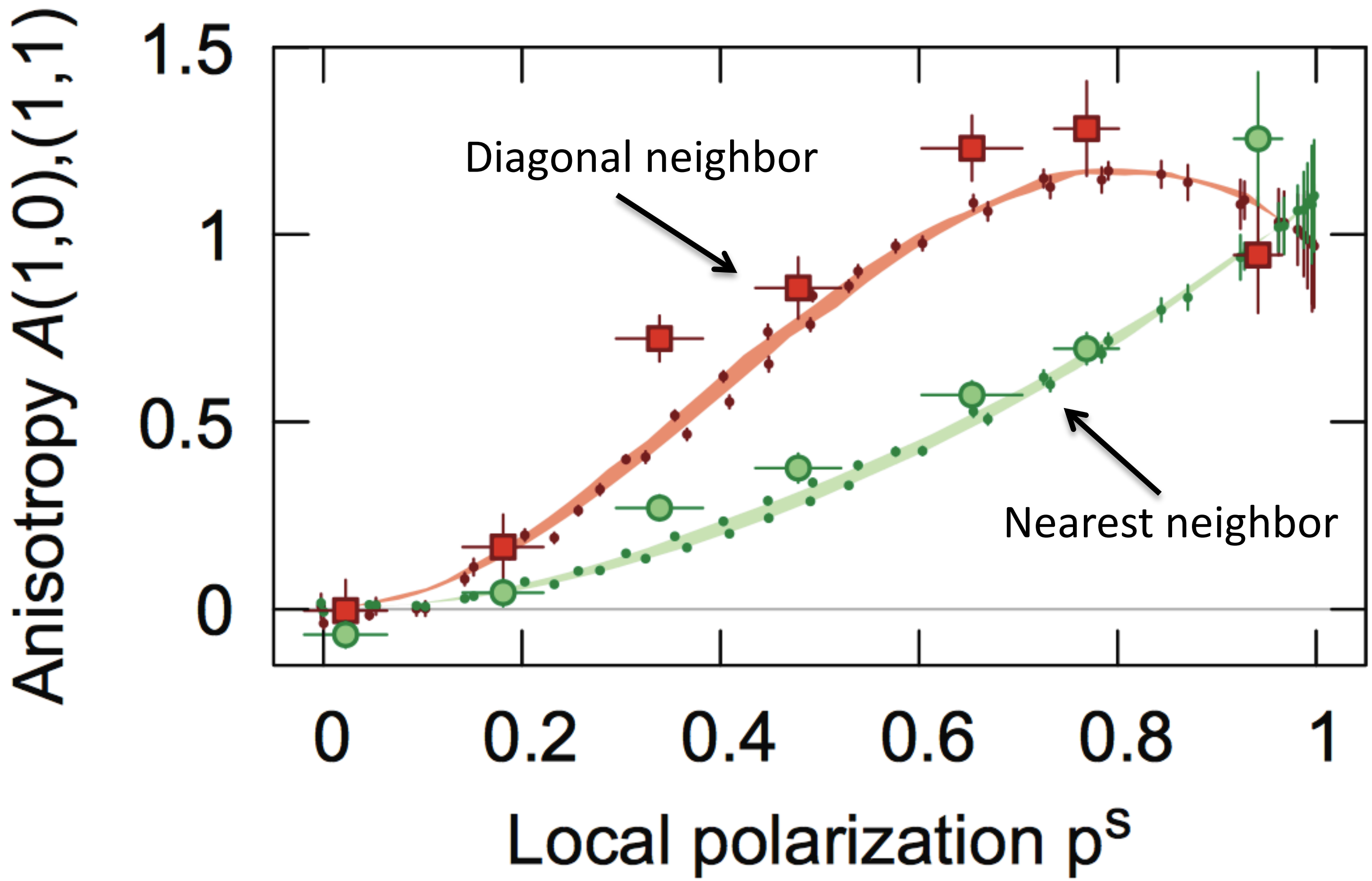
Low temperature thermometry in attractive Hubbard systems



Density thermometry good for T/t > 1

Doublon density thermometry good for T/t < 1

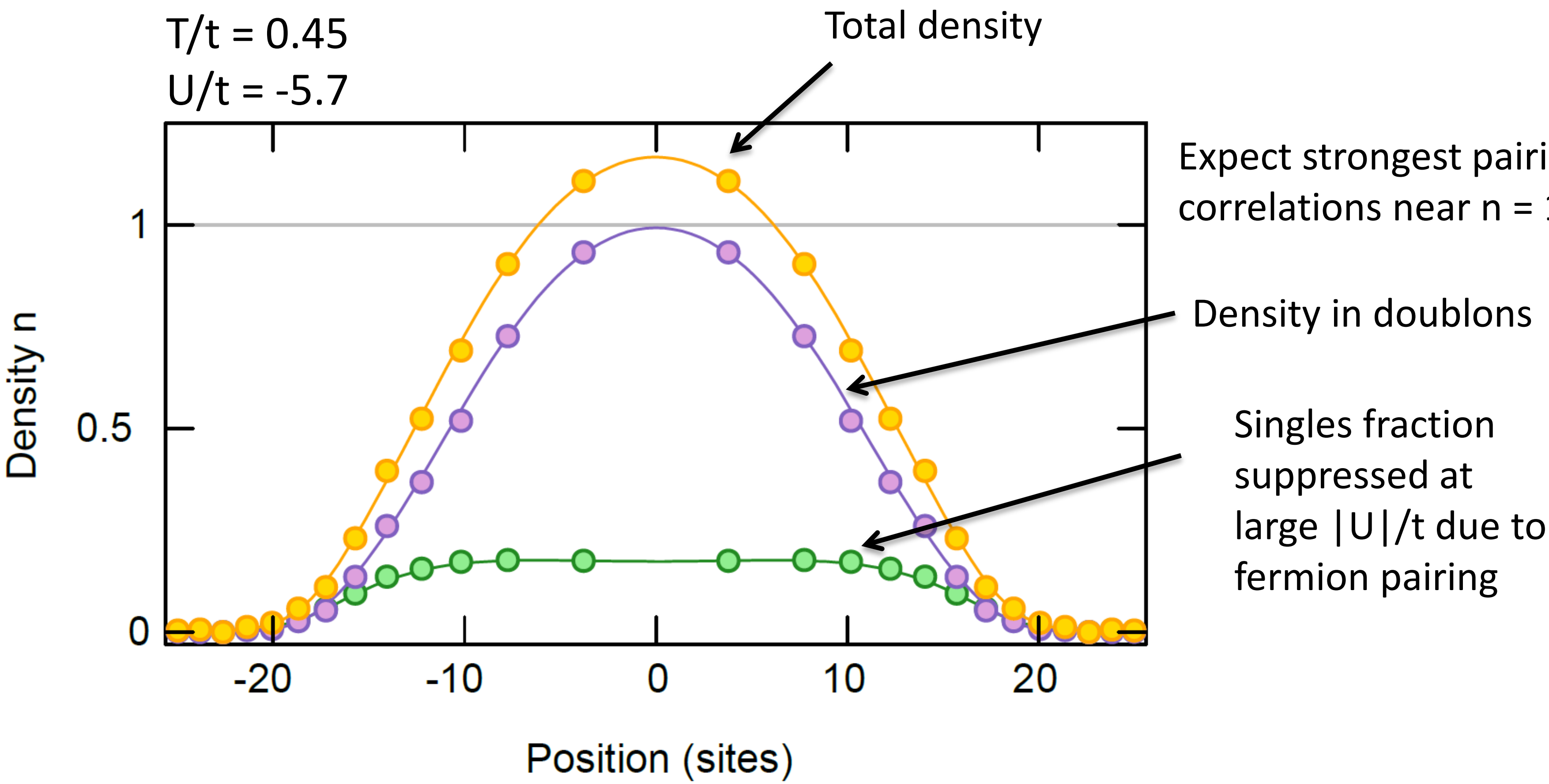
Spin correlator anisotropy



Anisotropy increases for larger distances:
At zero *T*, in-plane correlations become long-range, orthogonal correlations do not.

Density profile of attractive lattice gas

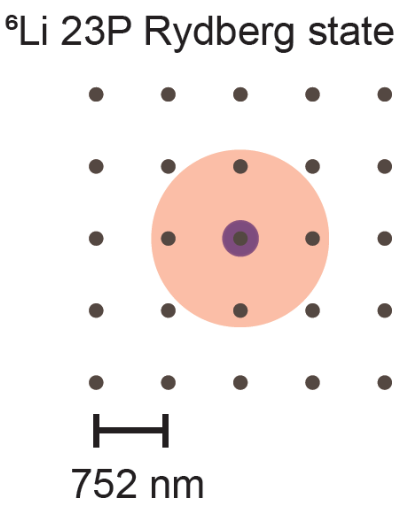
Experimental data with DQMC fit
T/t = 0.45
U/t = -5.7

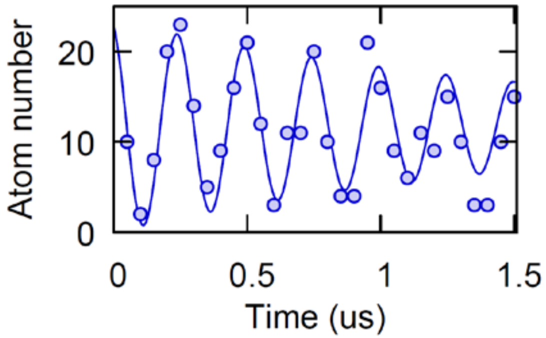


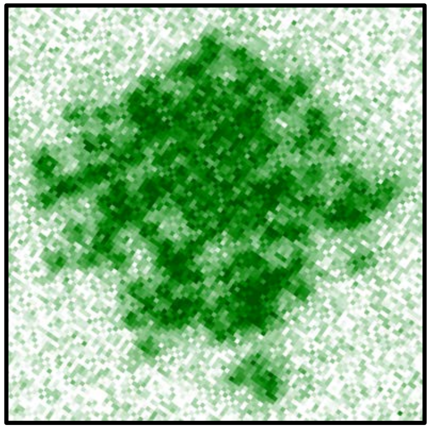
Expect strongest pairing correlations near n = 1

Rydberg excitation of ^{6}Li

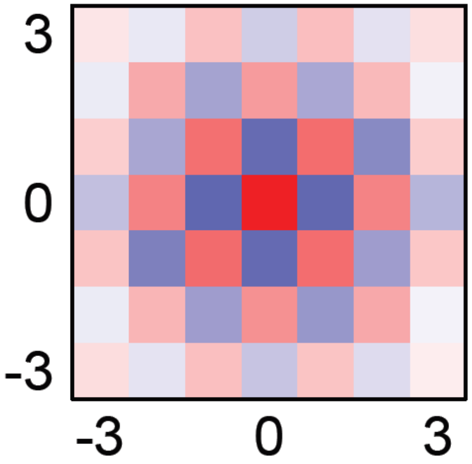
- Direct excitation at 230nm to 23P
- Towards Rydberg dressing of Fermions
- Rabi frequency: up to 6 MHz



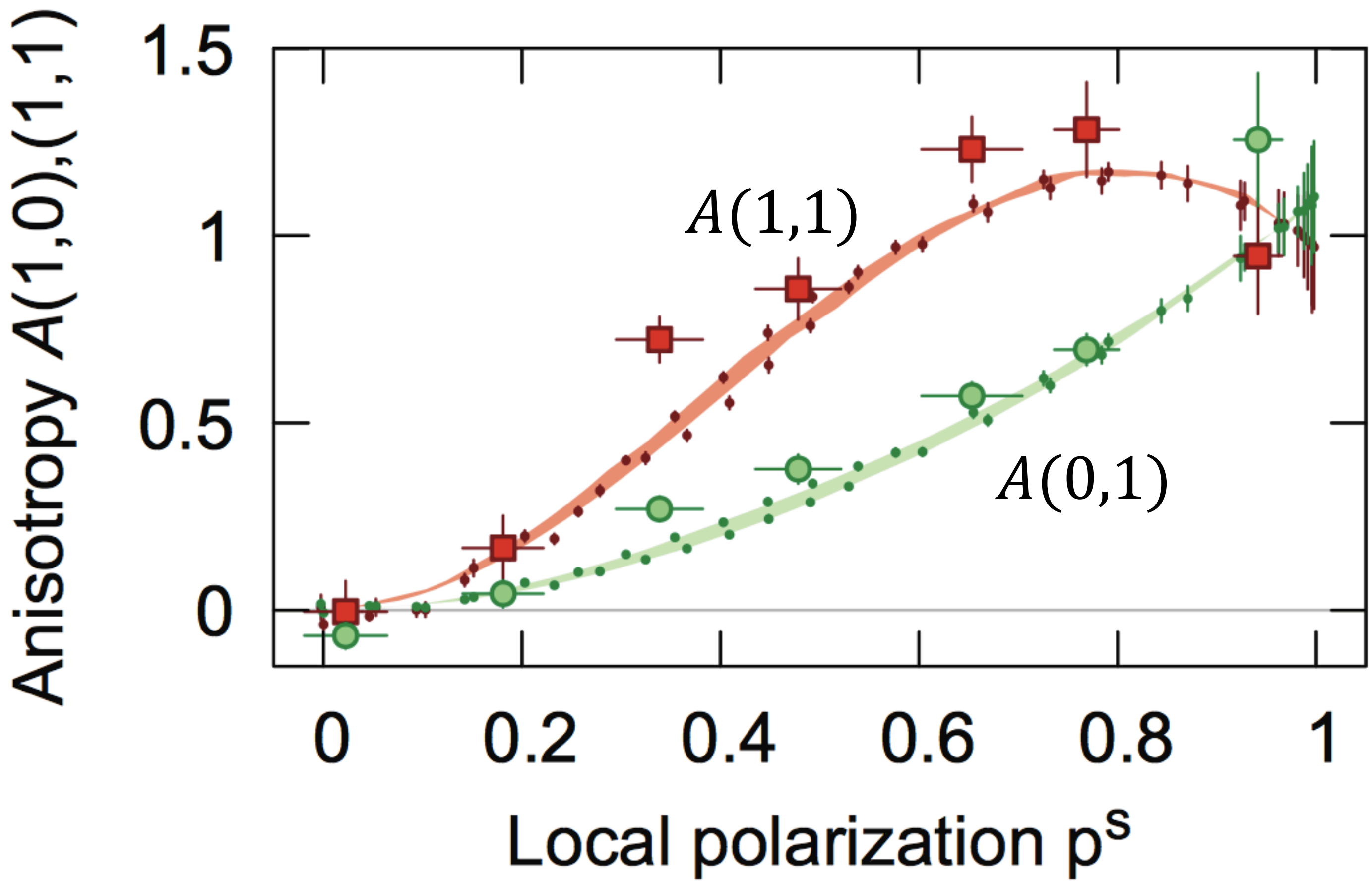




Pair correlation:



Spin correlator anisotropy

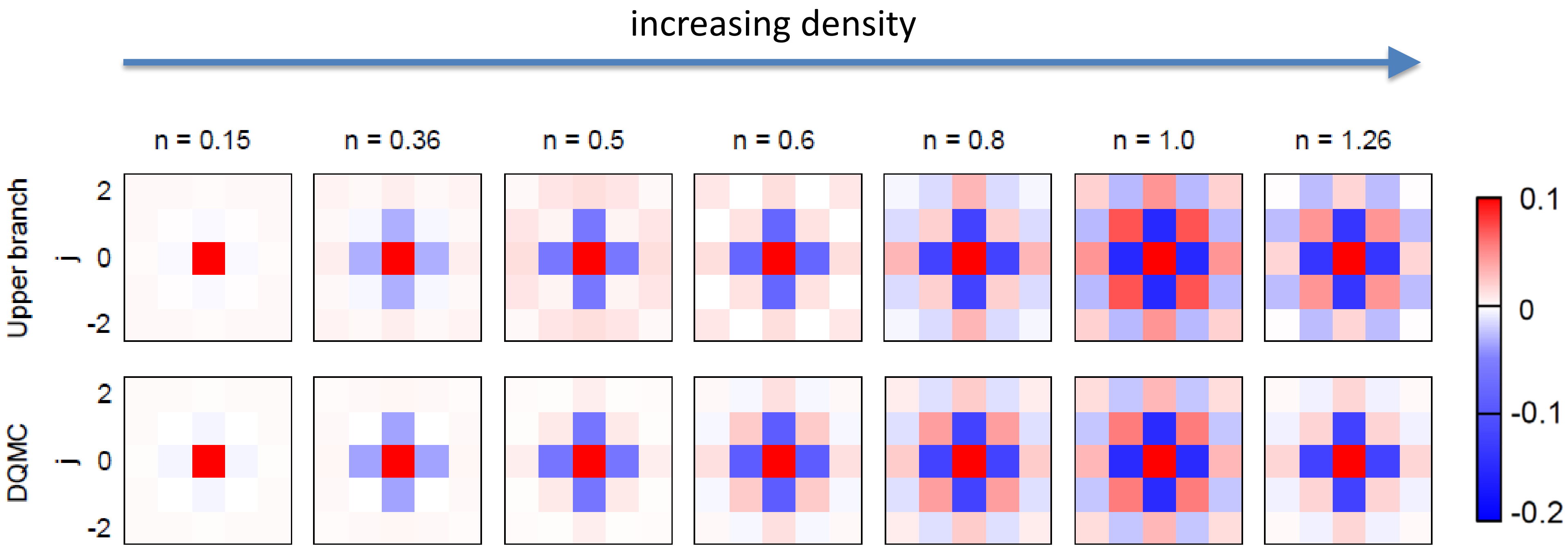


Anisotropy increases for larger distances:
At *T = 0*, in-plane correlations become long-range, orthogonal correlations not.

$$A(\mathbf{d}) = 1 - C^z(\mathbf{d})/C^{\perp}(\mathbf{d})$$

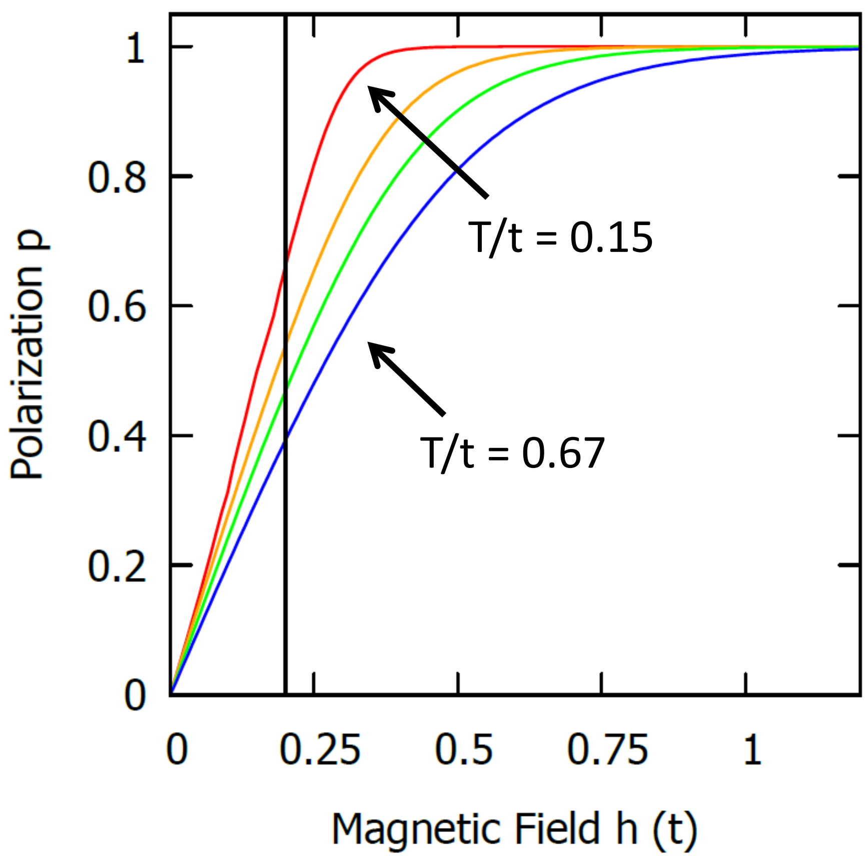
Charge density wave correlations

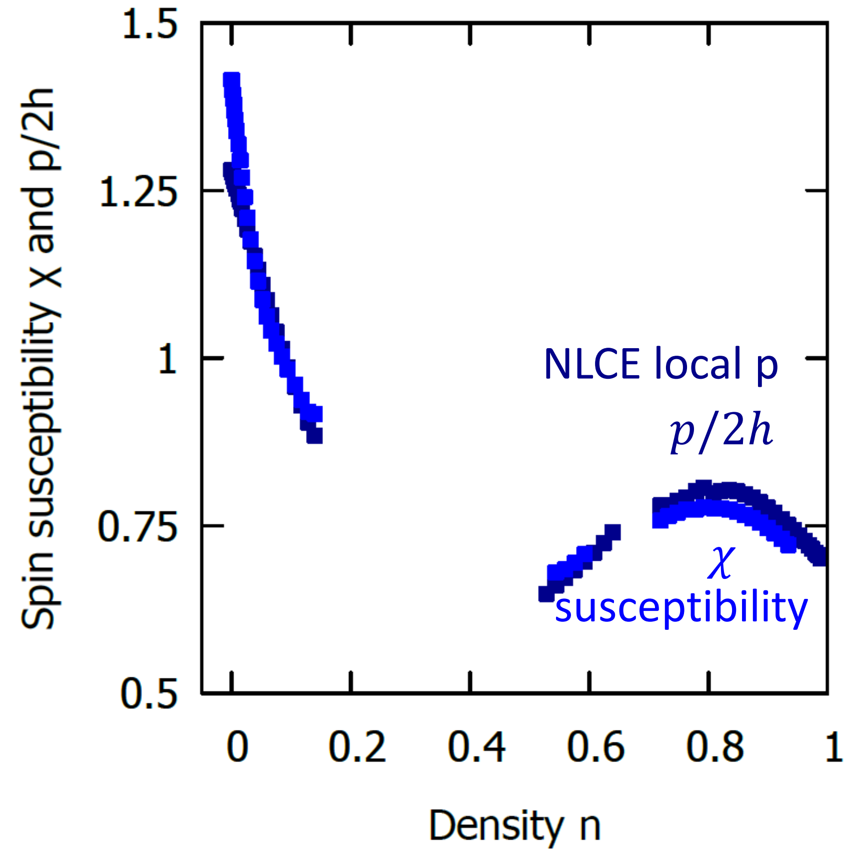
Measure: doublon-doublon correlator at U/t = -5.7



- Superfluidity competes with charge density wave order away from half-filling and eventually wins.

Local Polarization ↔ Spin-Susceptibility

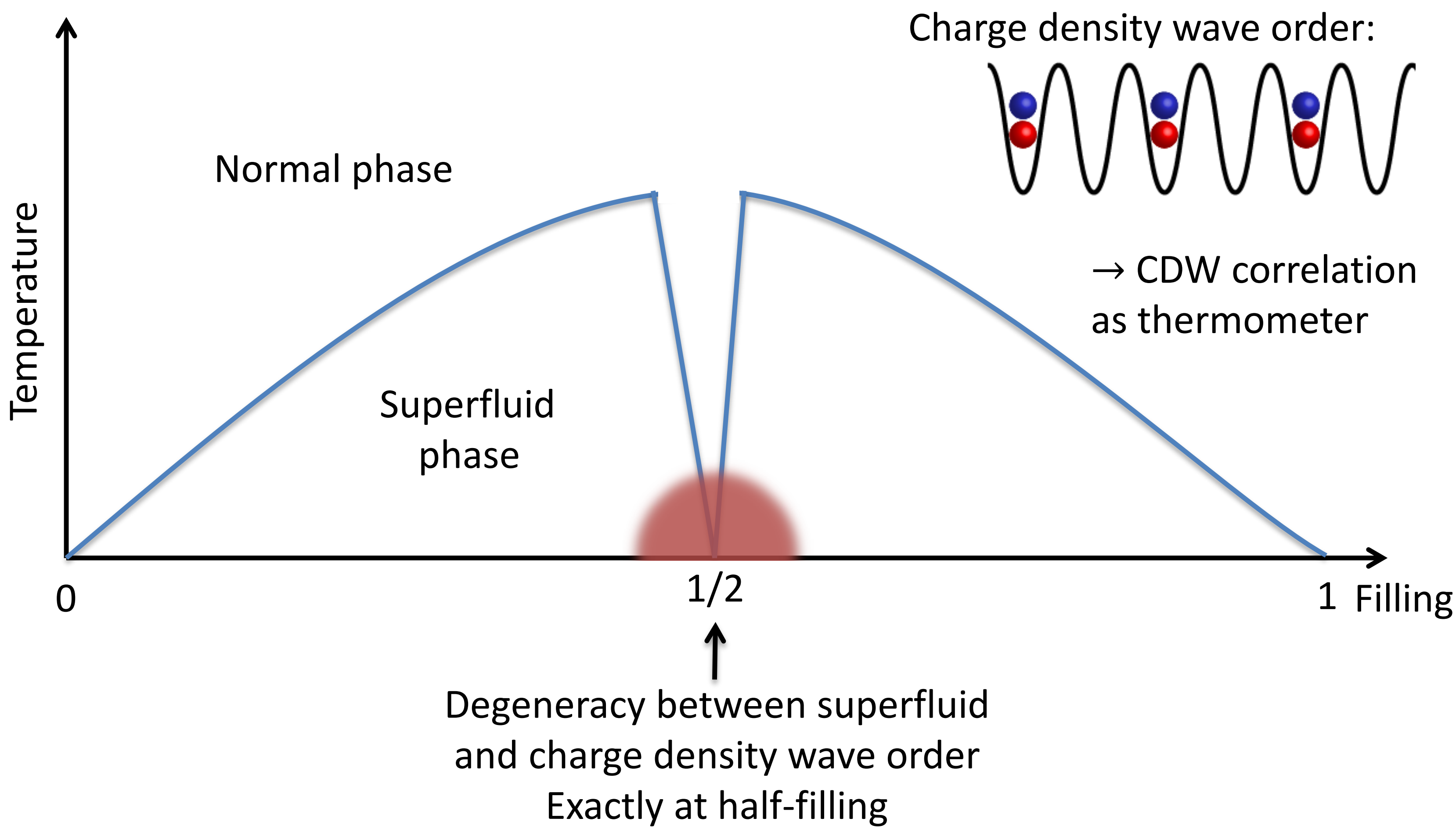




- Linear regime to
- Susceptibility from fluctuation-dissipation theorem (light blue)
- „

Correlation thermometry

- Superfluid phase correlations are not accessible with quantum gas microscopy (need interferometry).

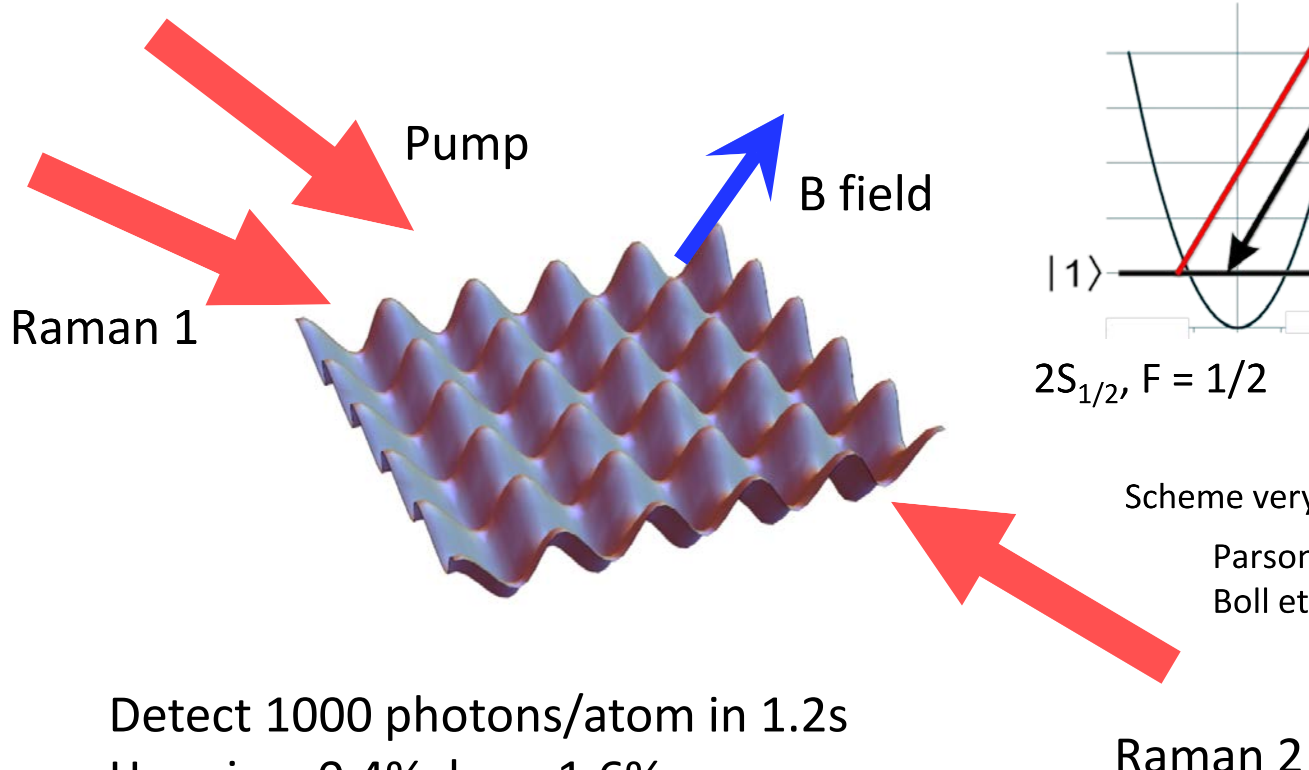


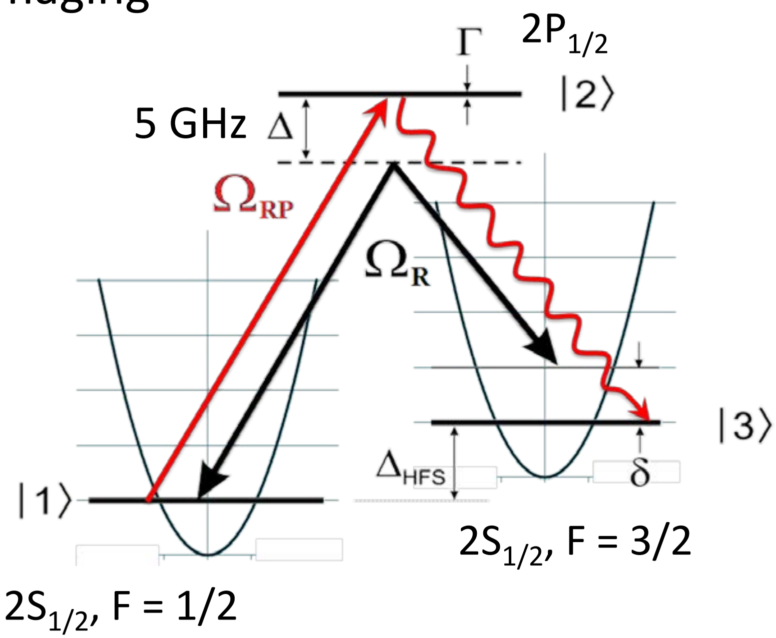
Raman sideband cooling

- Raman cooling via D1 for fluorescence imaging

  In-plane lattice frequency: 1.5 MHz

  Axial confinement: 0.1 MHz





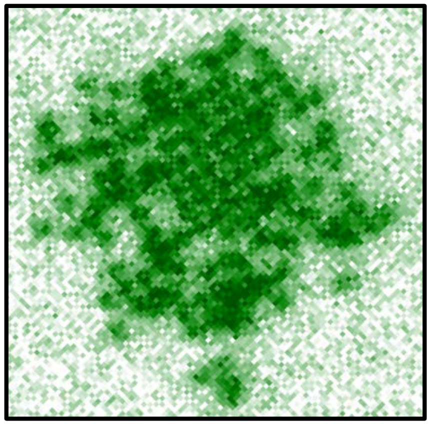
Detect 1000 photons/atom in 1.2s

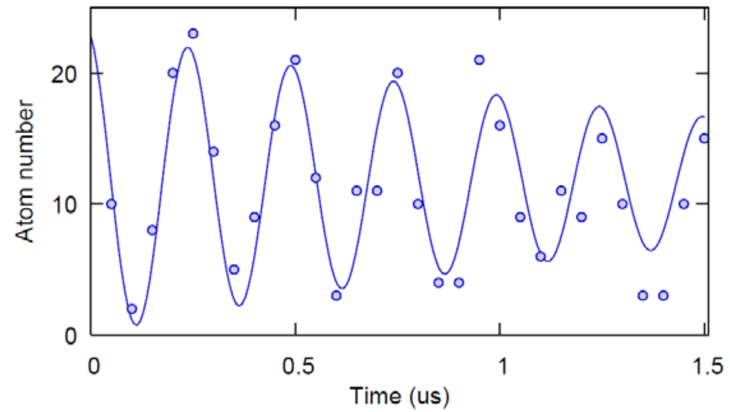
Hopping: 0.4%, loss: 1.6%

Scheme very similar to:

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

Boll et *al.*, Science **353**, 1257 (2016)





Atom number
Time (us)
0
10
20
0
0.5
1
1.5

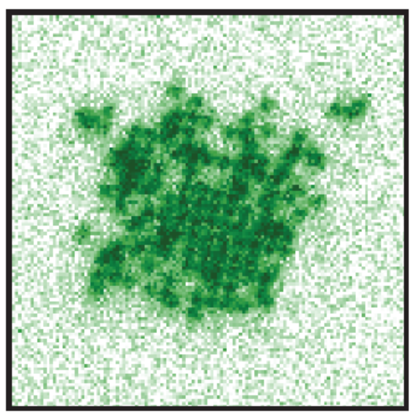
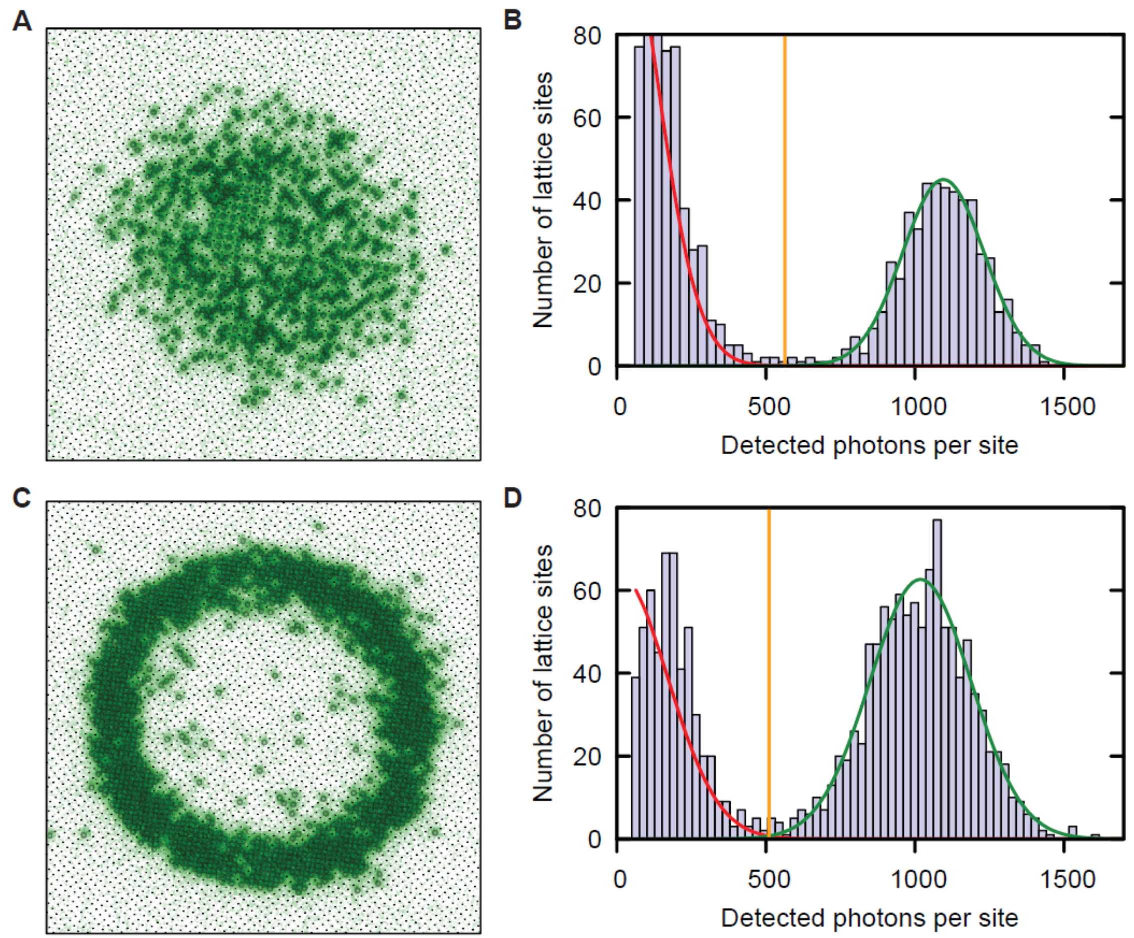


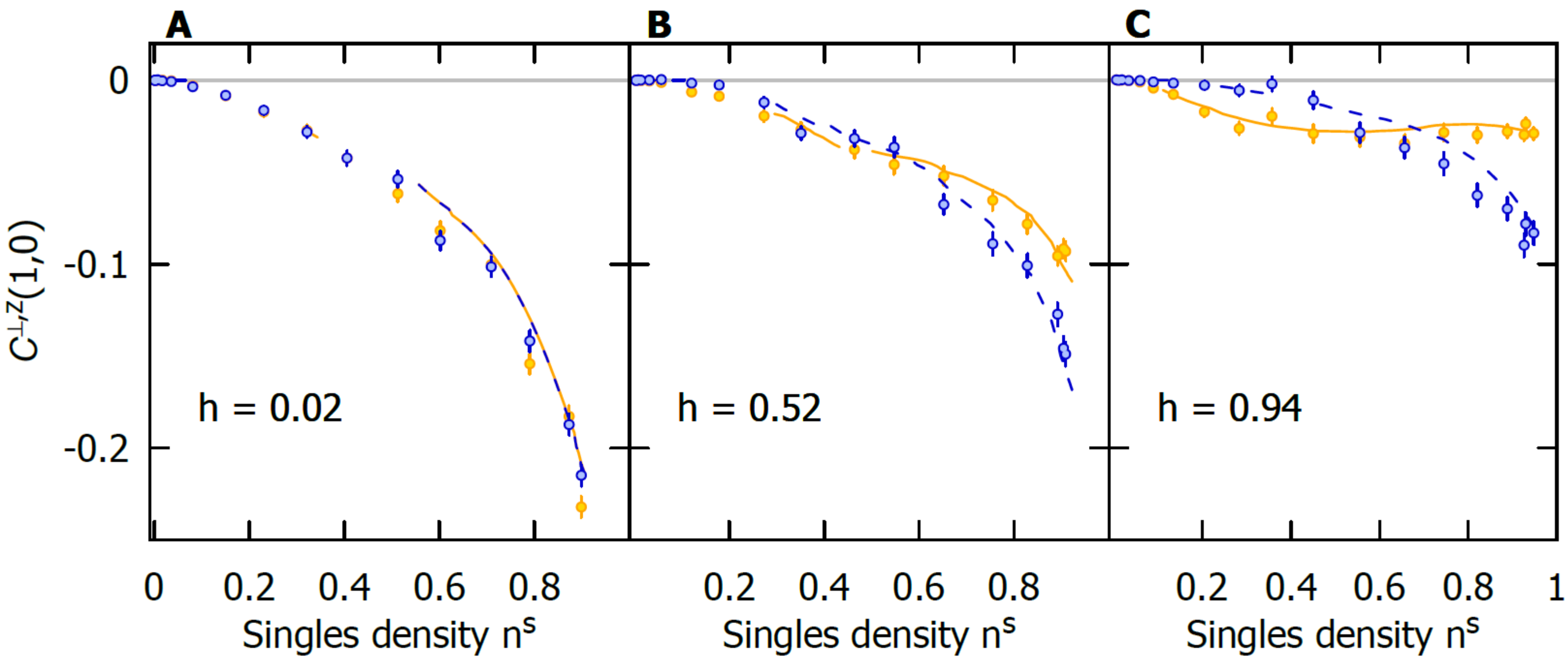
Image Reconstruction

- Hopping and loss from ~ 40 consecutive shots
- Hopping $=$ $0.4(2)\%$
- Loss $=$ $1.6(3)\%$



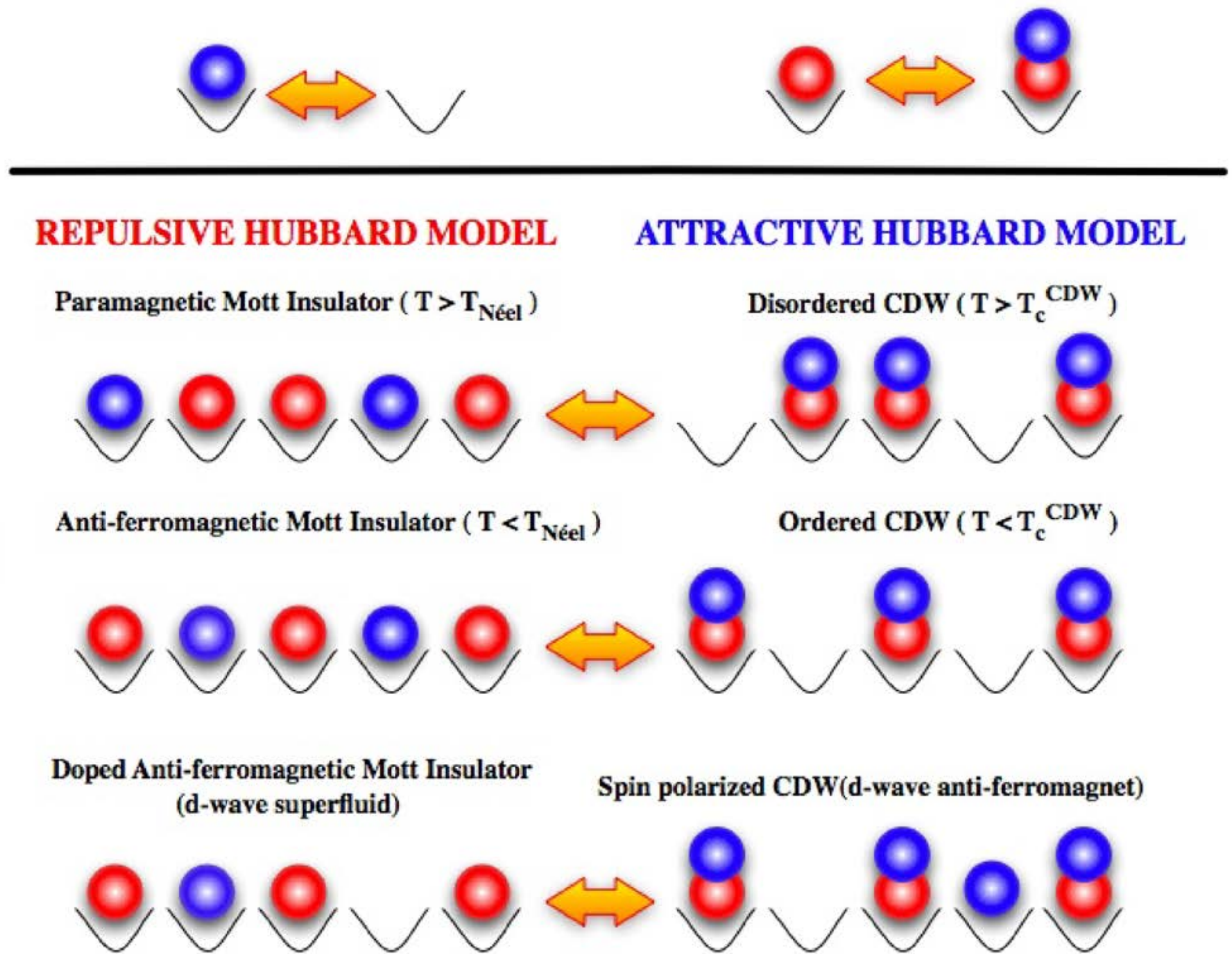
Reconstruction method: Nature **467**, 68 (2010)

Spin Correlators Vs. Doping



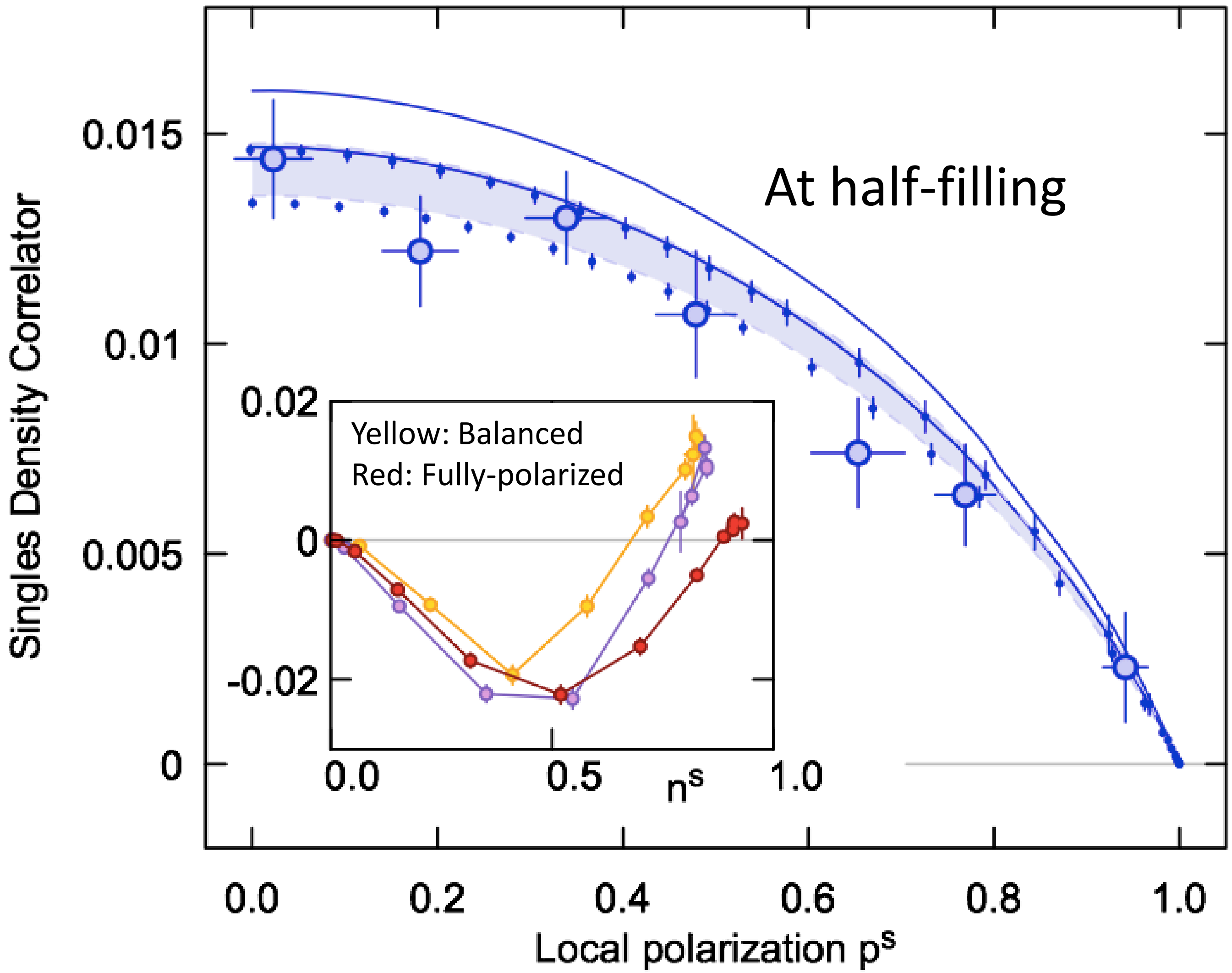
- Transitions to polarized gas at edge.
- Polarized gas: ,
- Polarized fermi gas, density correlations negative

A dictionary between the models



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

Singles density correlations → doublon-hole pairs



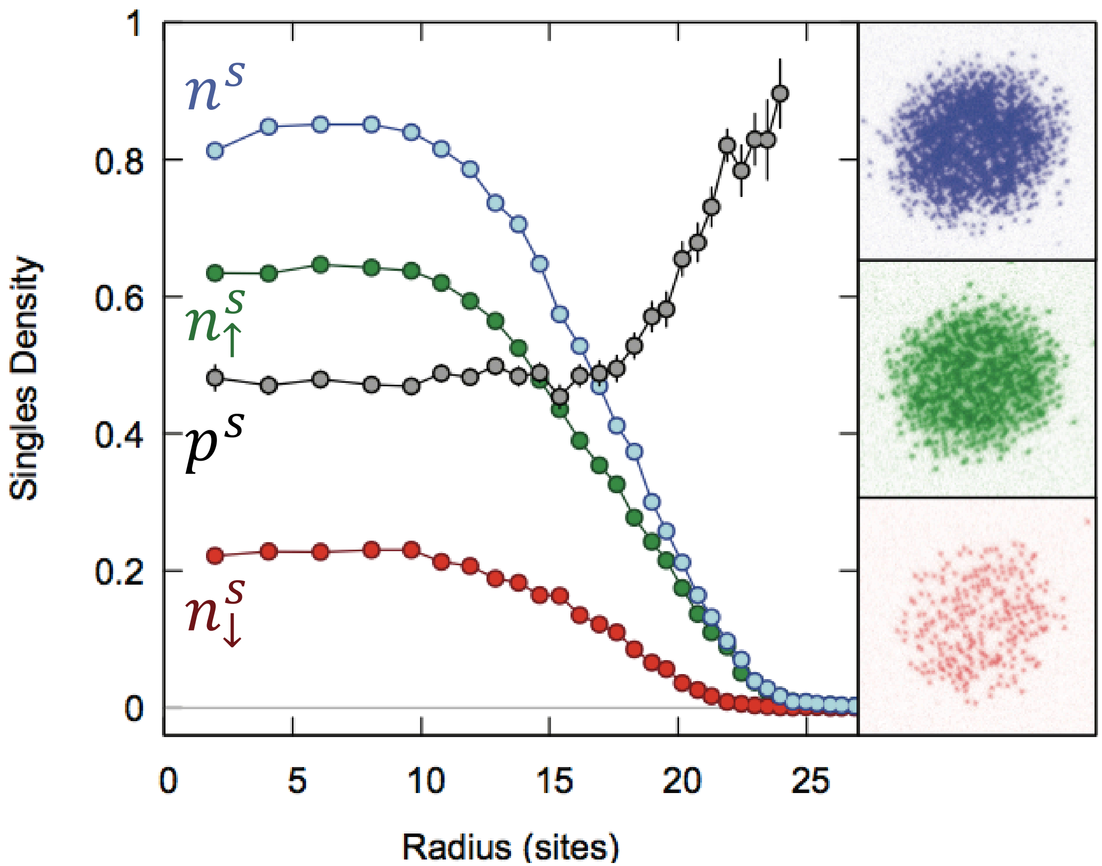
Suppressed particle-hole pair fluctuations for polarization

bosons:
Science 334, 200 (2011)

Fermions, $p^s = 0$:
Science 353, 1260 (2016)

Spin susceptibility in the repulsive Hubbard model

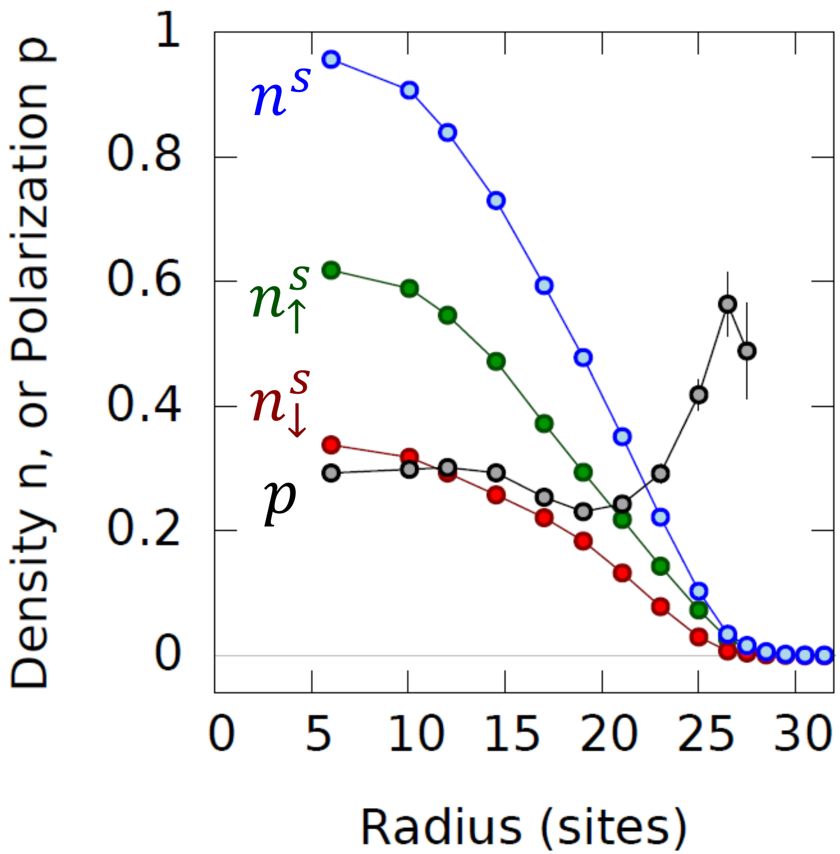
- Polarization profile in trap for small imbalance gives susceptibility vs. doping (linear regime). Entire trap is at constant *h*.

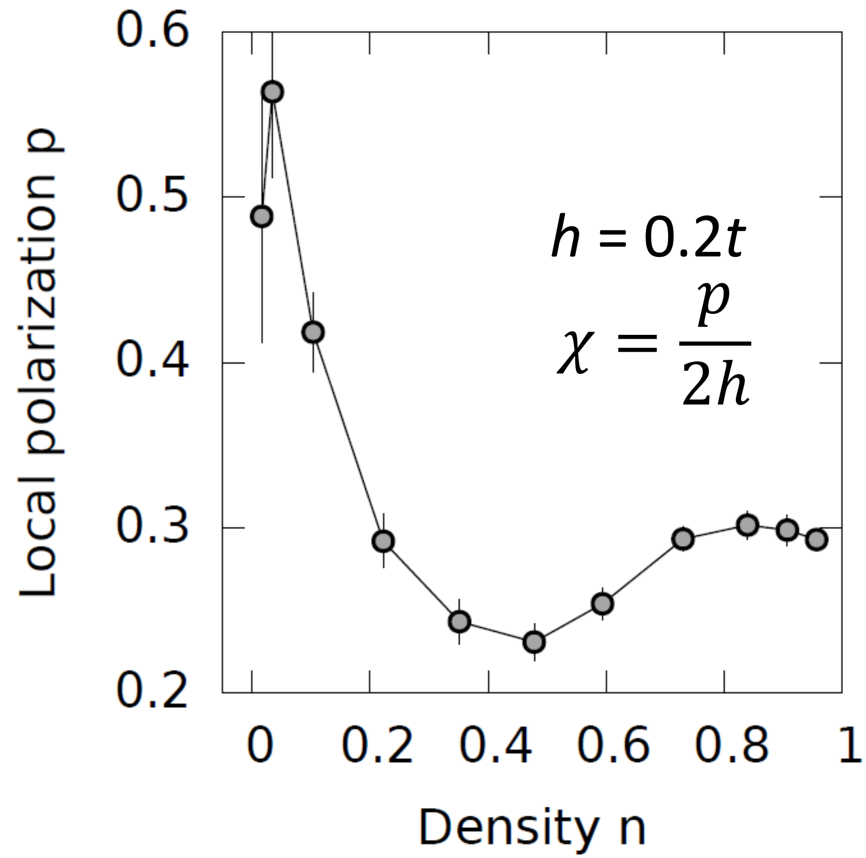


U/t = 8:

Susceptibility almost flat in doped AFM.

More interesting behavior at larger interaction (U/t = 15)



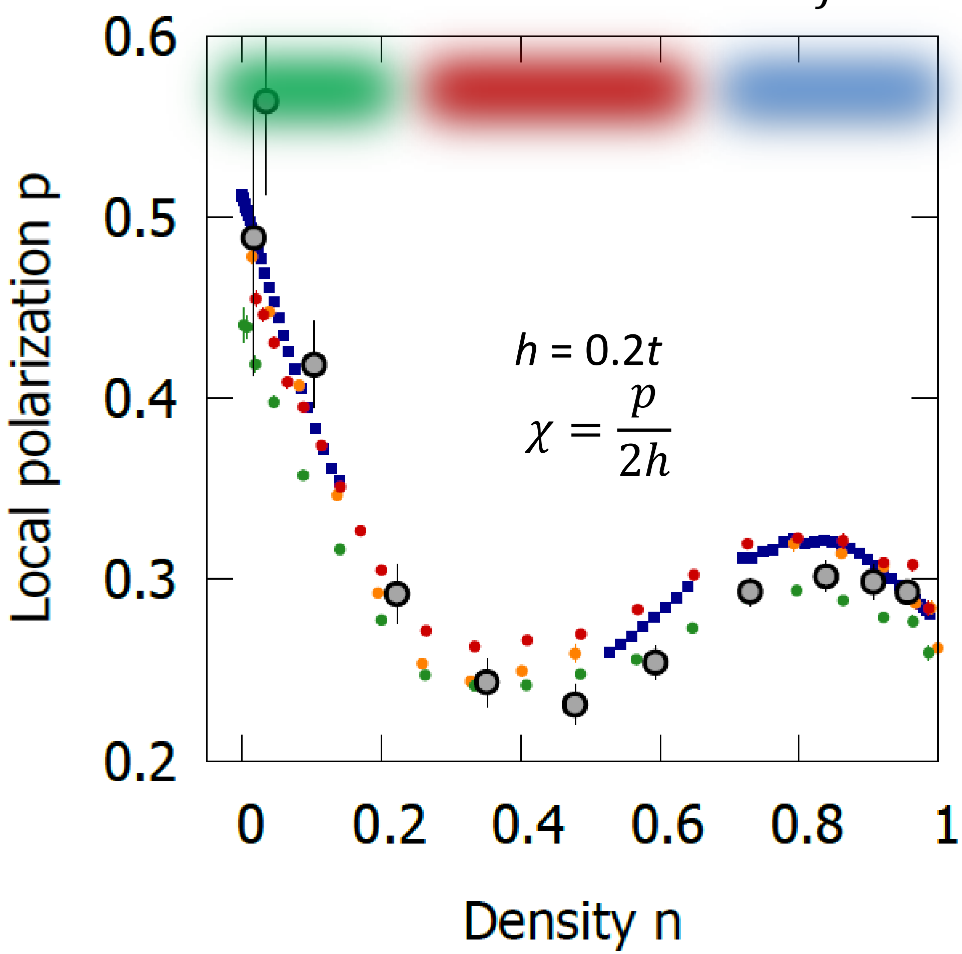


Spin-Susceptibility

non-degenerate gas

Metallic region $\chi \propto 1/t$

AF region $\chi \propto \frac{1}{J} = U/4t^2$



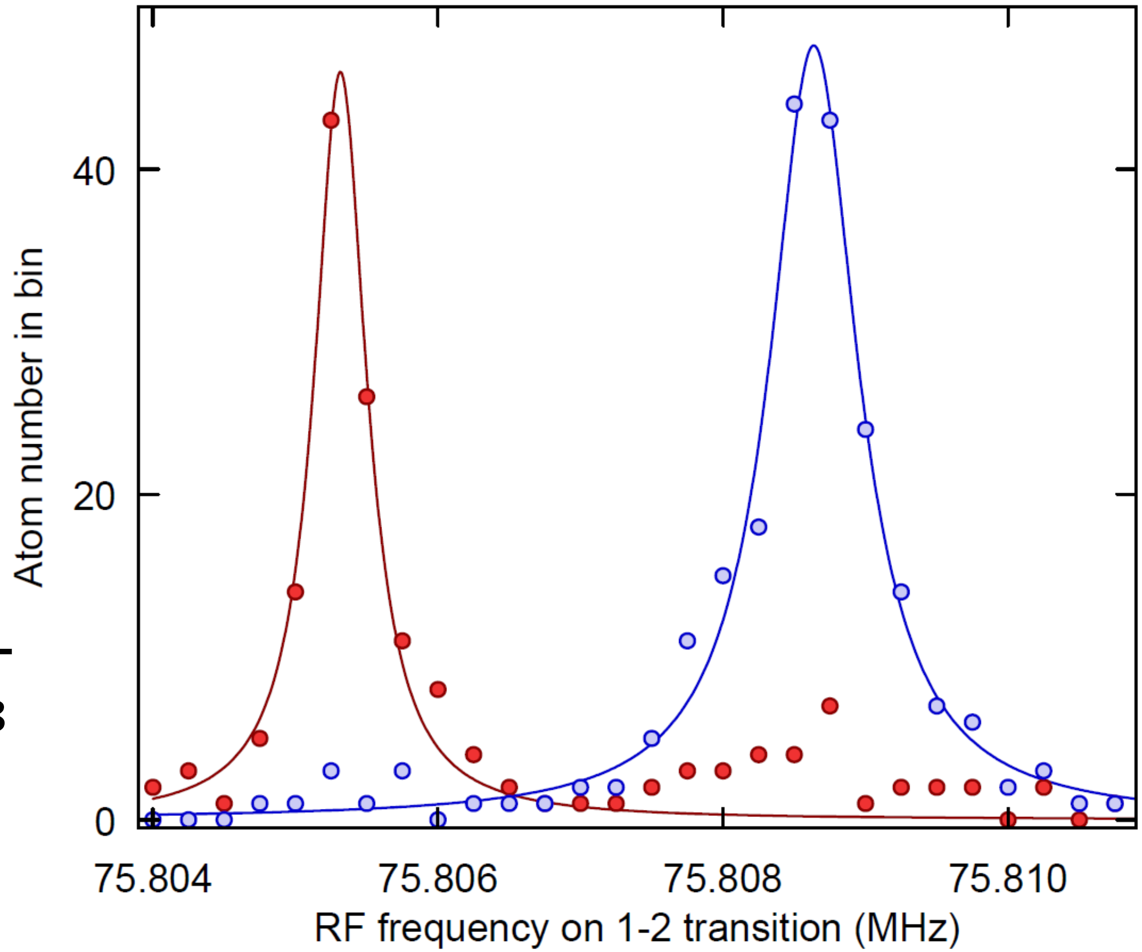
$$\chi = \frac{1}{n}\frac{\partial\langle S^z\rangle}{\partial h}\bigg|_{\mu} = \frac{p}{2h} \ (\textit{linear regime})$$

Hubbard model (exp. & theory) reproduces peak in cuprate susceptibility at about 20% doping.

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

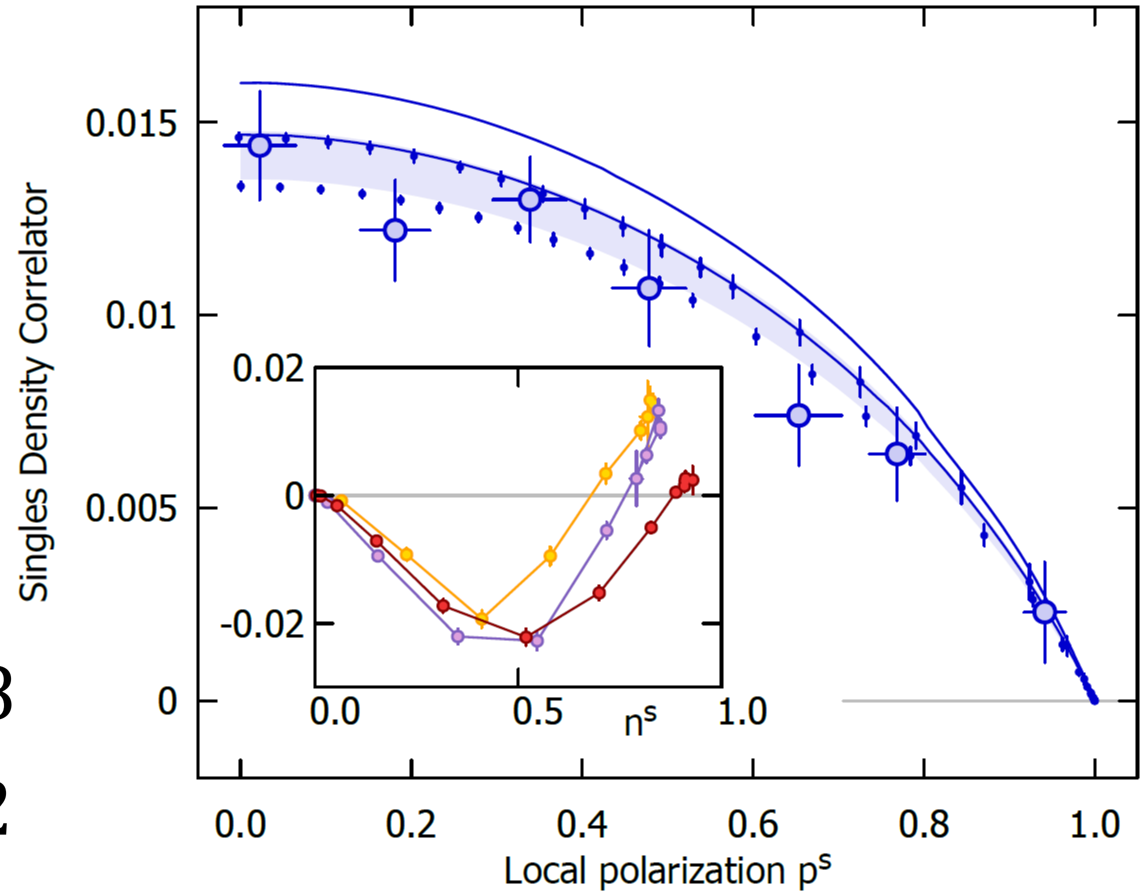
Interaction Measurement

- Lattice depth = $10.5E_r$ at $448a_o$
- Red, BI region
- Blue, MI region
- $U_{13} = \delta U \dfrac{a_{13}}{a_{13}-a_{23}}$

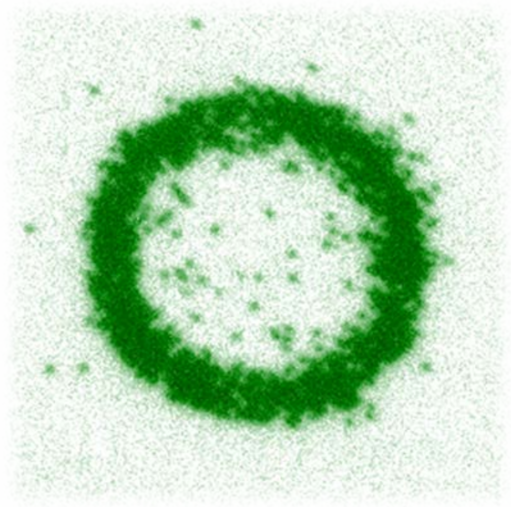


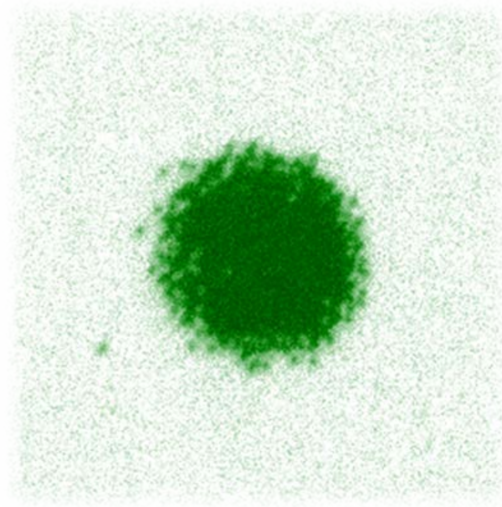
Singles Density Correlators

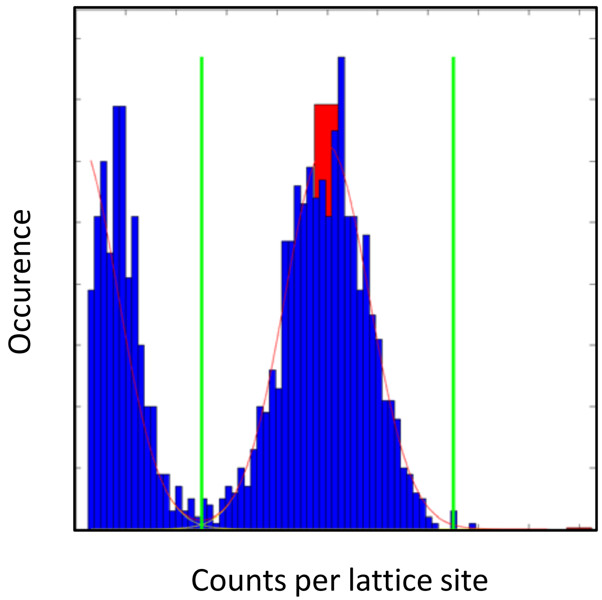
- Temperatures agree with spin correlators
- Inset: versus doping.
- Red: $p^s = 0.94$
- Purple: $p^s = 0.48$
- Yellow: $p^s = 0.02$



Site resolved imaging & reconstruction





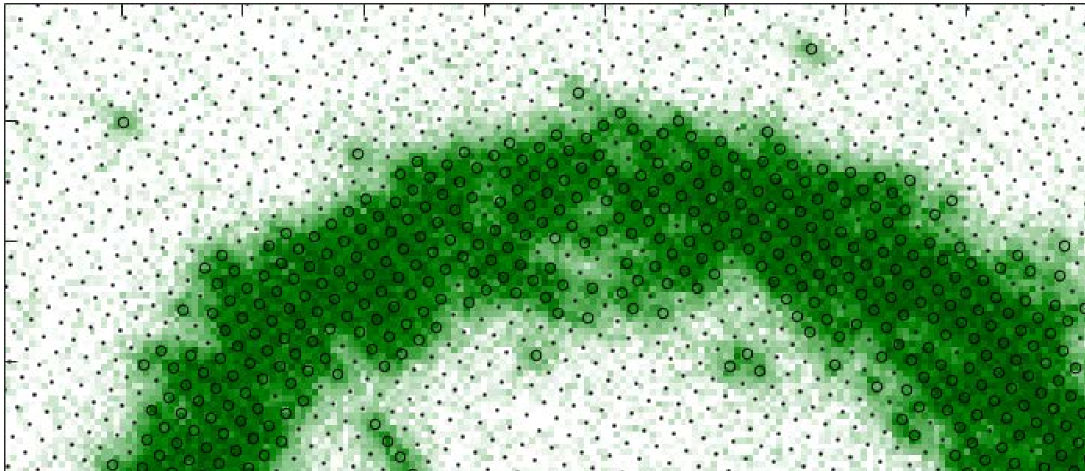


~ 1000 atoms visible

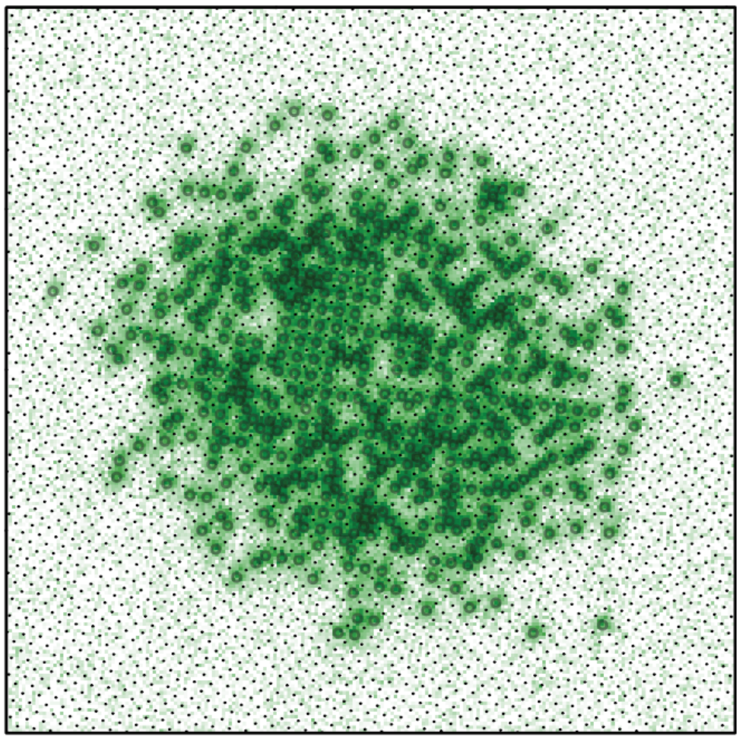
Hopping ~ 0.5 % per picture

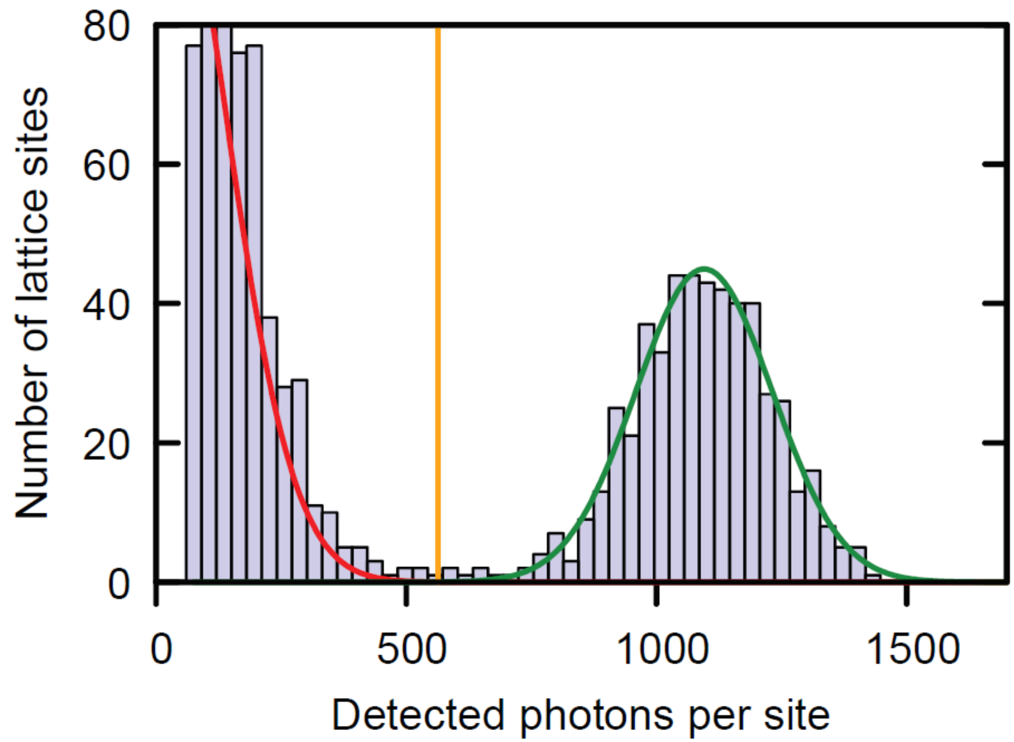
Loss ~ 1.5 % per picture

NA = 0.5

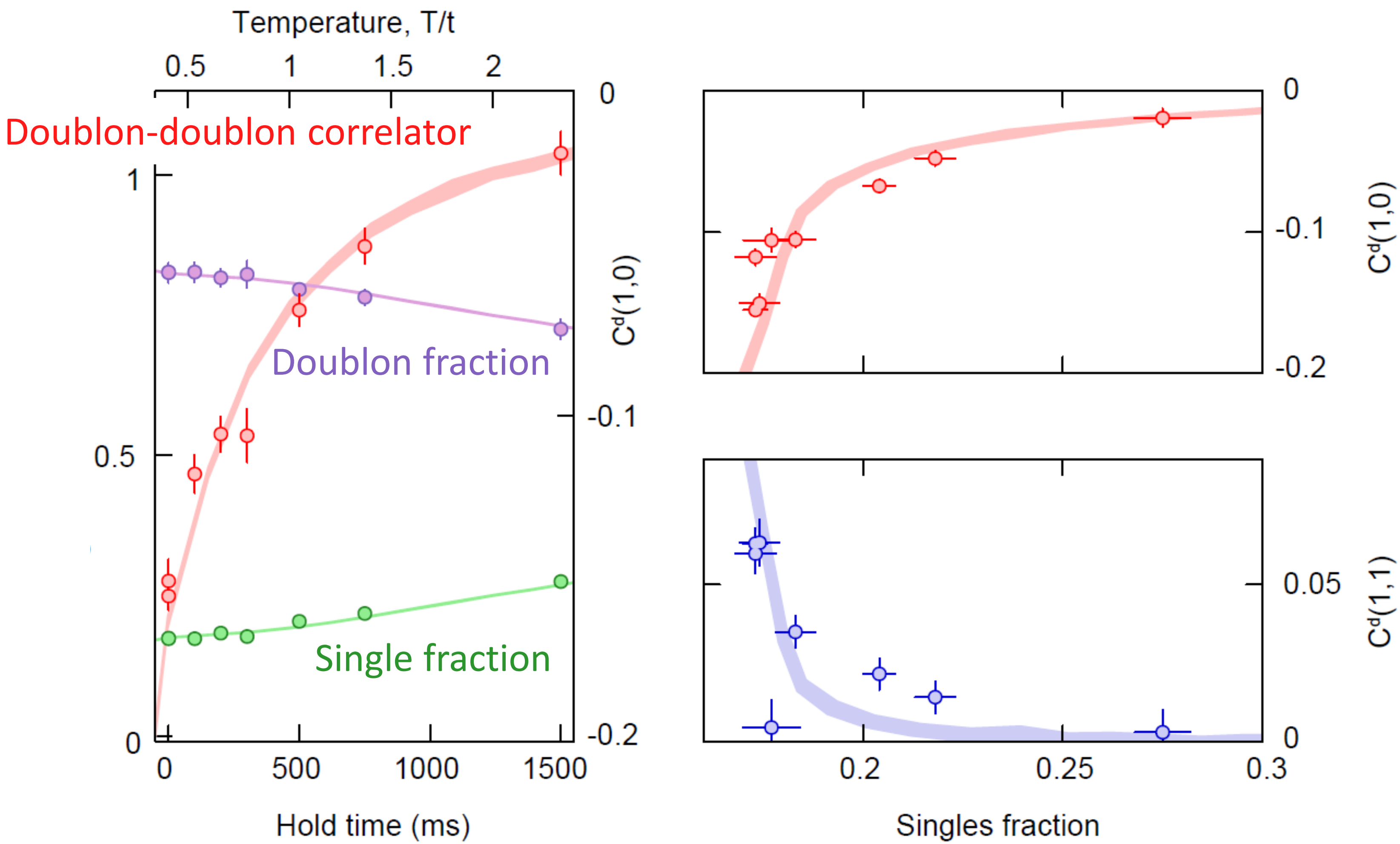


Imaging quality

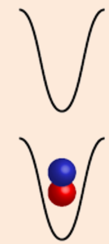




Thermometry in attractive Hubbard system

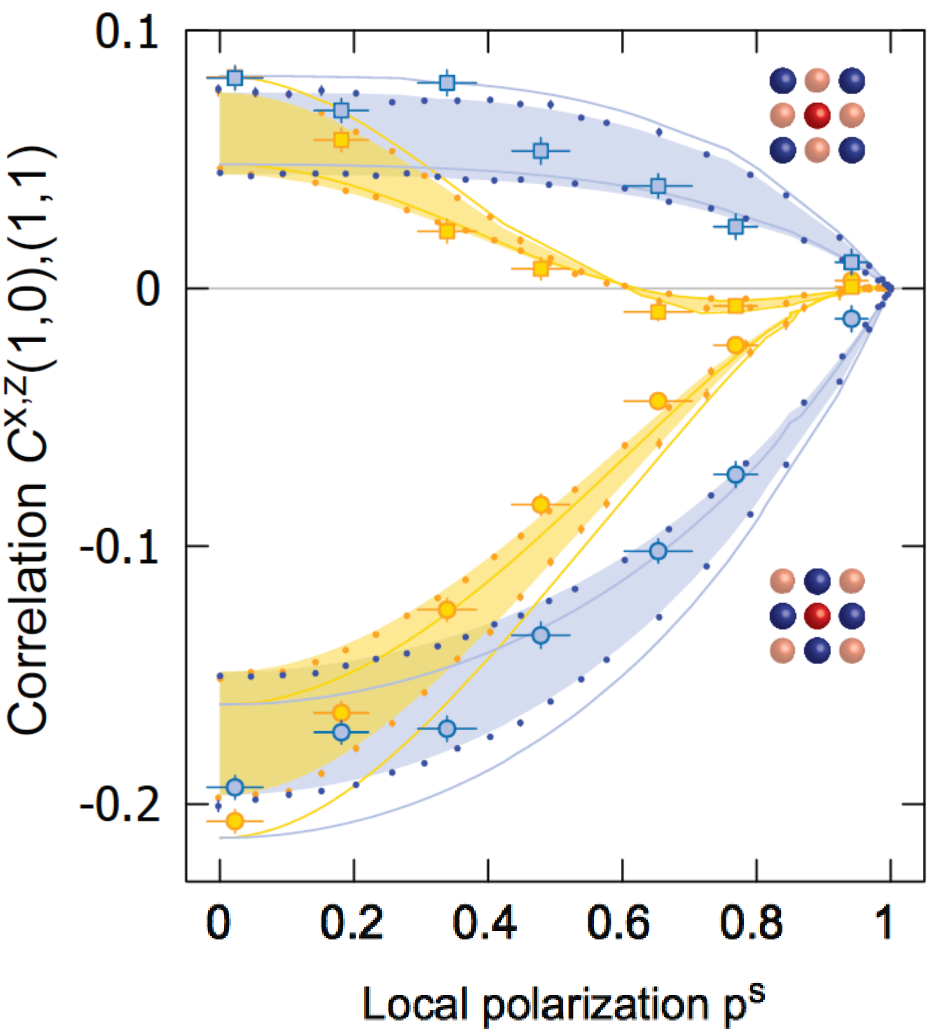


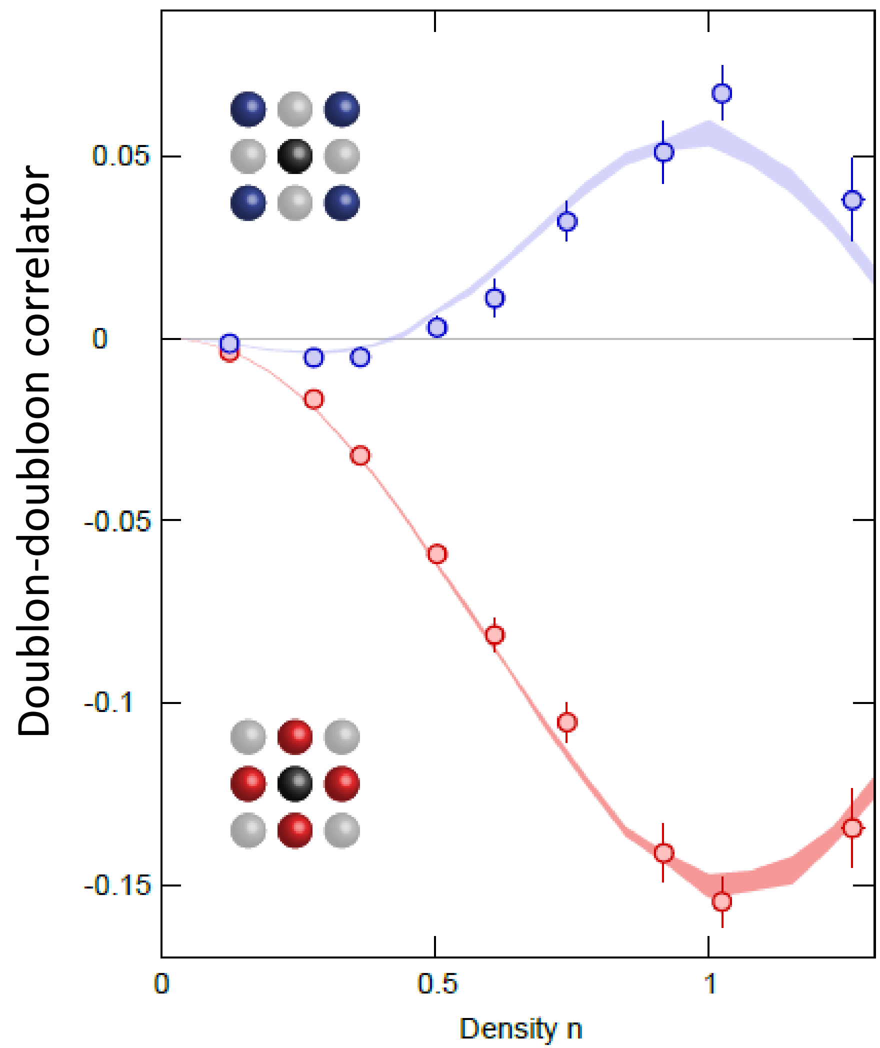
Mapping between the models

Repulsive U > 0	Attractive U < 0
	
Antiferromagnetic z-correlations Antiferromagnetic xy-correlations	Charge density wave correlations s-wave superfluid gap correlations
Spin-imbalanced repulsive model Doped repulsive model	Doped attractive model Spin imbalanced attractive model
Anisotropic antiferromagnetic correlations	Superfluid correlations stronger than charge density wave correlations
d-wave superfluid	d-wave antiferromagnet

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

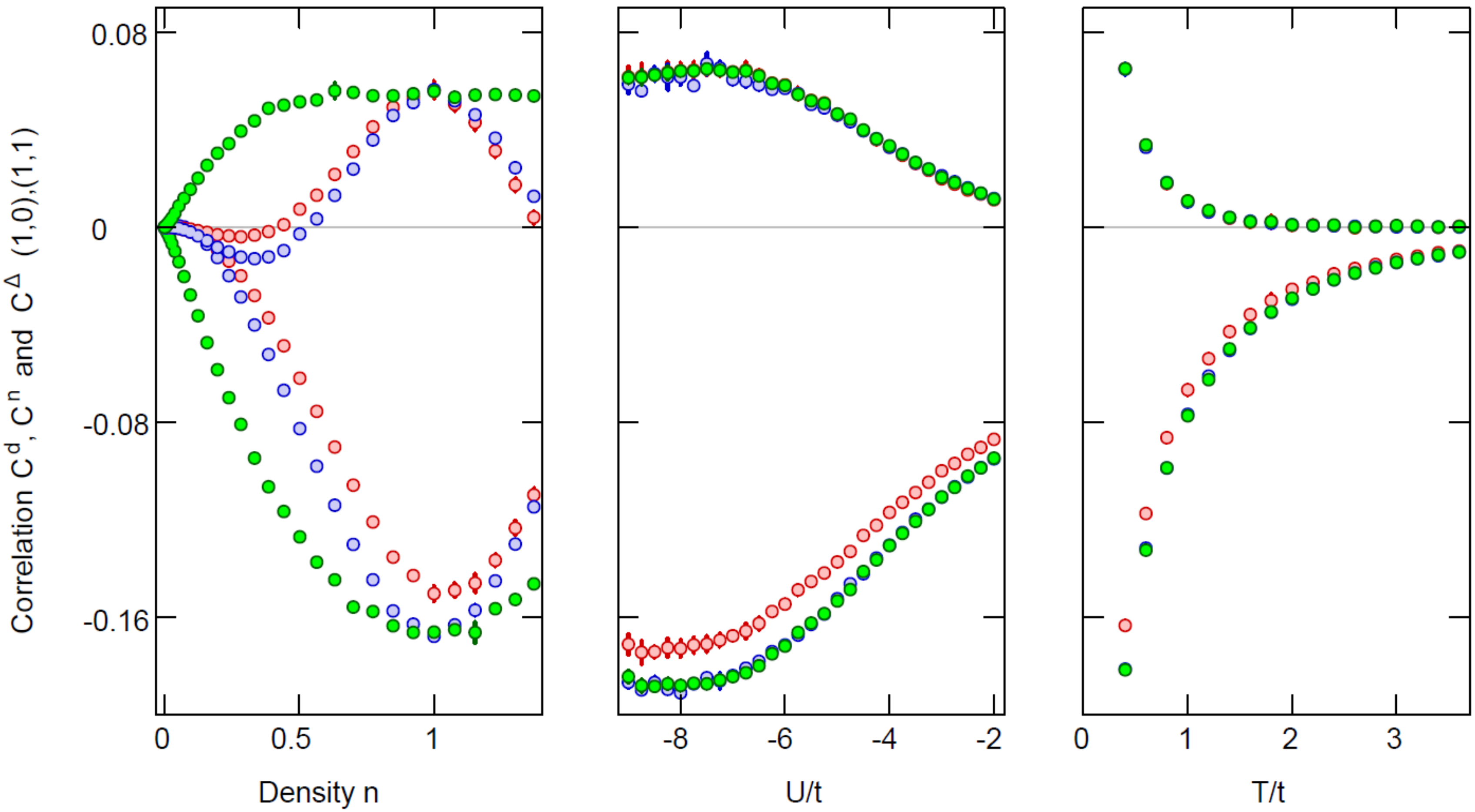
Correlator symmetry





Superfluid correlations

- Doublon-doublon correlations are lower bound for superfluid correlations



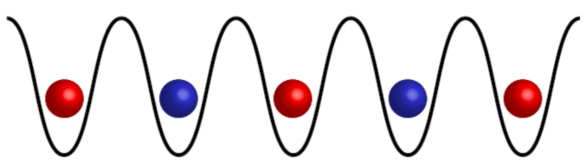
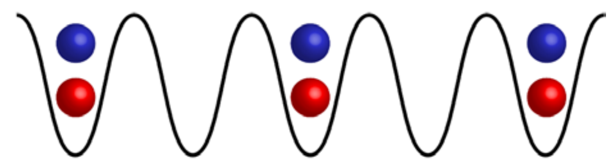
Mapping

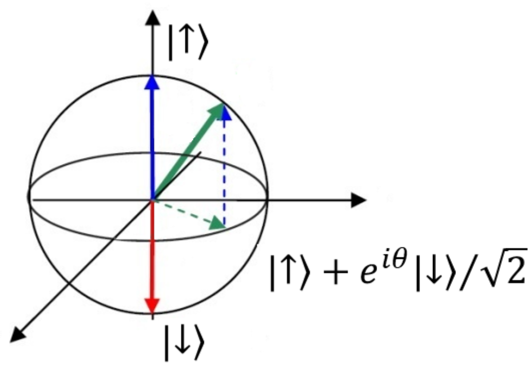
- Repulsive Hubbard $\longleftrightarrow$ Attractive Hubbard

$$c_{\mathbf{r},\uparrow} \longleftrightarrow c_{\mathbf{r},\uparrow}$$

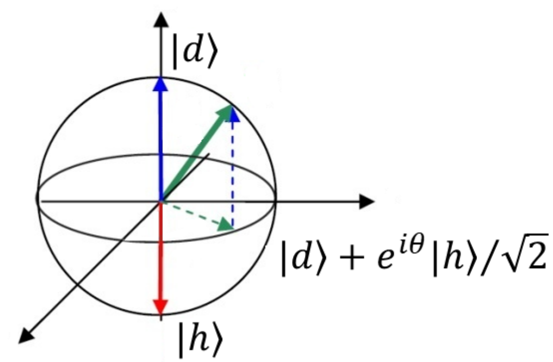
$$c_{\mathbf{r},\downarrow} \longleftrightarrow (-1)^{r_x+r_y}c^{\dagger}_{\mathbf{r},\downarrow}$$

- Anti-ferromagnet $\longleftrightarrow$ CDW

 $\longleftrightarrow$ 



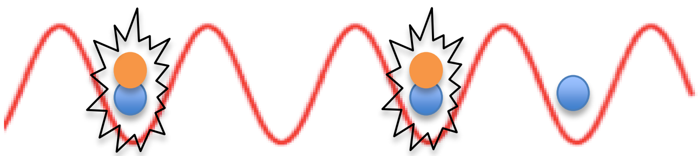
$\longleftrightarrow$



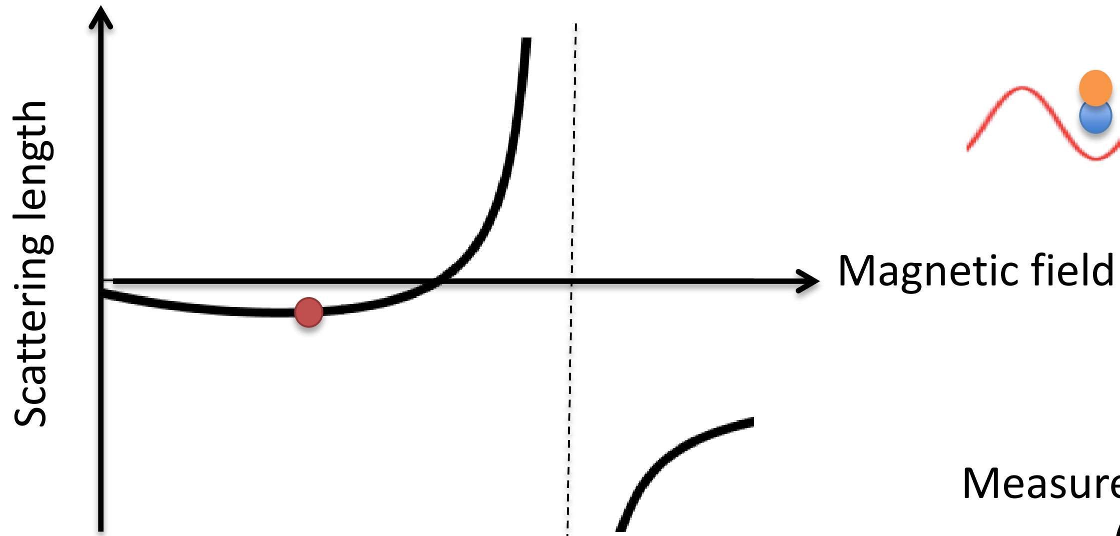
- Operators $S^{\pm}_{\mathbf{r}}, S^{z}_{\mathbf{r}} \longleftrightarrow \eta^{\pm}_{\mathbf{r}}, \eta^{z}_{\mathbf{r}}$
- Spin Imbalance (h) $\longleftrightarrow$ Doping (μ)

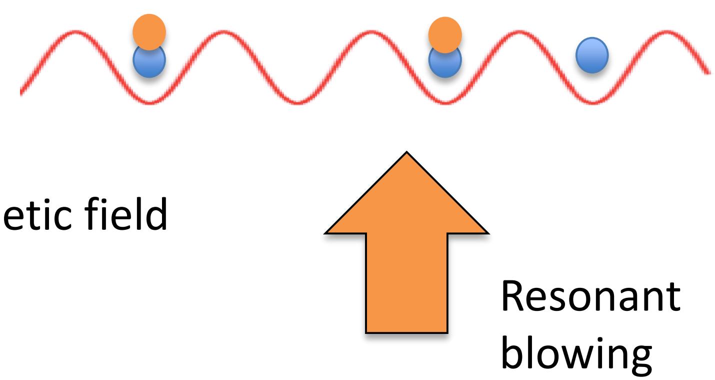
Getting around parity imaging

- Typical quantum gas microscope: light-assisted collisions -> parity imaging.
- But want to distinguish vacancies, singles, doubles.



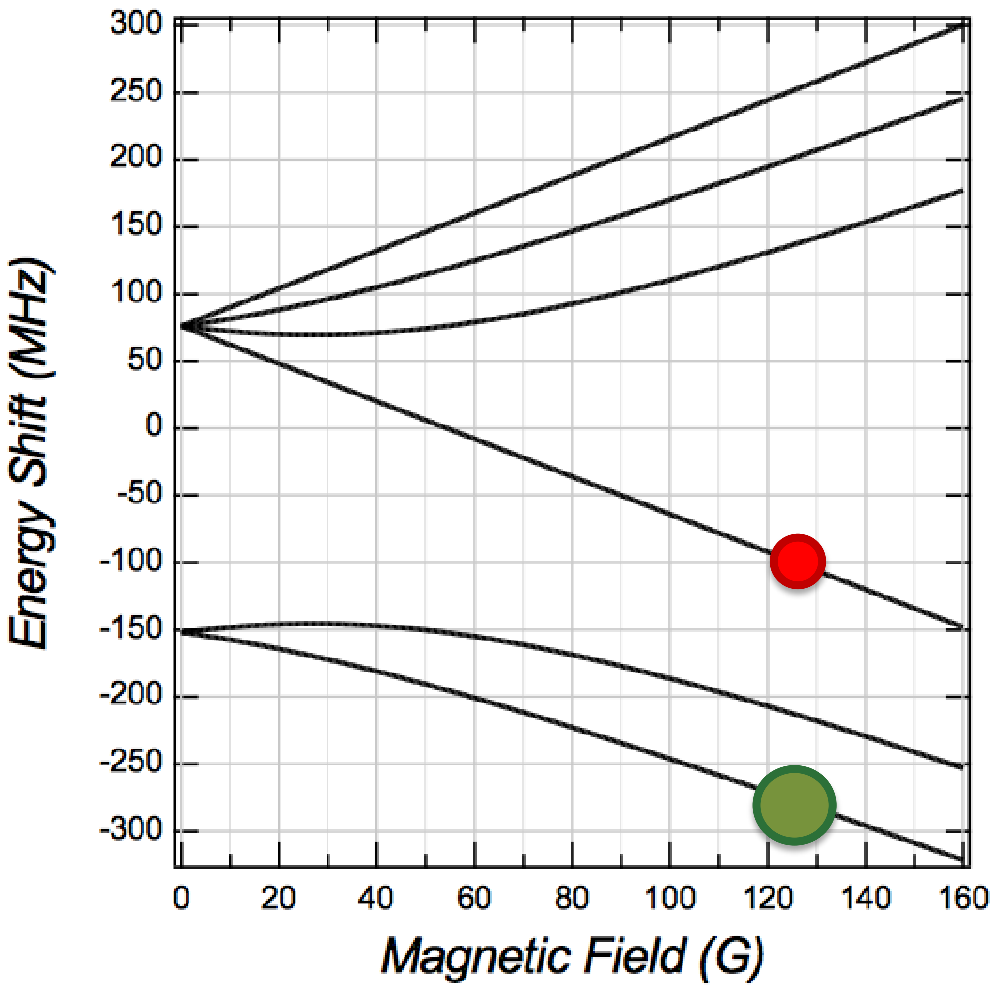
- Light-assisted collisions are density dependent.





Measures true density of blue spins
(not singles density)

Preparing spin-imbalanced lattice gases



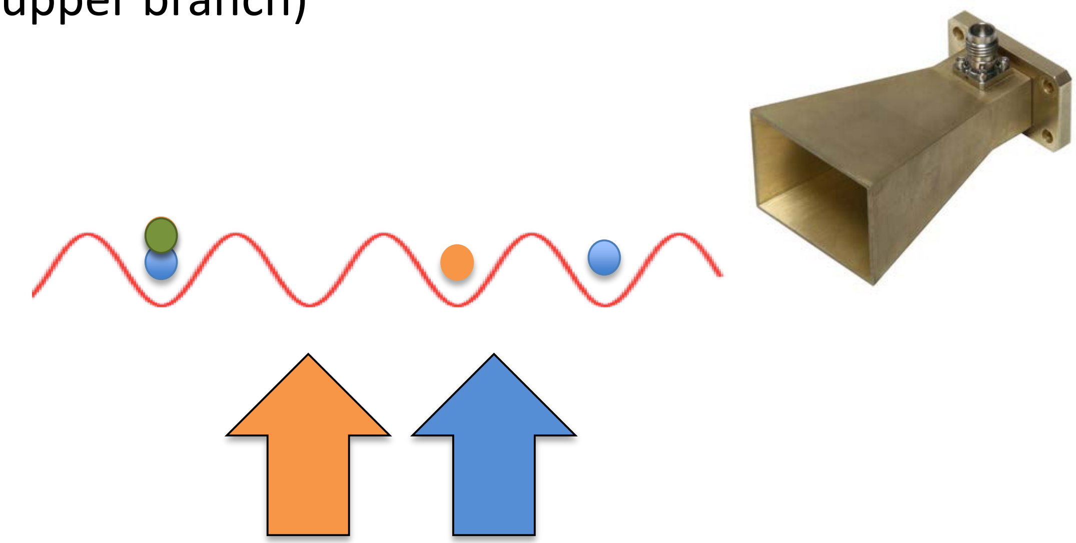
- 1-3 mixture of lithium
- Evaporate in gradient
- Load into lattice at U/t = 8 (594 G, $448a_0$)

$$t = h \times 450(25)\ \mathrm{Hz}$$

Getting around parity imaging

- Even better: combine with radiofrequency spectroscopy of pinned atoms to measures doubles density.
- Works also on lower branch of Feshbach resonance

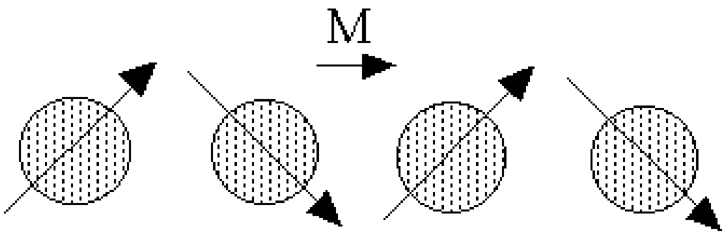
  (do RF transfer to upper branch)



Challenges

- Can we prepare spin-imbalanced gases in a single-band Hubbard regime at low temperatures?

  Answer: yes, can reach T/t = 0.4 without “fancy” techniques in repulsive gases.

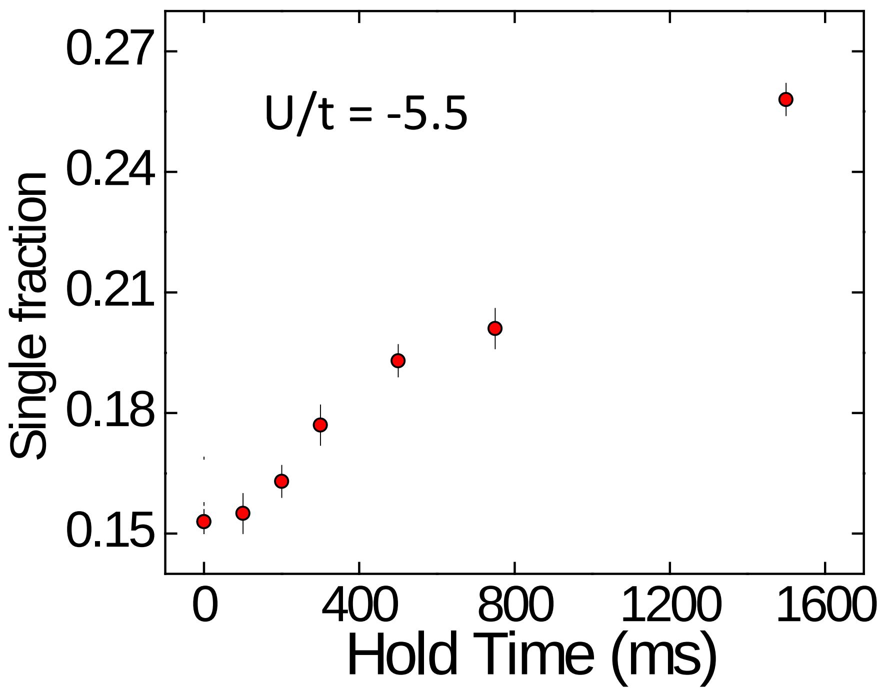


- How we do correlation thermometry on attractive Hubbard systems?

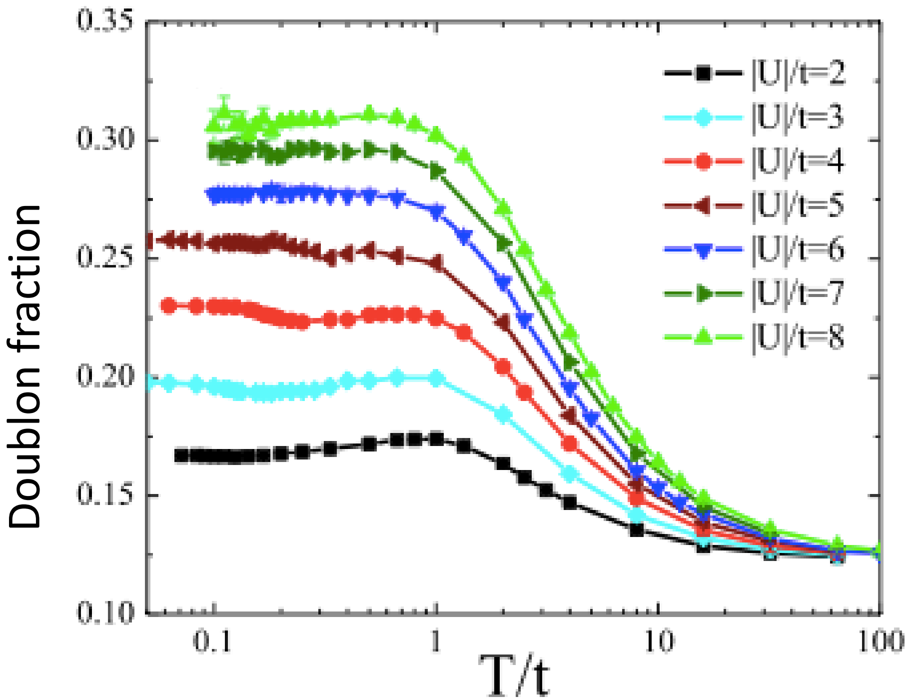
  Answer: yes, we have found a good thermometer in T/t = 0.2 to 1 range.

Singles fraction as a thermometer at high temperatures

PRL 104, 066406 (2010)



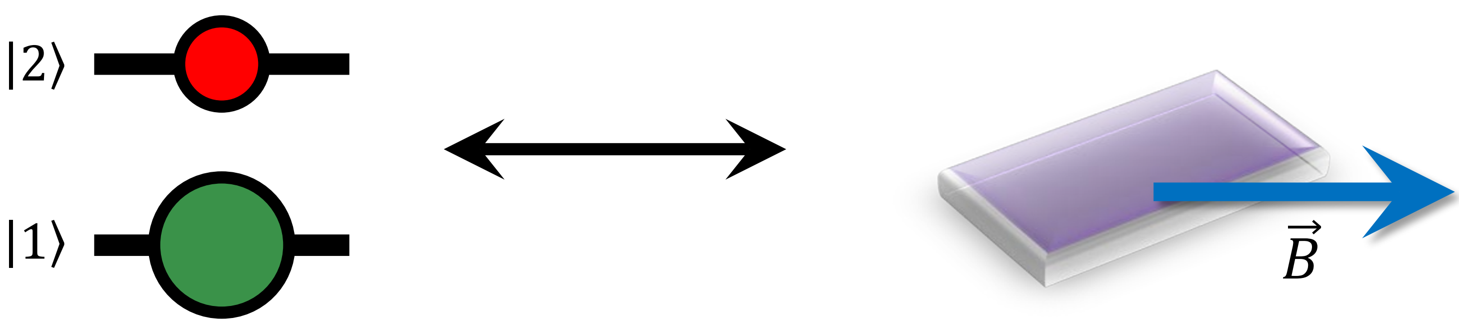
Singles fraction increases as gas heats up during hold time.



As a thermometer, singles fraction stops working at around T/t = 1

Spin imbalance

- Half filling = one atom per site (Mott insulator)
- Spin is conserved, imbalance prepared before loading to lattice
- Condensed matter system:
  Spin imbalance by applied magnetic field



Spin-polarization

Zeeman field

More interesting behavior at larger interaction (U/t = 15)

- Half filling → antiferromagnet

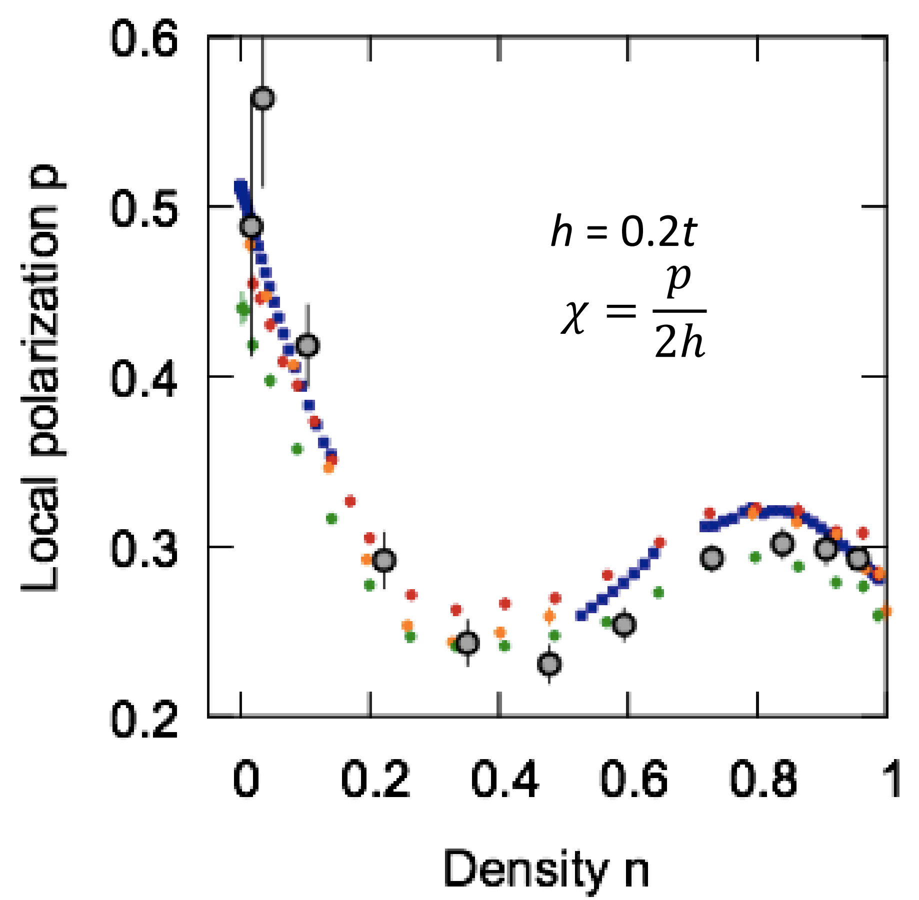
$$\chi_{AF} \propto 1/J = U/4t^2$$

- Small doping: non-degenerate gas of holes in AFM increase susceptibility.
- Intermediate doping: metal

$$\chi_m \propto 1/t$$

Smaller susceptibility than AFM at large U/t.

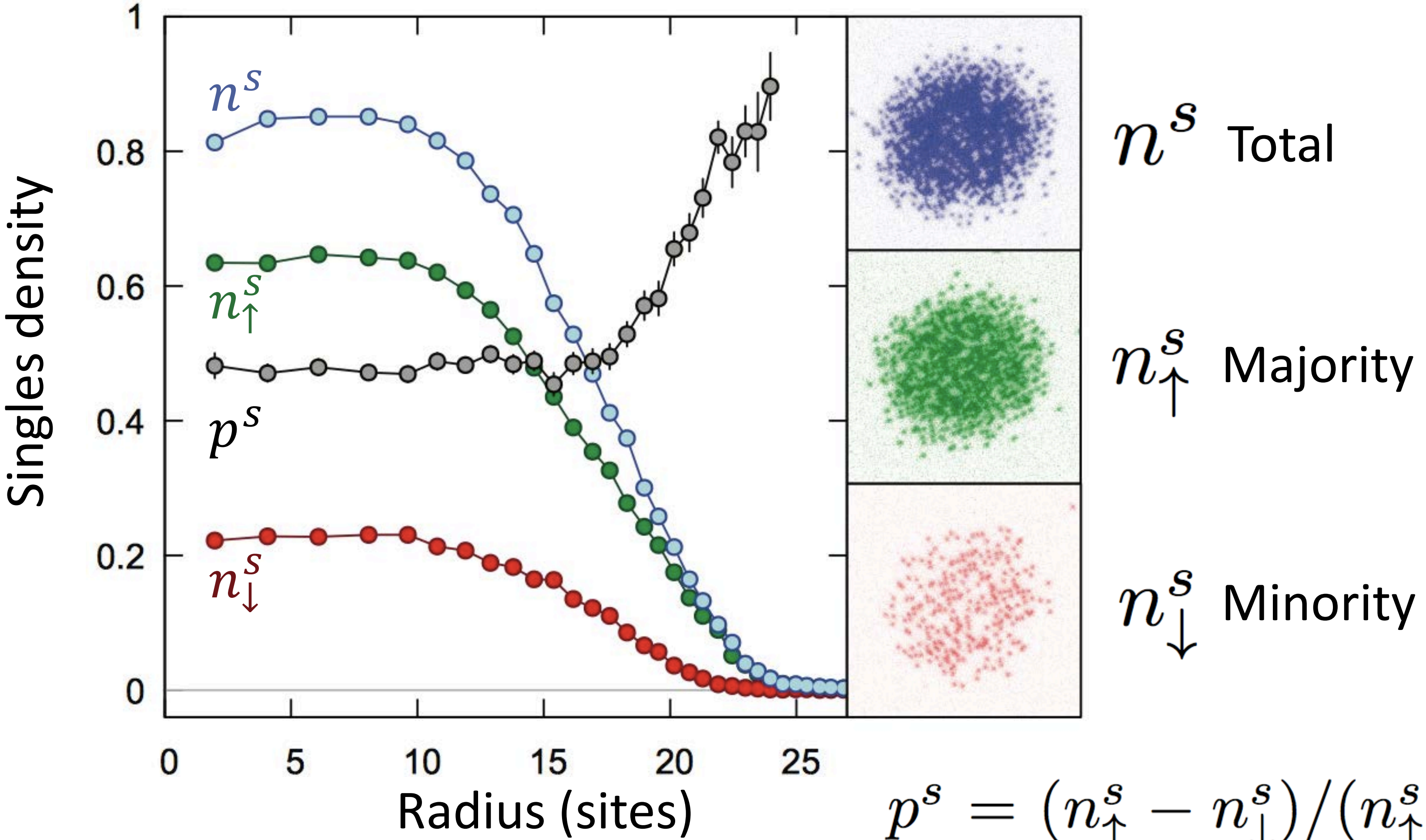
- Large doping: non-degenerate gas of particles.



Hubbard model (exp. & theory) reproduces peak in cuprate susceptibility at about 20% doping.

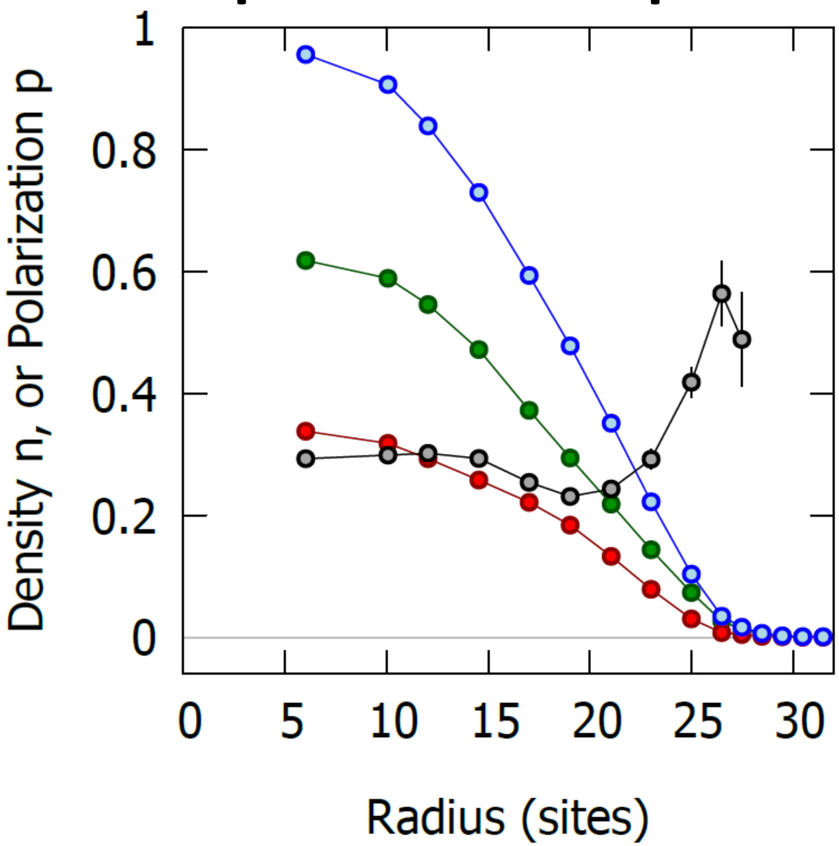
Spin-imbalanced Mott insulators

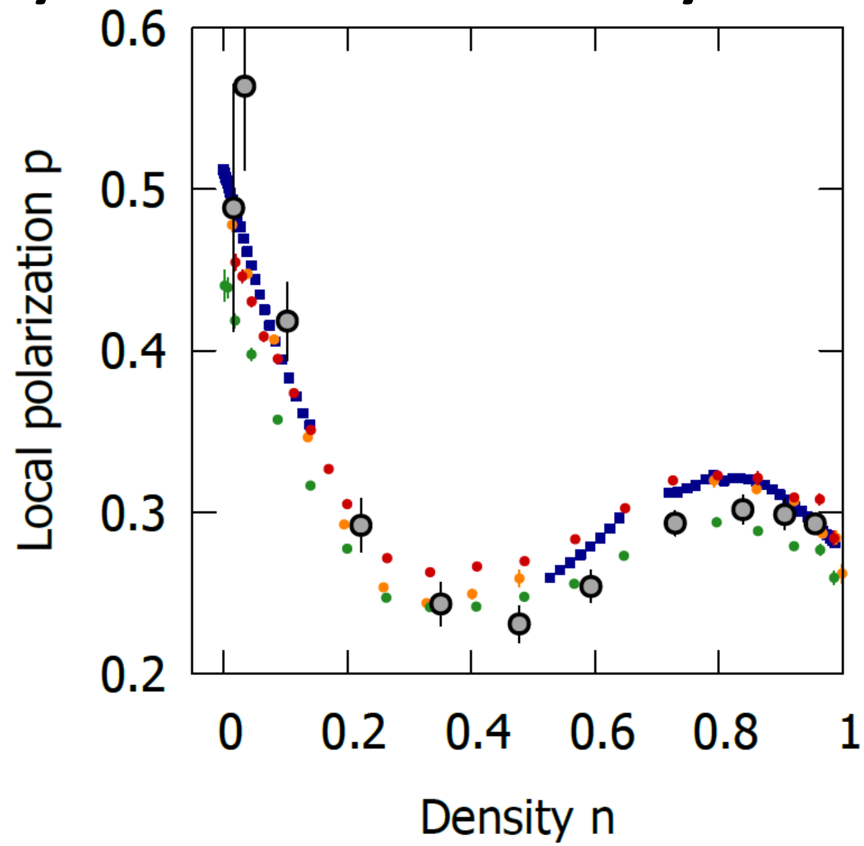
Mott physics is not affected by imbalance
Polarization is constant in Mott insulator region



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

Spin-Susceptibility versus Density





- (*linear regime*)
- AF region,
- Metallic region,

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

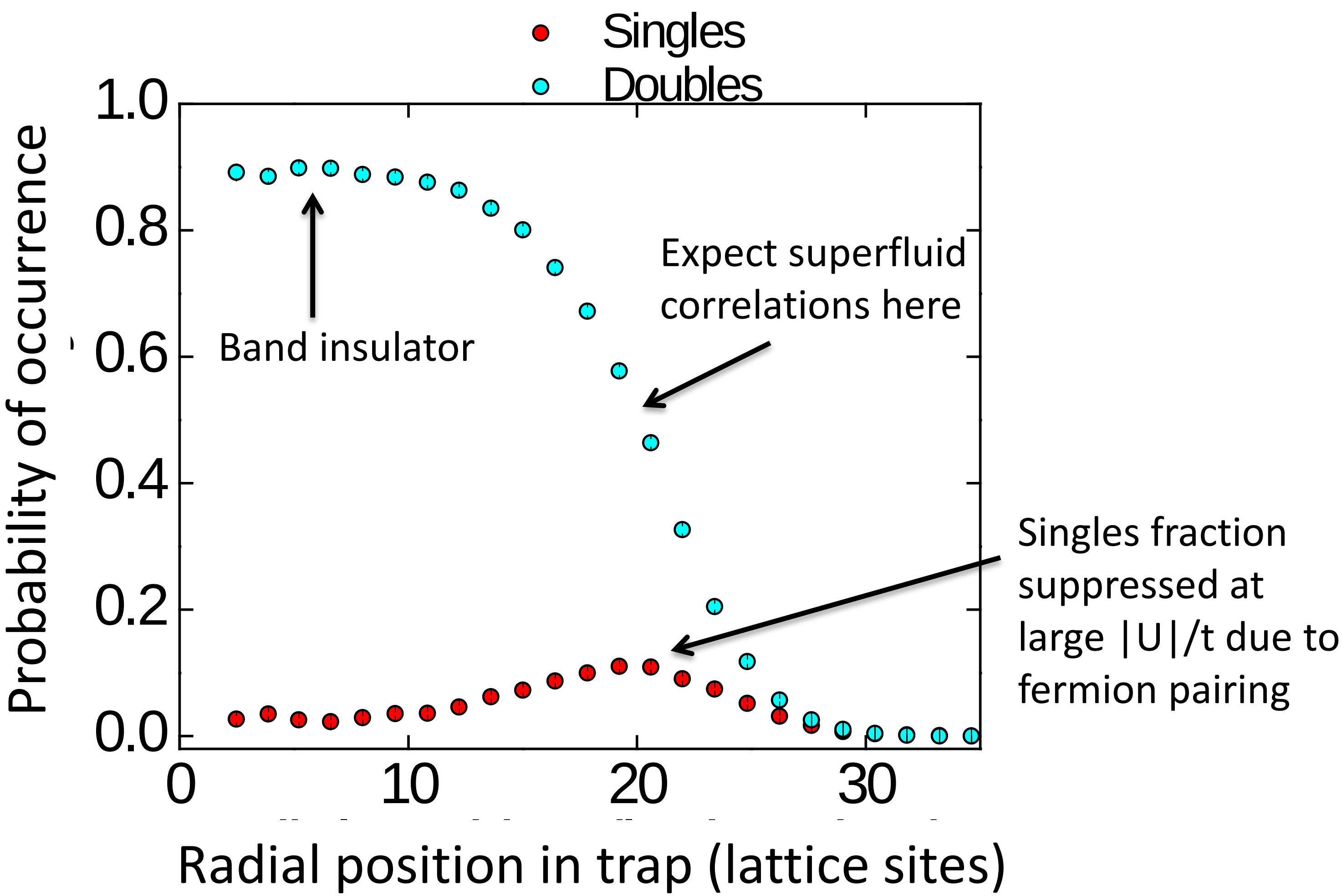
A dictionary between the models

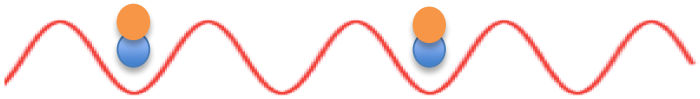
Phys. Rev. A **79**, 033620 (2009)

Repulsive U	Attractive U
Mott insulator	Preformed pairs
Antiferromagnetic z-correlations Antiferromagnetic xy-correlations	Charge density wave correlations s-wave superfluid gap correlations
Spin-imbalanced repulsive model Doped repulsive model	Doped attractive model Spin imbalanced attractive model
Anisotropic antiferromagnetic correlations	Superfluid correlations stronger than charge density wave correlations
d-wave superfluid	d-wave antiferromagnet

Aside: by measuring charge density wave correlations, we know we must have s-wave superfluid correlations in our single-band Hubbard model!

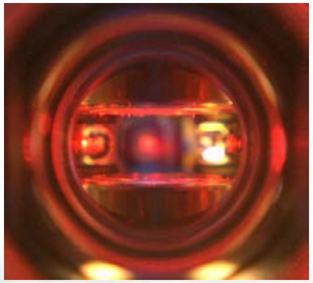
Density profile of attractive lattice gas

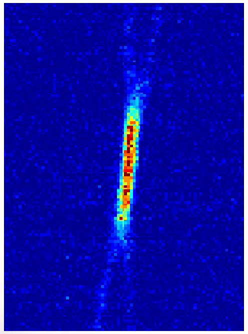


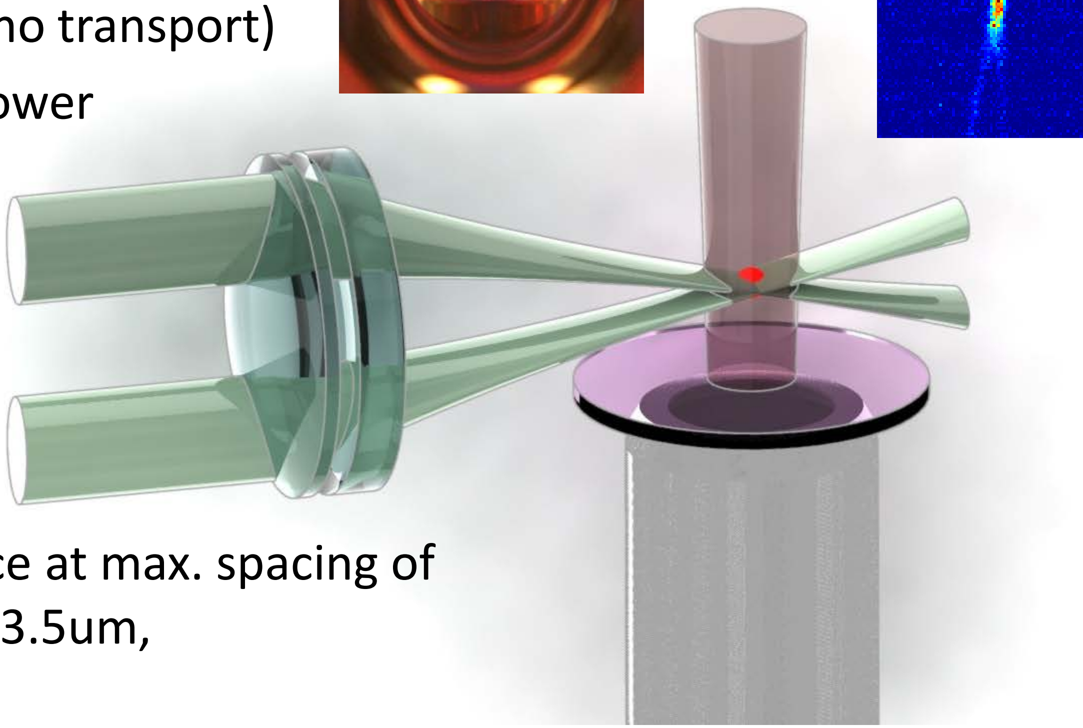


A simplified Fermi gas microscope

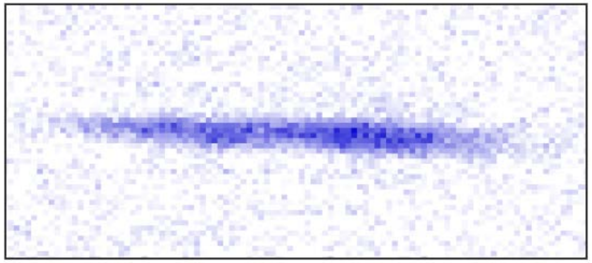
- Single chamber
- ^{6}Li Oven + Zeeman slower
- MOT through objective (no transport)
- Load straight into high power ODT for evaporation.

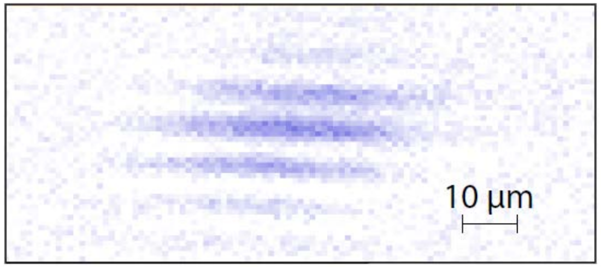






- Load into light sheet.
- Load into accordion lattice at max. spacing of 12um, then compress to 3.5um, trap frequency 20 kHz.





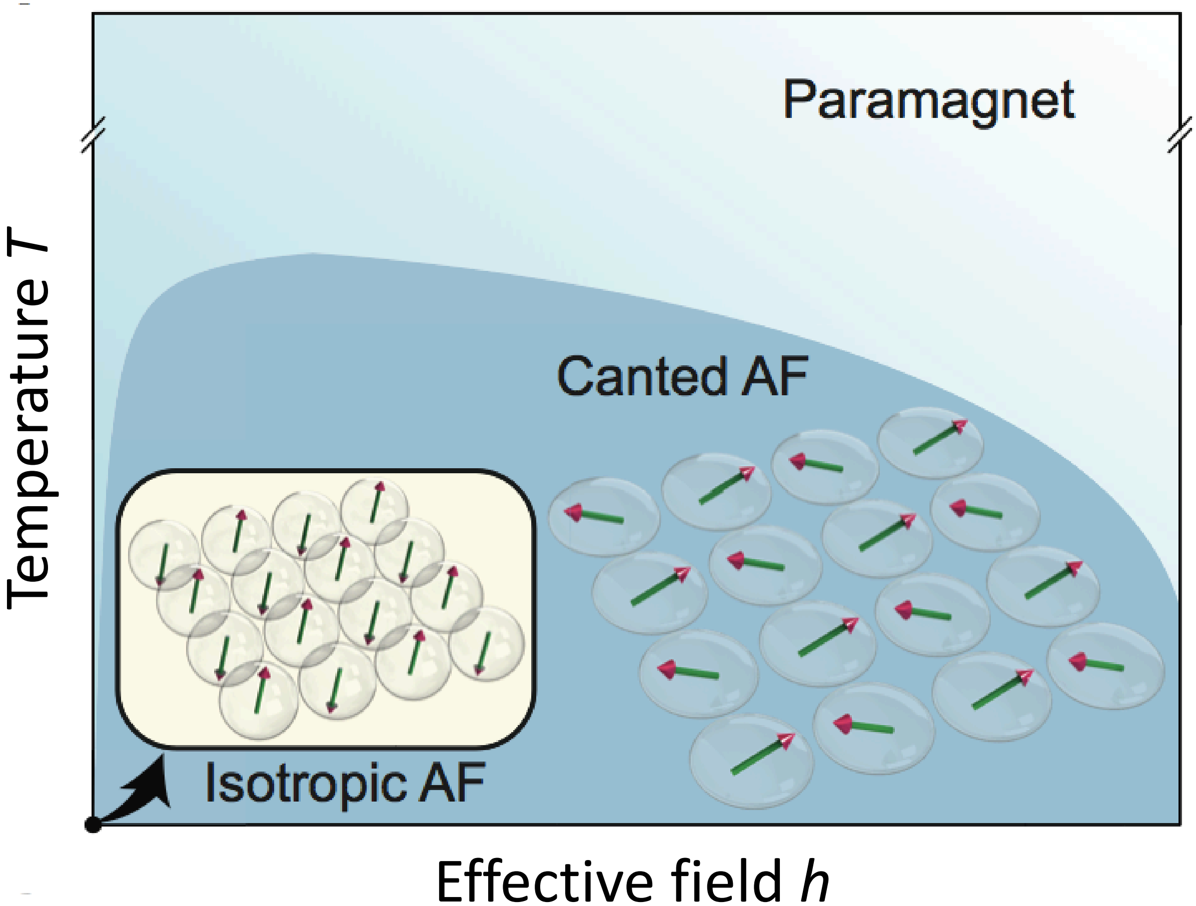
Spin-imbalance at half-filling

Heisenberg model in an effective field

$$\mathcal{H} = J \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j - 2h \sum_i S_i^z$$

$$h = (\mu_\uparrow - \mu_\downarrow)/2$$

$$S_{\mathbf{i}}^z = \frac{1}{2}(n_{\mathbf{i},\uparrow} - n_{\mathbf{i},\downarrow})$$



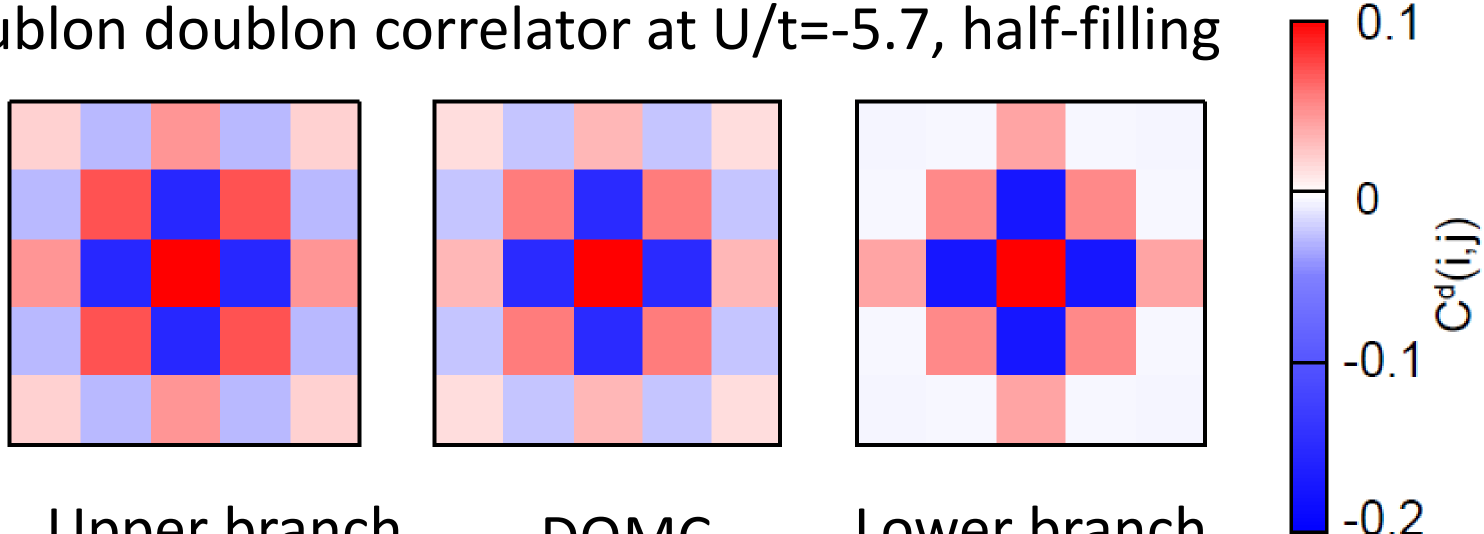
$h = 0$:
SU(2) symmetric AFM
Exponentially decaying correlations, diverging correlation length at $T = 0$

$|h| > 0$:
BKT-transition to canted AFM

AFM correlations build up preferably in XY plane.

Observation of charge density wave correlations

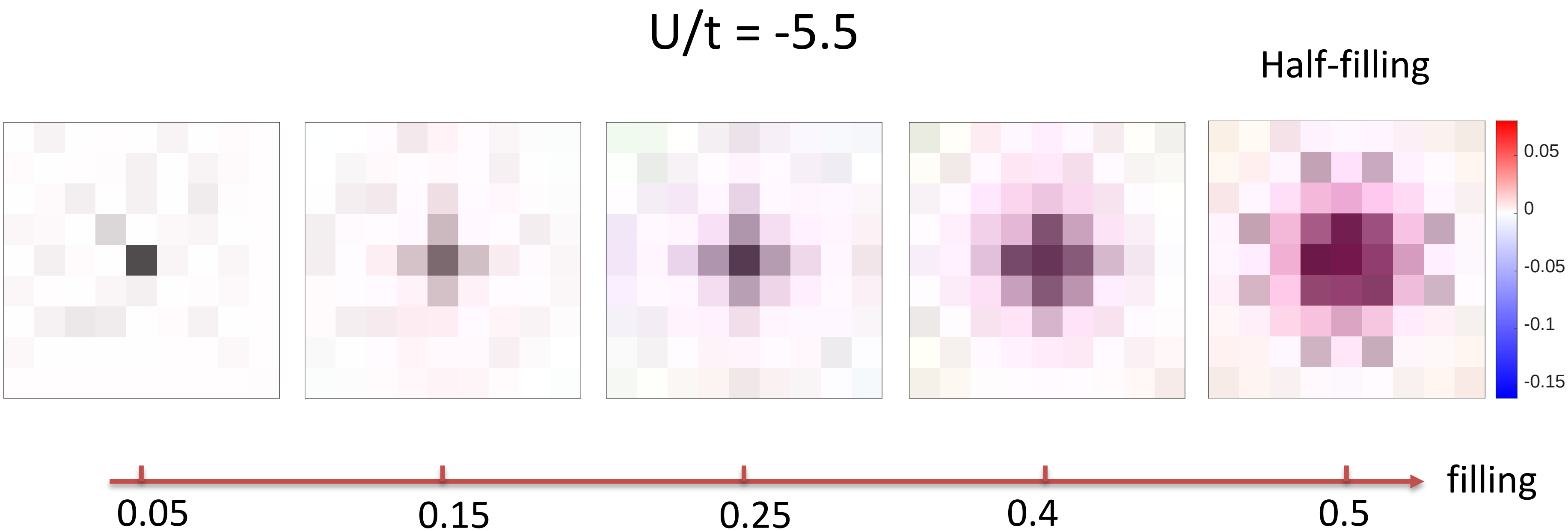
Doublon doublon correlator at U/t=-5.7, half-filling



Upper branch DQMC Lower branch

- Yields T/t = 0.45
- thermometry in regime where singles fraction loses sensitivity.

Charge density wave correlations get weaker away from half-filling



- Superfluidity competes with charge density wave order away from half-filling and eventually wins.

Motivation: the FFLO phase

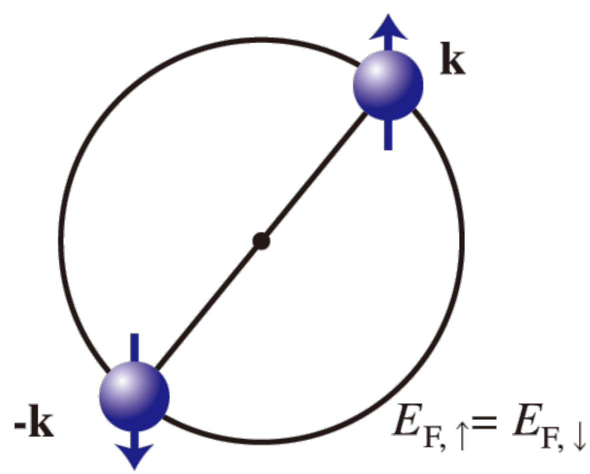
- FFLO phase: superfluid with spatially inhomogeneous gap. Needs spin-imbalance + attractive interactions.

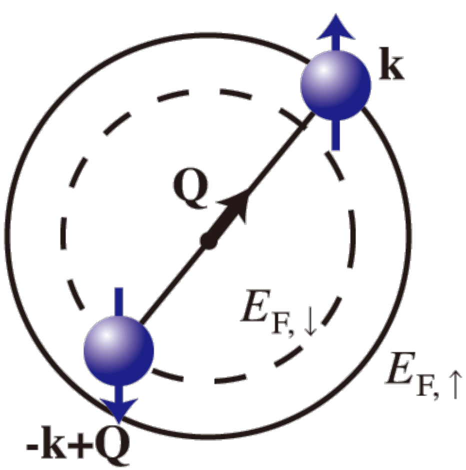
Continuum system (no lattice):

- Balanced superfluid: condensate of Q=0 pairs (JILA, MIT)
- Spin-imbalance in 3D: phase separation, Clogston limit (MIT, Rice)

Missing: Fulde-Ferrell-Larkin-Ovchinnikov (1964): Q≠0

BCS

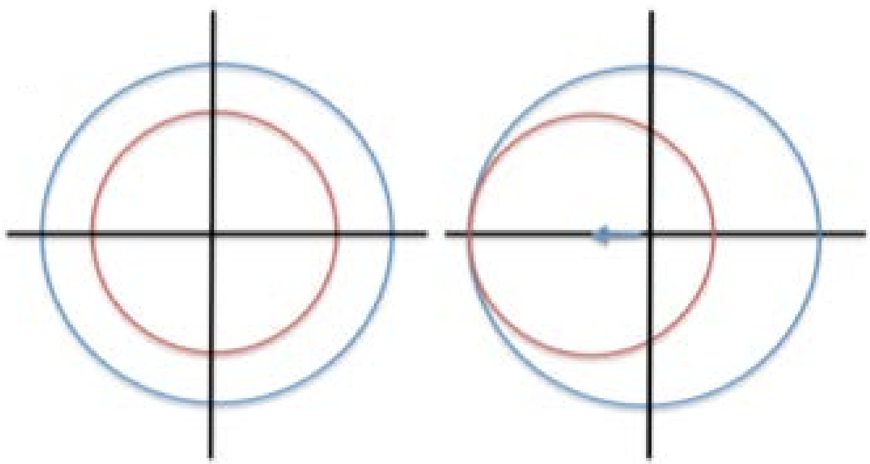




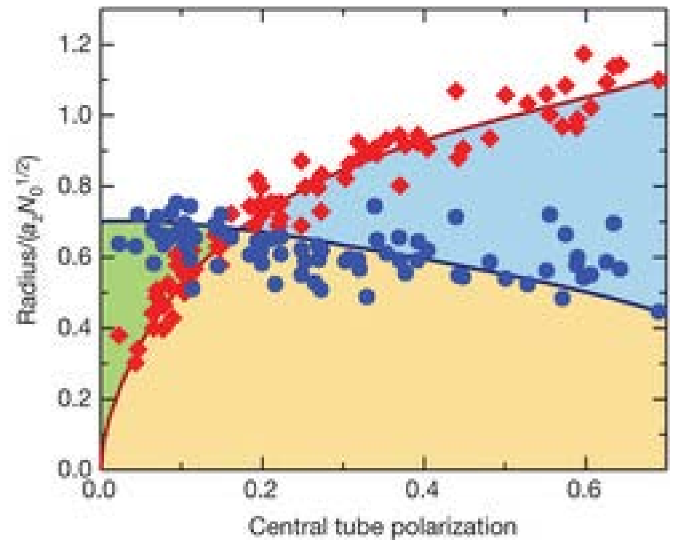
FFLO

Enhancing the FFLO phase: lower dimensionality

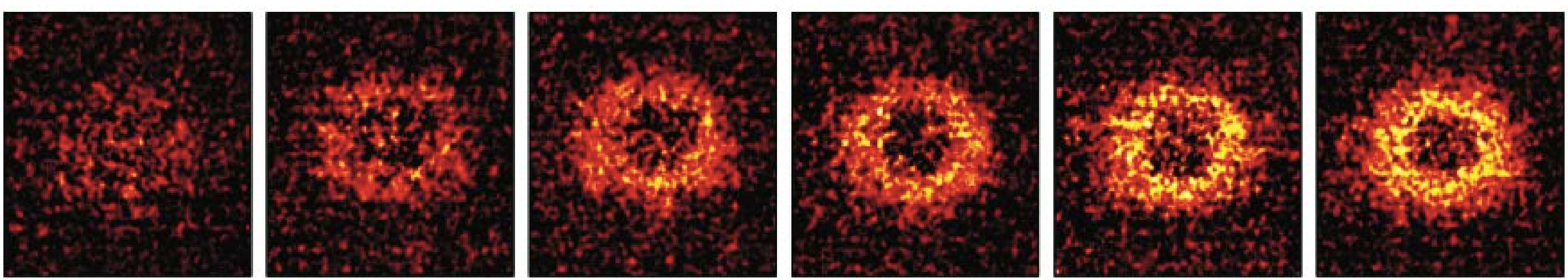
Lower dimensionality (1D or 2D) is better.



1D (Rice): consistent with FFLO

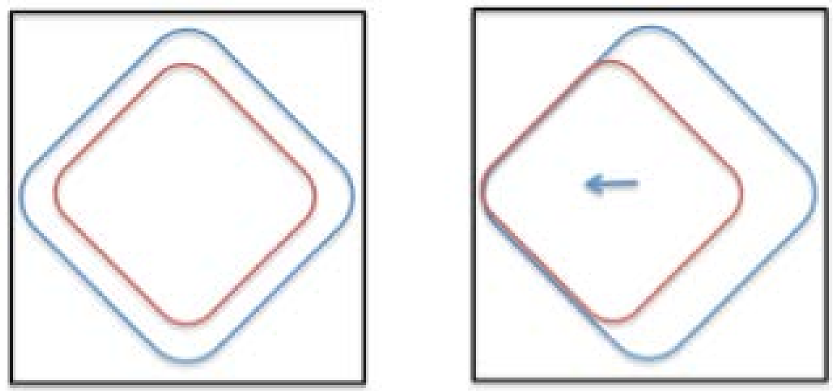


2D (J. Thomas group, Princeton): phase separation, observed like in 3D at MIT/Rice



Enhancing the FFLO phase: Fermi surface nesting

Adding a lattice provides better Fermi surface nesting.



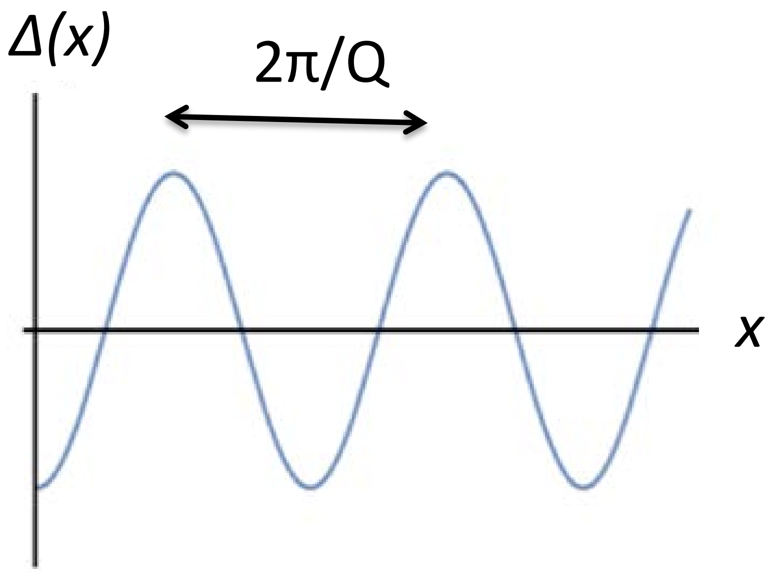
Hubbard model, $U/t=-4$, FFLO @ $T/t \approx 0.1$ (Troyer group)

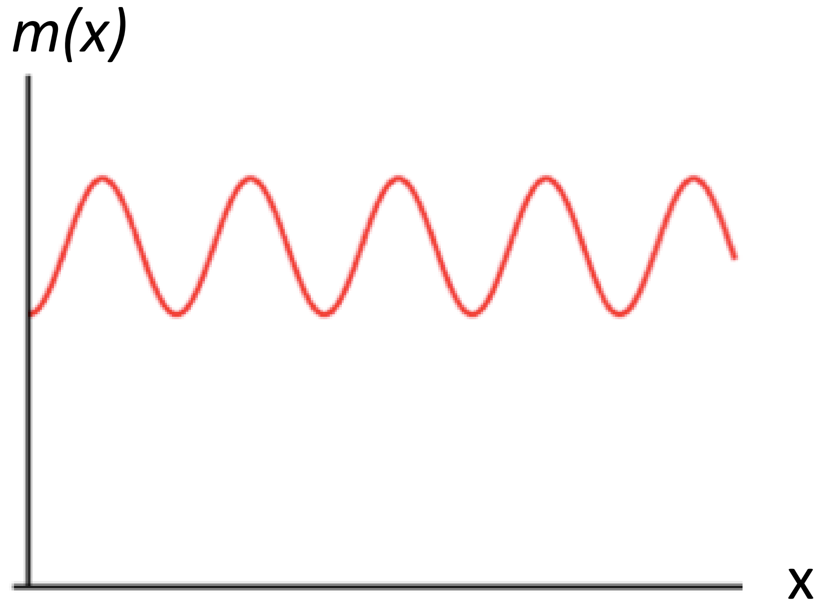
Direct detection options:

Momentum space: condensation at Q (weak signatures, blurred by trap averaging in time of flight).

Real space detection?

Direct signatures of the FFLO phase





Periodic modulation of gap

Periodically varying polarization

Proposal: detection of FFLO correlations in a Hubbard lattice with quantum gas microscopy.