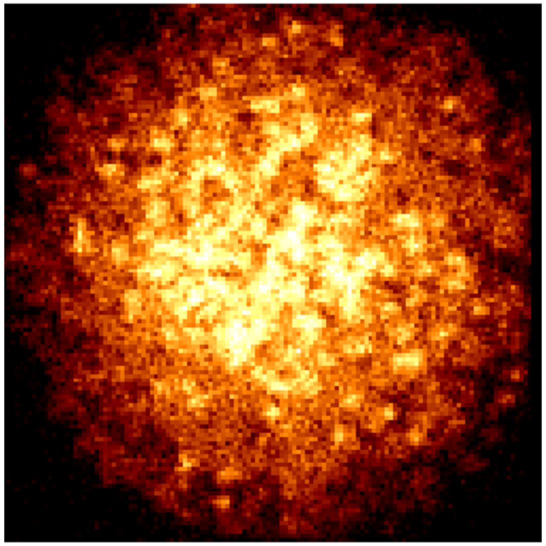
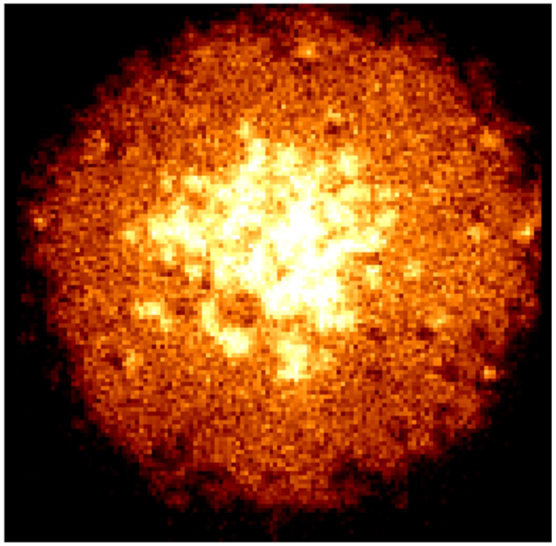
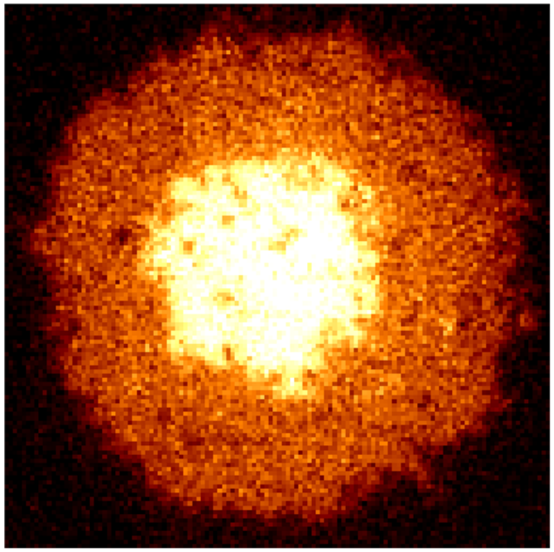
ICTS Summer School, May 17th, 2021

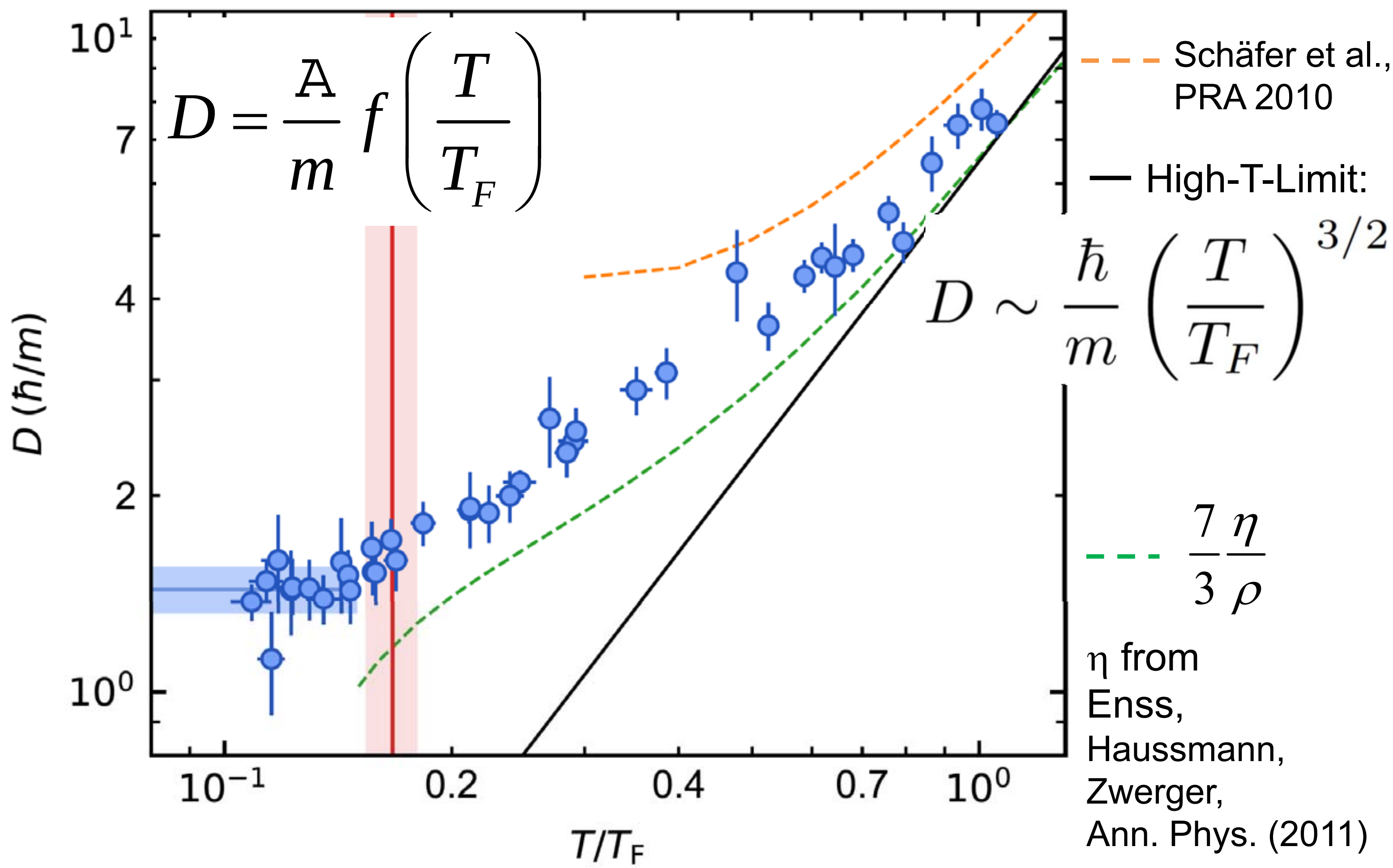
1. Superfluid Fermi Gases (cont.)
2. Quantum Simulation and Quantum Storage with Fermi Gases

Martin Zwierlein
Massachusetts Institute of Technology
Center for Ultracold Atoms

GORDON AND BETTY MOORE FOUNDATION

Quantum Limited Sound Diffusion



P. Patel, Z. Yan, B. Mukherjee, R. Fletcher, J. Struck, MZ, Science, 370, 1222-1226 (2020)

Unitary Two-Fluid Hydrodynamics

For 1D flow, linearized:

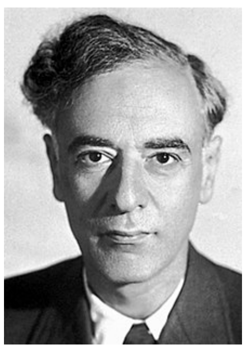
Laszlo Tisza

$$\frac{\partial \rho}{\partial t} + \frac{\partial j}{\partial z} = 0$$

Continuity equation

$$\frac{\partial j}{\partial t} + \frac{\partial p}{\partial z} = \frac{4}{3}\eta \frac{\partial^2 v_n}{\partial^2 z}$$

Navier-Stokes eq.
viscosity
damps normal fluid



Lev Landau

$$\frac{\partial s}{\partial t} + \frac{\partial (v_n s)}{\partial z} = \frac{\kappa}{T}\frac{\partial^2 T}{\partial^2 z}$$

Entropy moving
with normal fluid,
thermal conduction
increases entropy

Superfluid flow:

$$\frac{\partial v_s}{\partial t} + \frac{\partial \mu / m}{\partial z} = \rho_s \zeta_3 \frac{\partial^2 (v_s - v_n)}{\partial^2 z}$$

bulk viscosity
normal-superfluid
interconversion

+Thermodynamics relating p, ρ, T, s, μ

No other transport coefficients (ζ_1, ζ_2, ζ_4)
due to scale invariance (Son, Stringari&Pitaevskii)

First and Second Sound

Two fluids → Two sound modes

Review: Stringari&Pitaevskii
arXiv:1510.01306

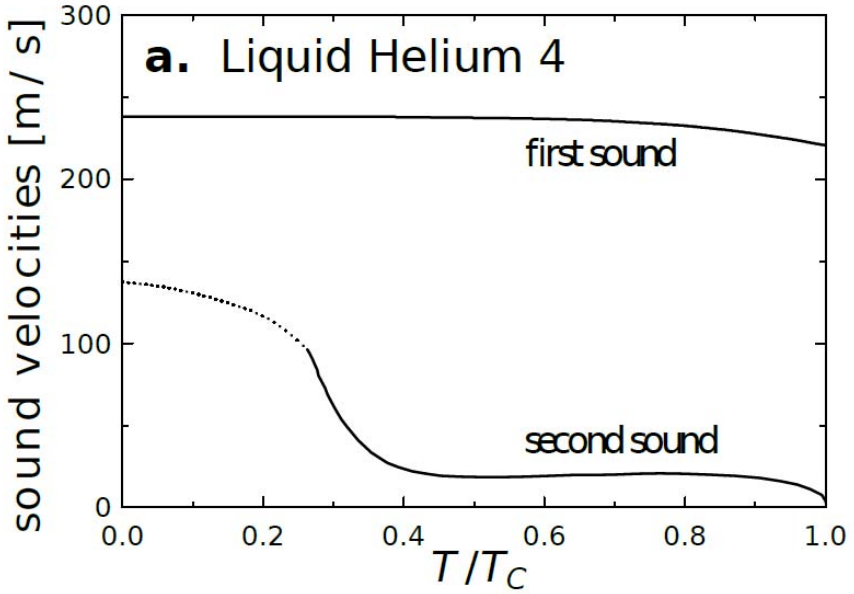
For small expansivity: Density and Heat

$$c_{10}^2 = \left.\frac{\partial p}{\partial \rho}\right|_{S,N} = \frac{1}{\rho \kappa_s}$$

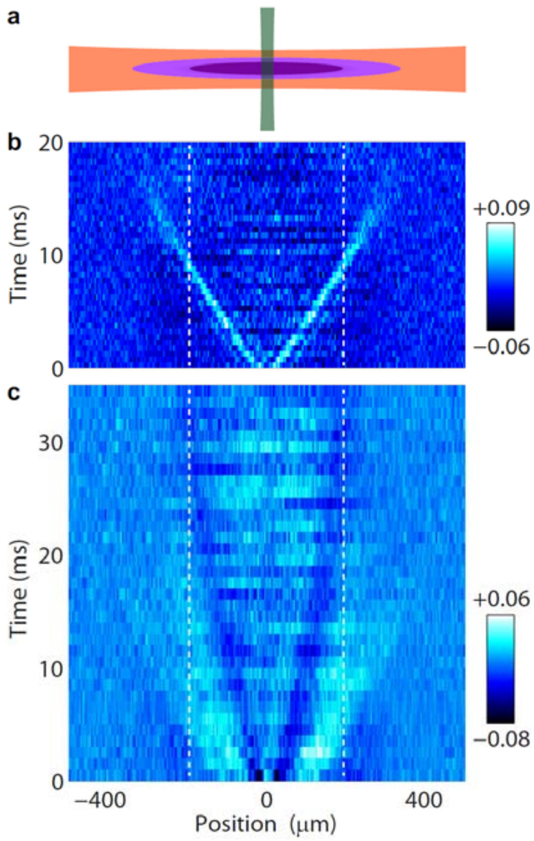
First sound, a density wave
normal and superfluid
oscillate in phase

$$c_{20}^2 = \frac{\rho_s}{\rho_n} \left.\frac{\partial T}{\partial \sigma}\right|_{\rho} \frac{\sigma^2}{\gamma} = \frac{\rho_s}{\rho_n} \frac{\sigma^2 T}{c_p}$$

Second sound, a heat wave,
normal and superfluid oscillate out of phase



Experimental observation in a trap



Innsbruck experiment
in quasi-1D geometry
→ Allowed to heat radially
and thanks to the non-zero
expansivity at unitarity
observe second sound
in the density

Sidorenkov et al., Grimm, Stringari&Piatevskii, Nature 2013

On bosons: weakly interacting situation: JILA (D. Jin 1996), MIT

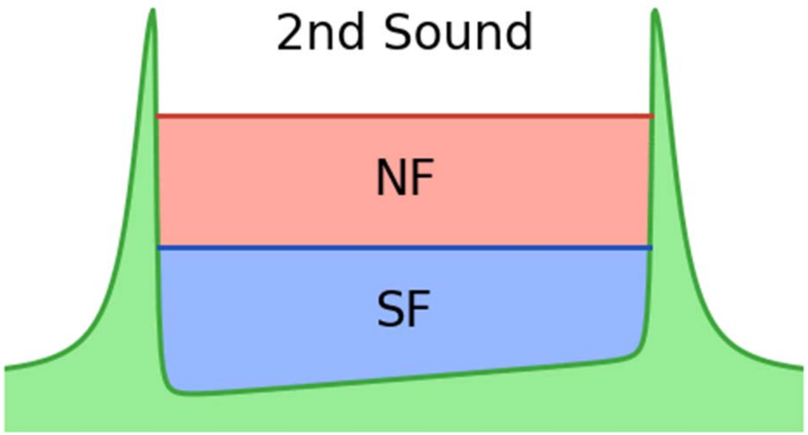
Hydrodynamic gas: van der Straten

Second sound in a box

(Isentropic) expansivity at unitarity $-\frac{1}{\rho}\frac{\partial\rho}{\partial T}\Big|_S = -\frac{3}{2}\frac{1}{T}$ always non-zero

→ Can drive temperature wave using potential acting on density

Apply oscillating gradient to the box



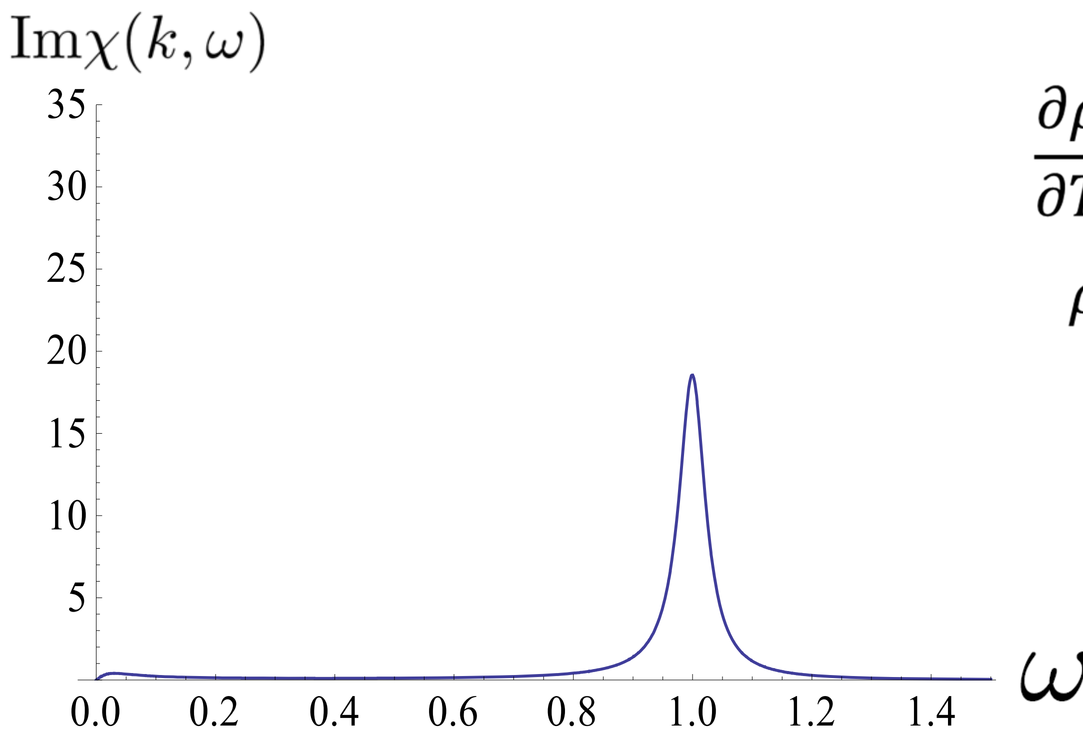
Observation of Second Sound in Quasi-1D geometry:
Sidorenkov et al., Grimm, Stringari&Piatevskii, Nature 2013

On bosons: weakly interacting situation: JILA (Debbie Jin 1996), MIT
Hydrodynamic gas: van der Straten

Density response to a potential drive

Hohenberg, Martin 1965

$$\chi(k,\omega) = \frac{\delta\rho}{\delta V} = \frac{\rho k^2 N(\omega,k)}{(\omega^2 - c_1^2 k^2 + i\,\Gamma_1\omega)(\omega^2 - c_2^2 k^2 + i\,\Gamma_2\omega)}$$



$$\left.\frac{\partial\rho}{\partial T}\right|_p \neq 0$$

$$\rho_s = 0$$

Density response to a potential drive

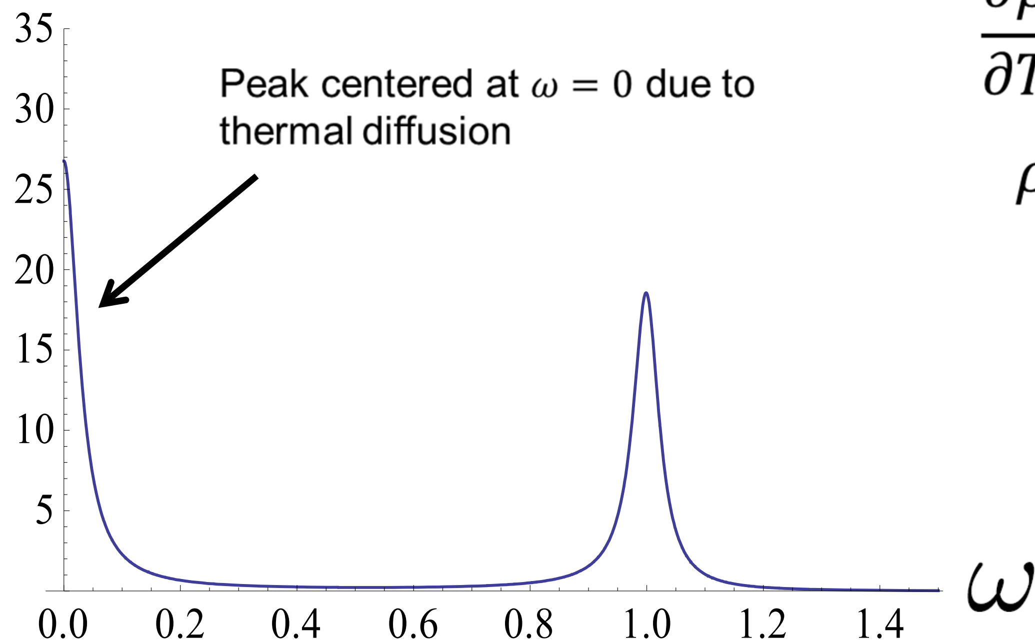
Hohenberg, Martin 1965

$$\chi(k,\omega) = \frac{\delta\rho}{\delta V} = \frac{\rho k^2 N(\omega,k)}{(\omega^2 - c_1^2k^2 + i\,\Gamma_1\omega)(\omega^2 - c_2^2k^2 + i\,\Gamma_2\omega)}$$

Step response

Response for Brillouin Scattering e.g. Greytak (1970s…)

$$\frac{1}{\omega}\mathrm{Im}\chi(k,\omega)$$



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Density response to a potential drive

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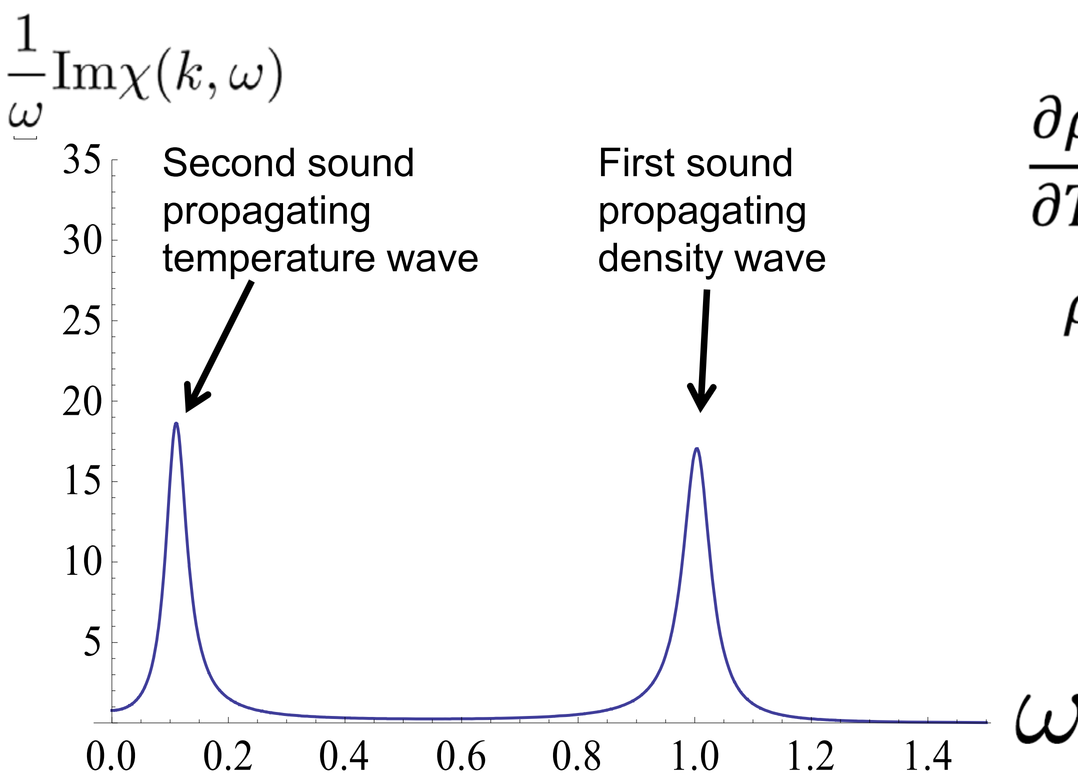

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Density response to a potential drive

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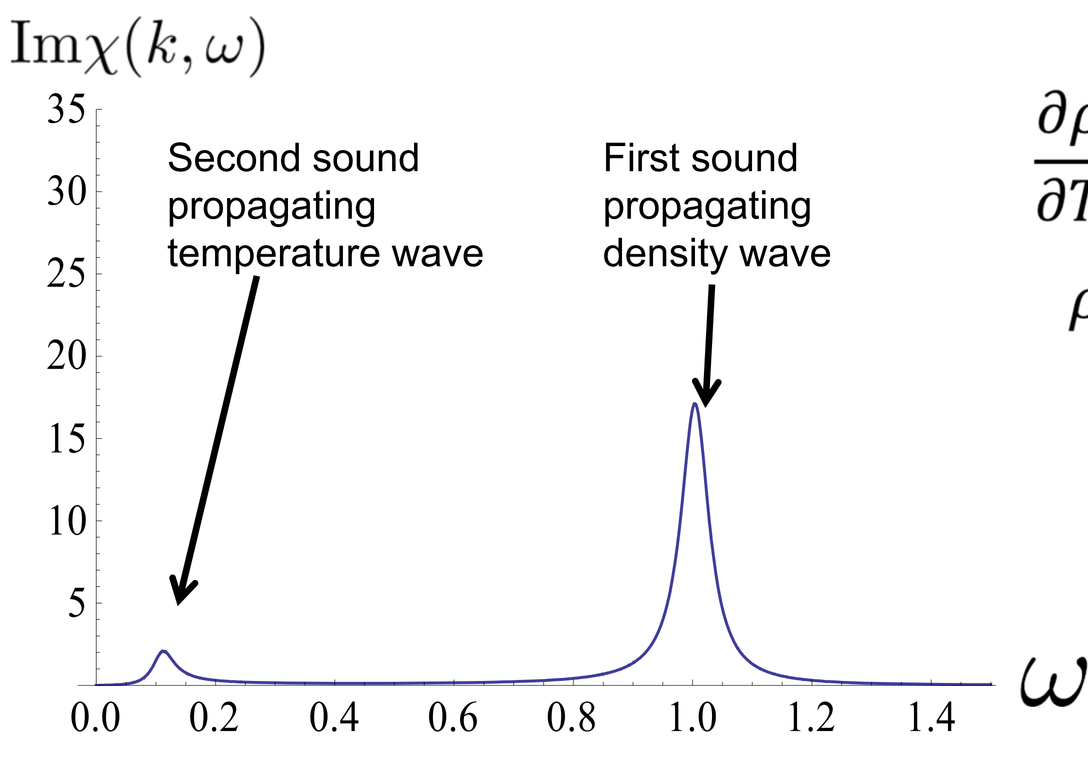
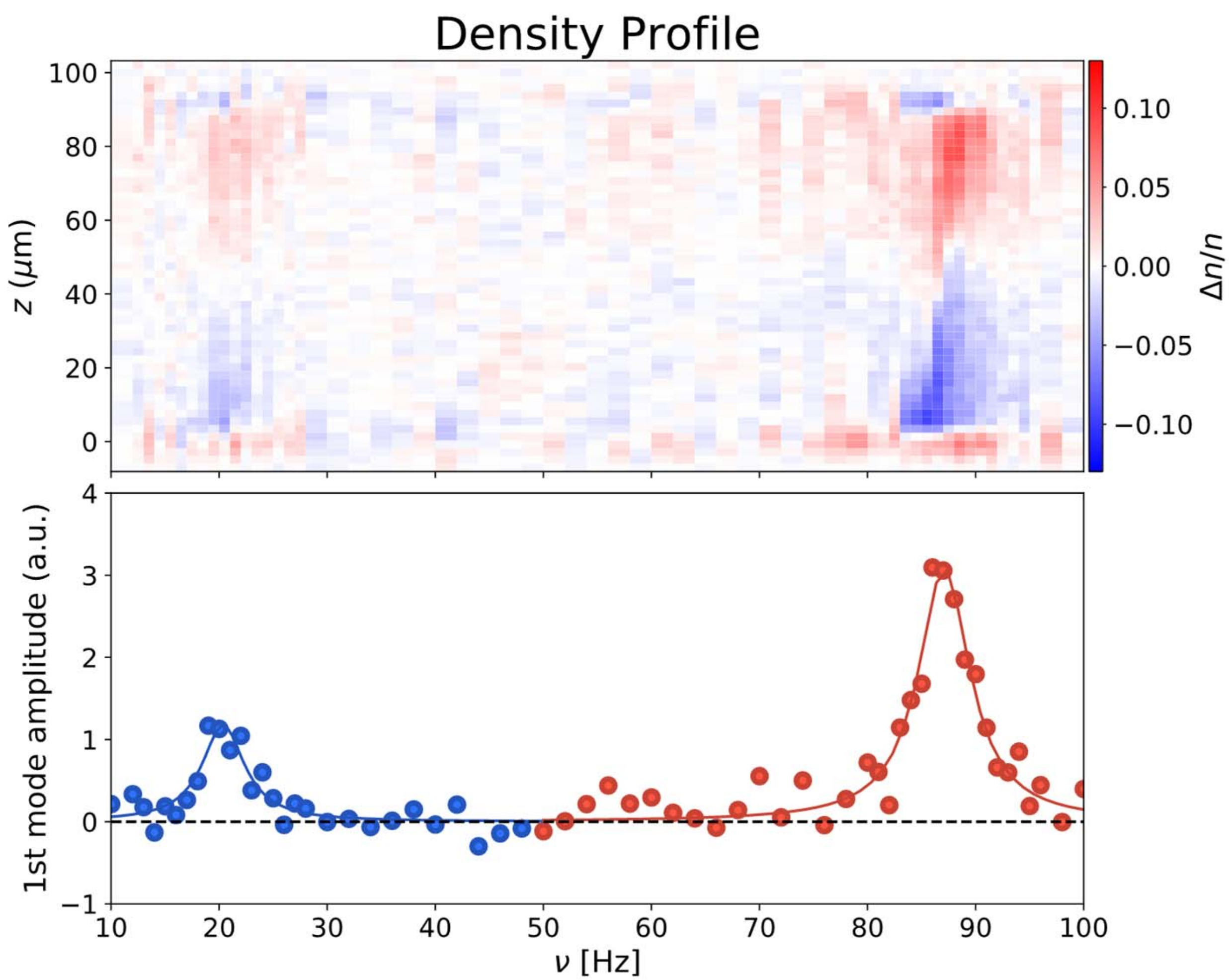
Back to density response



$$\left.\frac{\partial\rho}{\partial T}\right|_p \neq 0$$

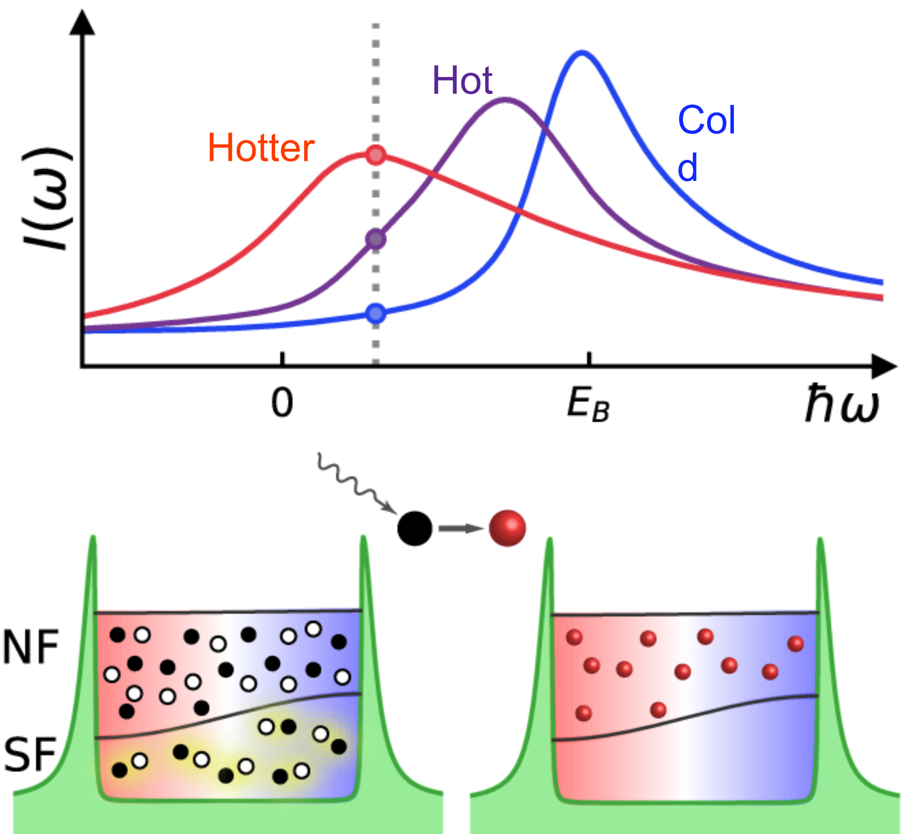
$$\rho_s \neq 0$$

Second Sound seen in Density

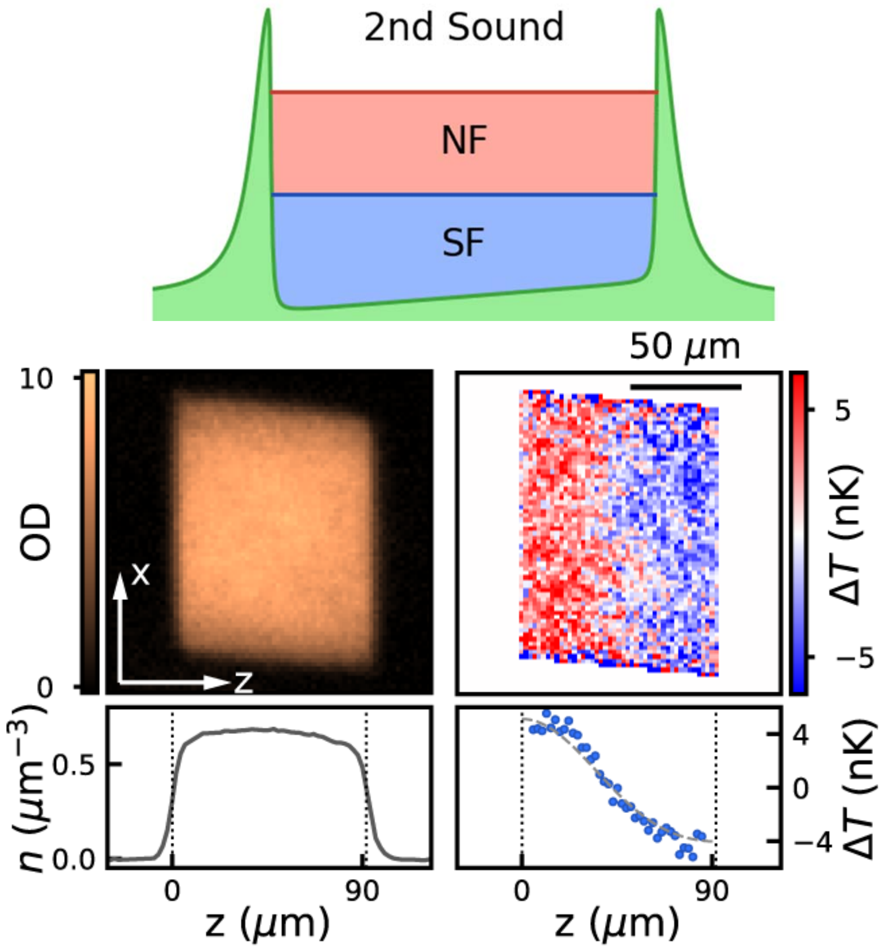


A local thermometer for heat transport

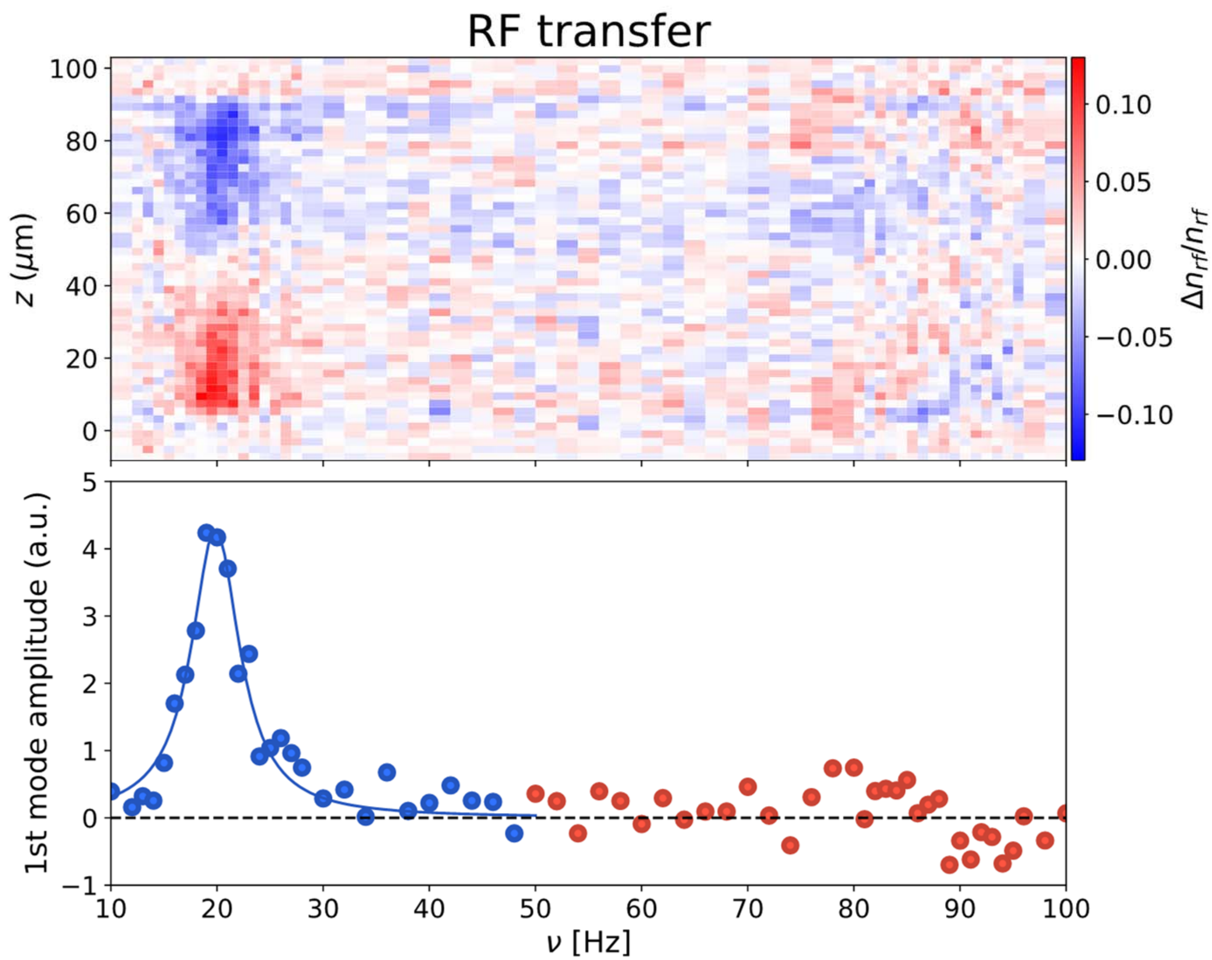
RF absorption spectra



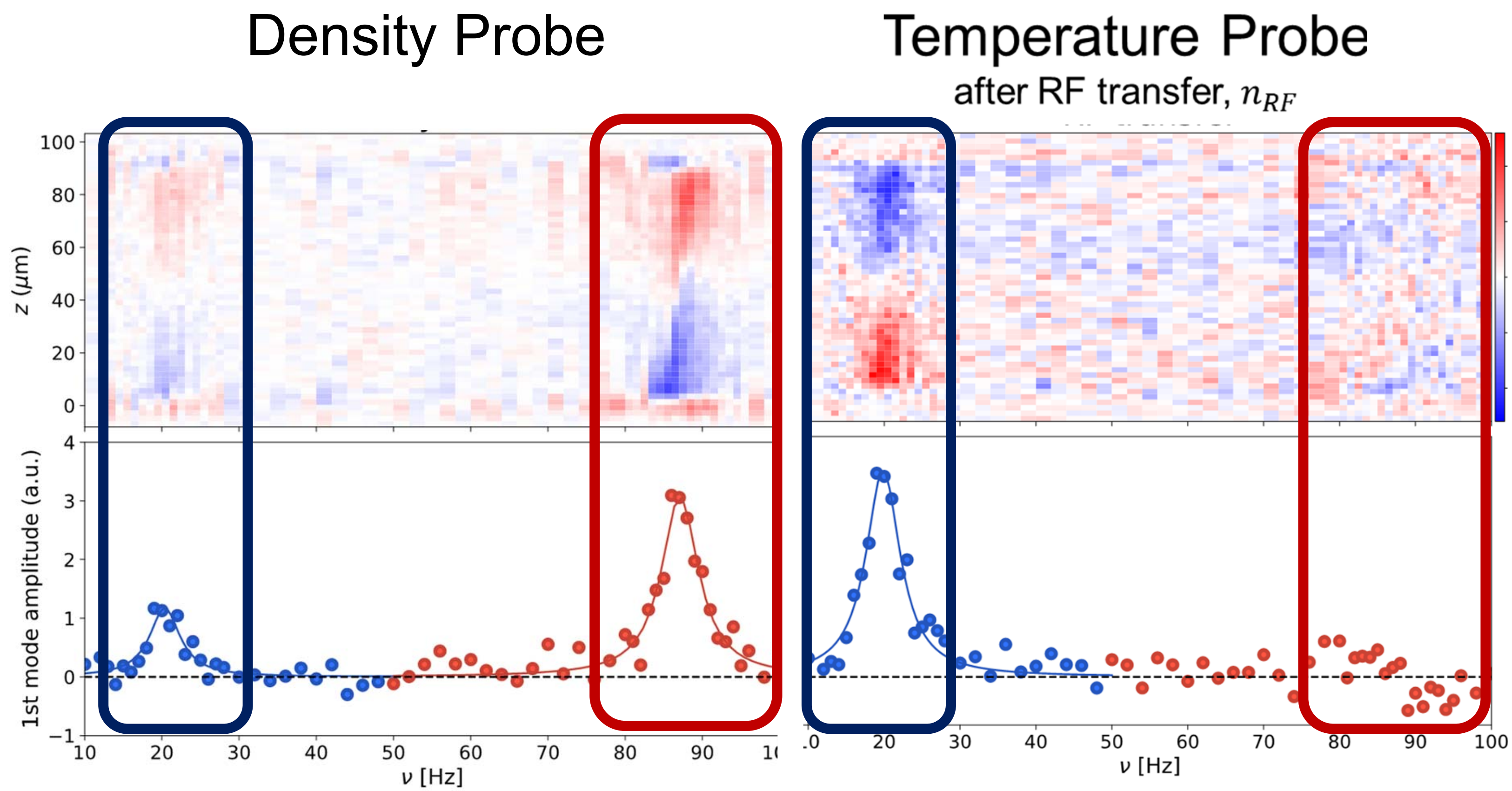
2nd Sound Creation



Second Sound with local thermometer

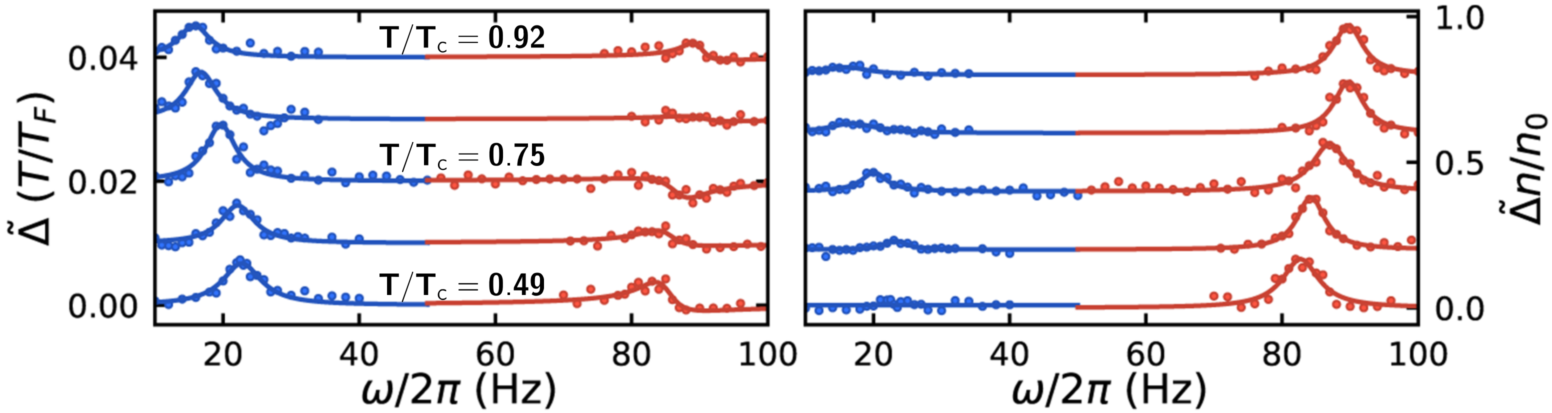


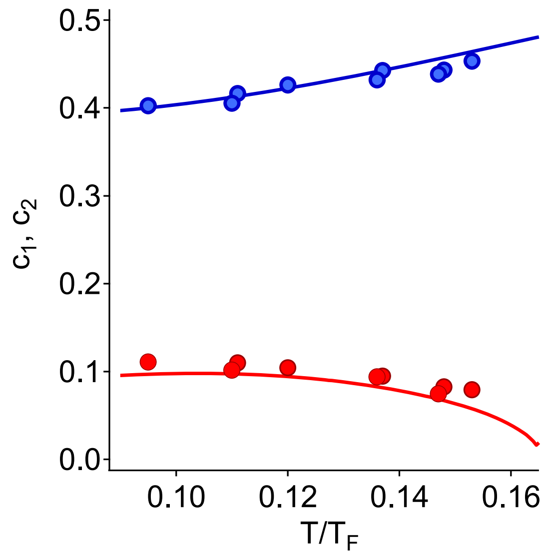
First and Second Sound



→ Speeds and Decay rates of First and Second sound

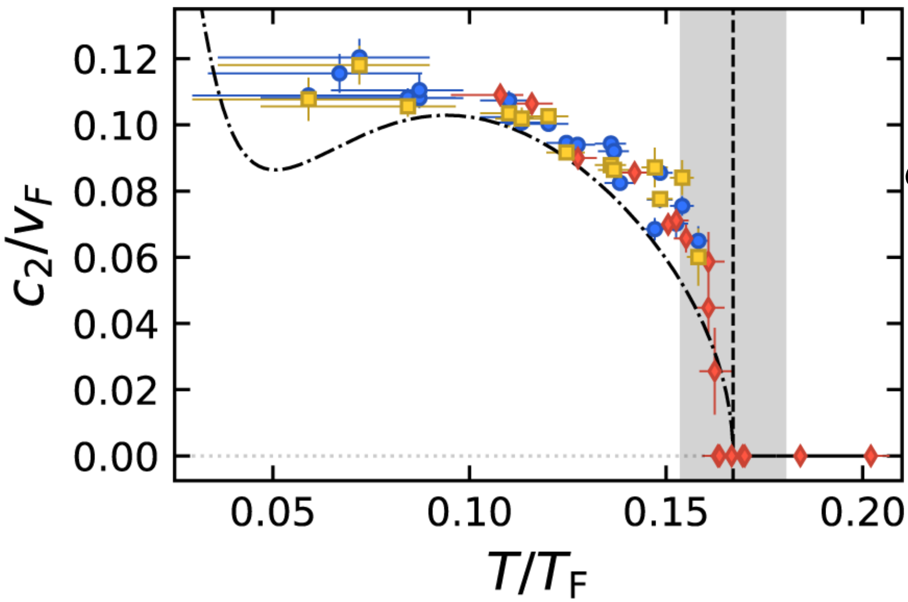
Speed of first and second sound



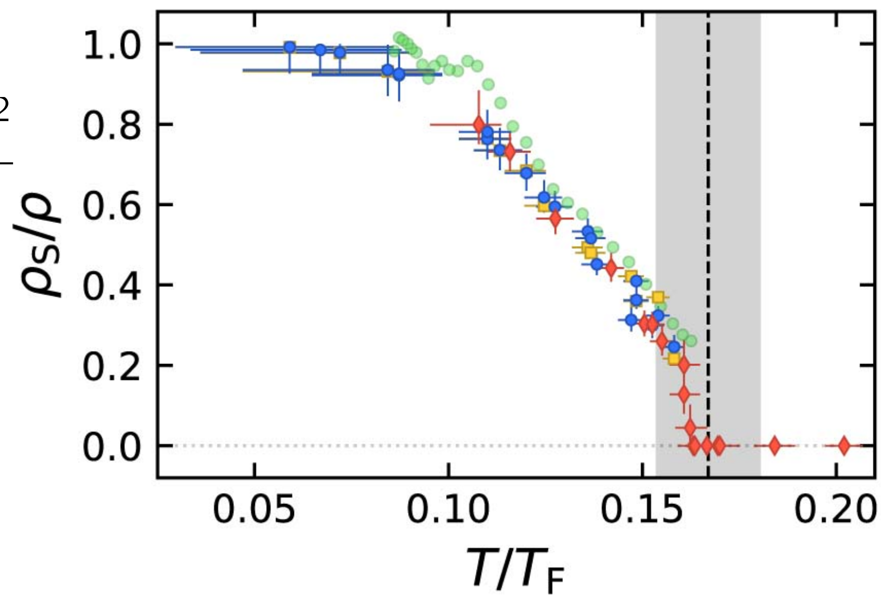


Z. Yan, P. Patel, B. Mukherjee, R. Fletcher, MZ, in prep. (2021)

Superfluid fraction



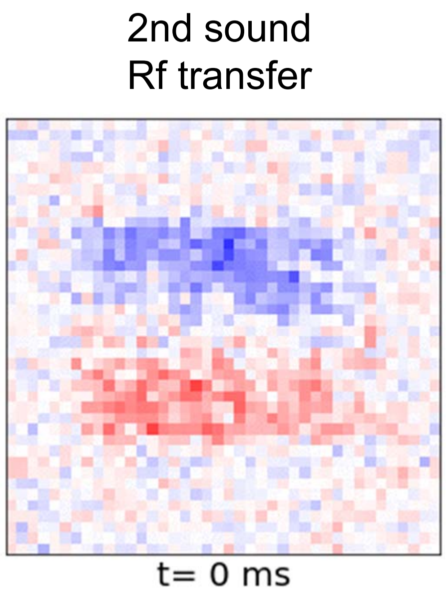
$$c_2^2 = \frac{\rho_S}{\rho_N} \frac{T S^2}{C_p}$$

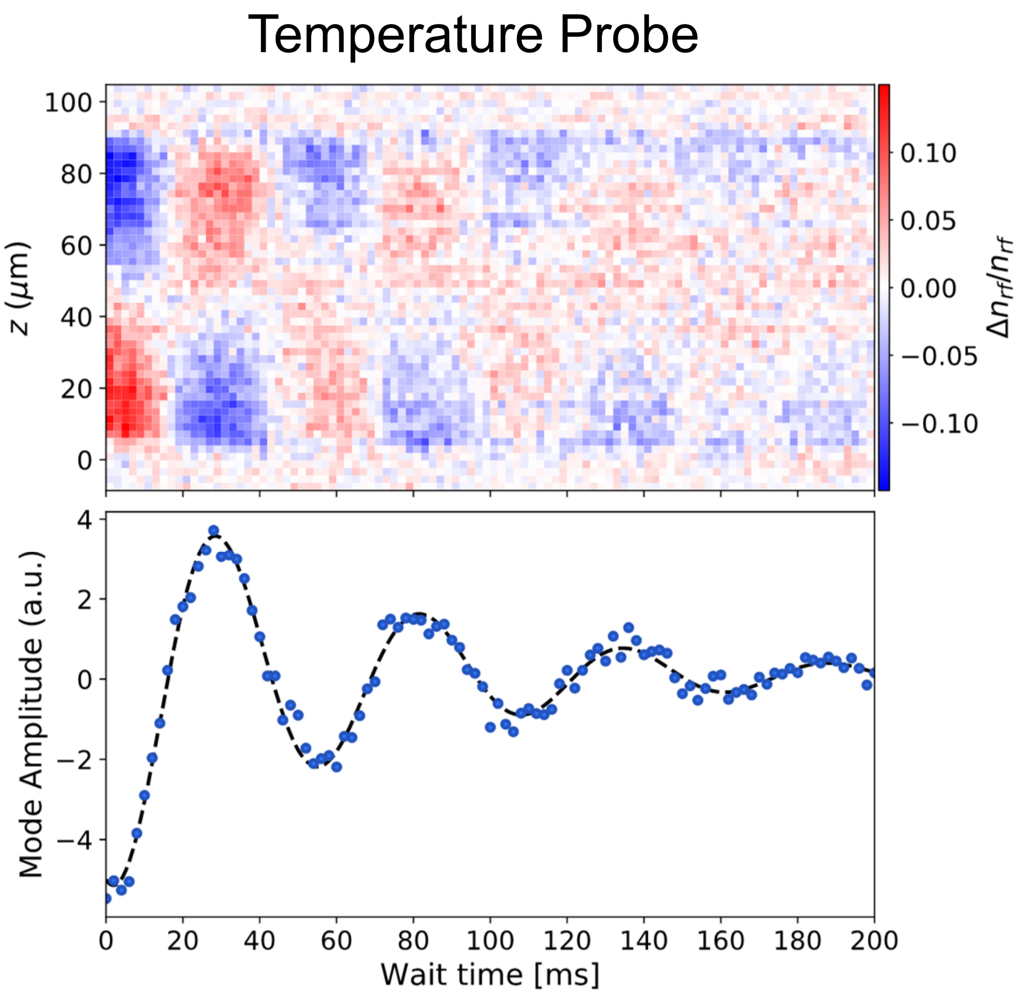


- Steady state response
- Free evolution, resonant shaking
- Free evolution, local heater

Z. Yan, P. Patel, B. Mukherjee, R. Fletcher, MZ, in prep. (2021)

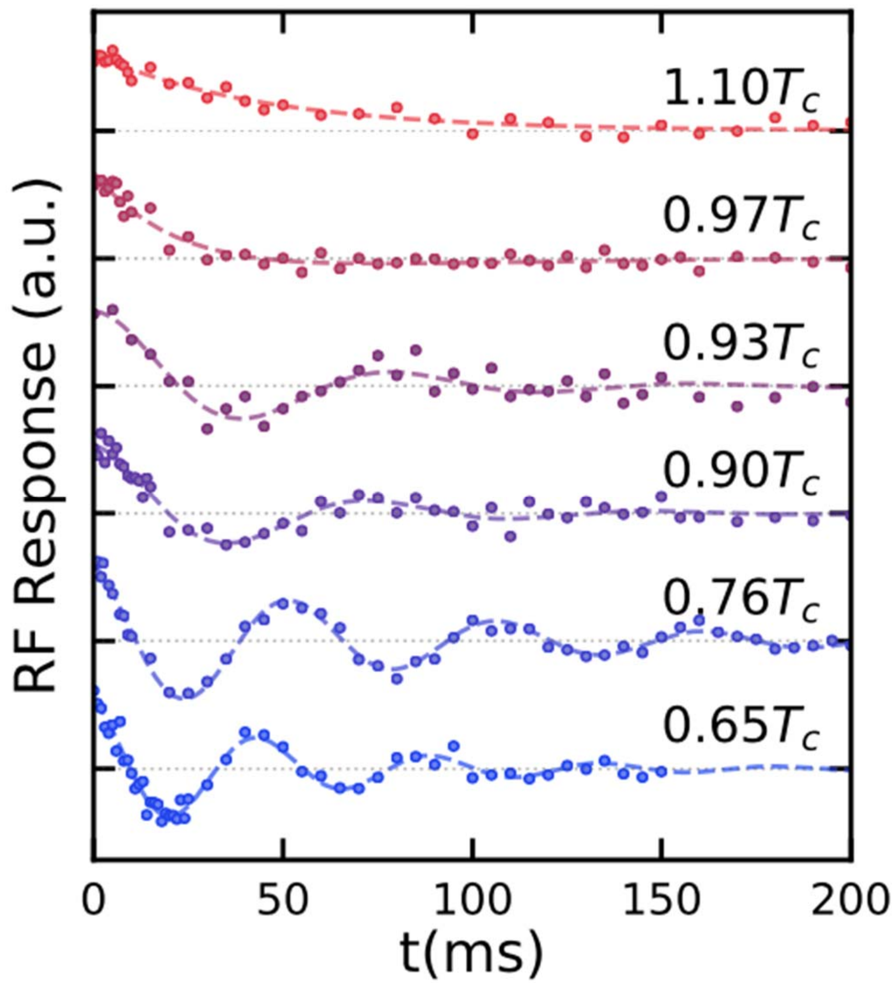
Damping of Second Sound





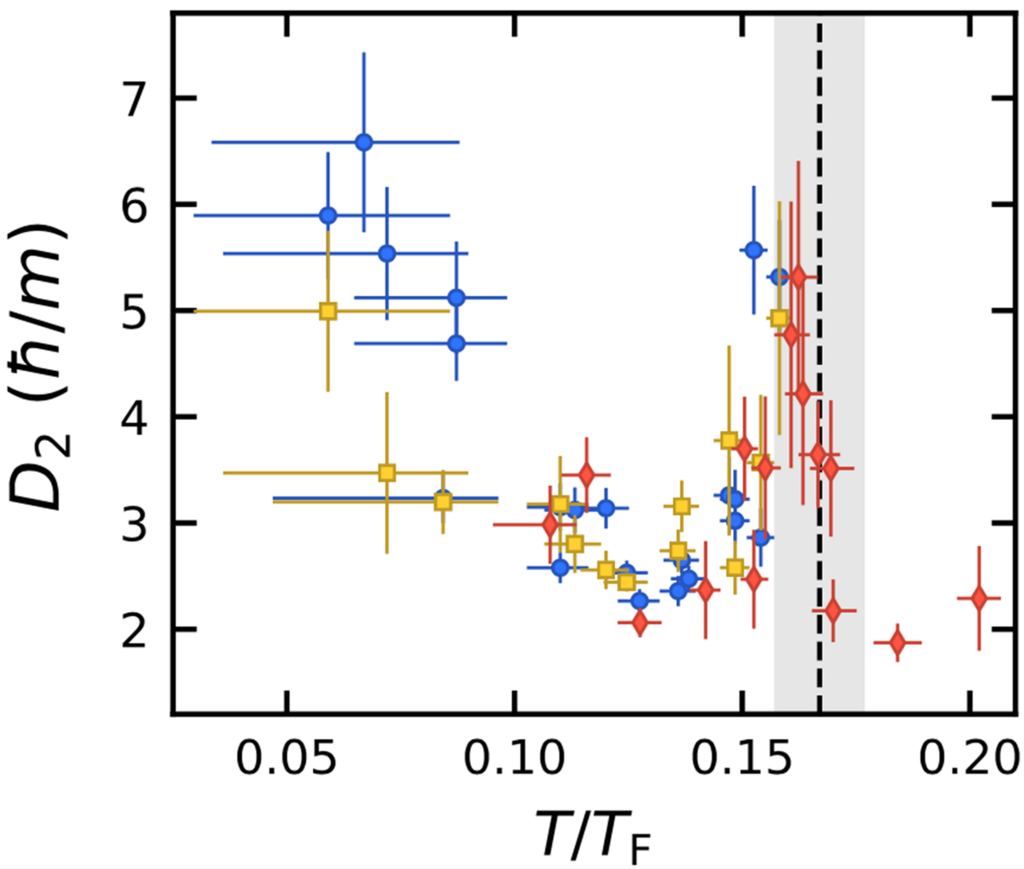
Z. Yan, P. Patel, B. Mukherjee, R. Fletcher, MZ, in prep. (2021)

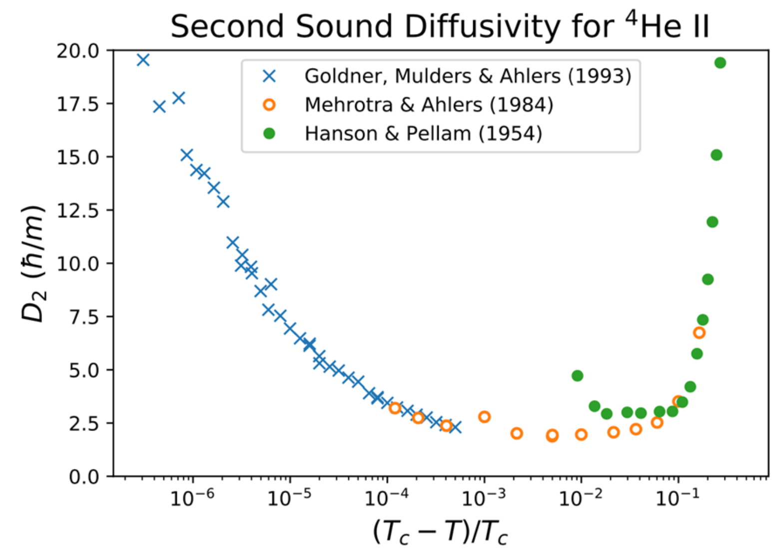
Transition from normal to superfluid



Diffusivity of Second Sound

$$D_2 = \Gamma_2 / k^2$$



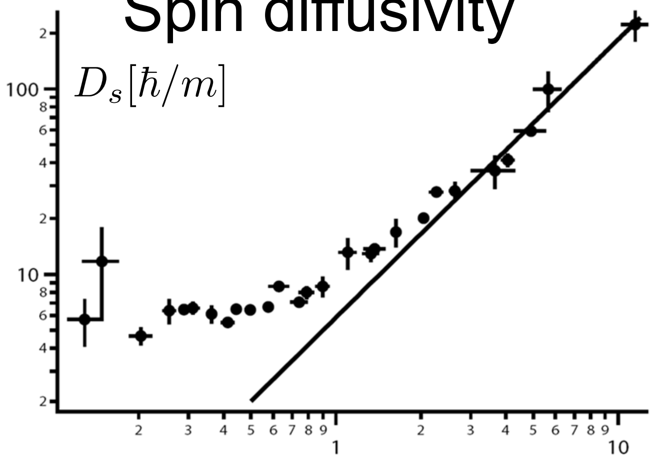


$$D_2 = \frac{\kappa}{c_p} + \frac{\rho_s}{\rho_n}\left(\xi_3 \rho + \frac{4}{3}\frac{\eta}{\rho}\right)$$

Z. Yan, P. Patel, B. Mukherjee, R. Fletcher, MZ, in prep. (2021)

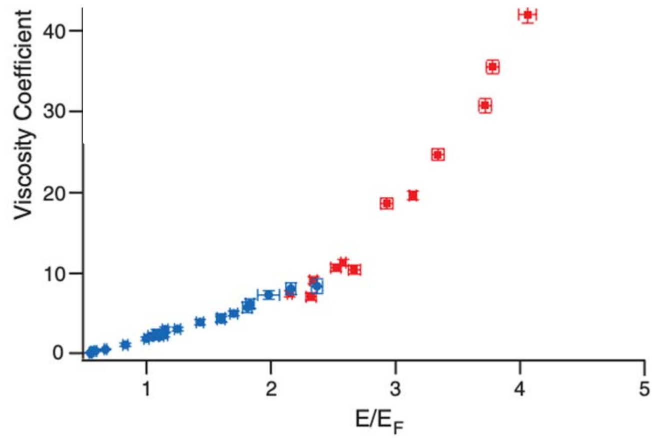
Diffusivities in the Unitary Gas

Spin diffusivity



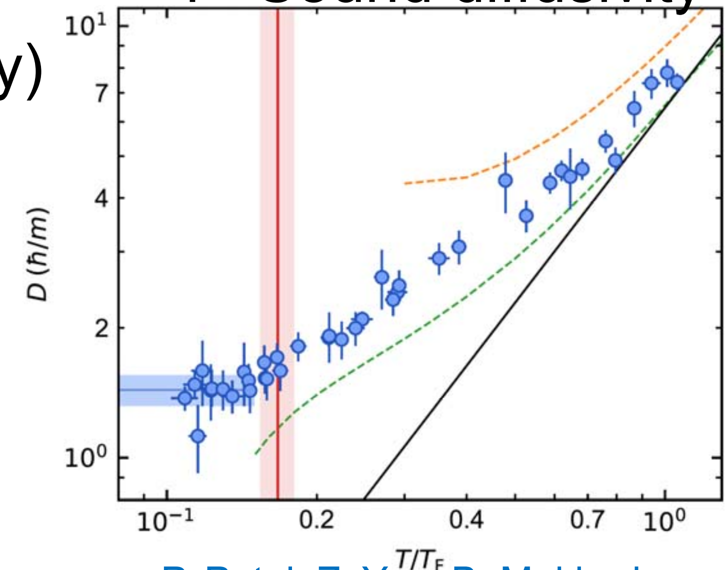
A.T. Sommer, M.J.H. Ku, G. Roati, MZ, Nature 472, 201 (2011)

Kinematic viscosity (= momentum diffusivity)



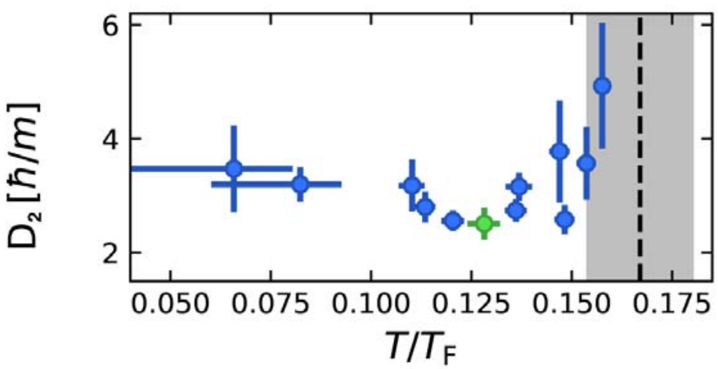
Cao et al., John Thomas group, Science 331, 58 (2011)

1st Sound diffusivity



P. Patel, Z. Yan, B. Mukherjee, R. Fletcher, J. Struck, MZ, Science 370, 1222 (2020)

2nd Sound diffusivity



Diffusivity (charge, spin, momentum, thermal)

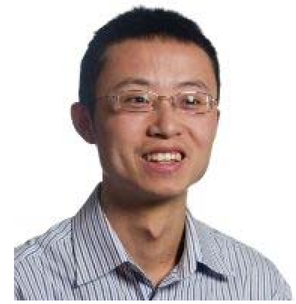
$$D \quad vl \quad \frac{A}{m}$$

Creating strongly interacting Fermi Gases

Matthew Nichols

Thomas Hartke

Dr. Ningyuan Jia

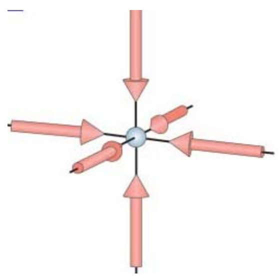


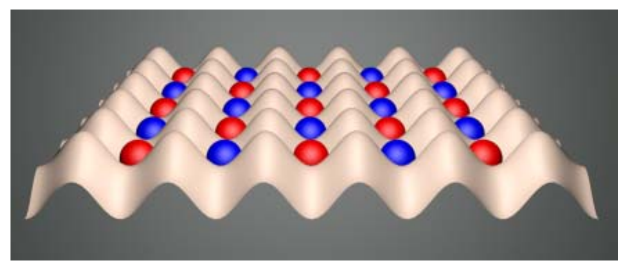
Dr. Hao Zhang

Former members: Melih Okan, Lawrence Cheuk

Theory collaborators: Senthil Todadri, Ehsan Khatami

Optical Lattices → e.g. Fermi-Hubbard model



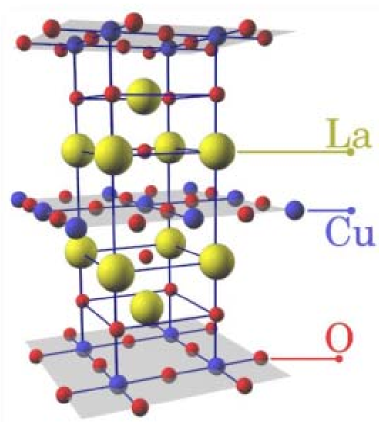


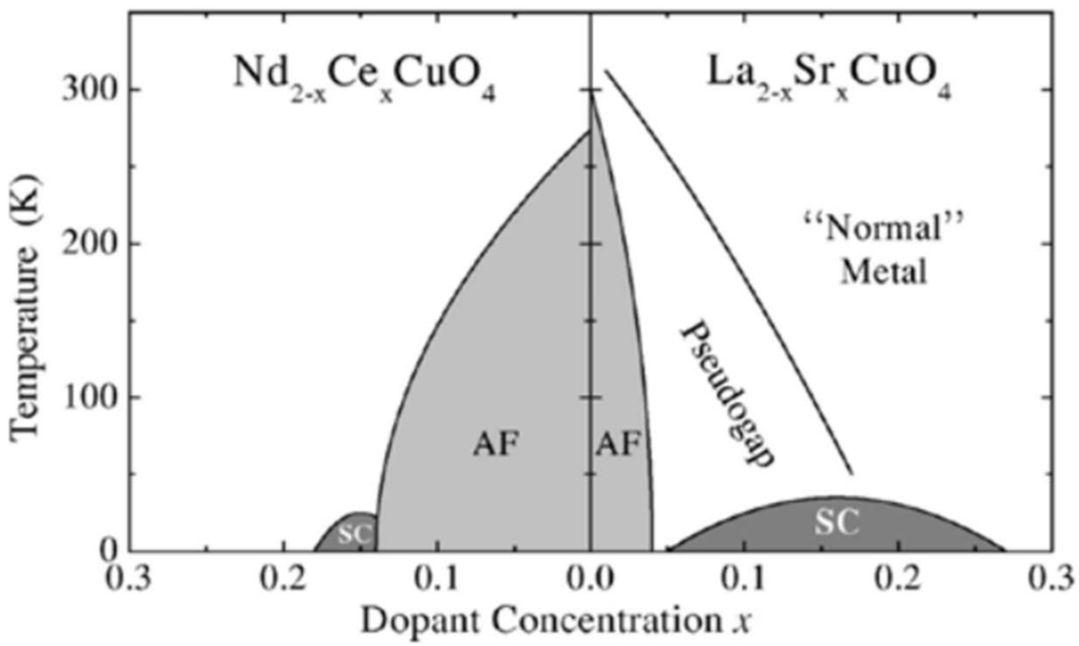
Quantum Gases → Quantum Solids

Fermi-Hubbard Model

$$H = -t \sum_{\langle i,j \rangle, \sigma} c_{i\sigma}^{\dagger} c_{j\sigma} + U \sum_{i} \hat{n}_{i\uparrow} \hat{n}_{i\downarrow}$$

Introduced to describe strongly correlated electrons
Believed to contain essential features of
High-Temperature Superconductors



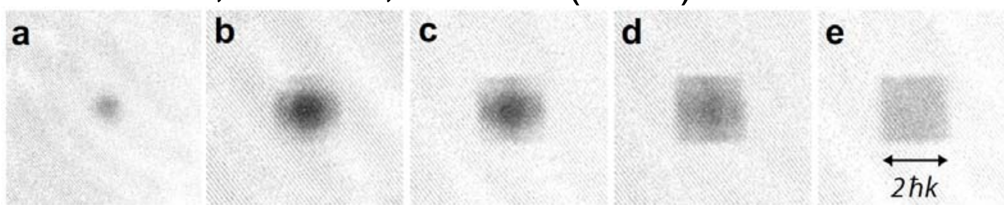


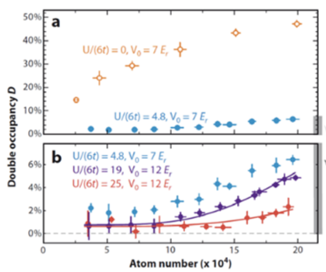
Damascelli et al., RMP 2003

Realization with Ultracold Fermions

Fermionic atoms in a 3D optical lattice

Köhl et al., PRL 94, 080403 (2005)

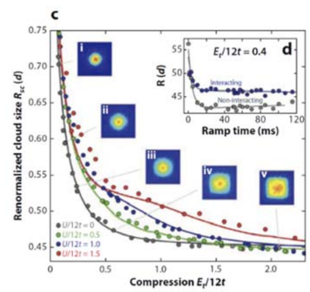




Reduction of Double Occupancy

Jördens et al

Nature 455:204-07 (2008)

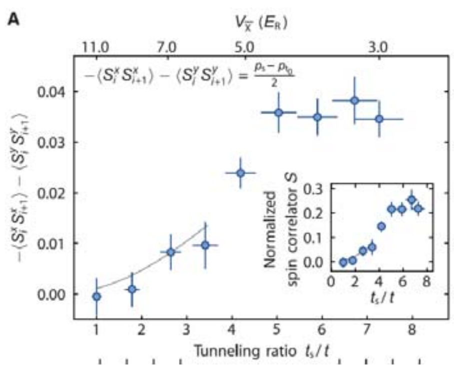


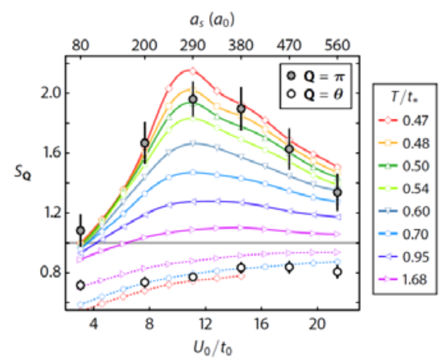
Reduction of Compressibility:

Schneider et al, Science 322,1520 (2008)

Observation of short-range antiferromagnetic correlations:

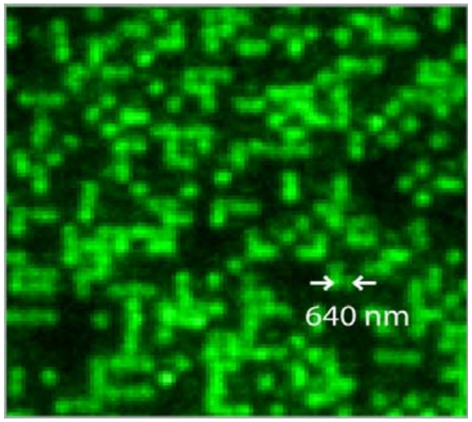
Greif et al., Science 340, 1307 (2013)



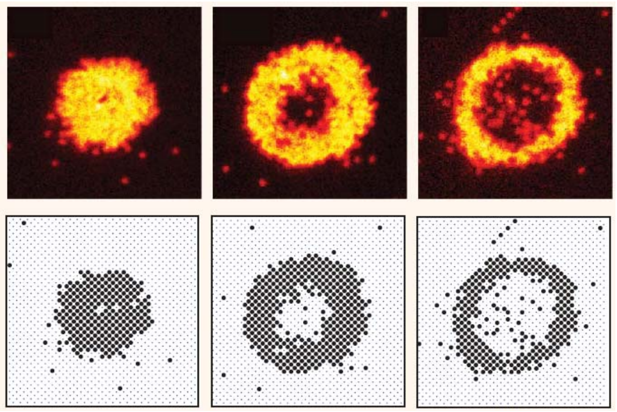


Hart et al., Nature 519, 211 (2015)

Quantum Gas Microscopy



Bosons
^{87}Rb



Bakr *et al.*, Nature 462, 74-77 (2009)

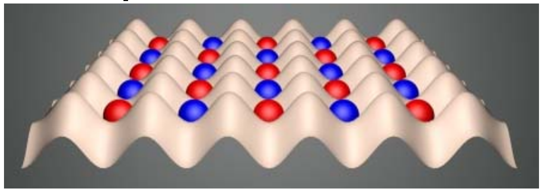
Sherson *et al.*, Nature 467, 68-71 (2010)

Also, recently: ^{174}Yb bosons, Miranda et al., PRA 91, 063414 (2015)
Yamamoto et al., NJP 18, 023016 (2016)

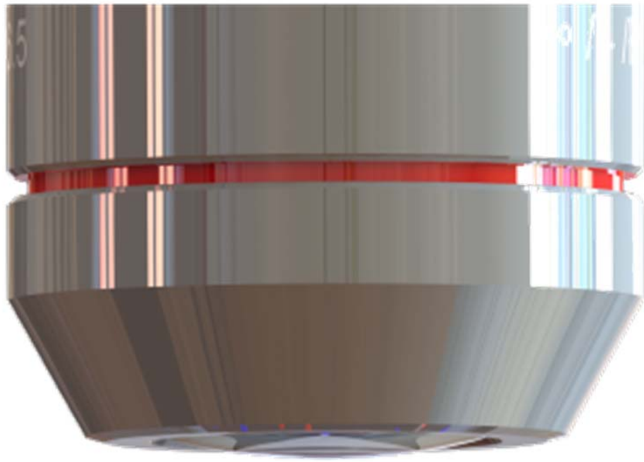
Great Prospect for Fermi Gas Microscopes:

Single-site resolution imaging of fermions in optical lattices:

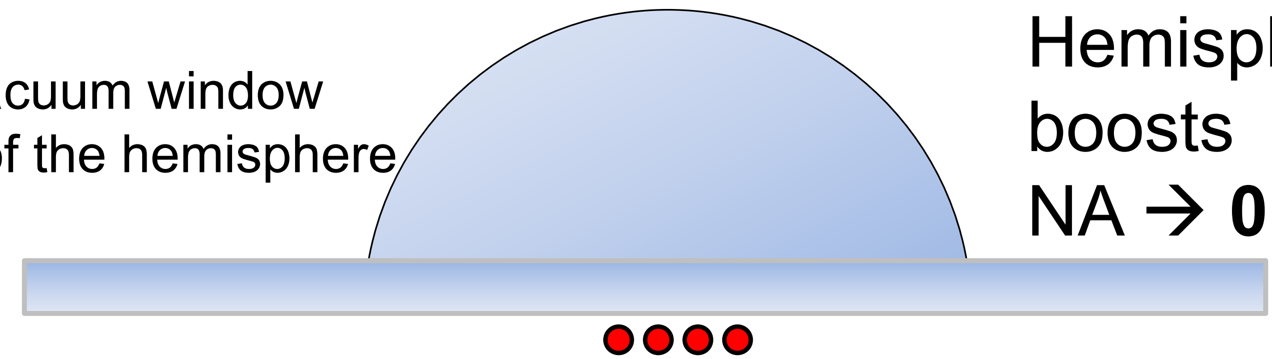
→ Clean, tunable, controllable systems
→ Directly measure magnetic order
→ Higher-order real-space correlations
→ Single site addressing, Quantum Gates, Implant Impurities…



Seeing individual fermions

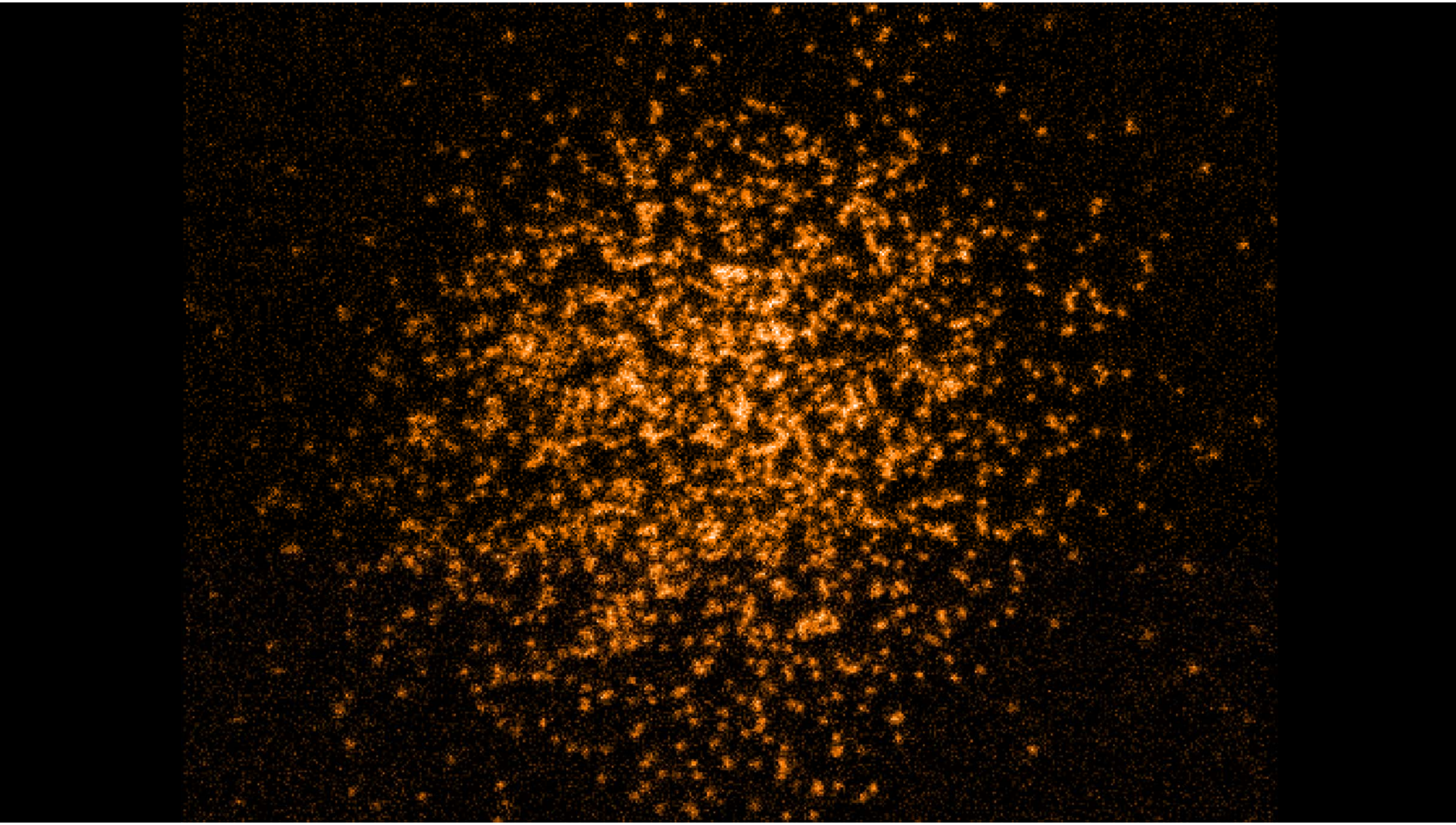


Commercial
Edmund Optics
High-NA
Microscope
NA = 0.6

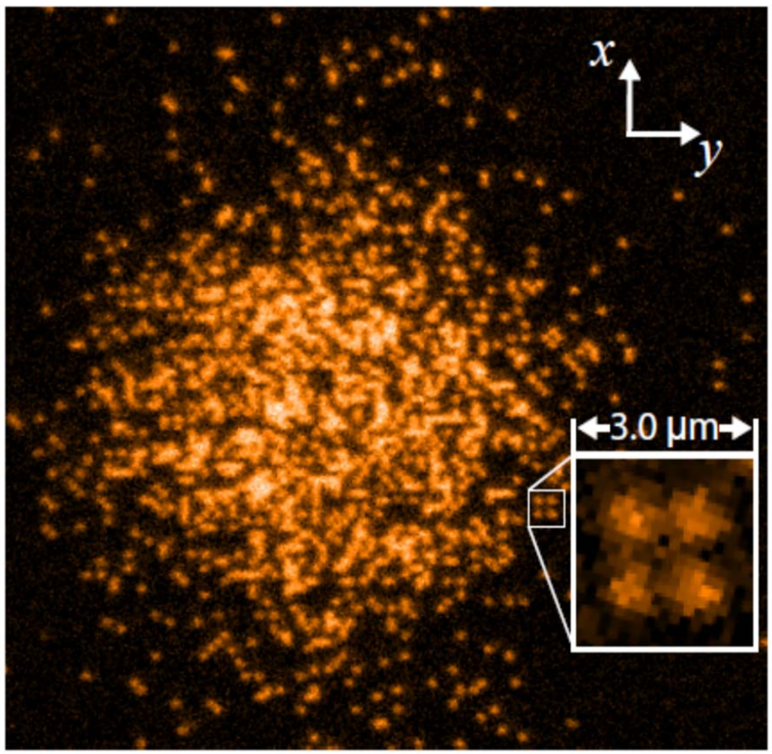


Hemisphere
boosts
NA → **0.9**

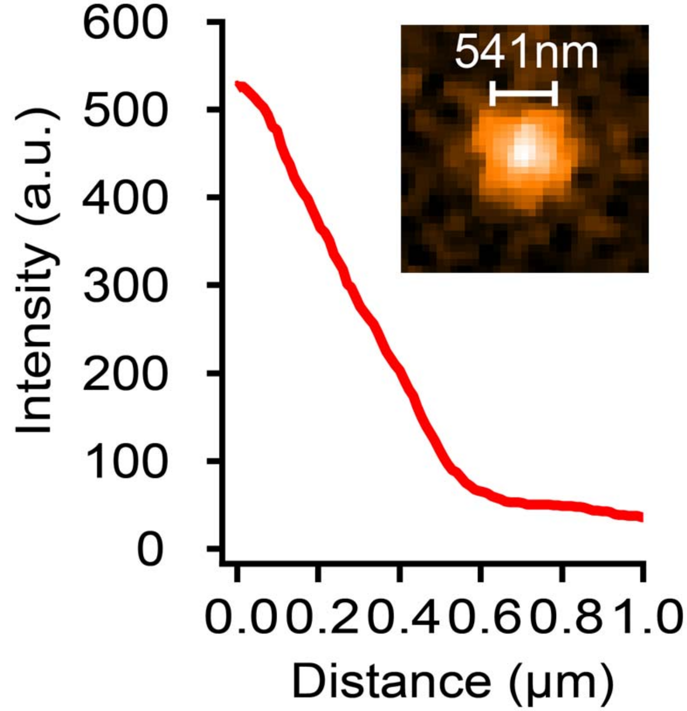
L. Cheuk, M. Nichols, M. Okan, T. Gersdorf, V. Ramasesh, W. Bakr, T. Lompe, MZ
PRL **114**, 193001 (2015)



Single-site resolution imaging for ^{40}K



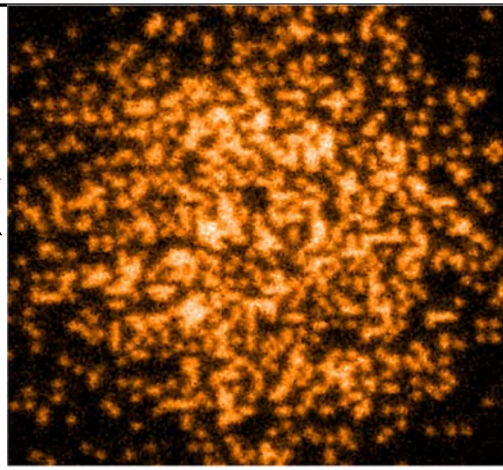
FWHM of 640nm



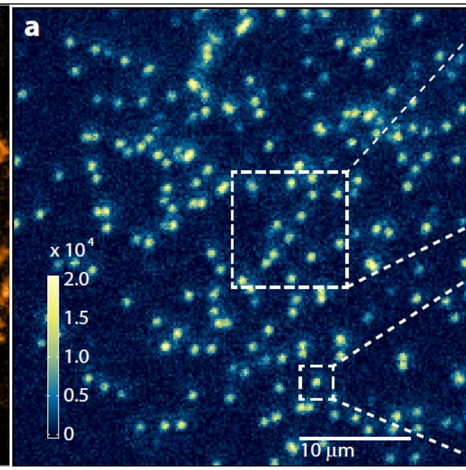
L. Cheuk, M. Nichols, M. Okan, T. Gersdorf, V. Ramasesh, W. Bakr, T. Lompe, MWZ
PRL **114**, 193001 (2015)

Proliferation of Fermi Gas Microscopes

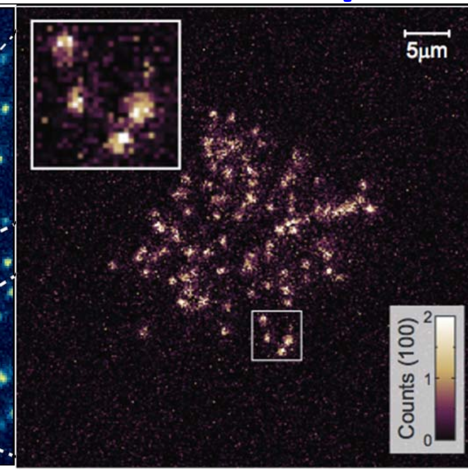
^{40}K



Zwierlein group, MIT
PRL **114**, 193001 (2015)

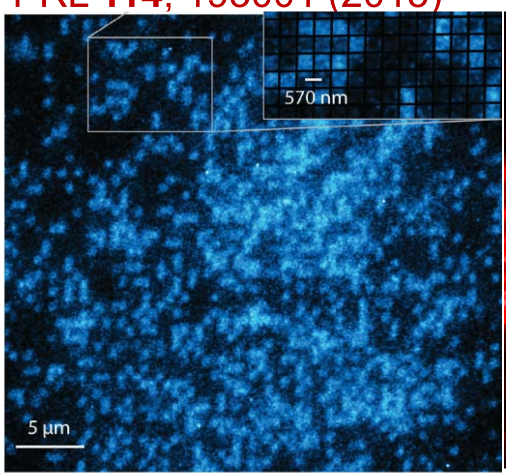


Kuhr group, Strathclyde
Nat. Phys. 11, 738 (2015)

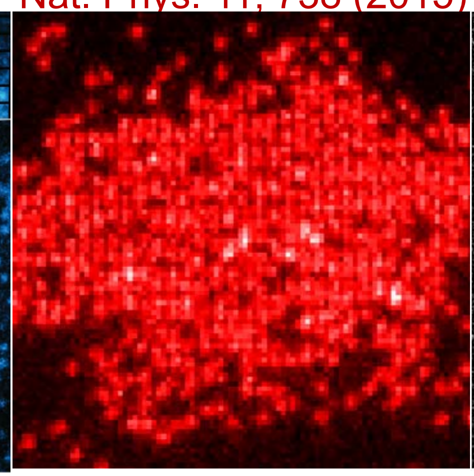


Thywissen group, Toronto,
PRA **92**, 063406 (2015)

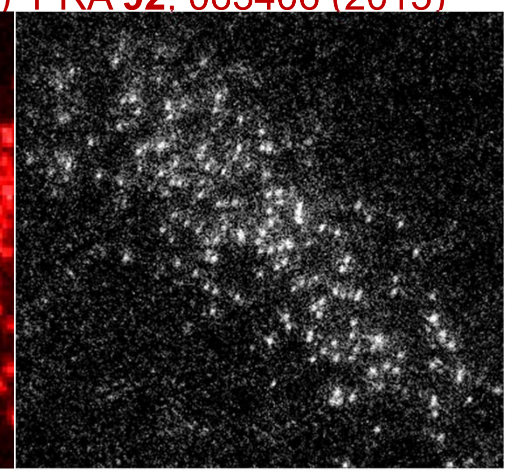
^{6}Li



Greiner group, Harvard
PRL **114**, 213002 (2015)



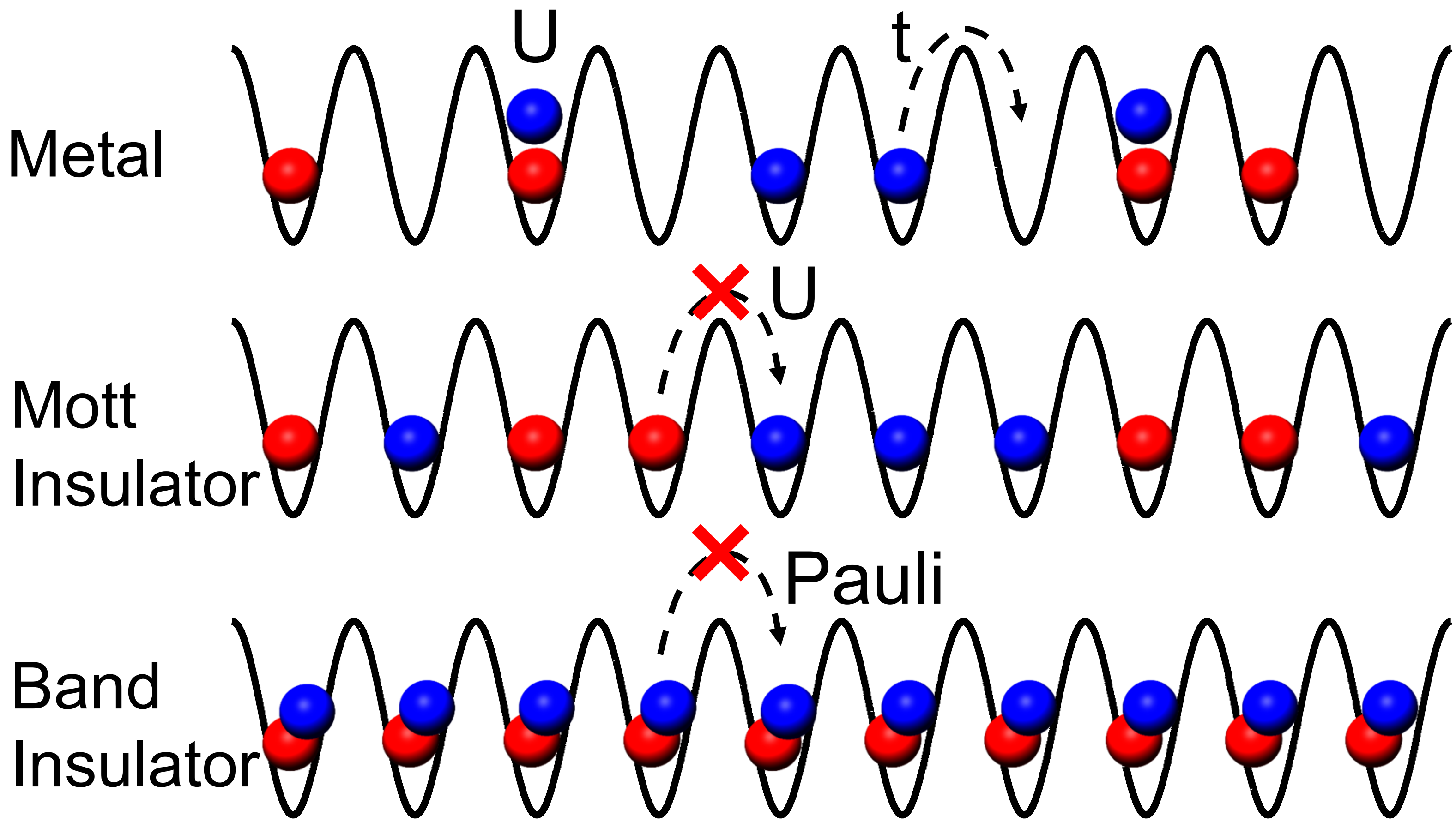
Gross/Bloch group, MPQ
PRL **115**, 263001 (2015)



Bakr group, Princeton
ultracold.princeton.edu

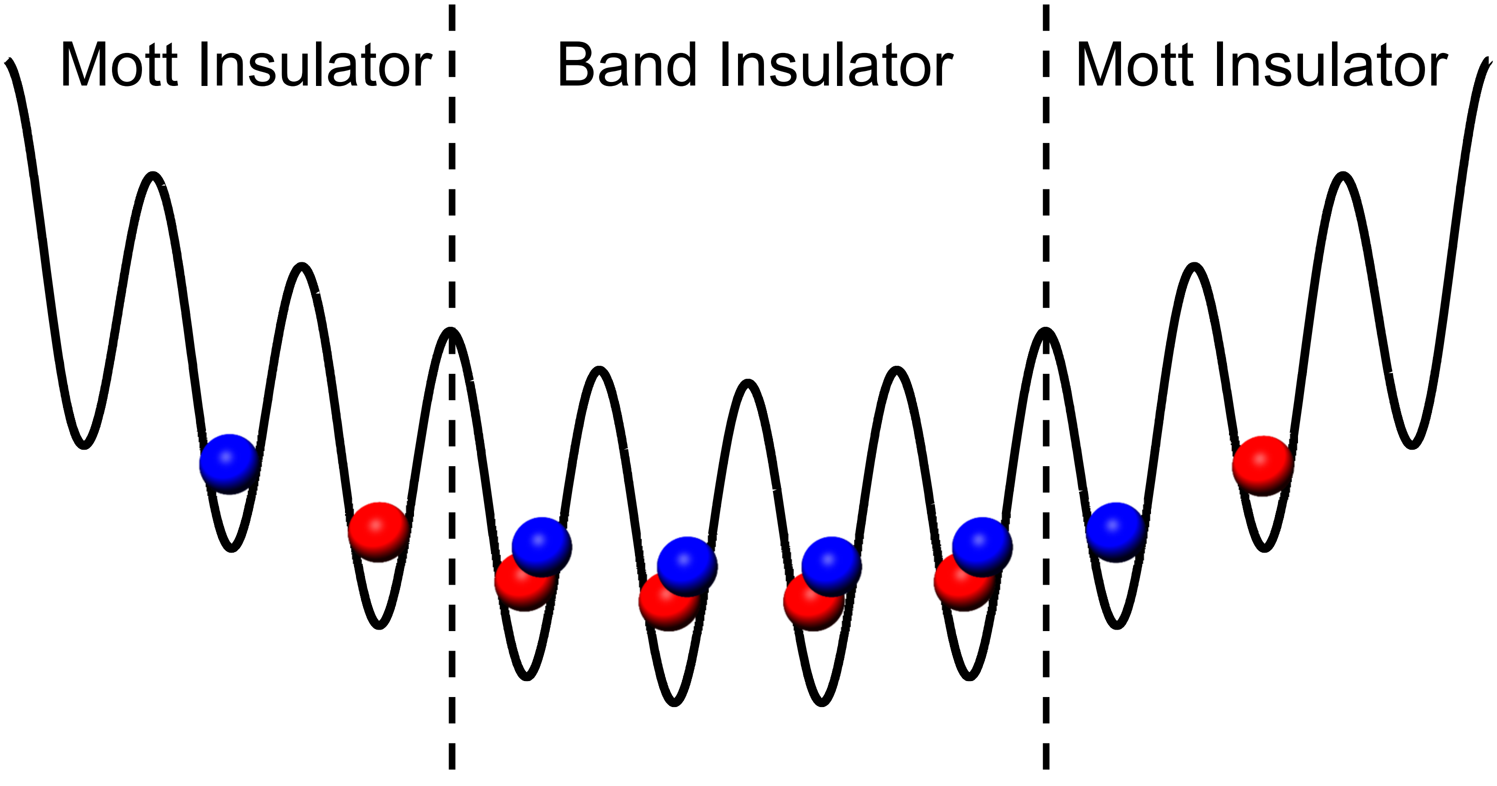
Fermi-Hubbard Model

Fermions hopping (t) and repelling (U) in a lattice



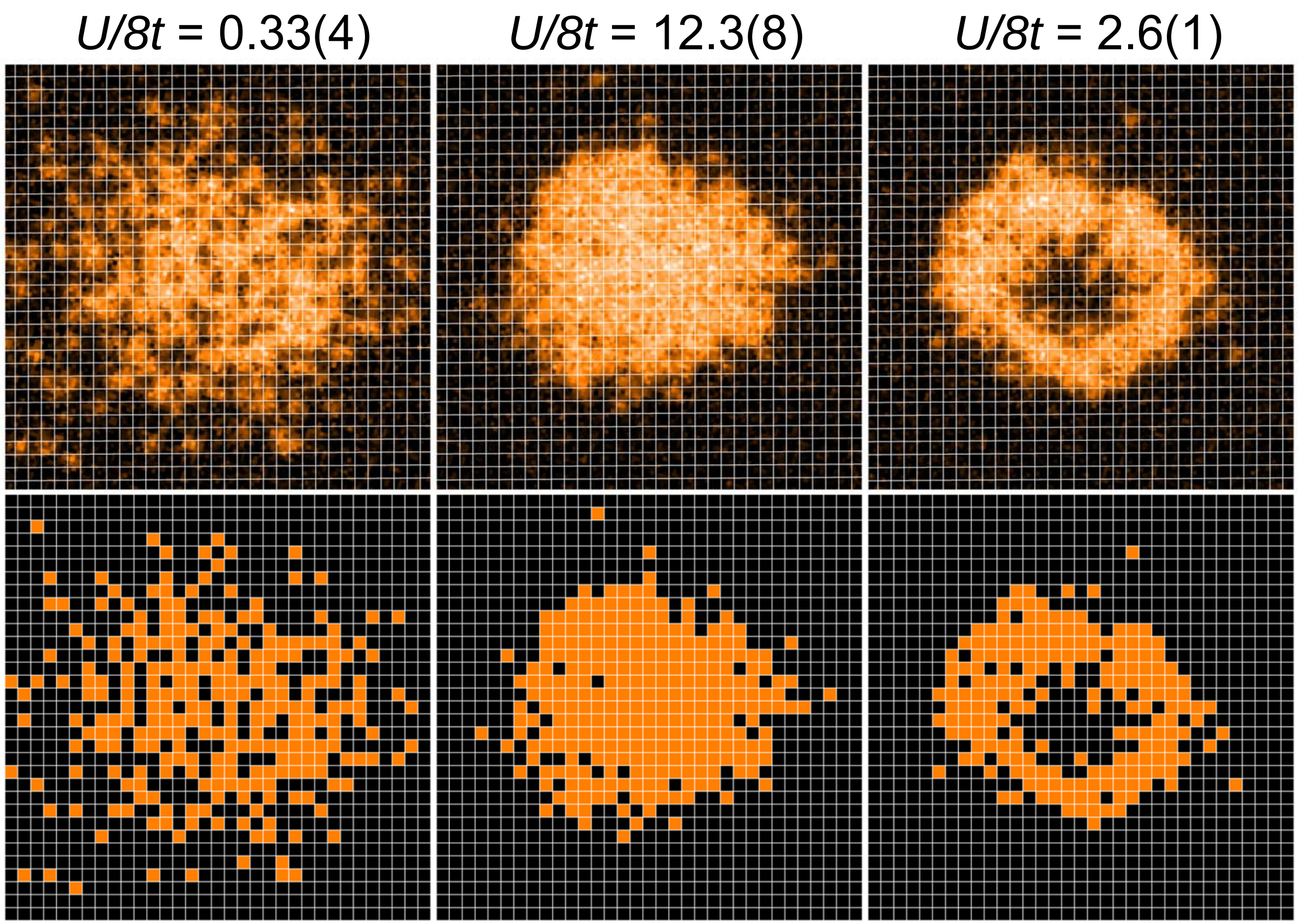
Fermi-Hubbard Model in a Trap

Fermions hopping (t) and repelling (U) in a lattice



At finite temperature: metallic states in between and outside

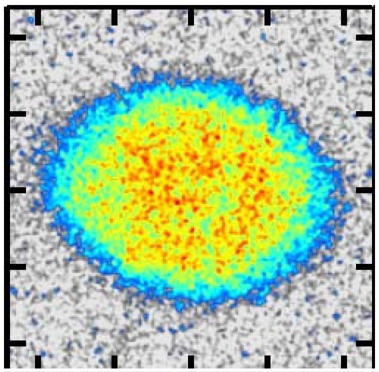
States of the Fermi-Hubbard Model



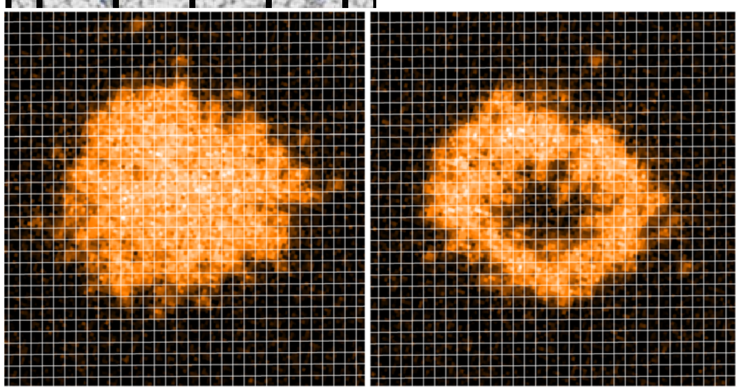
L. W. Cheuk, M. Nichols, K. Lawrence, M. Okan, H. Zhang, MWZ, PRL PRL **116**, 235301 (2016)

Fermionic Mott Insulators of ^{6}Li and ^{40}K

^{40}K

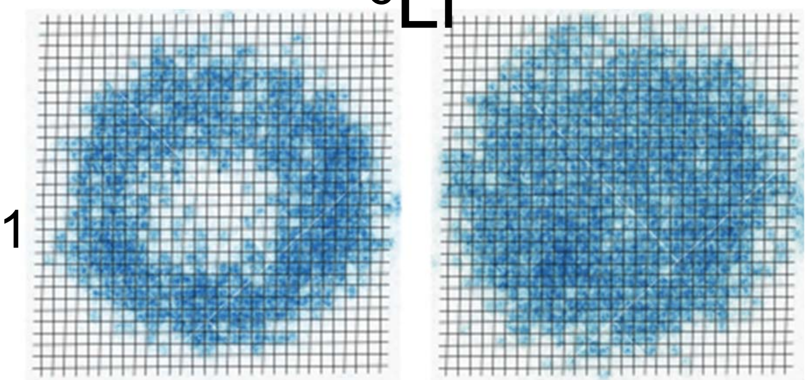


Köhl group
Cocchi et al.,
PRL 116, 175301
(2016)

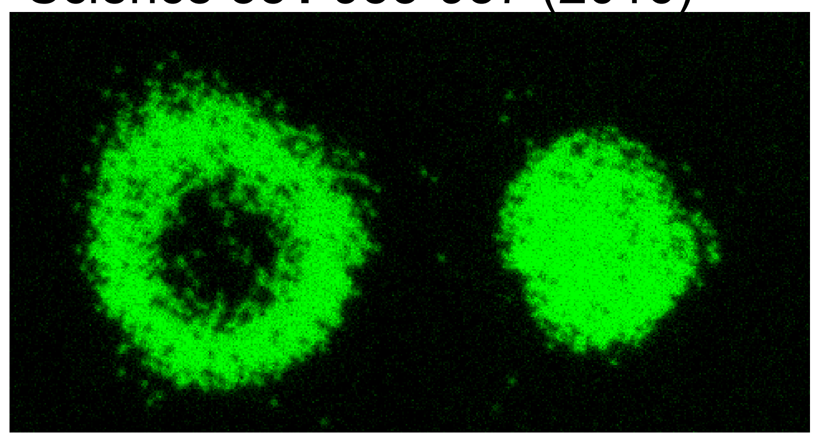


L.W. Cheuk, M.A. Nichols,
K. Lawrence, M. Okan,
H. Zhang, MWZ,
PRL **116**, 235301 (2016)

^{6}Li

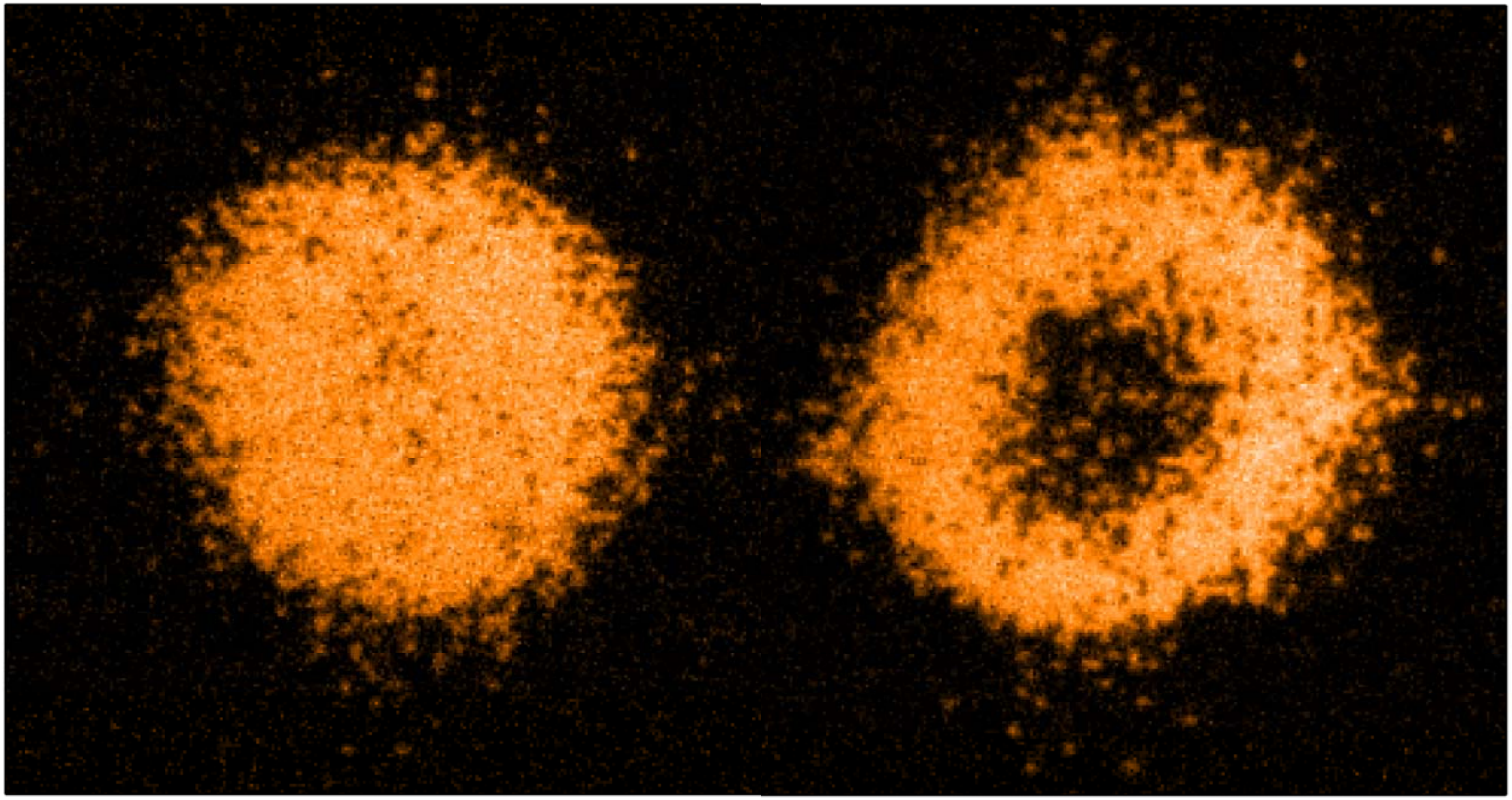


Greiner group, D. Greif et al,
Science **351** 953-957 (2016)

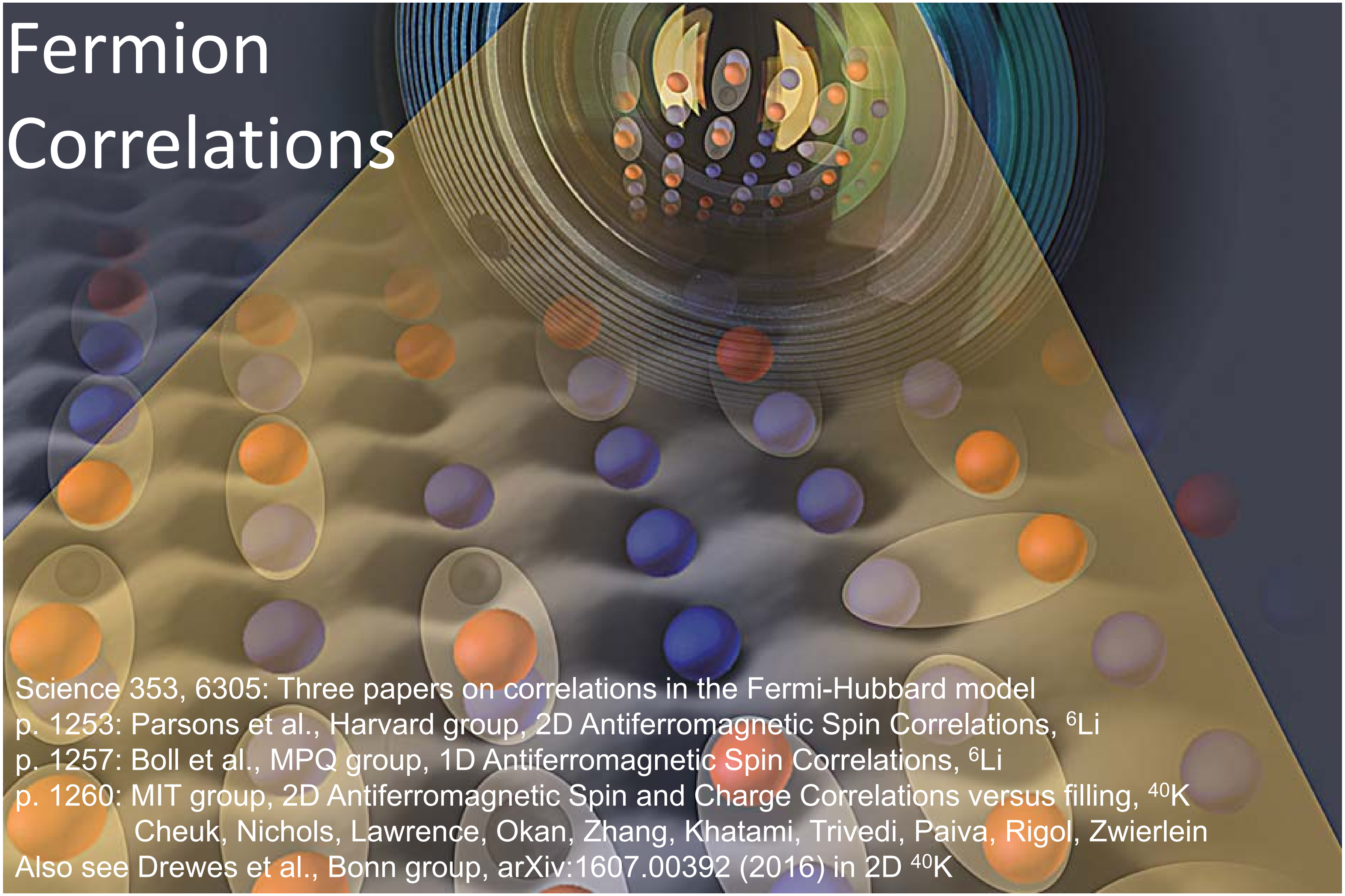


W. Bakr group, Brown et al.,
arXiv:1612.07746 (2016)

Fermionic Mott and Band Insulators



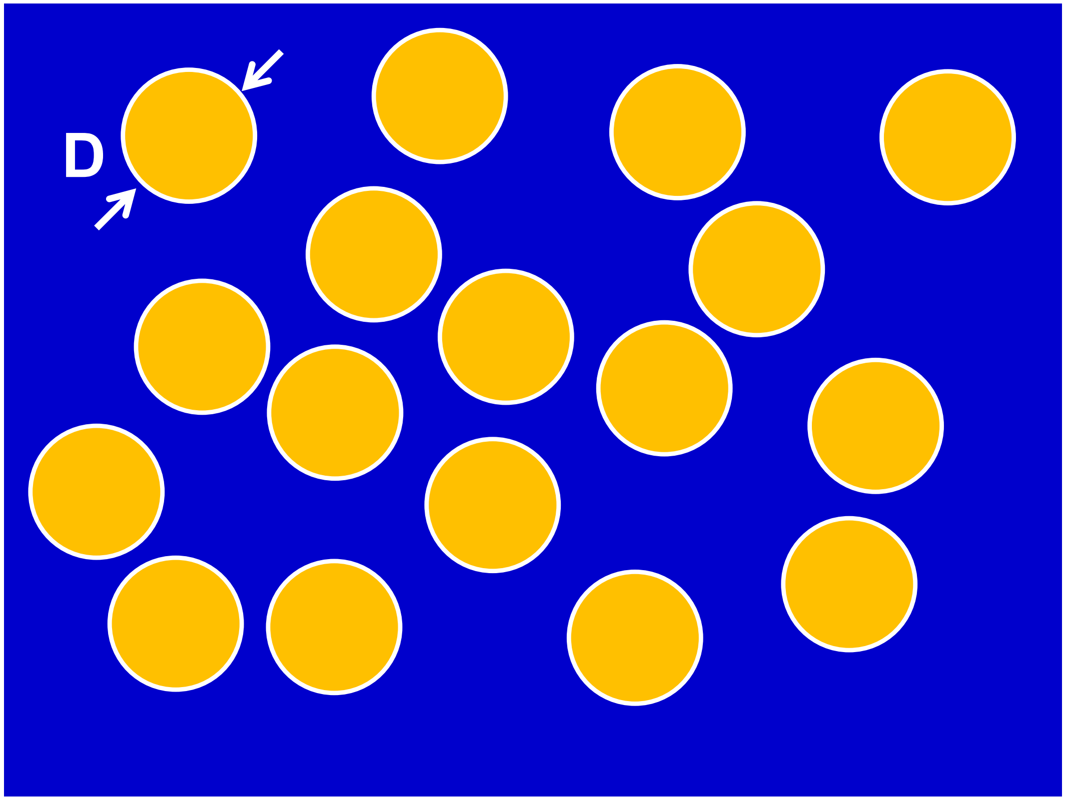
Fermion Correlations



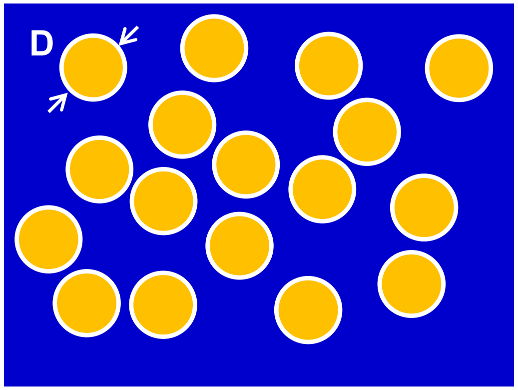
Science 353, 6305: Three papers on correlations in the Fermi-Hubbard model
p. 1253: Parsons et al., Harvard group, 2D Antiferromagnetic Spin Correlations, ^{6}Li
p. 1257: Boll et al., MPQ group, 1D Antiferromagnetic Spin Correlations, ^{6}Li
p. 1260: MIT group, 2D Antiferromagnetic Spin and Charge Correlations versus filling, ^{40}K
Cheuk, Nichols, Lawrence, Okan, Zhang, Khatami, Trivedi, Paiva, Rigol, Zwierlein
Also see Drewes et al., Bonn group, arXiv:1607.00392 (2016) in 2D ^{40}K

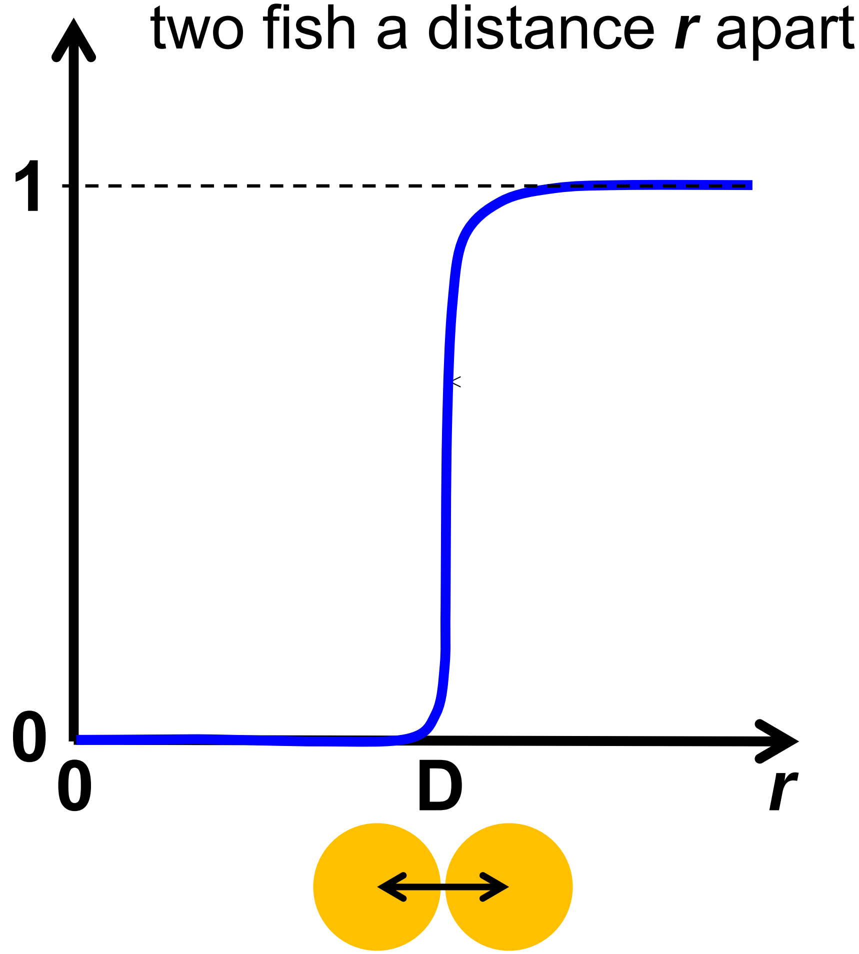
A *local* view at Fermi gases

A little simplification: Spherical Fish in 2D



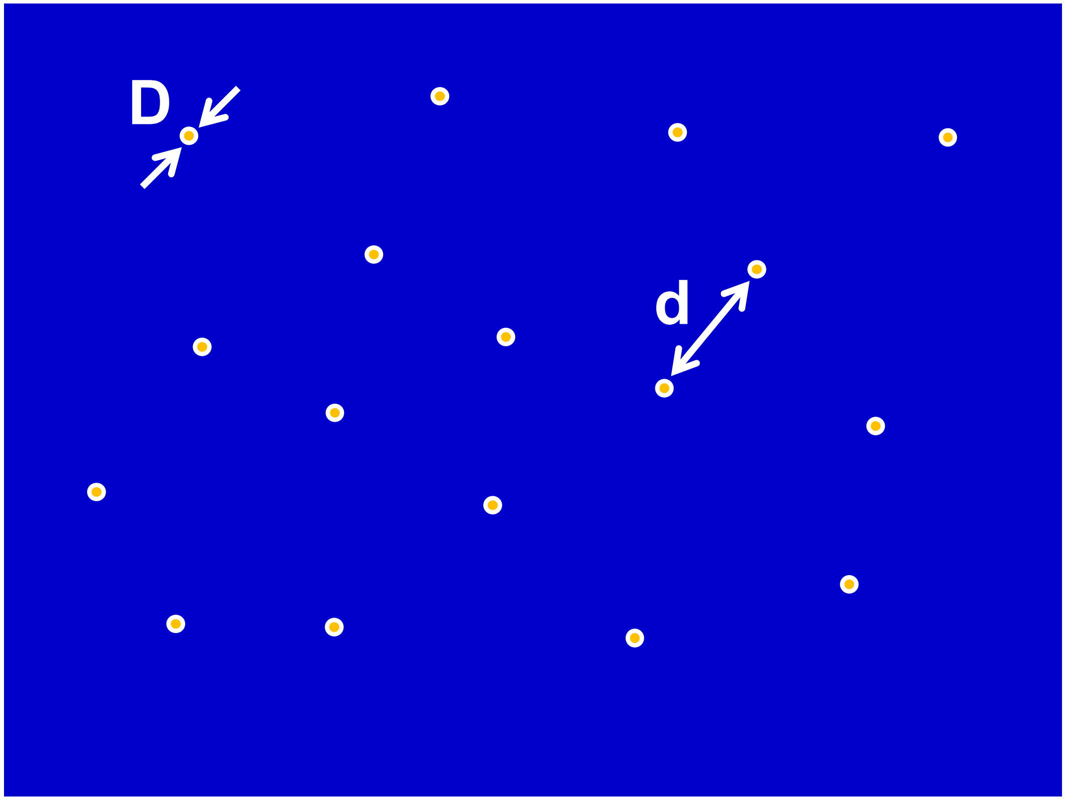
A little simplification: Spherical Fish in 2D





Now: A *local* view at Fermi gases

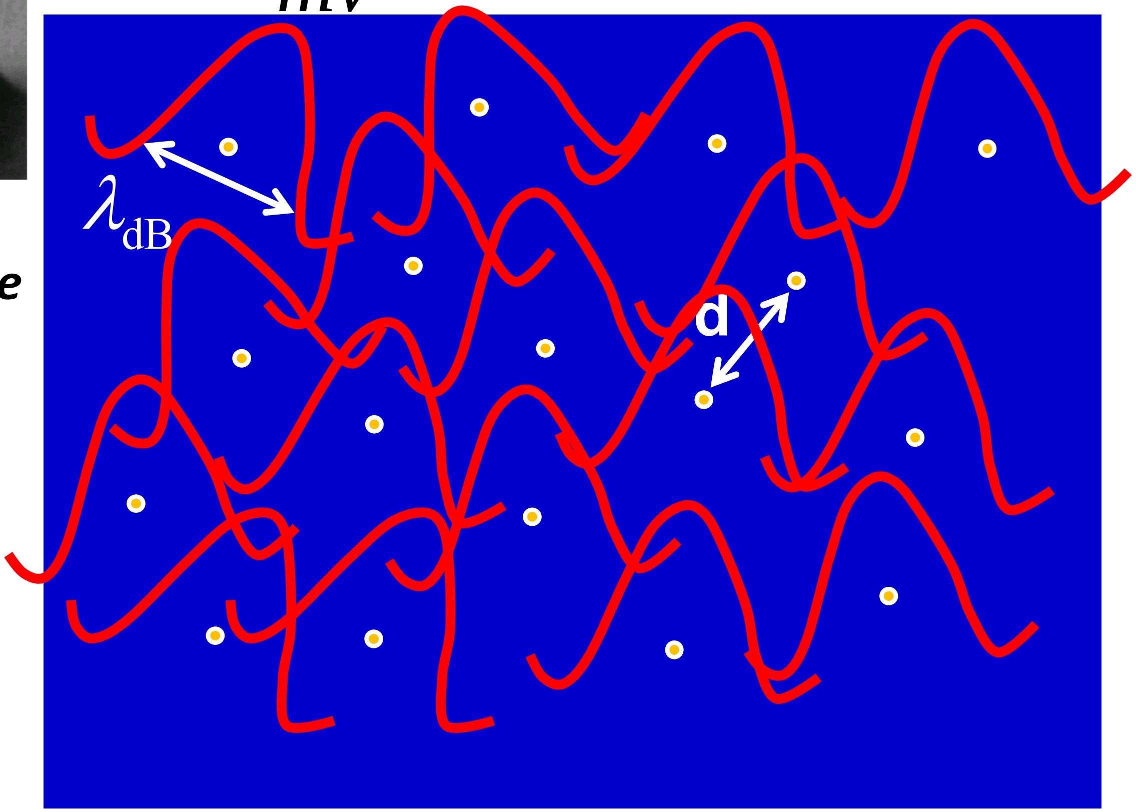
D for an atom: ~Ångströms <<< Interparticle Spacing *d*



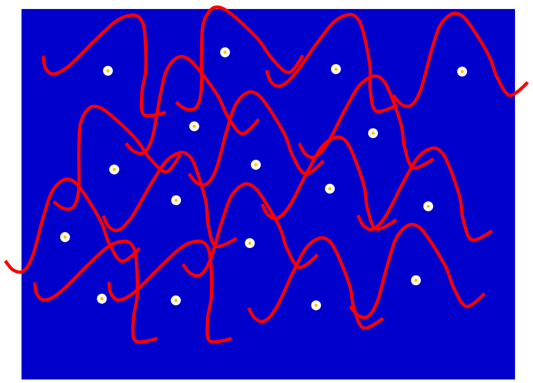
Now: A *local* view at Fermi gases

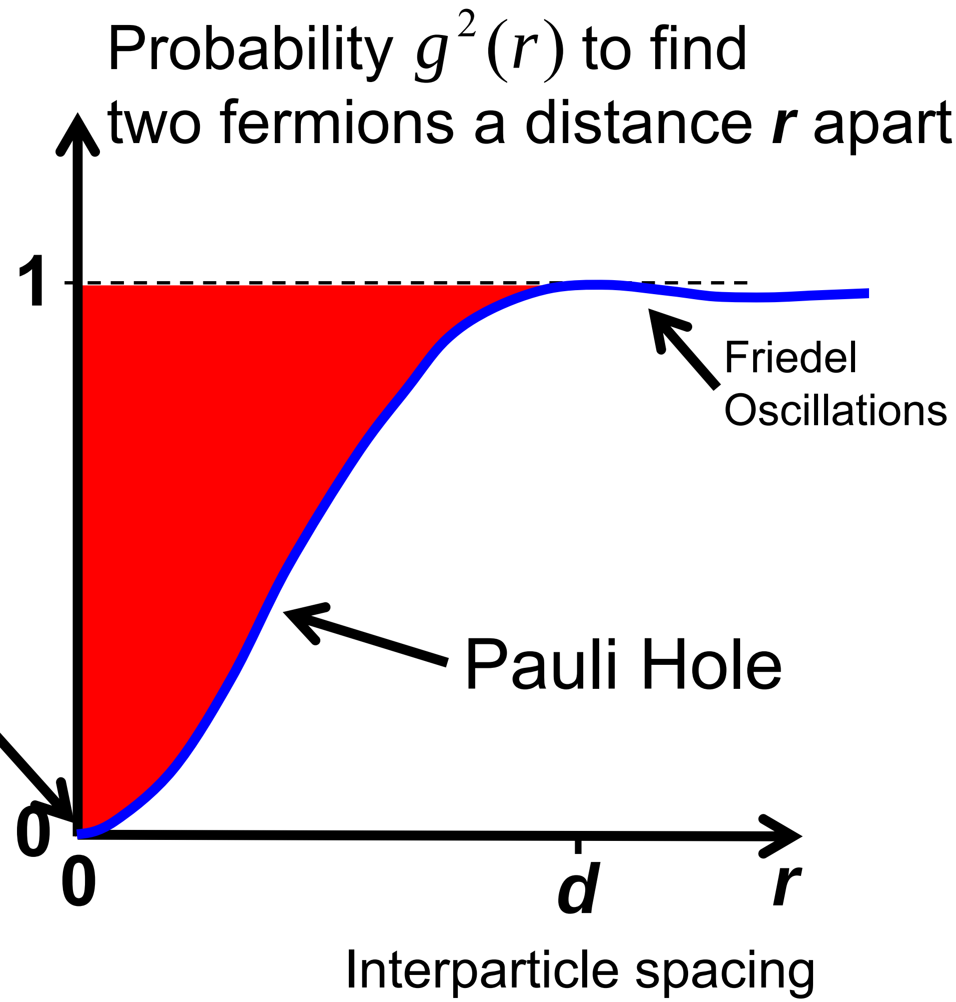
Louis de Broglie

$$\lambda_{\mathrm{dB}} = \frac{h}{mv} \approx \text{Interparticle Spacing } d \text{ at low T}$$



A *local* view at Fermi gases



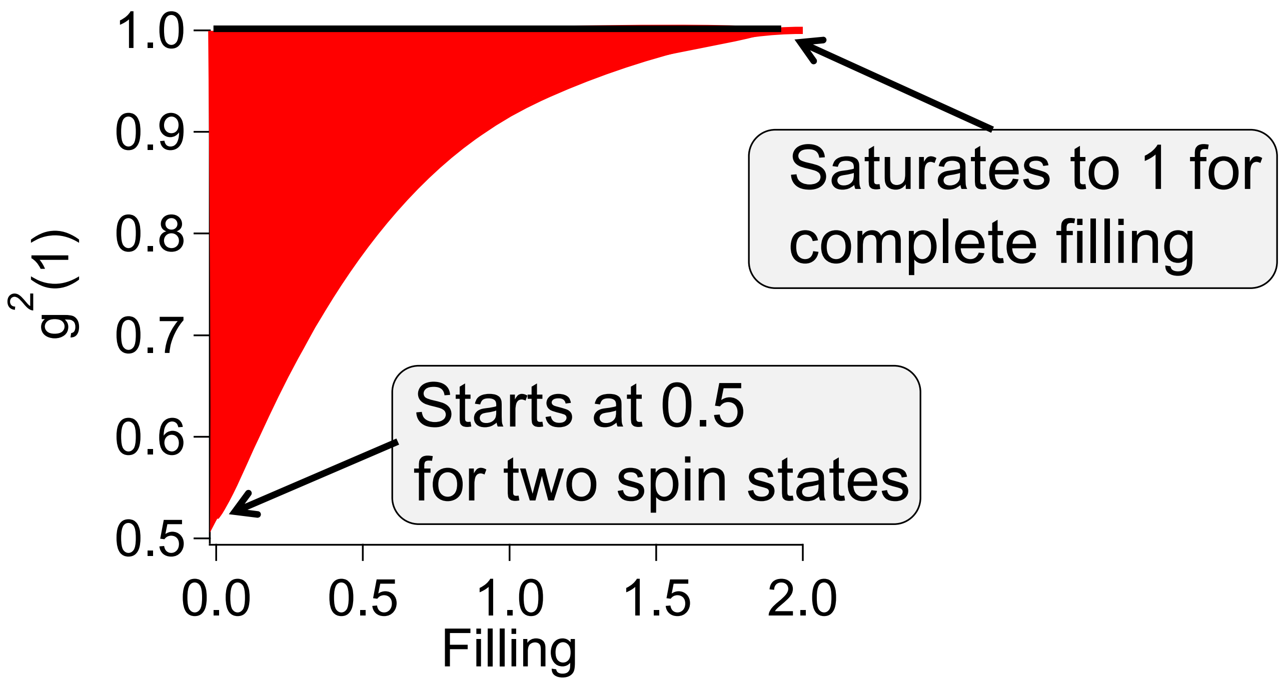


Signature of anti-bunching in TOF:
T. Rom et al., Nature 2006,
Jeltes et al., Nature 2007
Reduction of density fluctuations:
Sanner et al., PRL 2010,
Mueller et al., PRL 2010

Fermion Correlations in a Lattice Gas

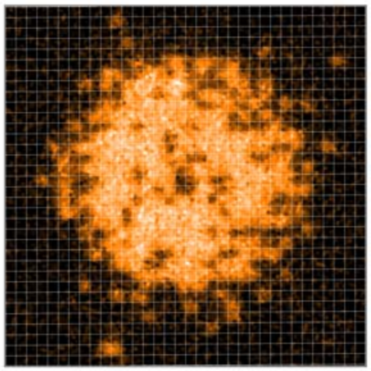
$$g_2(i) = \frac{\langle \hat{n}_i \hat{n}_0 \rangle}{\langle \hat{n}_i \rangle^2}$$

g_2 for fermions reduced below unity



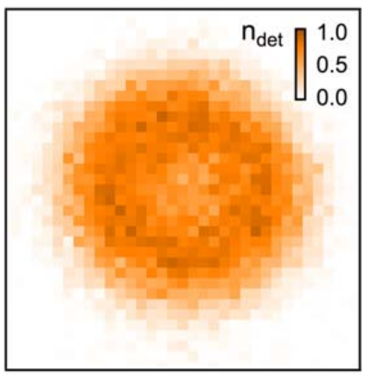
Low filling: lattice spacing << interparticle distance
→ One site away one is deep inside the Pauli hole

Measuring Charge Correlations

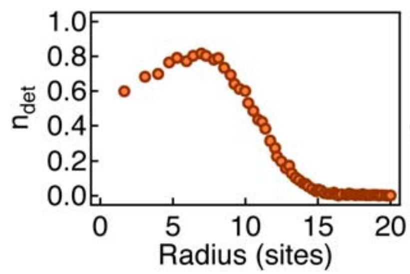


We measure singles
= "local magnetic moments"

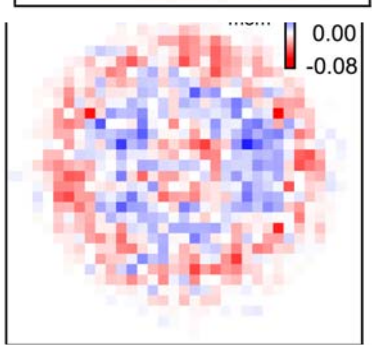
$$\hat{m}_{z,i}^{2} = (\hat{n}_{\uparrow,i} - \hat{n}_{\downarrow,i})^{2}$$



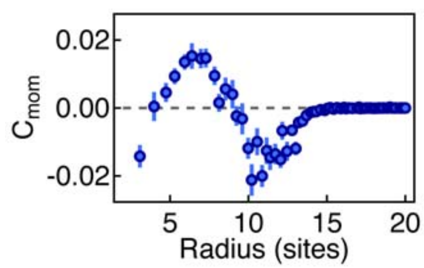
Singles density = Avg. Local Moment



$$m_{z,i}^{2} = \left\langle (\hat{n}_{\uparrow,i} - \hat{n}_{\downarrow,i})^{2} \right\rangle$$

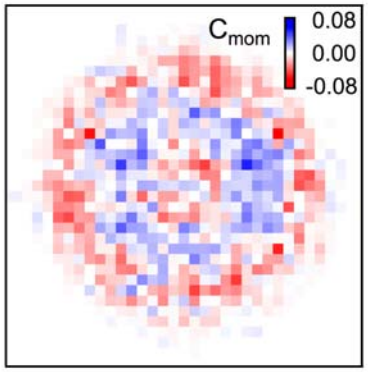


Correlations among Singles (Moments)



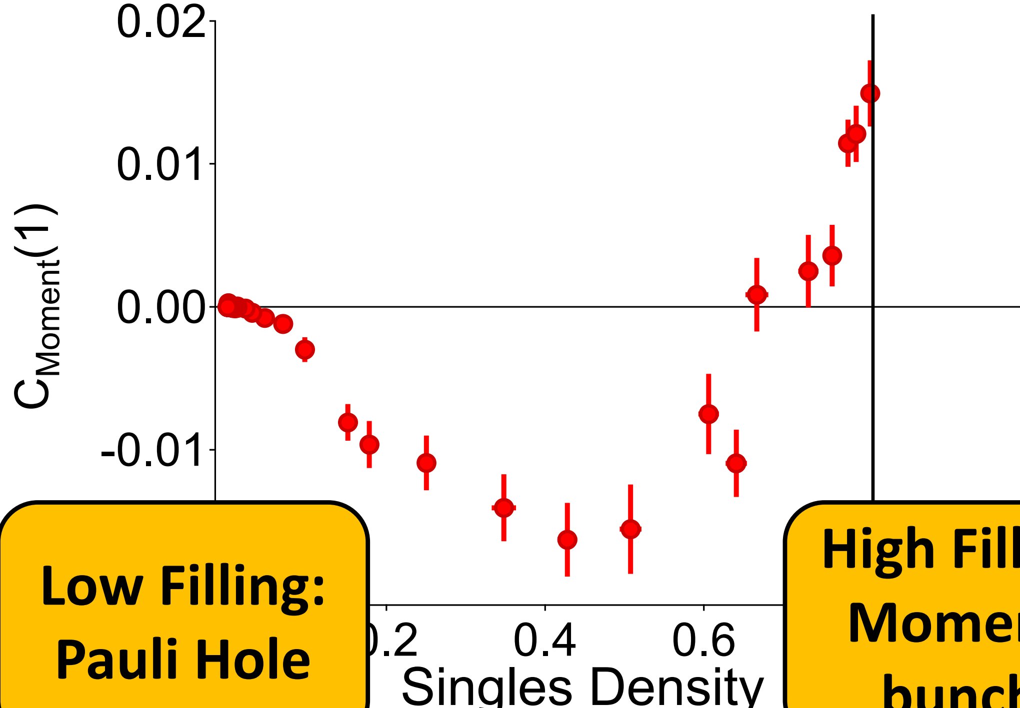
$$\left\langle m_{z,i}^{2} m_{z,j}^{2} \right\rangle_{c}$$

Moment Correlator: Seeing the Pauli Hole



$$C_{moment}(\mathrm{i},\mathrm{j}) = \left\langle m_{z,i}{}^{2} m_{z,j}{}^{2} \right\rangle - \left\langle m_{z,i}{}^{2} \right\rangle \left\langle m_{z,j}{}^{2} \right\rangle$$

Changes sign as a function of filling



Excellent agreement (no fit) with

New NLCE data
Marcos Rigol and
Ehsan Khatami

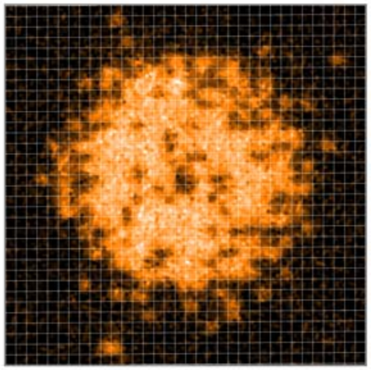
New DQMC data
Thereza Paiva
Nandini Trivedi

Low Filling: Pauli Hole

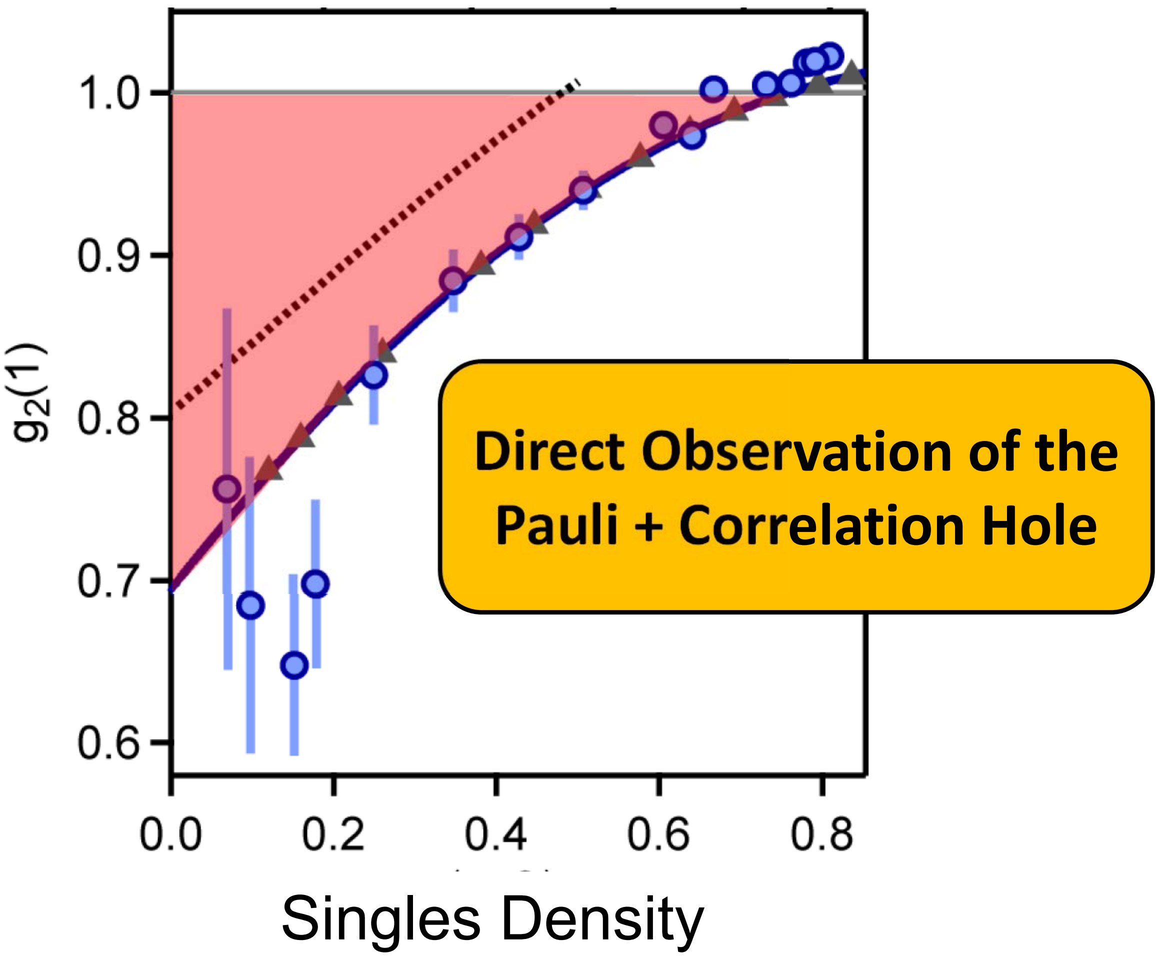
High Filling: Moments bunch!

Cheuk, Nichols, Lawrence, Okan, Zhang, Khatami, Trivedi, Paiva, Rigol, Zwierlein, Science 353, 1260 (2016)

Fermion Correlations in a Lattice Gas



$$g_2(i) = \frac{\langle \hat{n}_i \hat{n}_0 \rangle}{\langle \hat{n}_i \rangle^2}$$

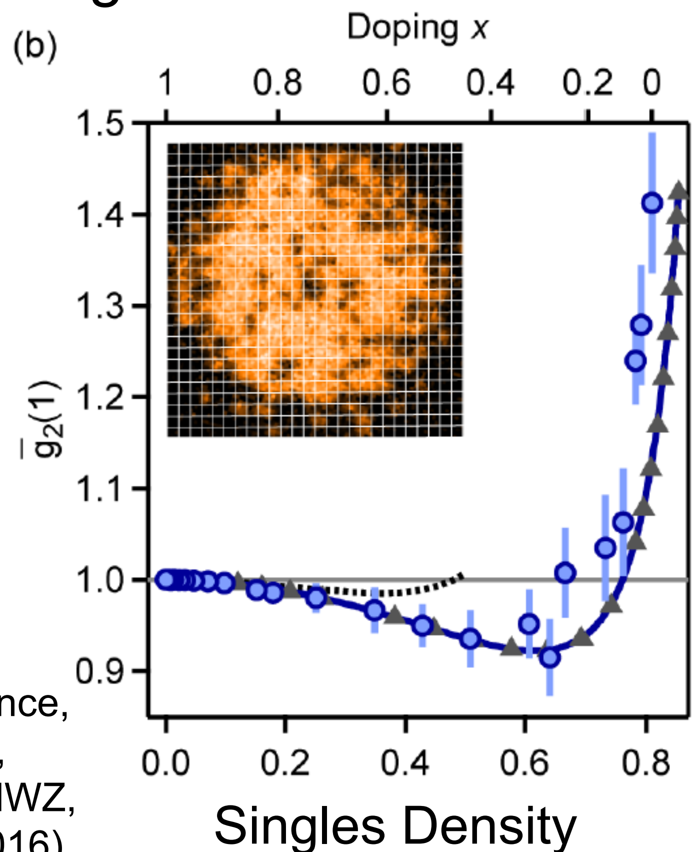


Cheuk, Nichols, Lawrence, Okan, Zhang, Khatami, Trivedi,
Paiva, Rigol, MZ, Science 353, 1260 (2016)

Pair correlation function for doublons & holes

$$< m_{z,i}^2 m_{z,j}^2 >_c = < (1 - m_{z,i}^2)(1 - m_{z,j}^2) >_c$$

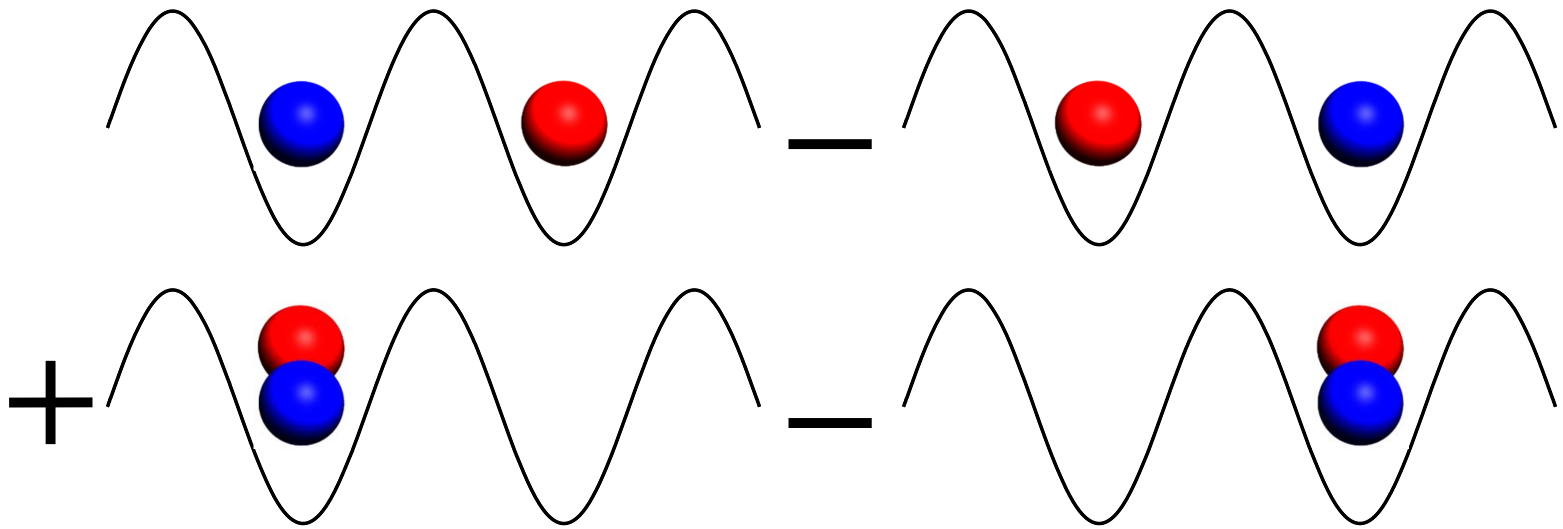
Correlations of Singles = Correlations of holes & doublons



Cheuk, Nichols, Lawrence, Okan, Zhang, Khatami, Trivedi, Paiva, Rigol, MWZ, Science 353, 1260, (2016)

Origin of Doublon-Hole Pair Correlations

Singlet wavefunction:

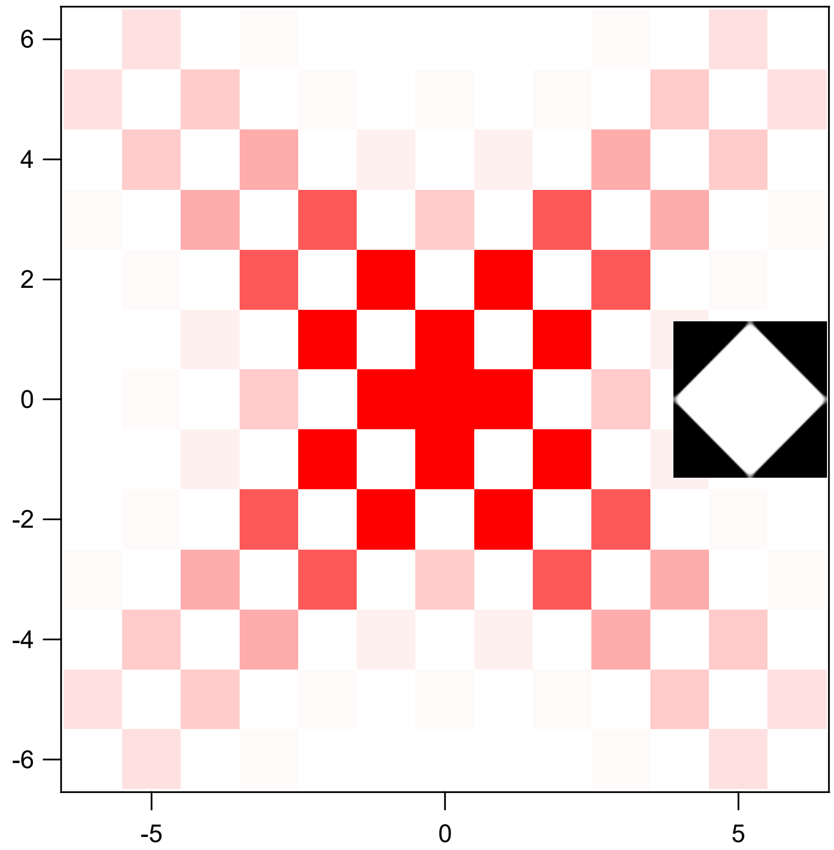


Doublon-Hole admixture to Singlet wavefunction

(already present for the double well)

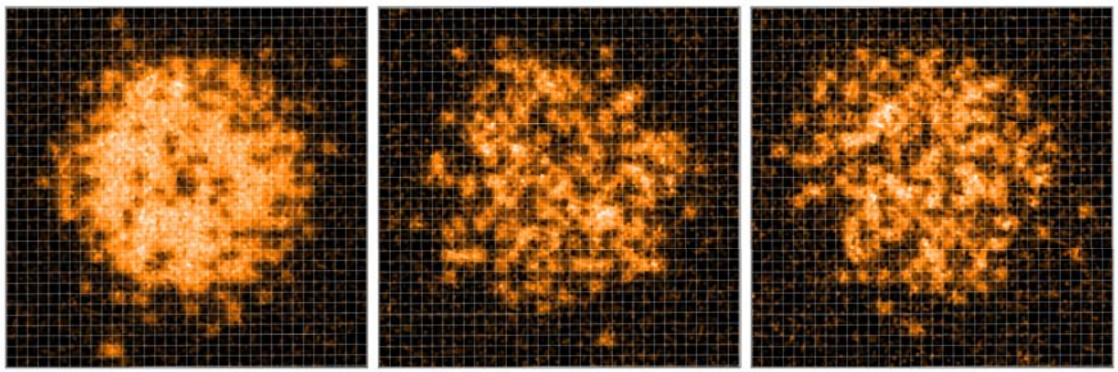
Spin Correlations

Density correlations of non-interacting fermions at half filling

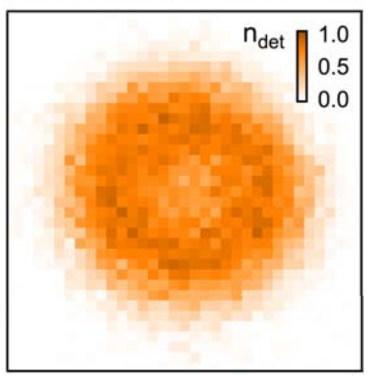


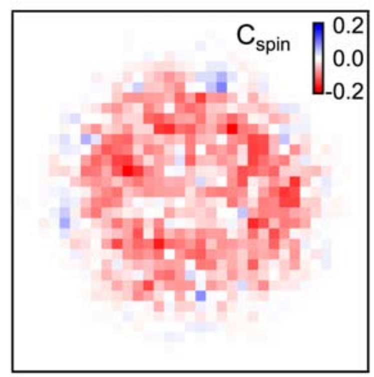
Measuring Spin and Charge Correlations

Singles m_z^2 Ups $n_\uparrow - n_\uparrow n_\downarrow$ Downs $n_\downarrow - n_\uparrow n_\downarrow$

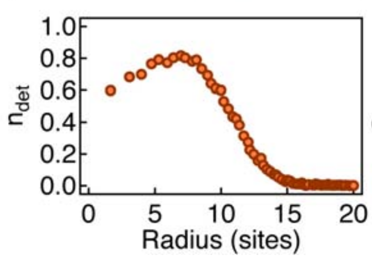


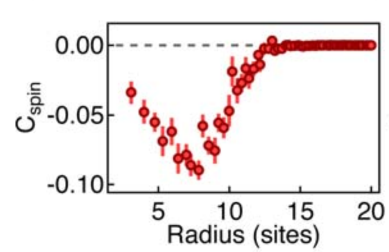
Singles Density $\langle m_z^2 \rangle$





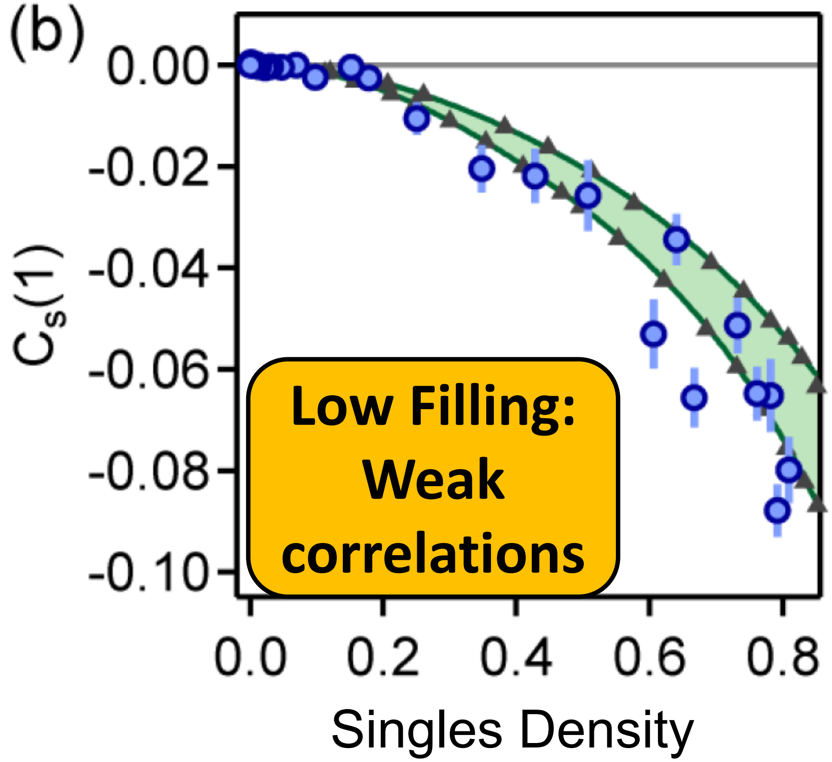
Spin Correlator $\langle m_{z,i} m_{z,j} \rangle$





Spin Correlations

$$C_{spin}(\mathrm{i},\mathrm{j}) = \langle m_{z,i} m_{z,\mathrm{j}} \rangle$$



Excellent agreement (no fit) with

New NLCE data
Marcos Rigol and Ehsan Khatami

New DQMC data
Thereza Paiva
Nandini Trivedi

High Filling: AF correlations develop

Cheuk, Nichols, Lawrence, Okan, Zhang, Khatami, Trivedi, Paiva, Rigol, Zwierlein, Science 353, 1260 (2016)

Harvard: Parsons et al., Science 353, 1253 (2016) in 2D ^{6}Li

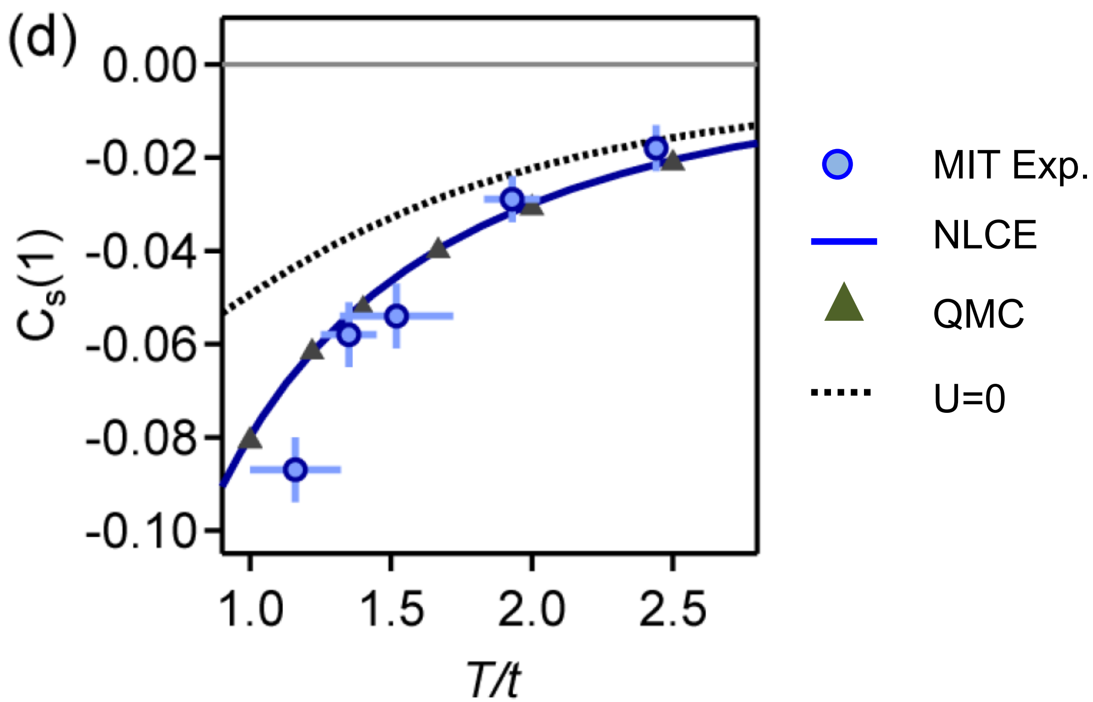
MPQ: Boll et al., Science 353, 1257 (2016) in 1D ^{6}Li

Bonn: Drewes et al., arXiv:1607.00392 (2016) in 2D ^{40}K

Spin Correlations

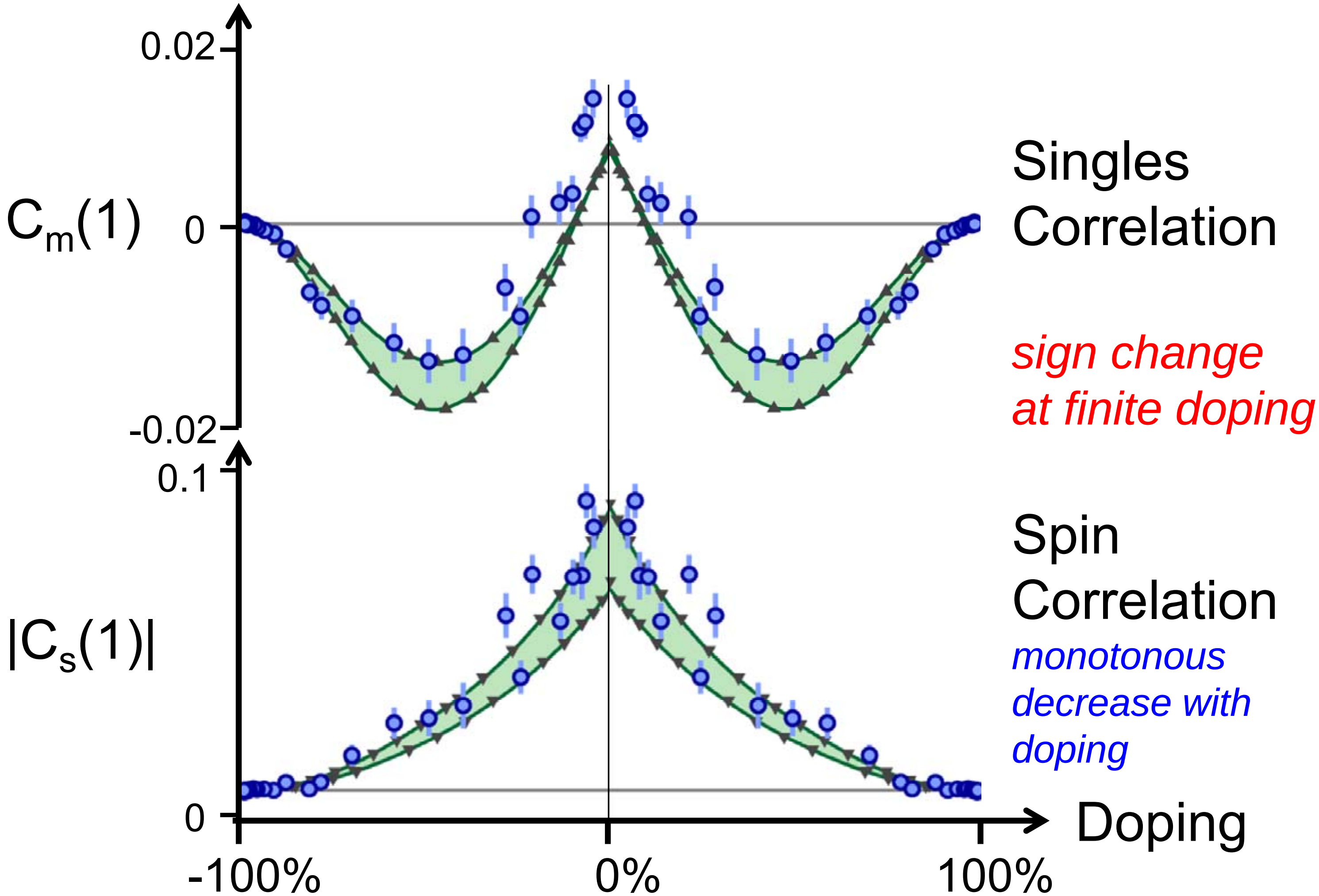
$$C_{spin}(\mathrm{i},\mathrm{j}) = \langle m_{z,i} m_{z,\mathrm{j}} \rangle$$

at half-filling



Cheuk, Nichols, Lawrence, Okan, Zhang, Khatami, Trivedi, Paiva, Rigol, Zwierlein, Science 353, 1260 (2016)
Harvard: Parsons et al., Science 353, 1253 (2016) in 2D ^{6}Li
MPQ: Boll et al., Science 353, 1257 (2016) in 1D ^{6}Li
Bonn: Drewes et al., arXiv:1607.00392 (2016) in 2D ^{40}K

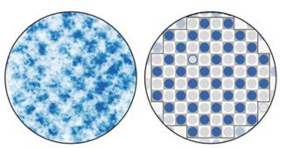
Summary: Spin and Charge Correlations



Fermi Gas Microscopes

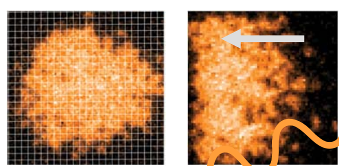
Unique tool to access e.g.

Microscopic

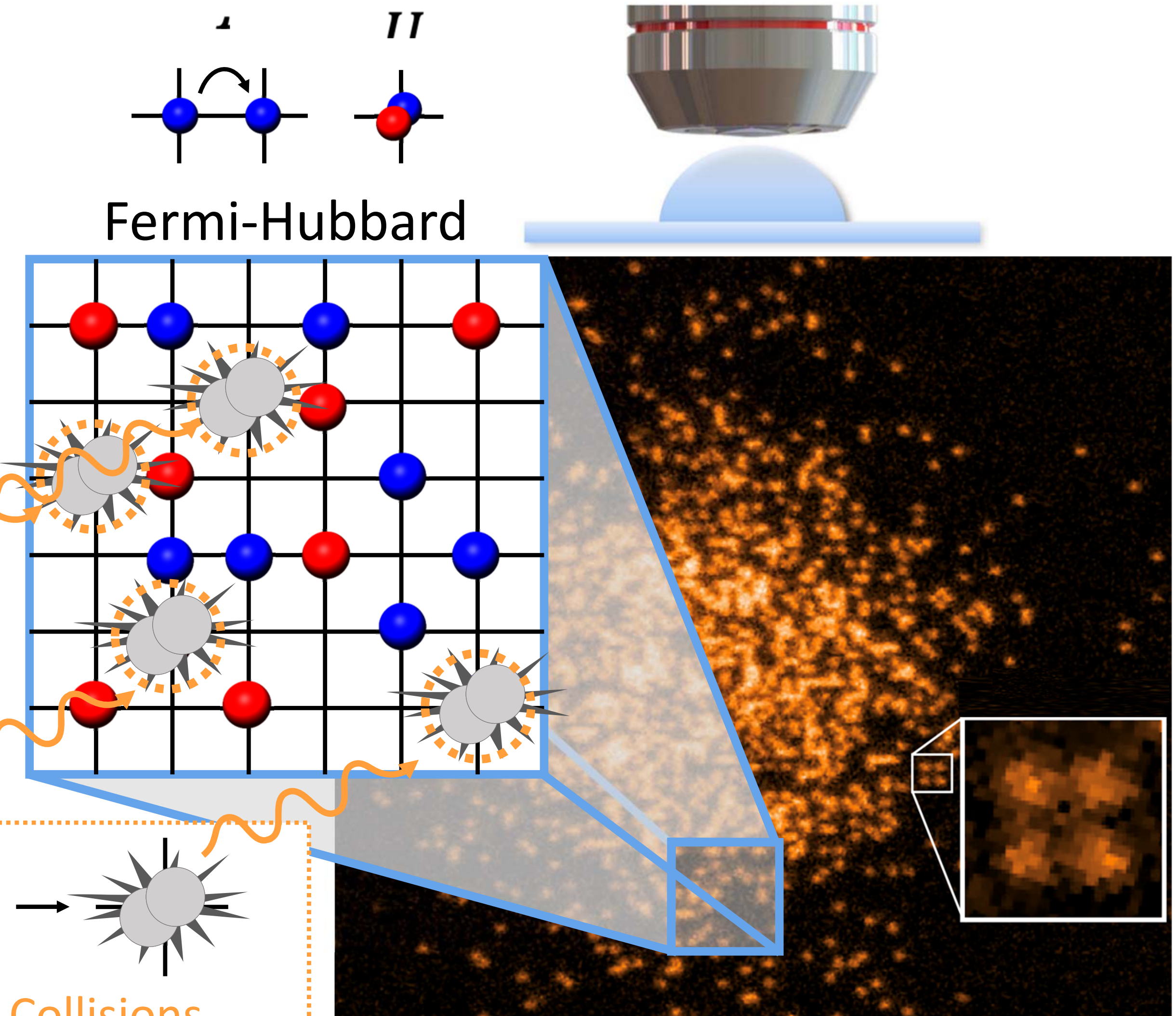


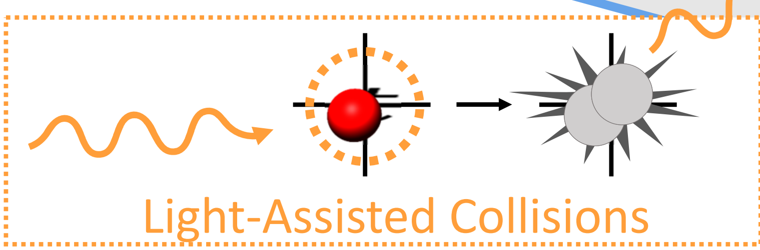
Parsons et al., Science 353 (6305), 1253 (2016), Boll et al., Science 353 (6305), 1257 (2016), Cheuk et al., Science 353 (6305), 1260 (2016), Mazurenko et al., Nature 545, 462 (2017), Koepsell et al., Nature 572, 358 (2019)

Macroscopic



Nichols et al., Science 363 (6425), 383 (2019), Brown et al., Science 363 (6425), 379 (2019), Guardado-Sanchez, PRX 10, 011042 (2020)

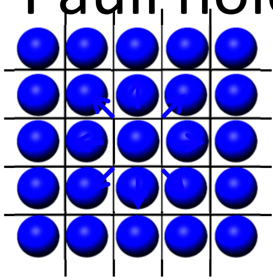




Accessing total density:

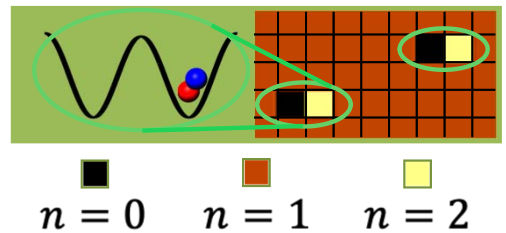
- Enables observing non-local density correlations

Pauli hole



Pauli Hole

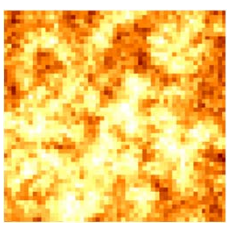
Doublon-Hole correlations

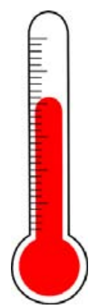


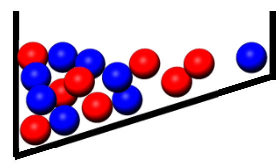
Doublon-Hole
Pairing

- Model-Free Thermometry via Fluctuation-Dissipation Theorem

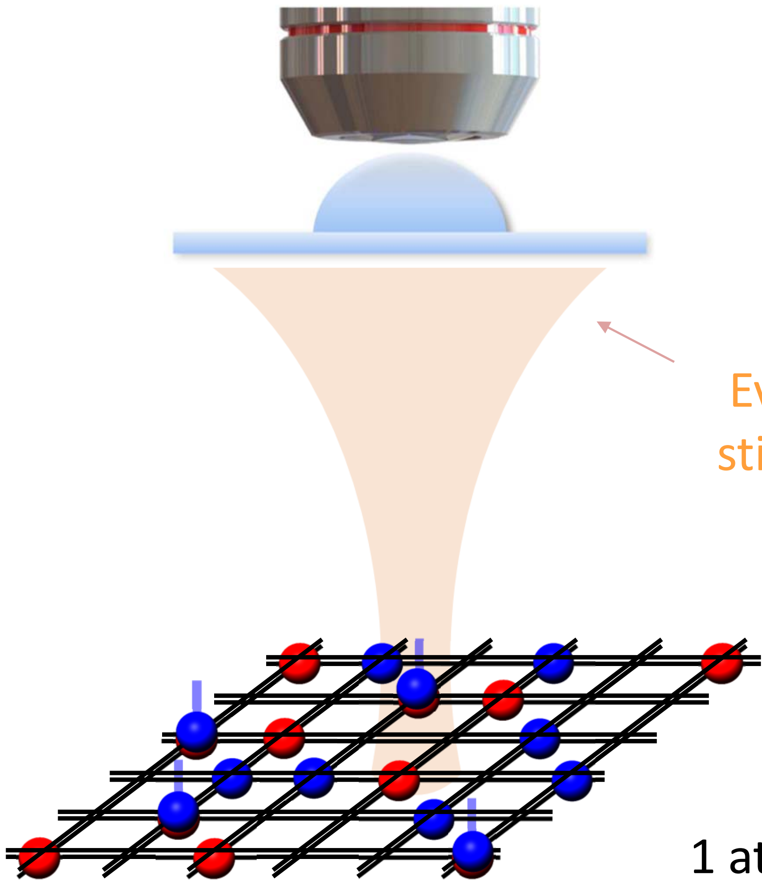
Fluctuations = Temperature × Compressibility







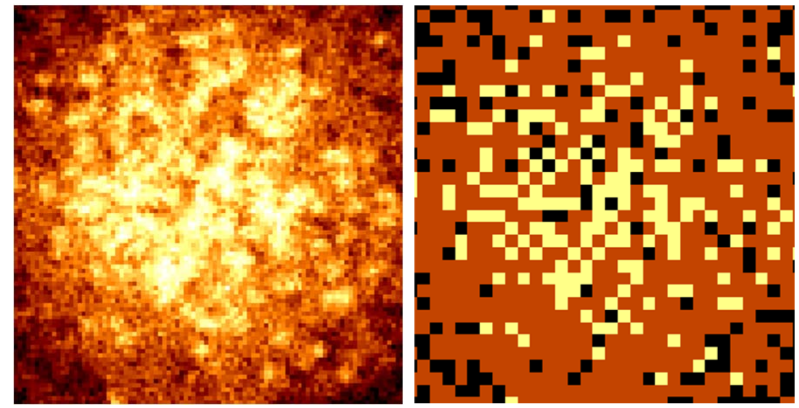
Total density readout via bilayer technique



Everything still in focus

Barely separate layers

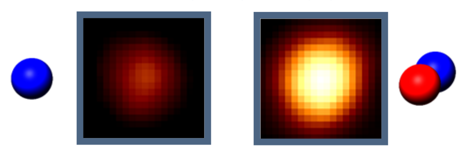
Single Image



Full Density Read-Out

Distinguishable intensities

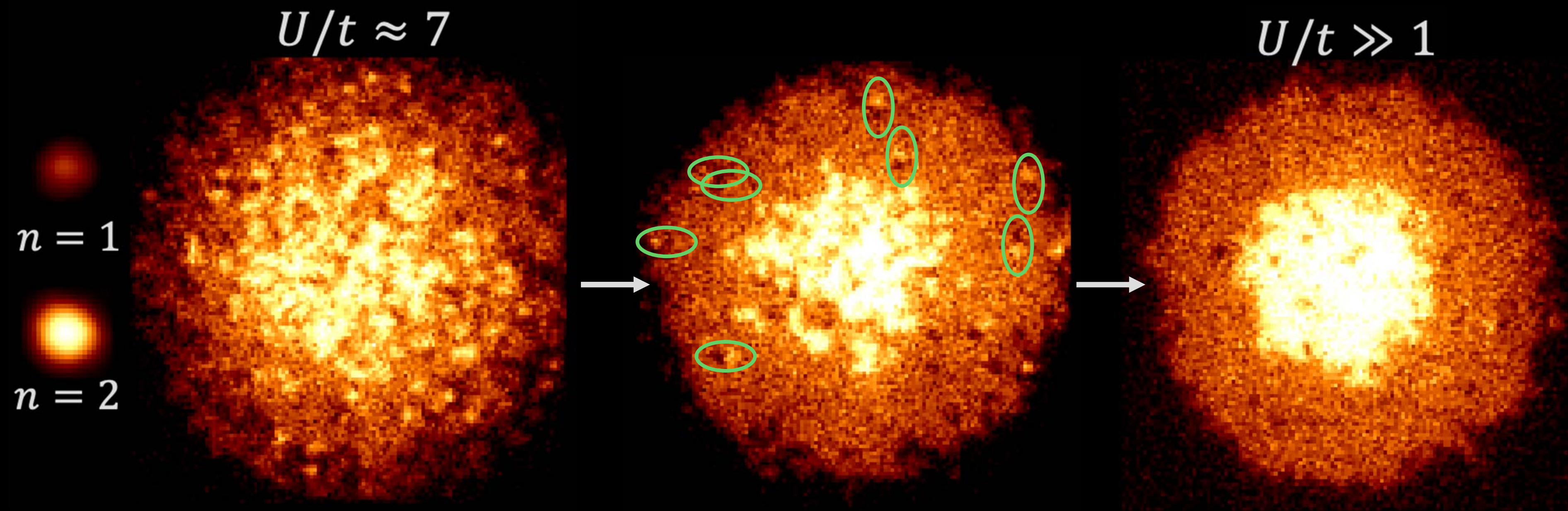
1 atom



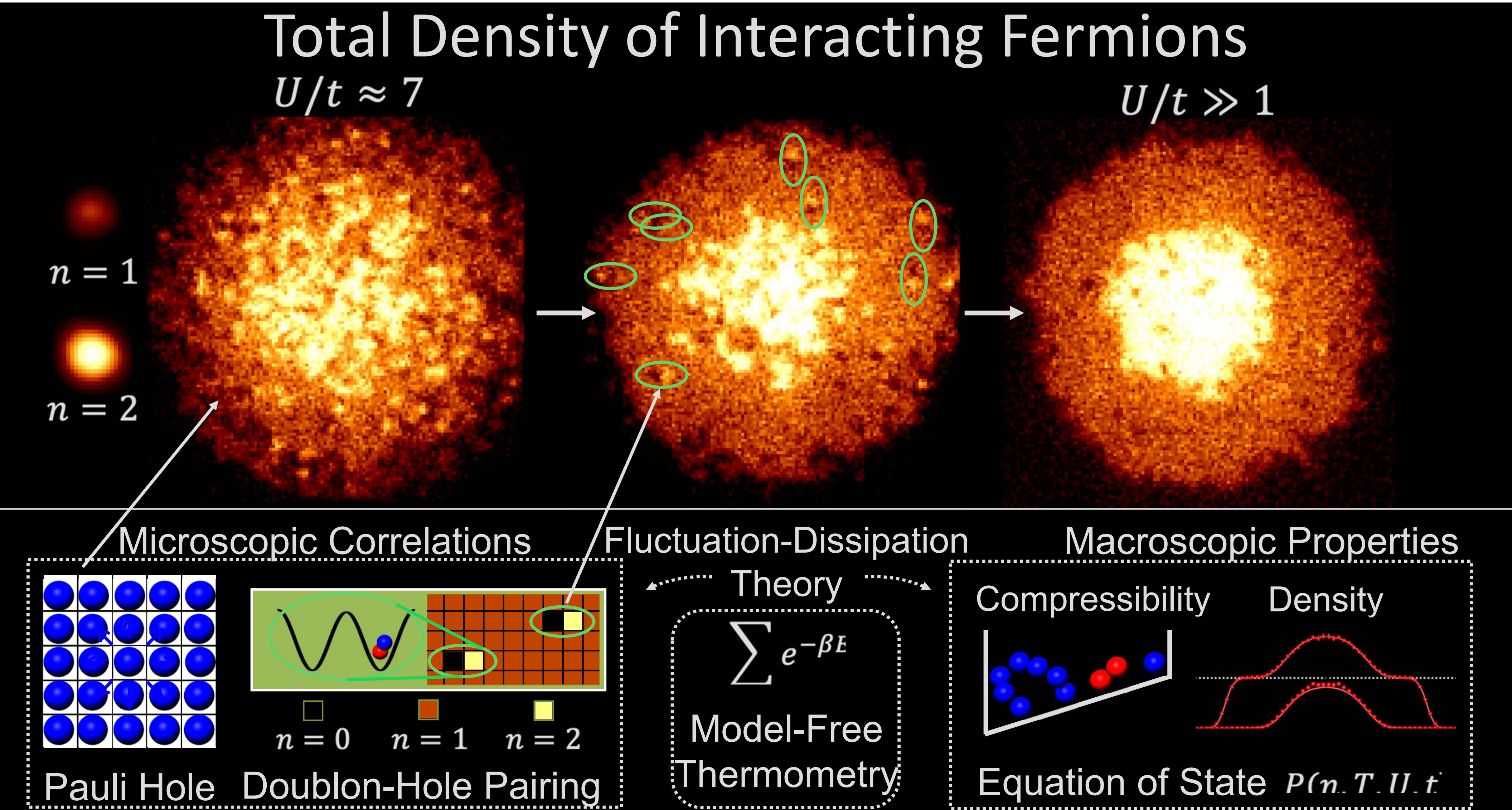
2 atoms

Imaging of separated layers: Preiss et al., Greiner group, PRA 91, 041602 (2015)

Total Density of Interacting Fermions



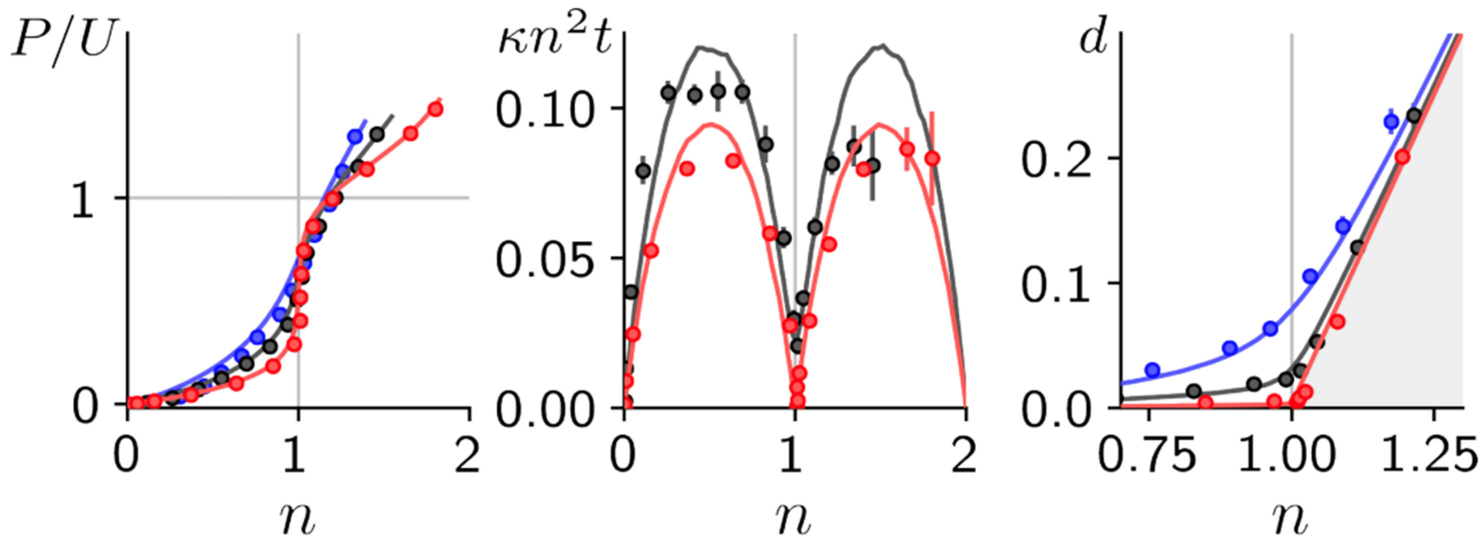
Thomas Hartke, Botond Oreg, Ningyuan Jia, Martin Zwierlein, Phys. Rev. Lett. 125, 113601 (2020)



Thomas Hartke, Botond Oreg, Ningyuan Jia, Martin Zwierlein, Phys. Rev. Lett. 125, 113601 (2020)

Equation of state of the Hubbard model

Pressure Compressibility Interaction Energy



Density

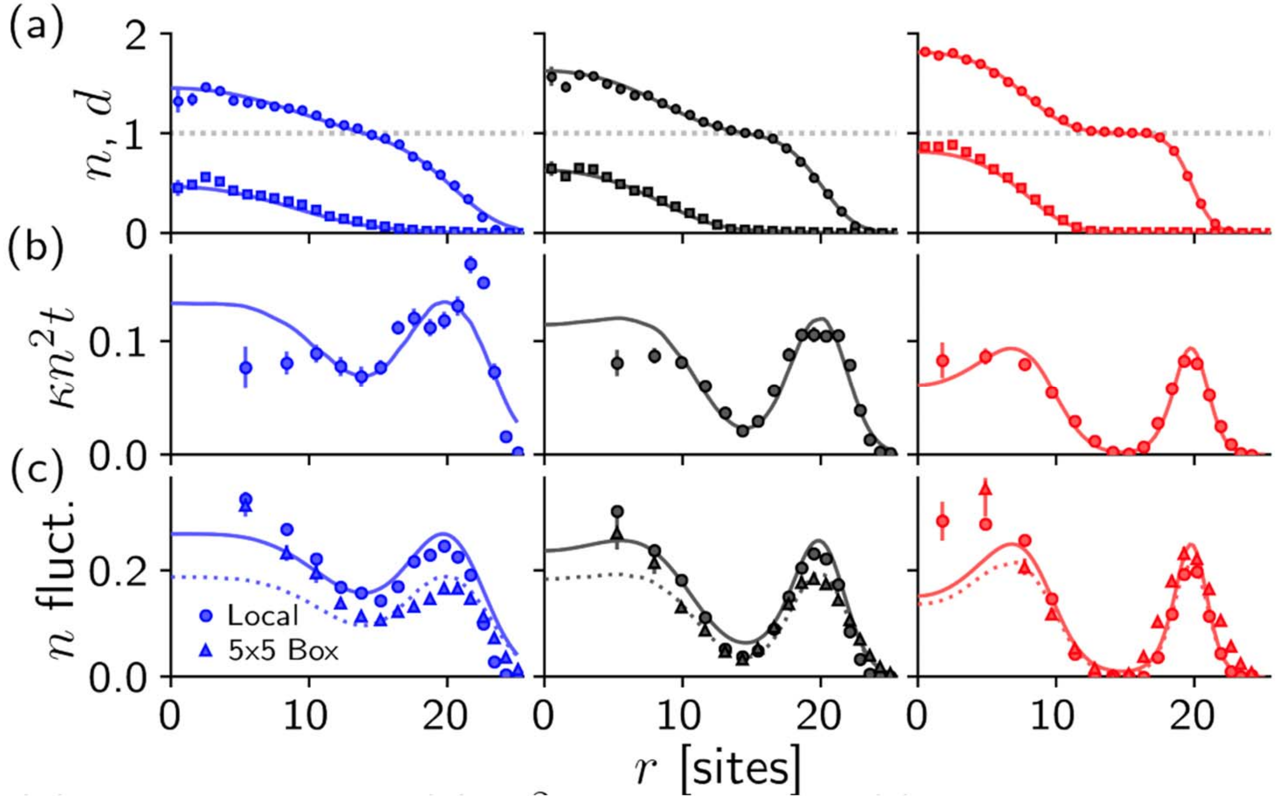
Thomas Hartke, Botond Oreg, Ningyuan Jia, Martin Zwierlein, Phys. Rev. Lett. 125, 113601 (2020)

Equation of State and Fluctuations

$$\kappa = \frac{1}{n}\frac{\partial n}{\partial P}\bigg|_T = \frac{1}{n^2}\frac{\partial n}{\partial \mu}\bigg|_T = -\frac{1}{n^2}\frac{\partial n}{\partial V}\bigg|_T$$

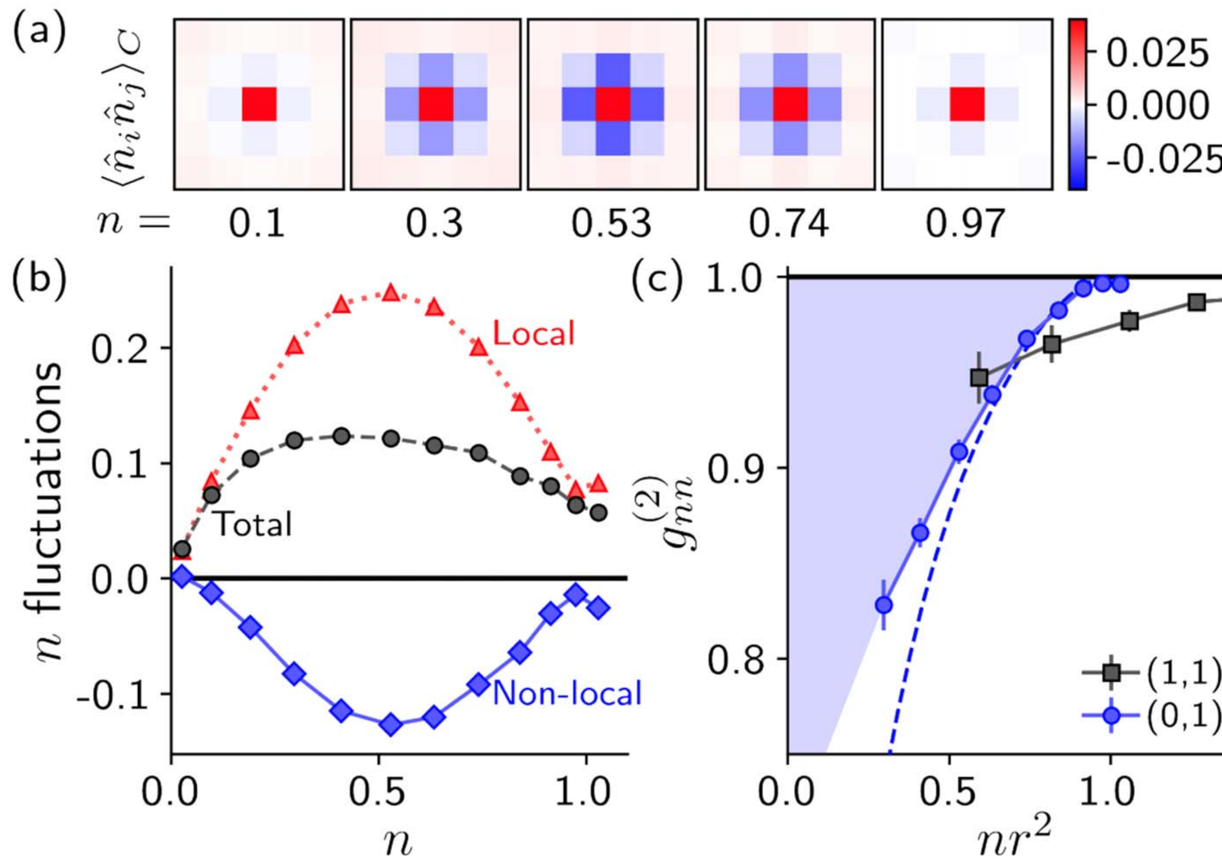
Compressibility:

Number Fluctuations:



Thomas Hartke, Botond Oreg, Ningyuan Jia, Martin Zwierlein, Phys. Rev. Lett. 125, 113601 (2020)

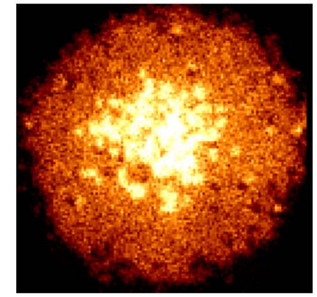
Non-local correlations – Pauli and correlation hole



Thomas Hartke, Botond Oreg, Ningyuan Jia, Martin Zwierlein, Phys. Rev. Lett. 125, 113601 (2020)

Model-Free Fluctuation Thermometry

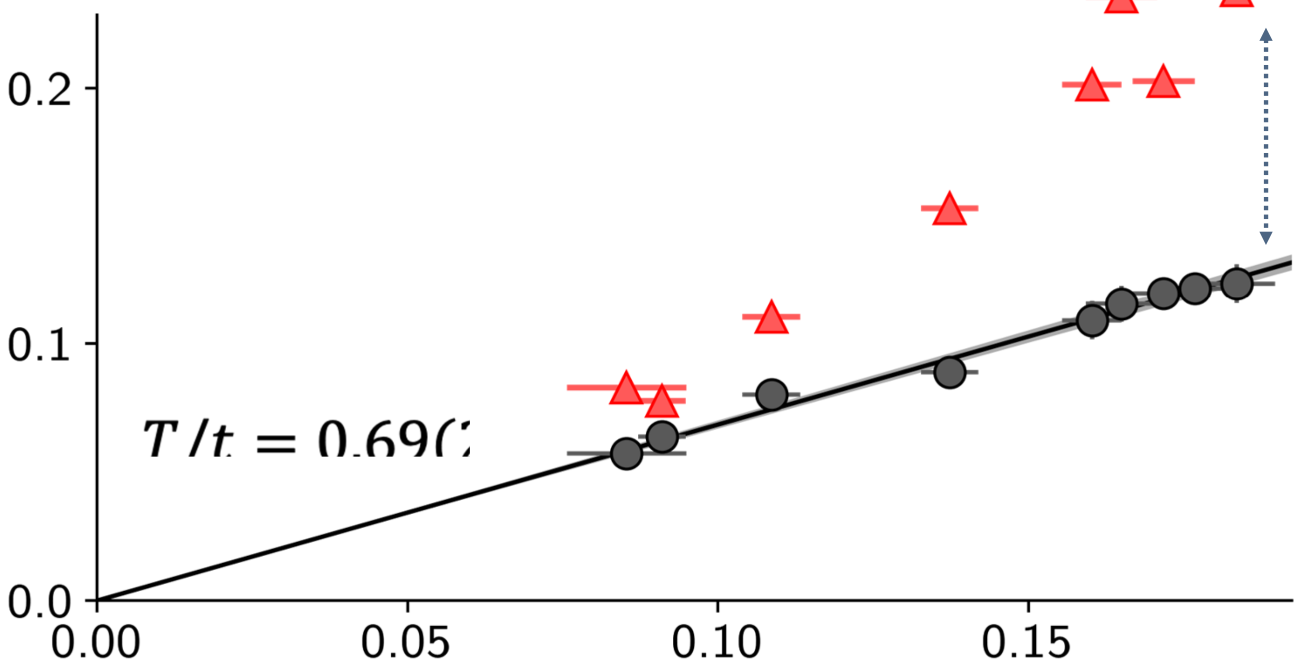
$$\sum_\delta \langle \hat{n}_i \hat{n}_{i+\delta} \rangle_C = T \times \frac{\partial n}{\partial \mu}$$



Full density readout

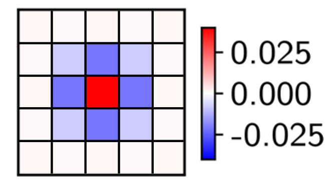
Density Fluctuations

$\sum_\delta \langle \hat{n}_i \hat{n}_{i+\delta} \rangle_C$



Local

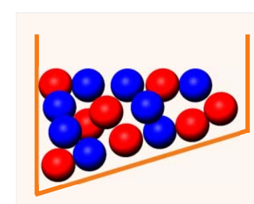
Non-local



Total $\langle \hat{n}_i \hat{n}_{i+\delta} \rangle - \langle \hat{n}_i \rangle \langle \hat{n}_{i+\delta} \rangle$

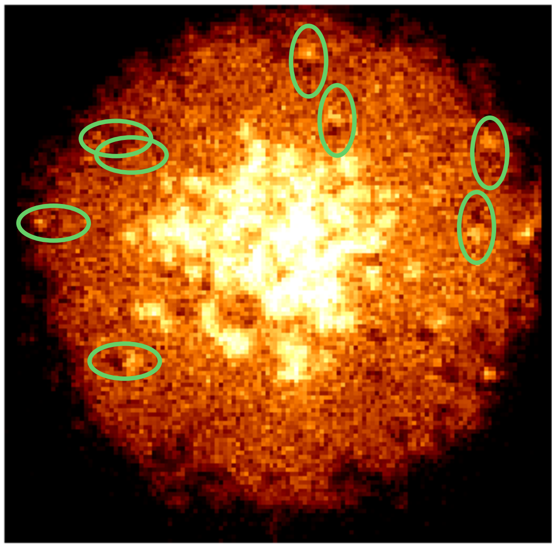
Compressibility

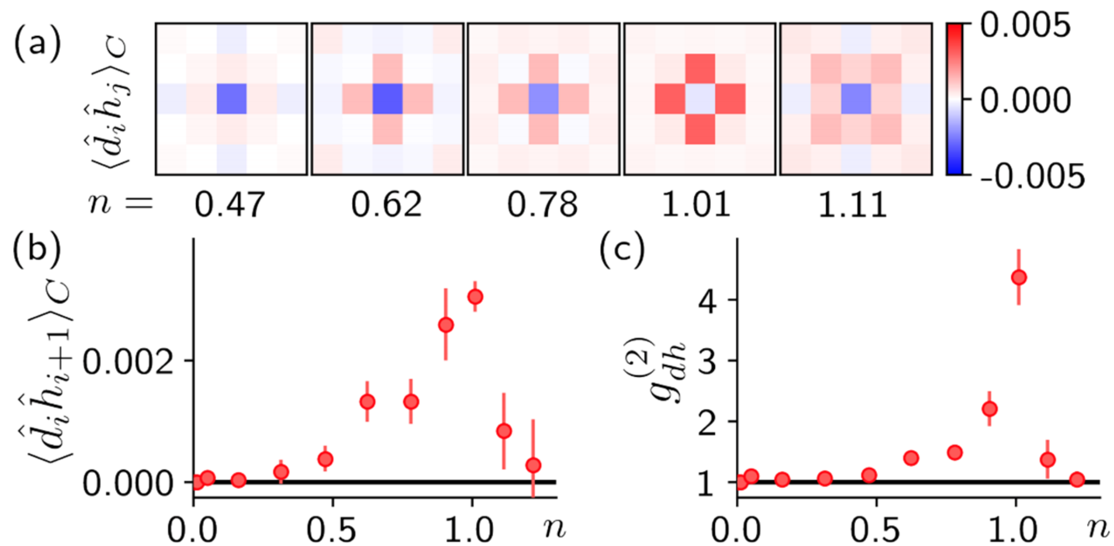
$\frac{\partial n}{\partial \mu}$ $[t^{-1}$



Thomas Hartke, Botond Oreg, Ningyuan Jia, Martin Zwierlein, Phys. Rev. Lett. 125, 113601 (2020)

Doublon-Hole Fluctuations

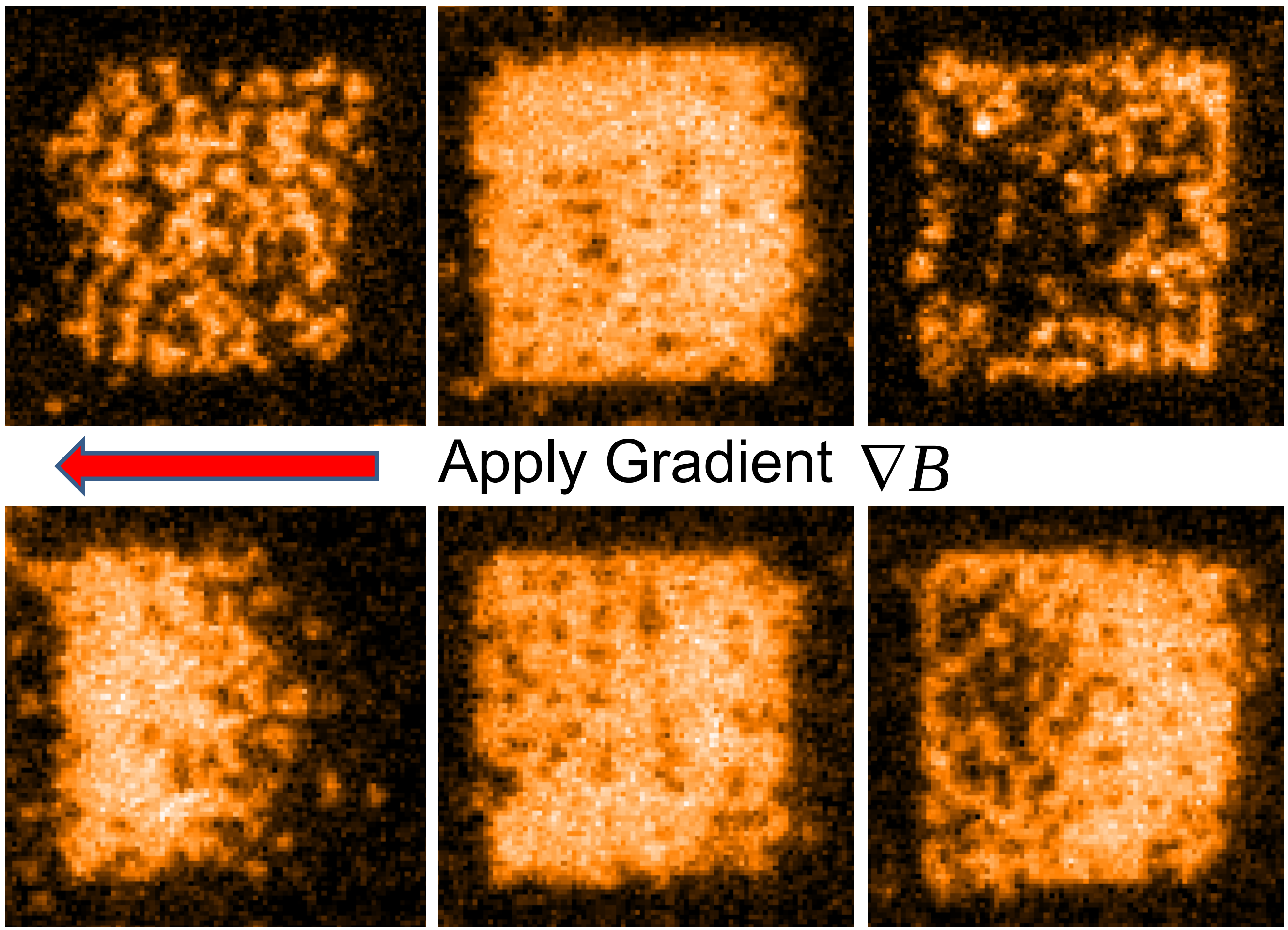




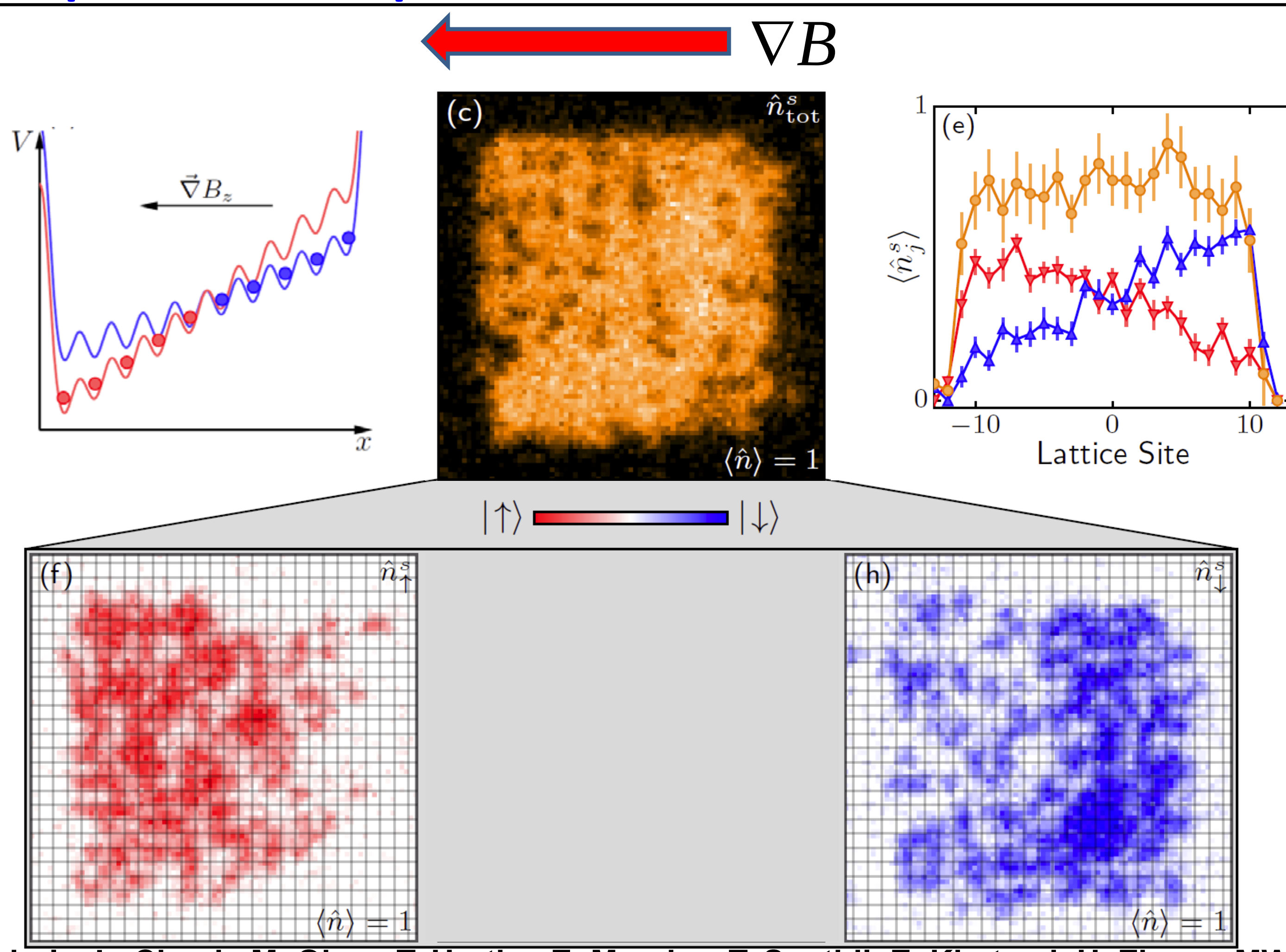
Thomas Hartke, Botond Oreg, Ningyuan Jia, Martin Zwierlein, Phys. Rev. Lett. 125, 113601 (2020)

Fermi-Hubbard Model in a Box

Metal, $n<1$ | Mott | Metal, $n>1$

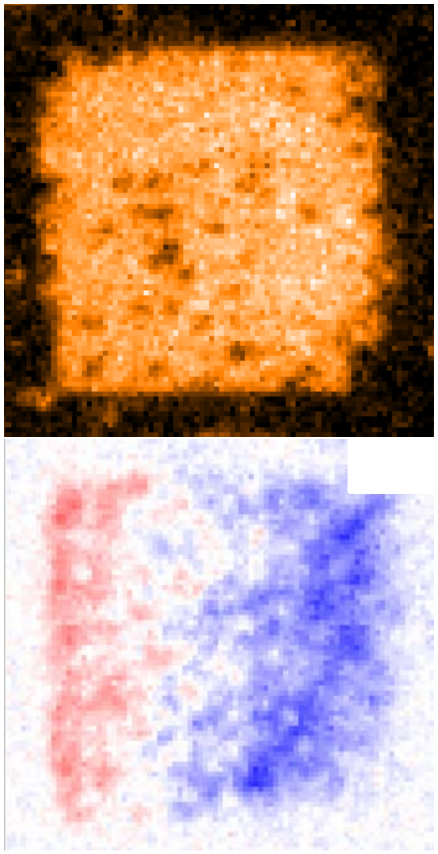


Spin Transport in a Mott Insulator



M. Nichols, L. Cheuk, M. Okan, T. Hartke, E. Mendez, T. Senthil, E. Khatami, H. Zhang, MWZ, Science 363, 383 (2019)

Spin Diffusion in a Fermi Mott Insulator



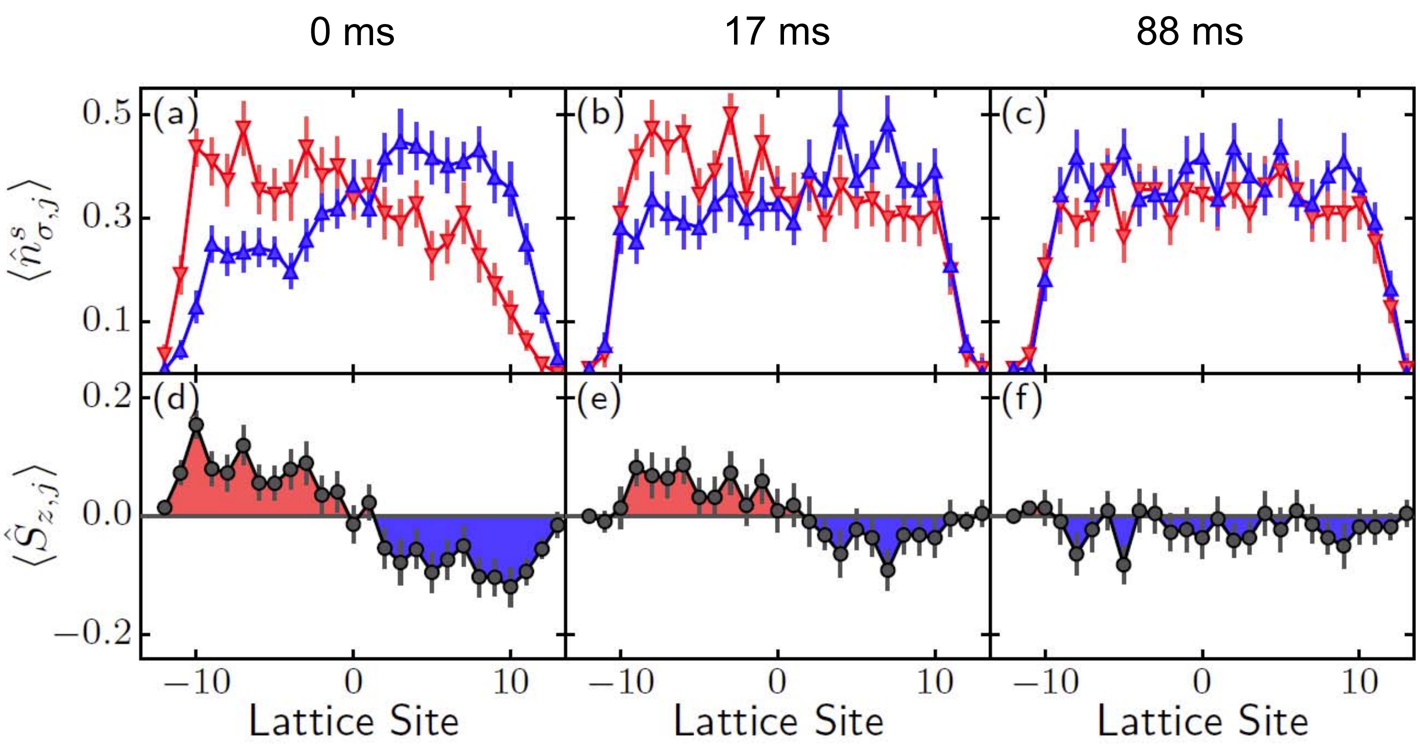
Large U/t limit:

Fermi-Hubbard at $t^2/U < T < U$
= Heisenberg Antiferromagnet

$$J_{ex} = 4\, t^2/U$$

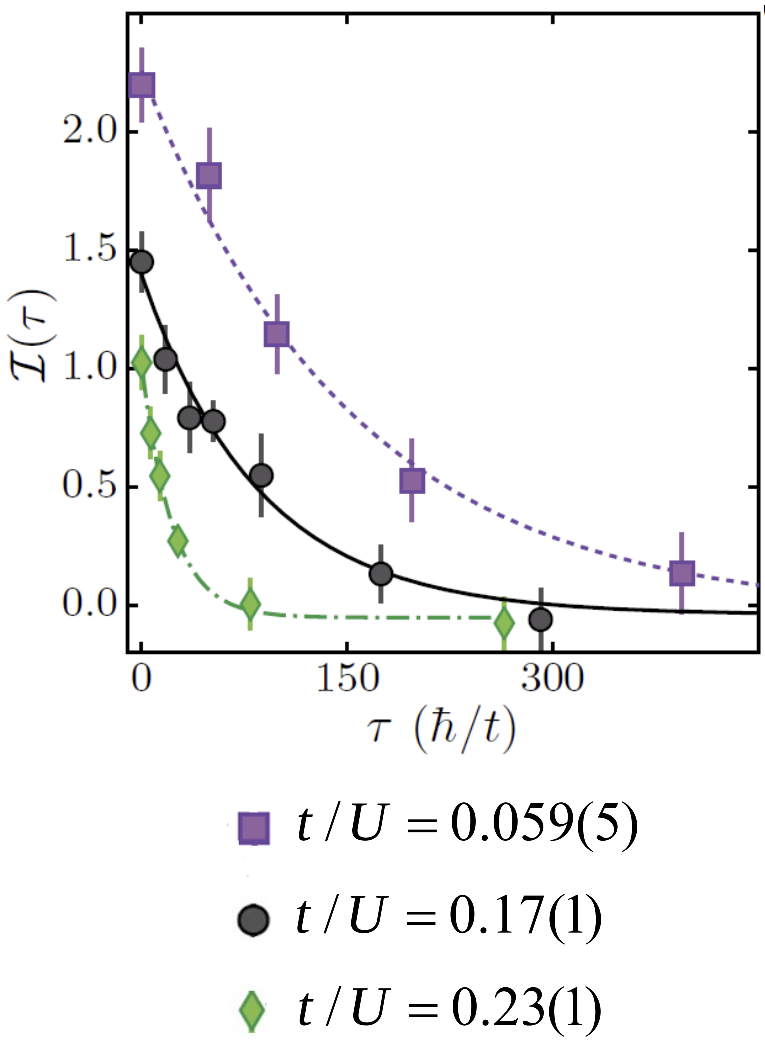
In Bose-Hubbard: see Hild et al., Phys. Rev. Lett. 113, 147205 (2014)

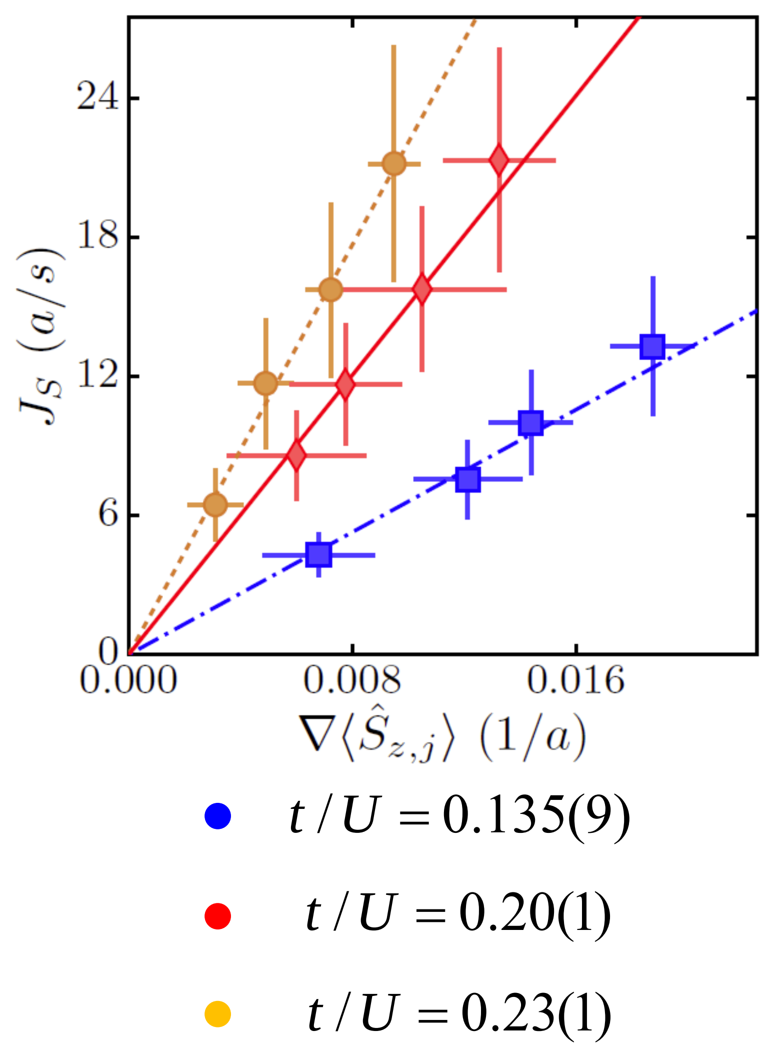
Decay of Spin Imbalance vs Time



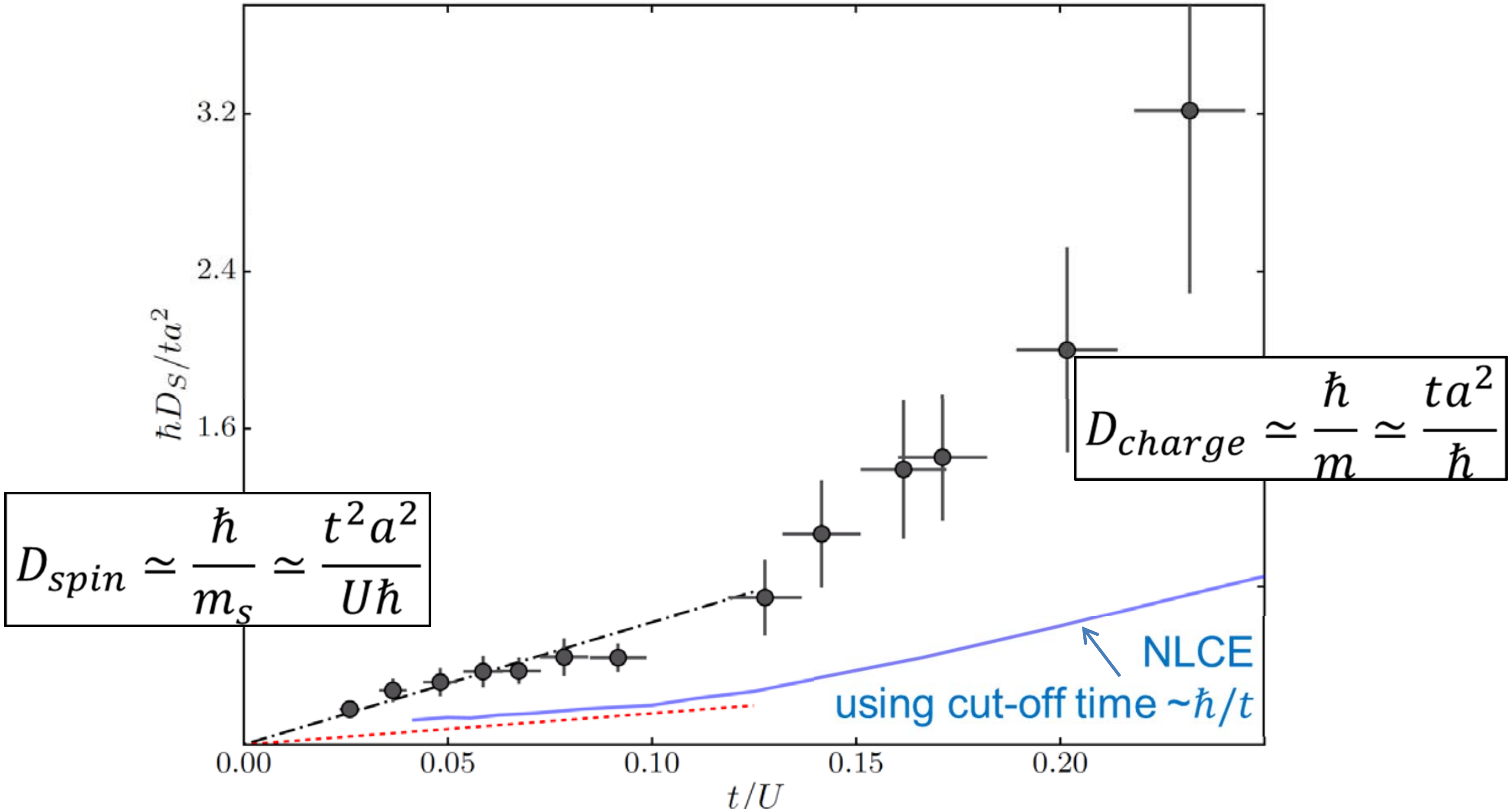
M. Nichols, L. Cheuk, M. Okan, T. Hartke, E. Mendez, T. Senthil, E. Khatami, H. Zhang, MWZ, Science 363, 383 (2019)

Decay of Spin Imbalance vs Time





Spin Diffusivity in a Mott Insulator

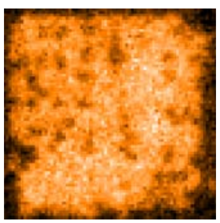


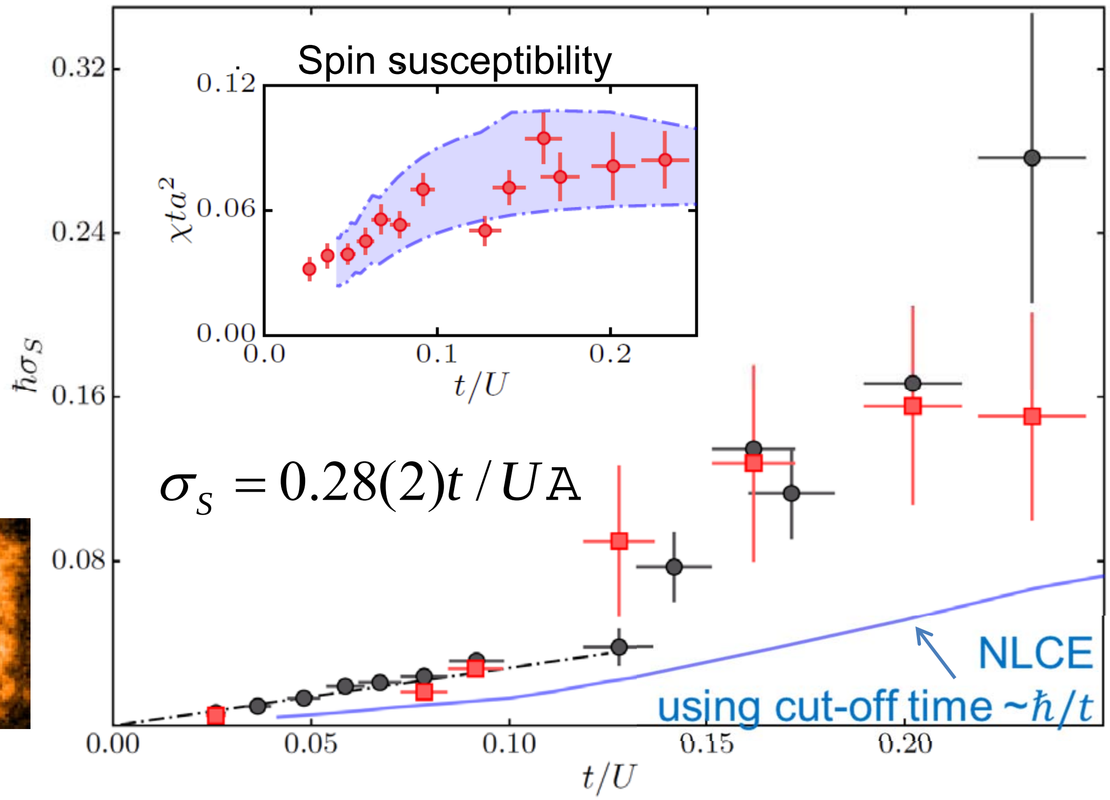
→ Spin transport due to both superexchange and doublon-hole assisted tunneling

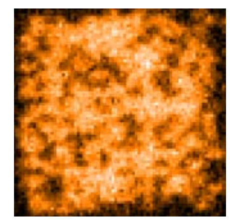
M. Nichols, L. Cheuk, M. Okan, T. Hartke, E. Mendez, T. Senthil, E. Khatami, H. Zhang, MWZ, Science 363, 383 (2019)

Spin Conductivity in the Mott Insulator

● Direct measurement ● From Einstein relation $D_S \chi = \sigma_S$







M. Nichols, L. Cheuk, M. Okan, T. Hartke, E. Mendez, T. Senthil, E. Khatami, H. Zhang, MWZ, Science 363, 383 (2019)

Transport in Strongly Correlated Quantum Gases

Unifying themes of strongly interacting Fermi systems:

Loss of quasi-particle description: $\tau^{-1} \approx E_F / \hbar$

Quantum-Limited diffusivities: $D \approx \frac{\hbar}{m}$

Quantum gas simulators are poised to further elucidate Interplay between charge, spin, heat and Hall transport

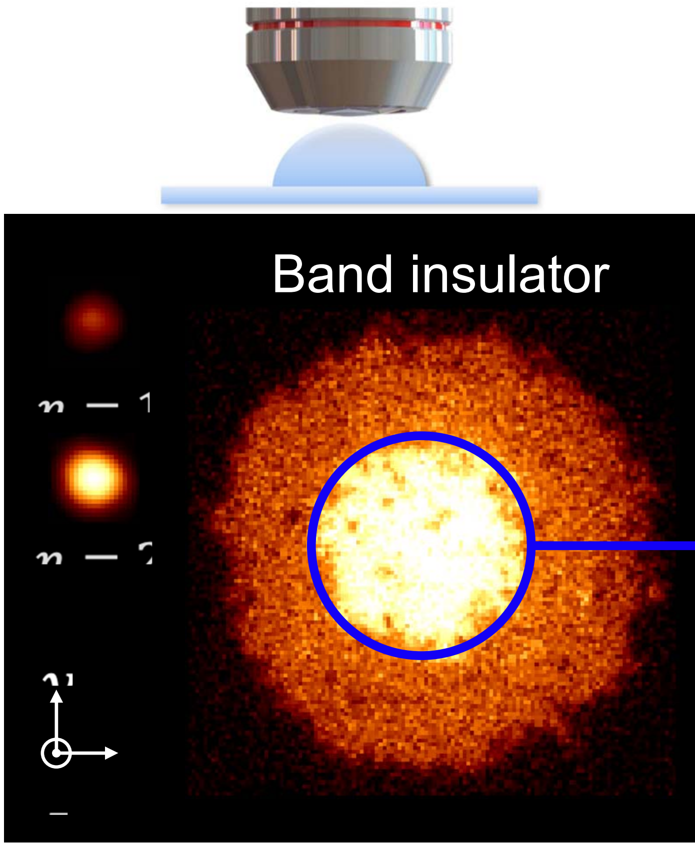
- Universal Sound Diffusion in a Strongly Interacting Fermi Gas
  Parth B. Patel, Zhenjie Yan, Biswaroop Mukherjee, Richard J. Fletcher, Julian Struck, MZ
  Science, 370, 1222 (2020)
- Spin Transport in a Mott Insulator of Ultracold Fermions
  Matthew Nichols, Lawrence Cheuk, Melih Okan, Thomas Hartke, Enrique Mendez, T. Senthil, Ehsan Khatami, Hao Zhang, MZ, Science 363, 383 (2019)
- Doublon-Hole Correlations and Fluctuation Thermometry in a Fermi-Hubbard Gas
  T. Hartke, B. Oreg, N. Jia, MZ, PRL 125, 113601 (2020)
- Bose polarons near quantum criticality
  Zoe Z. Yan, Yiqi Ni, Carsten Robens, MZ, Science, 368, 190-194 (2020)
- Geometric squeezing into the lowest Landau level
  Richard J. Fletcher, Airlia Shaffer, Cedric C. Wilson, Parth B. Patel, Zhenjie Yan, Valentin Crépel, Biswaroop Mukherjee, MZ, arXiv:1911.12347 (Science 2021, to be published)

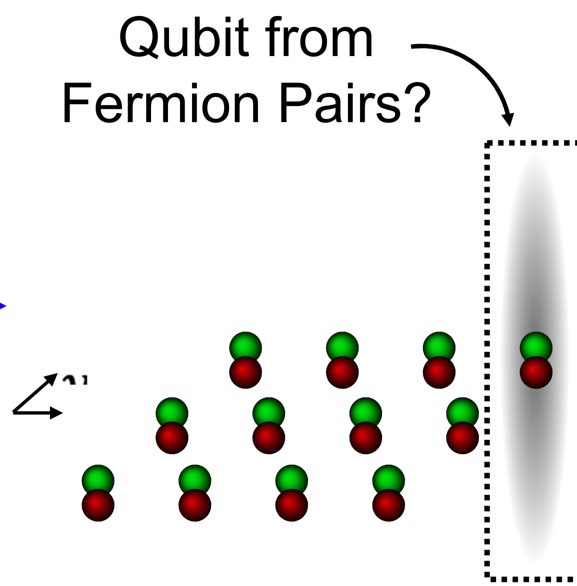
Bridging Quantum Simulation and Quantum Storage

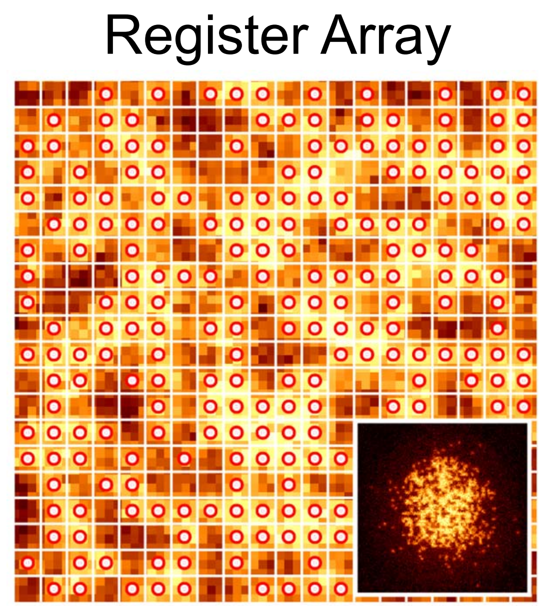
Quantum Register

Part 1
Qubit Architecture

Part 2
Experimental Demonstration





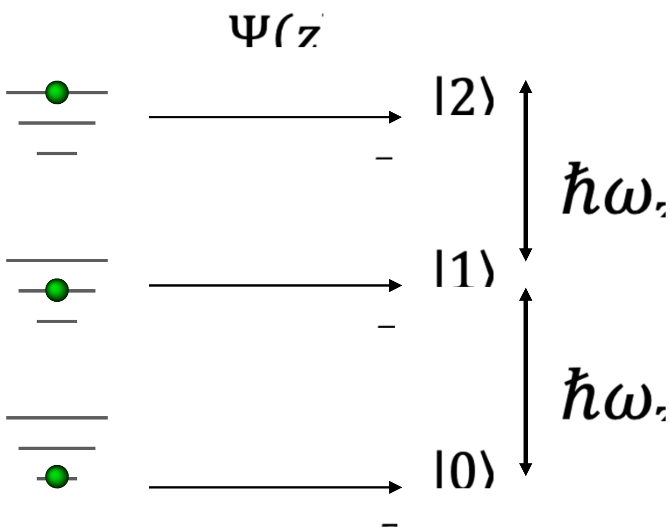


Part 1:

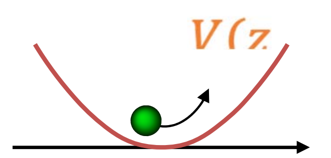
Building a qubit from the motion of atom pairs

Building a Degenerate Subspace from Pairs

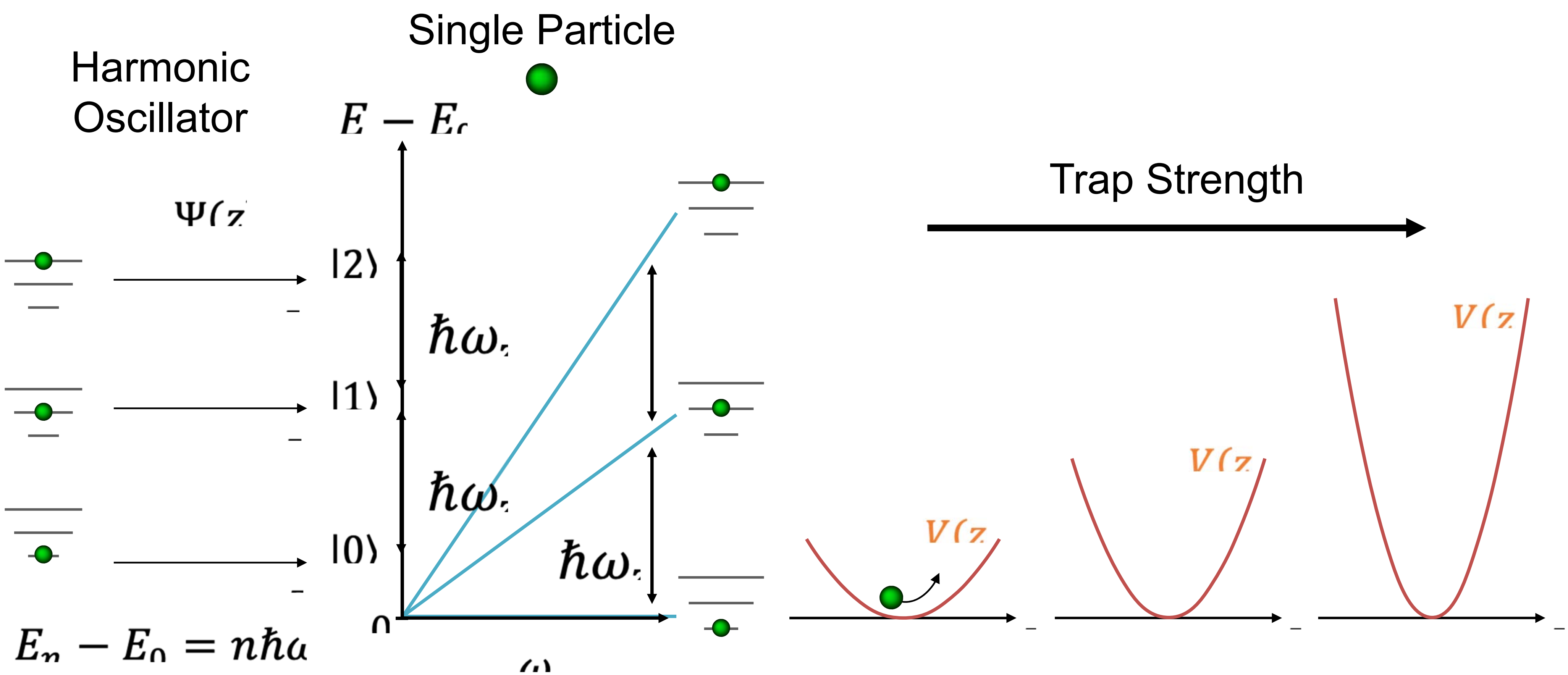
Harmonic
Oscillator



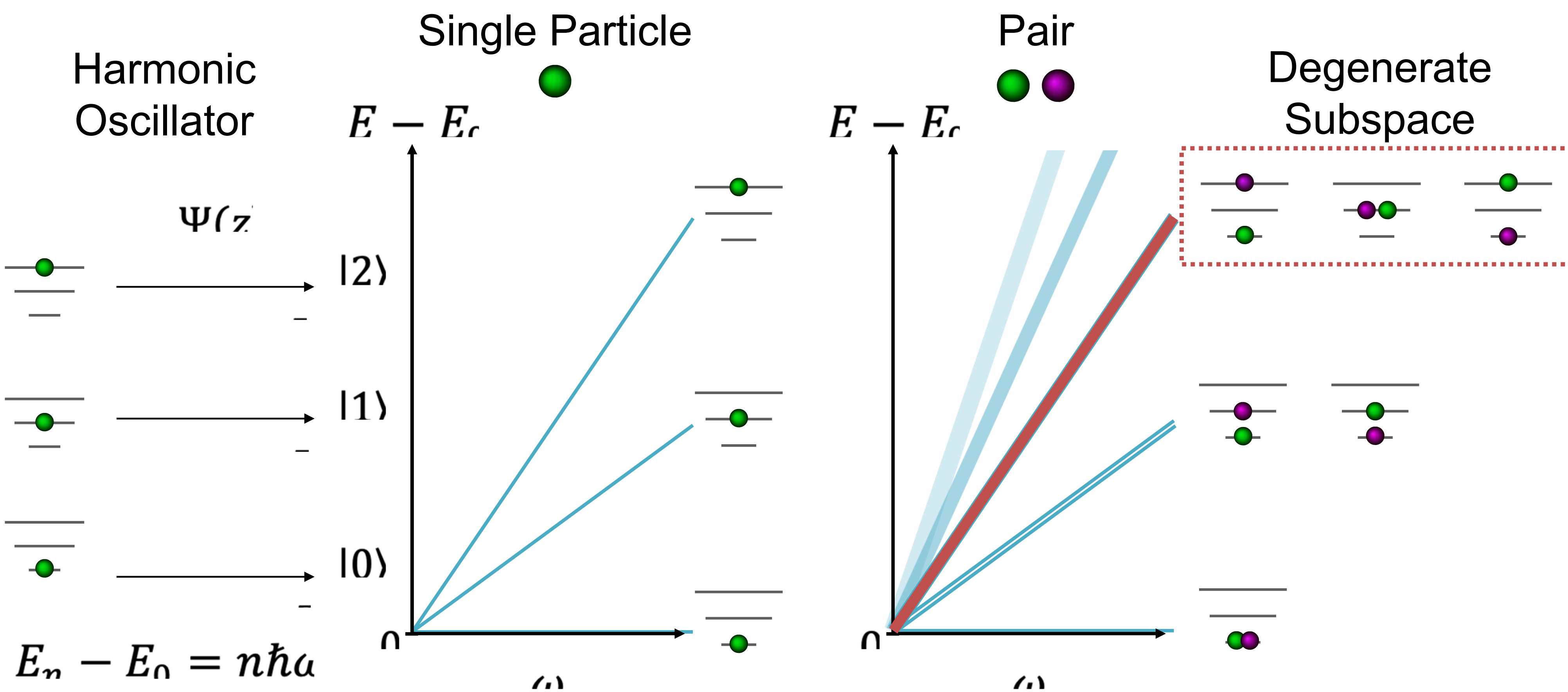
$E_n - E_0 = n\hbar\omega$



Building a Degenerate Subspace from Pairs

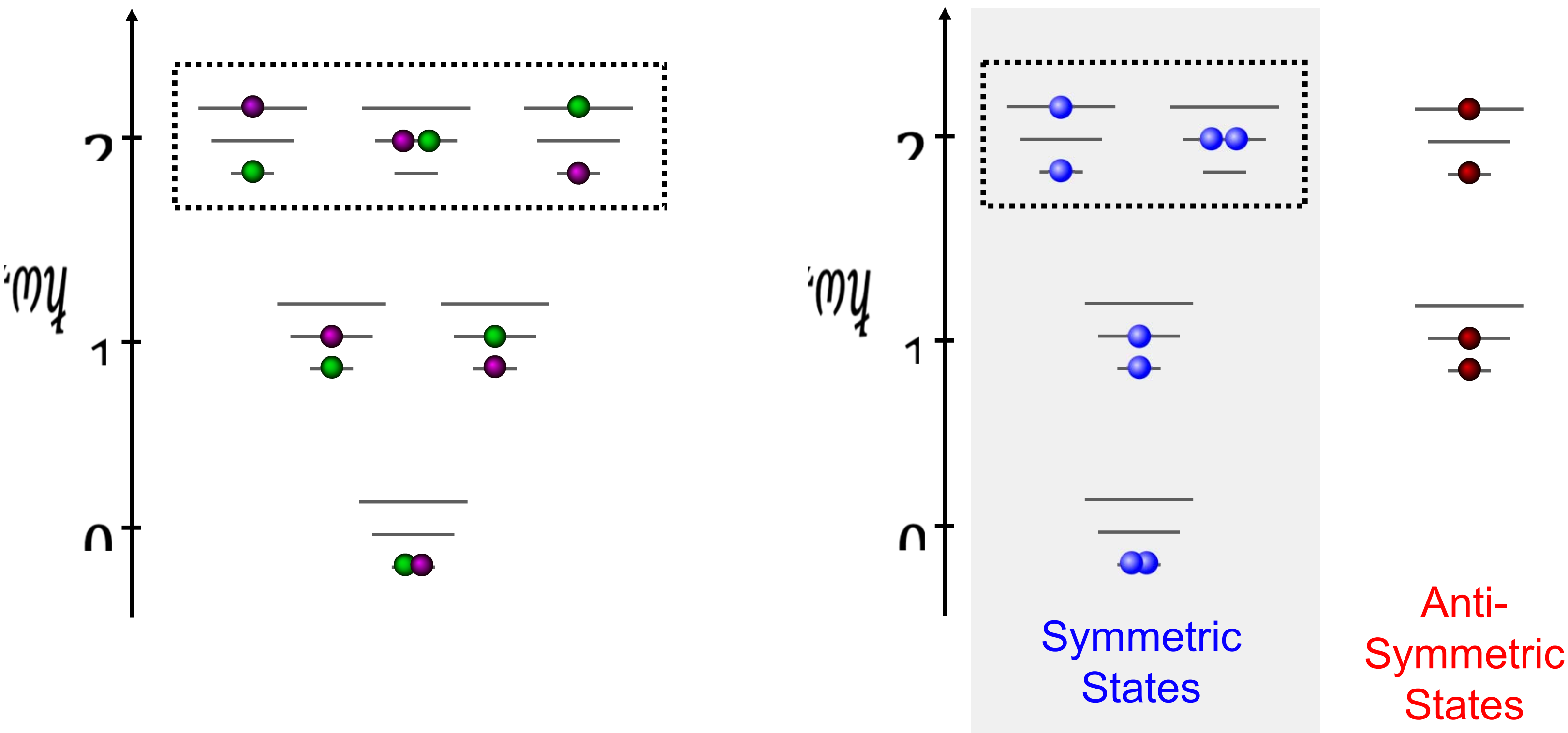


Building a Degenerate Subspace from Pairs

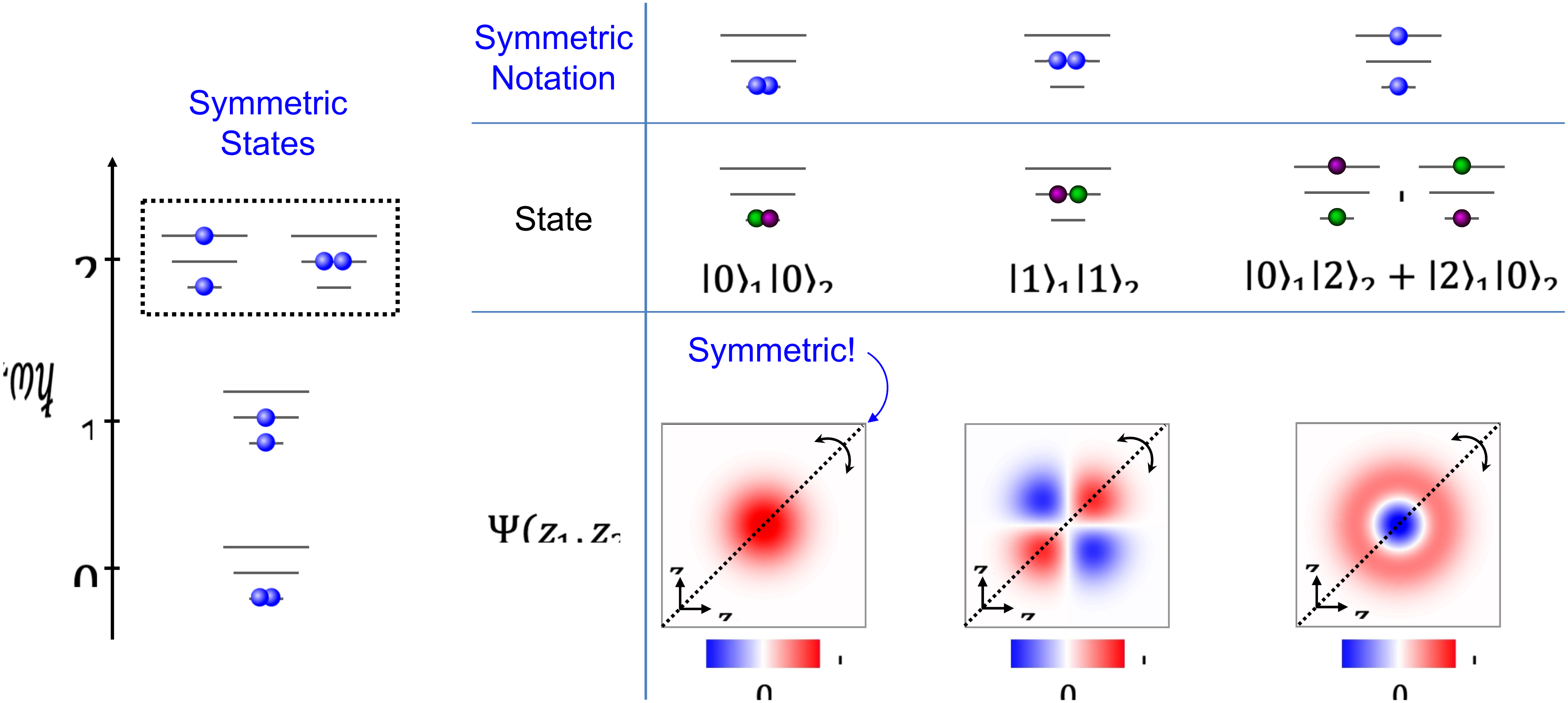


Symmetry Protection from Identical Particles

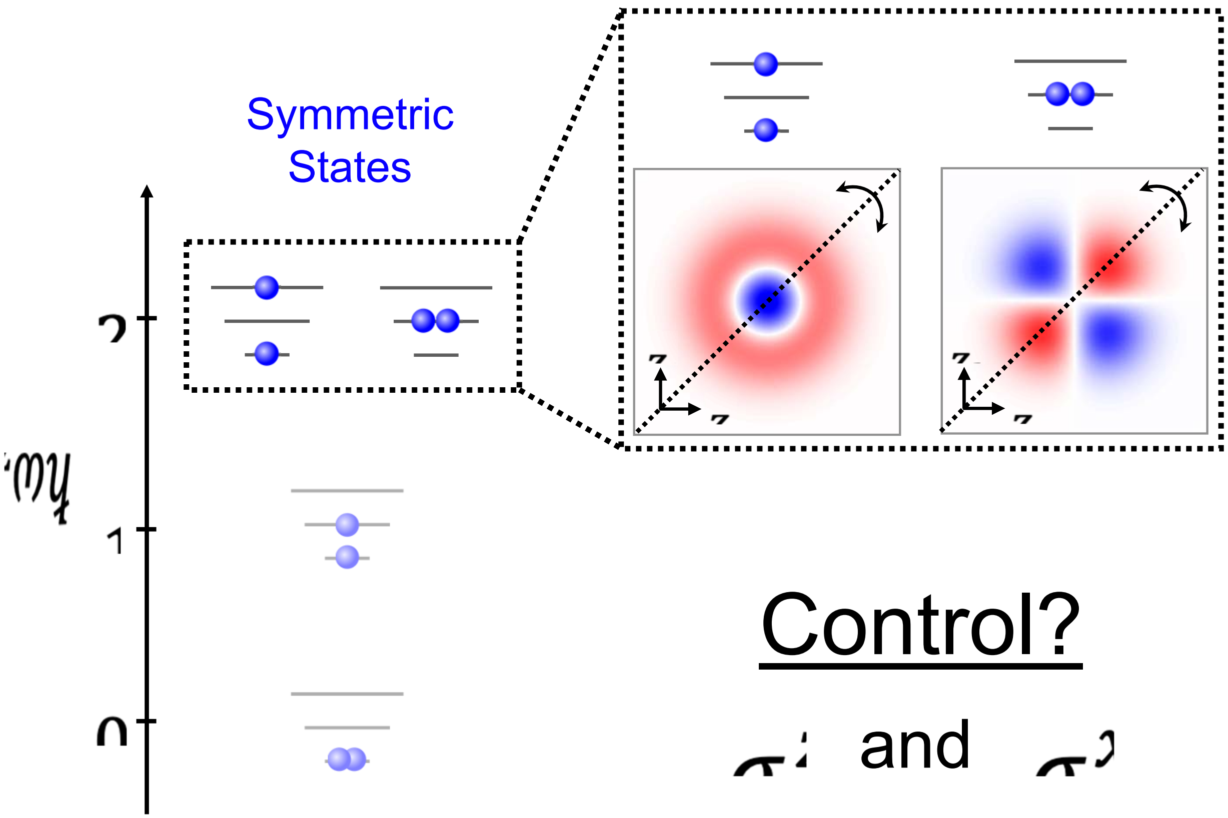
Distinguishable **Identical**



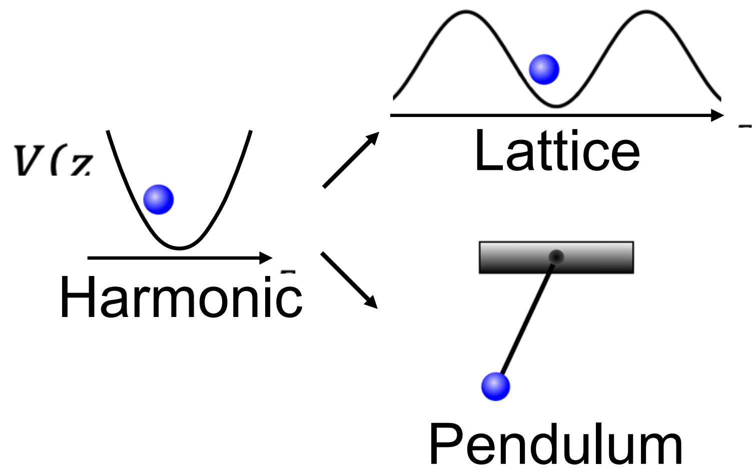
Symmetric Pair Wavefunctions $\Psi(z_1, z_2)$



Qubit from Pair Motion



1. Anharmonicity

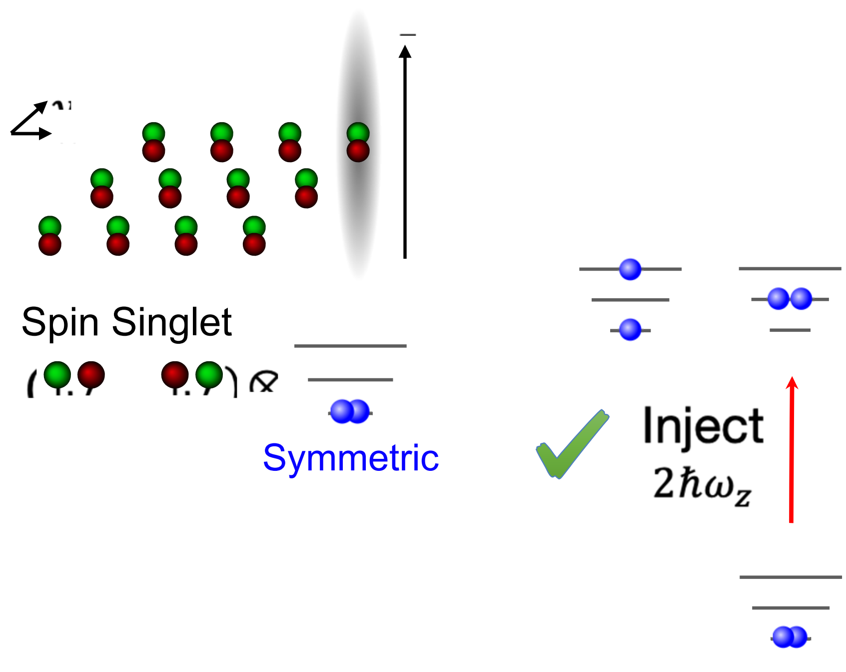


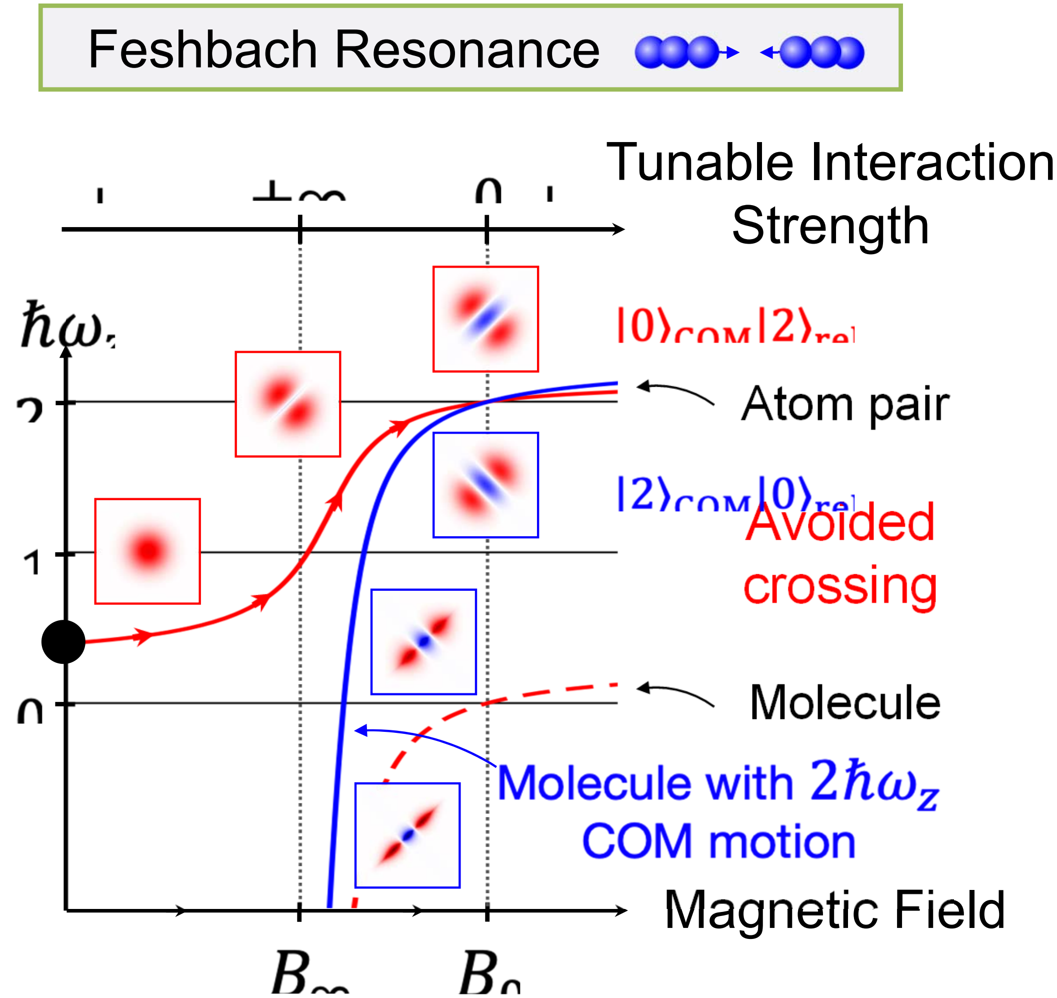
Control?

and

2. Interactions

Preparation

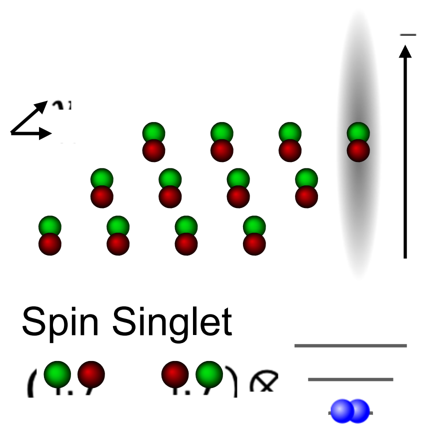


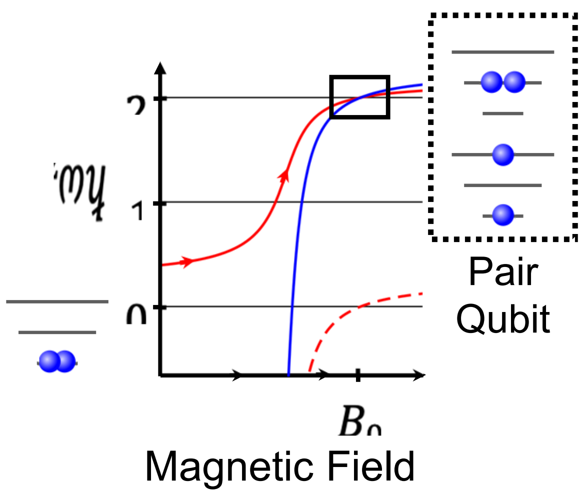


Busch et. al., Found. Phys. 28, 549 (1998).

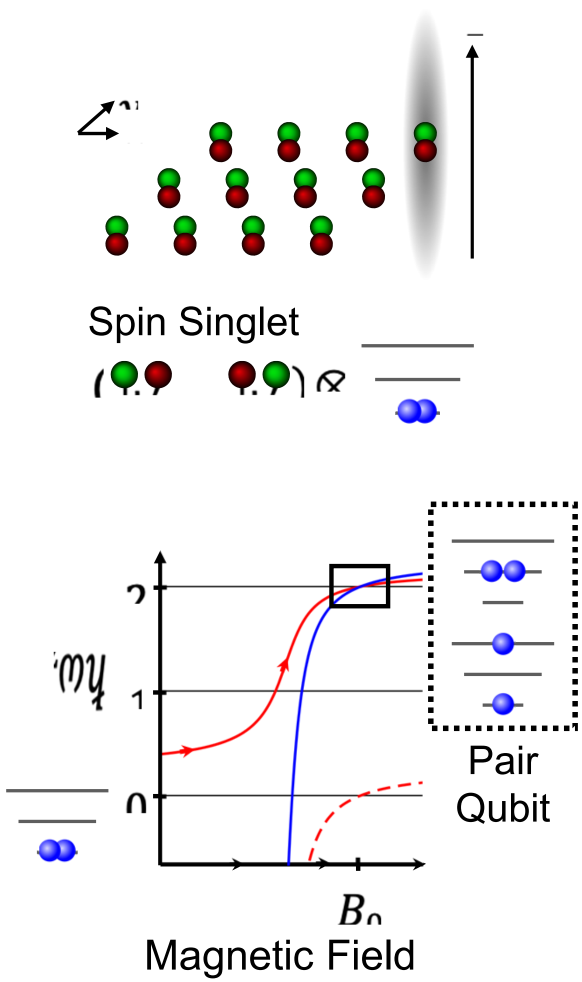
Z. Idziaszek and T. Calarco, PRA 71, 050701 (2005).

Preparation



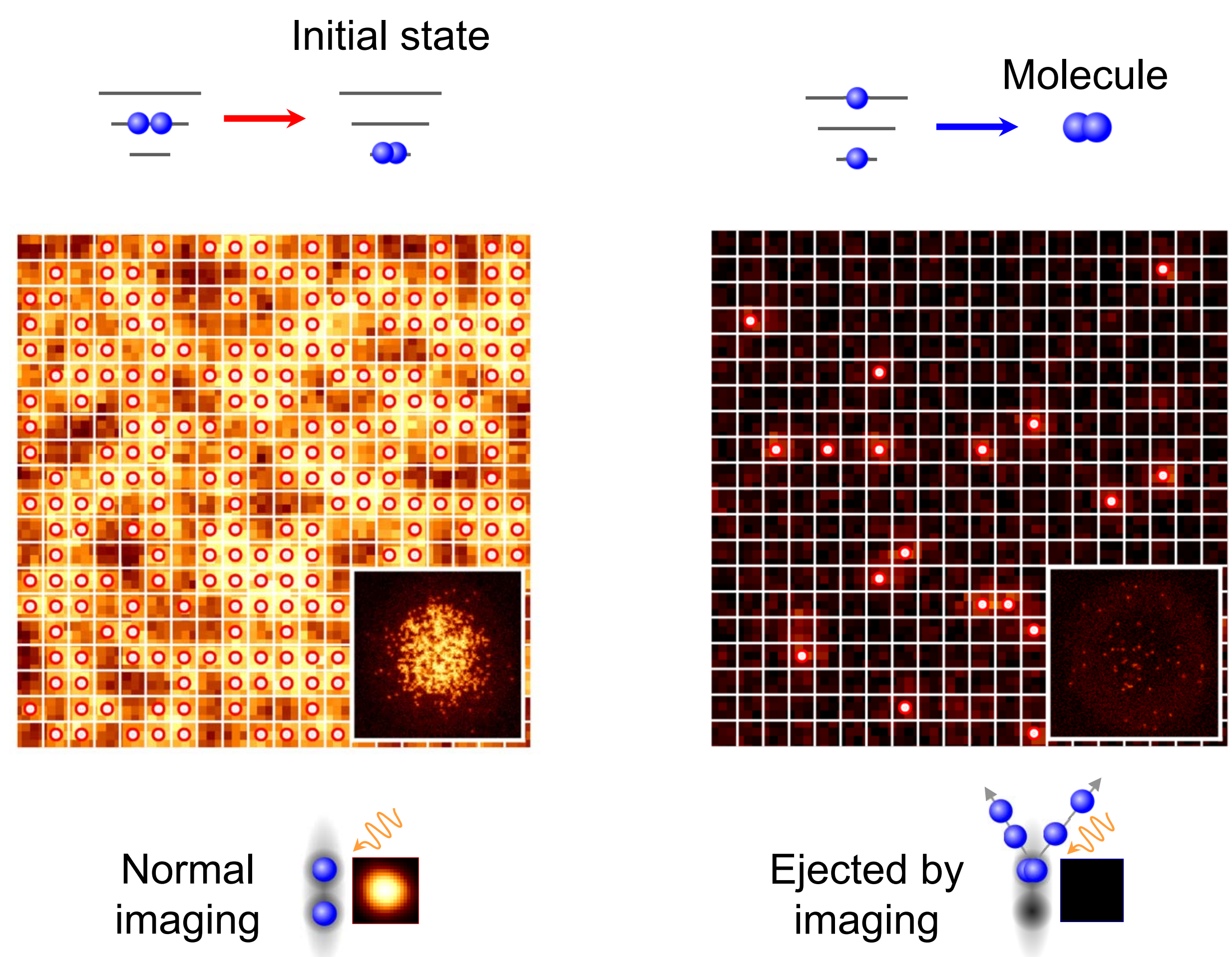


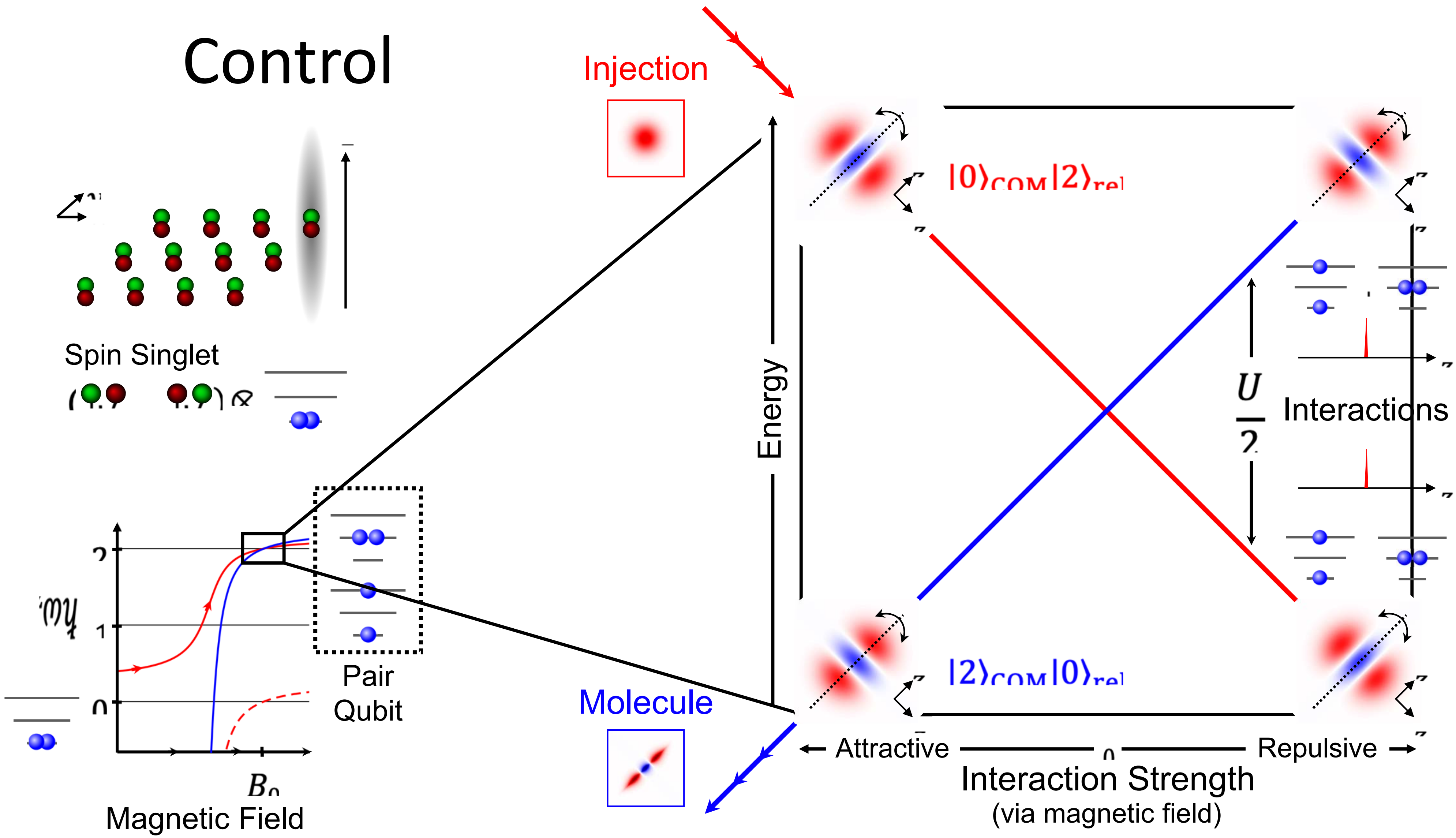
Preparation



Readout

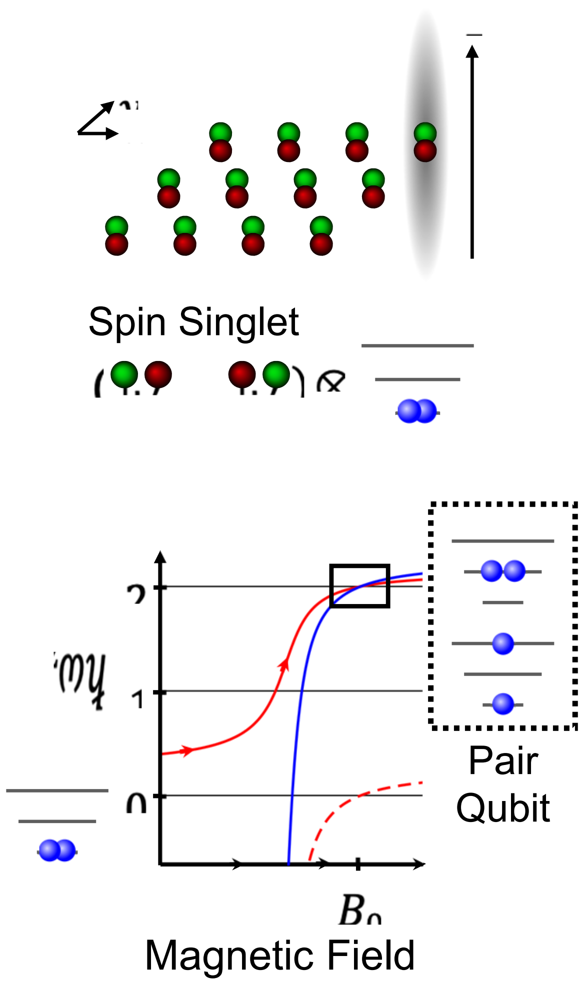
Reverse of preparation



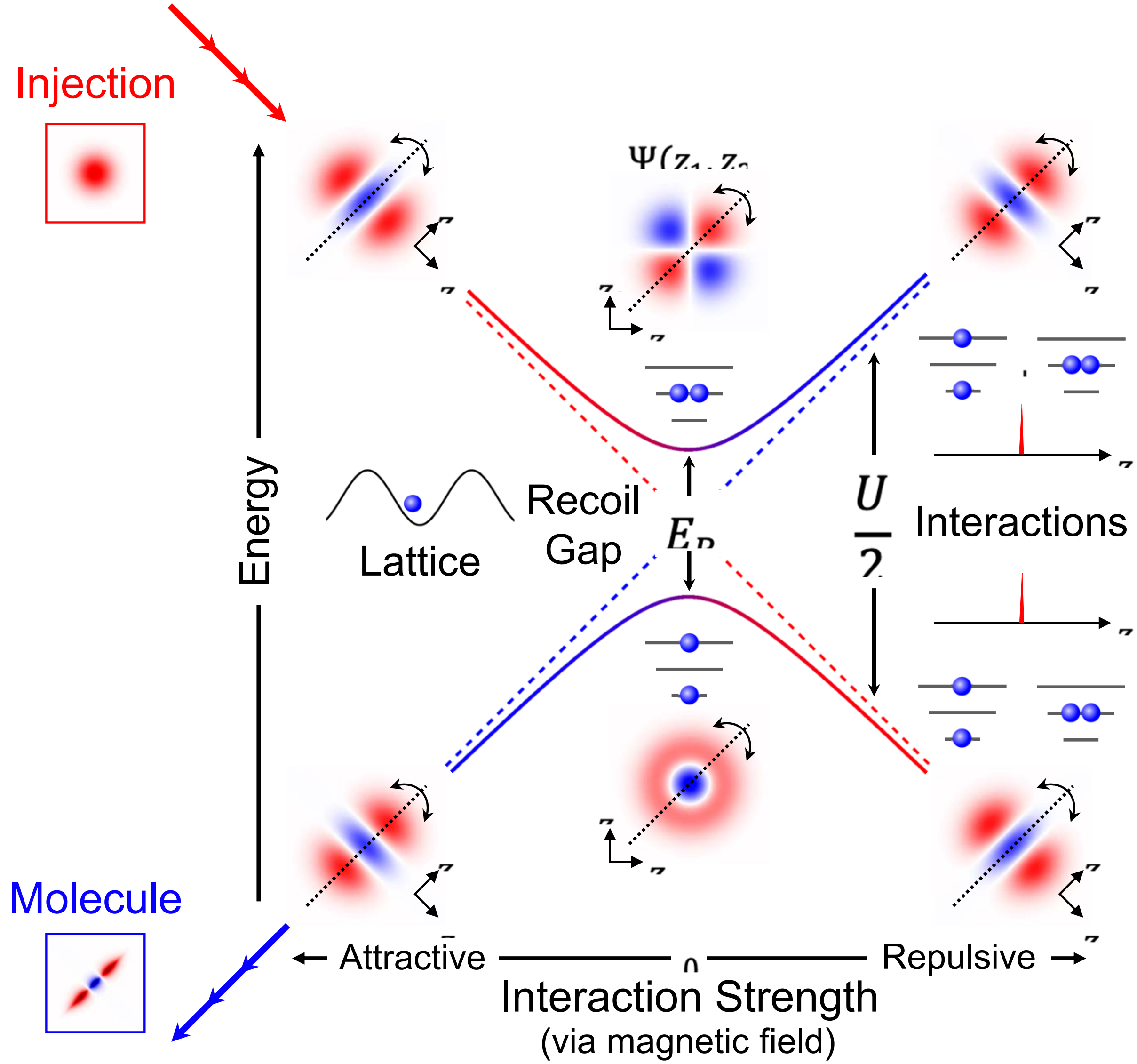


Control
Injection
Spin Singlet
Energy
Molecule
Pair
Qubit
Magnetic Field
Interactions
Attractive
Repulsive
Interaction Strength
(via magnetic field)

Control



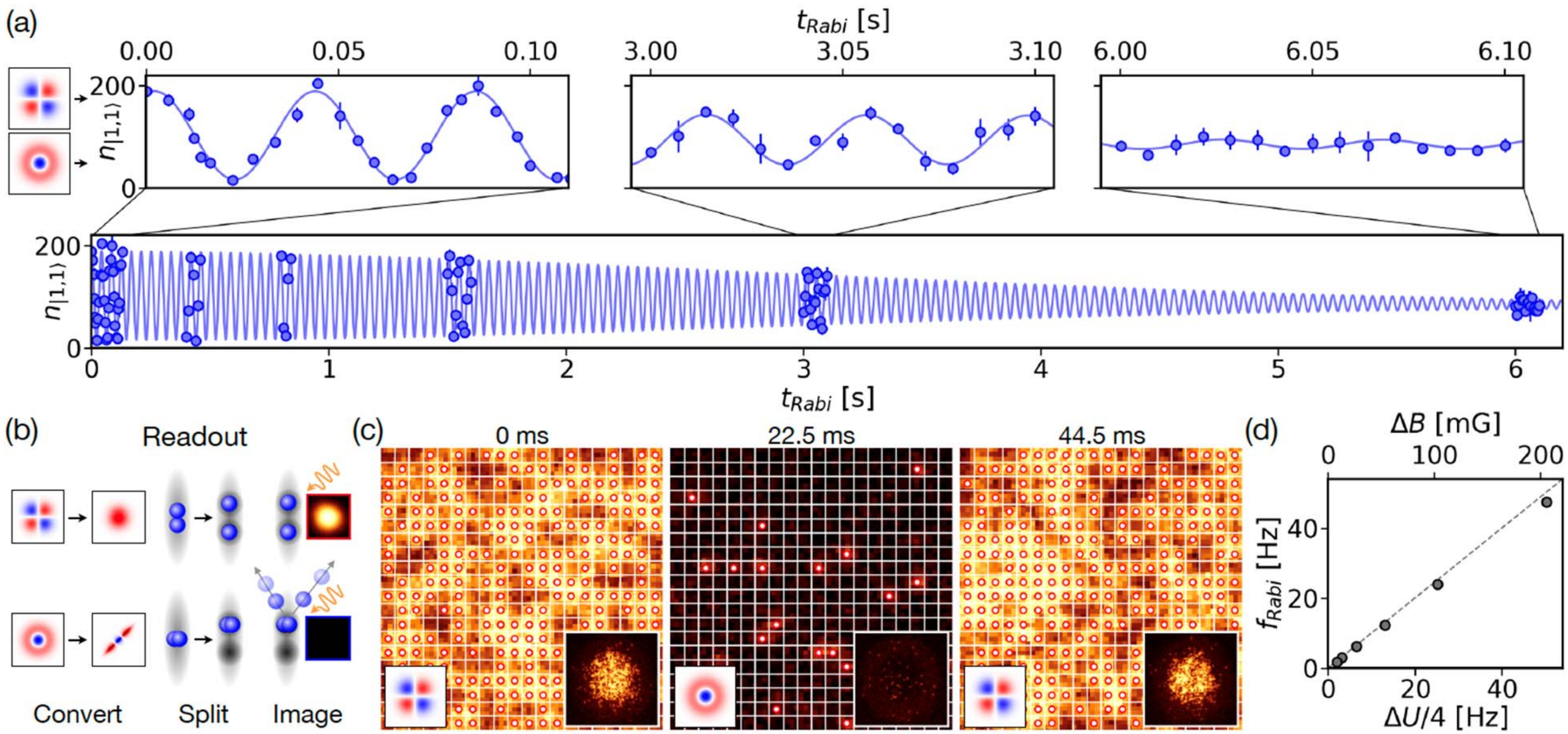
Spin Singlet
Pair
Qubit
Magnetic Field



Injection
Molecule
Energy
Lattice
Recoil
Gap
Interactions
Attractive
Repulsive
Interaction Strength
(via magnetic field)

Quantum Register of Fermion Pairs

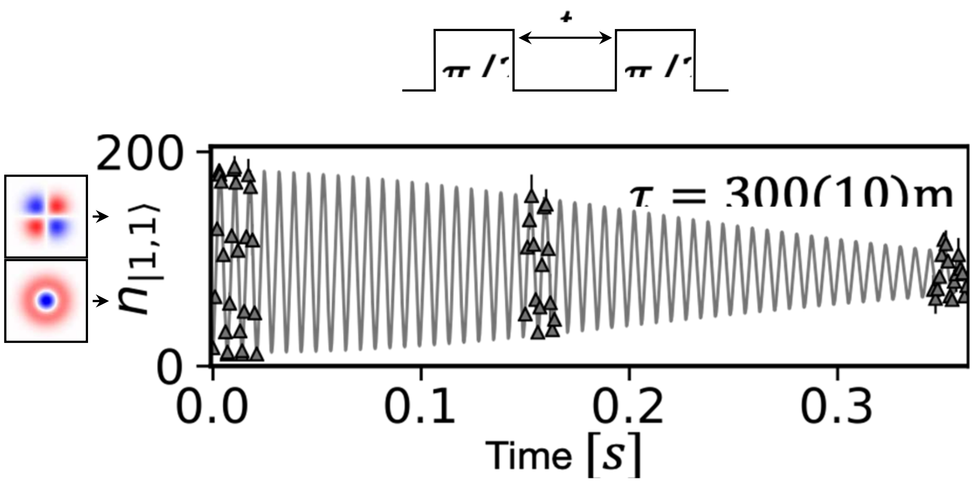
Thomas Hartke, Botond Oreg, Ningyuan Jia, MZ, soon on arXiv



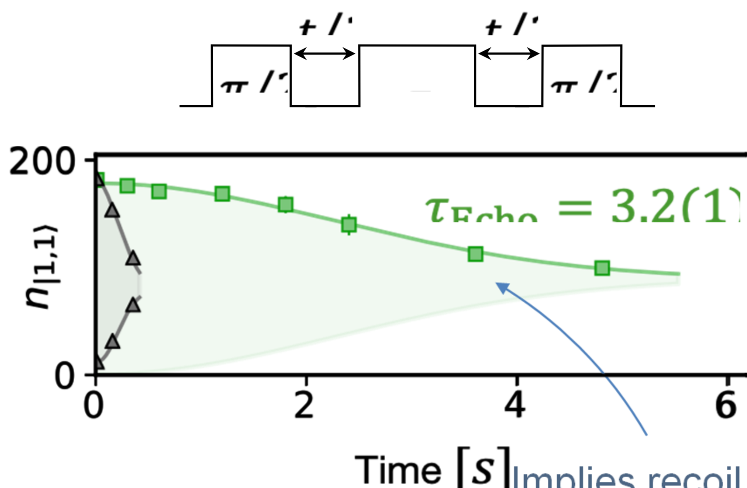
Bridging Quantum Simulation and (digital) Quantum Computation

Coherence Times

Ramsey

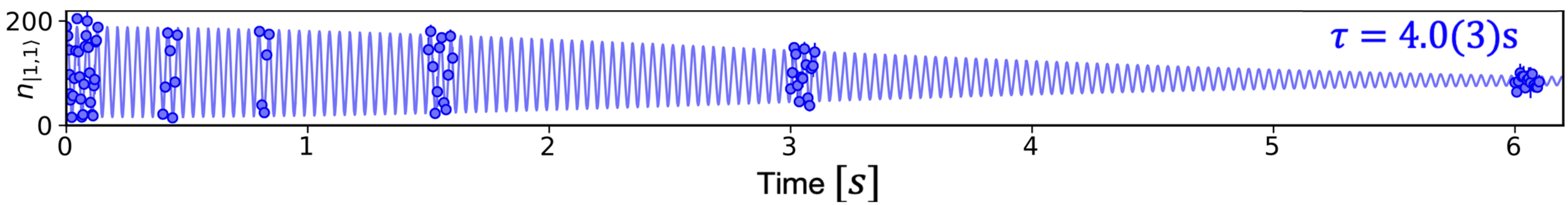


Echo

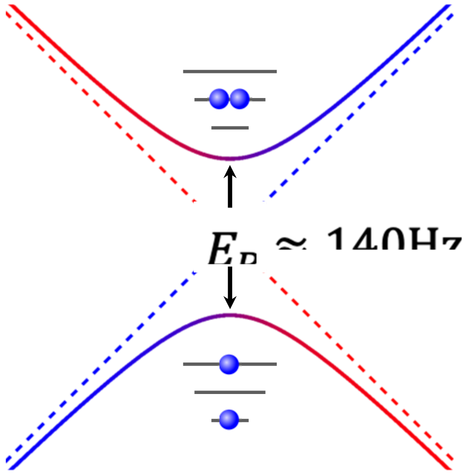


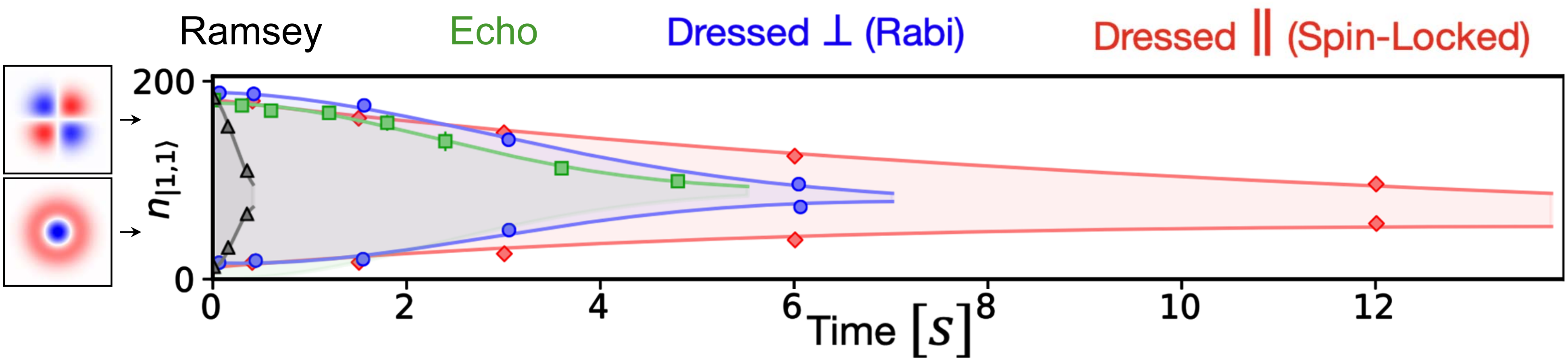
Implies recoil gap noise is static

Rabi



Summary of Coherence at the Recoil Gap

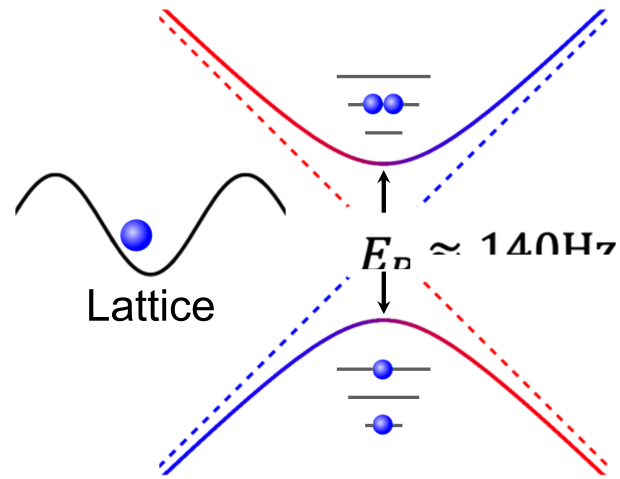


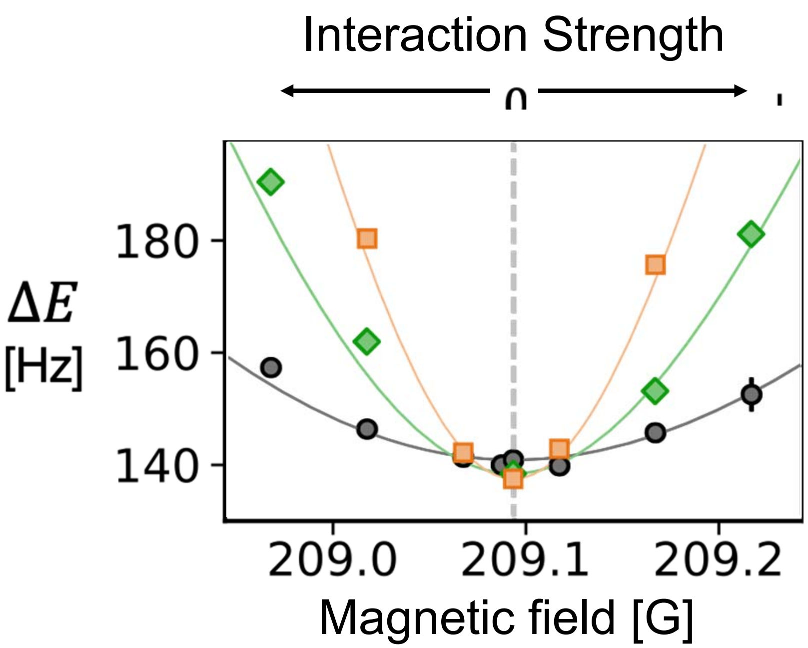


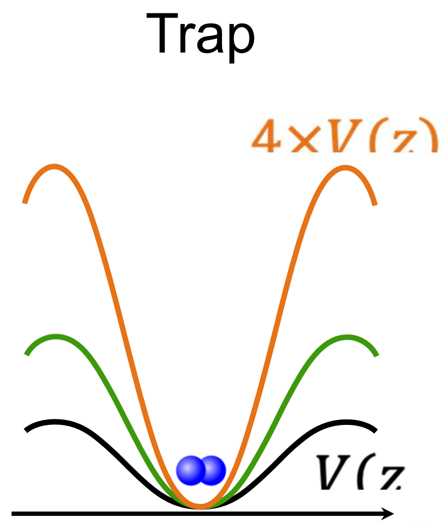
Stability of the Recoil Gap

$$E_R = \frac{\hbar^2\pi^2}{2ma_z^2}$$

Set by geometry only



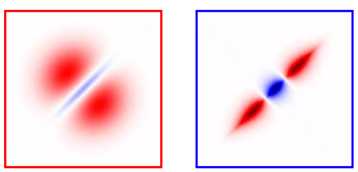


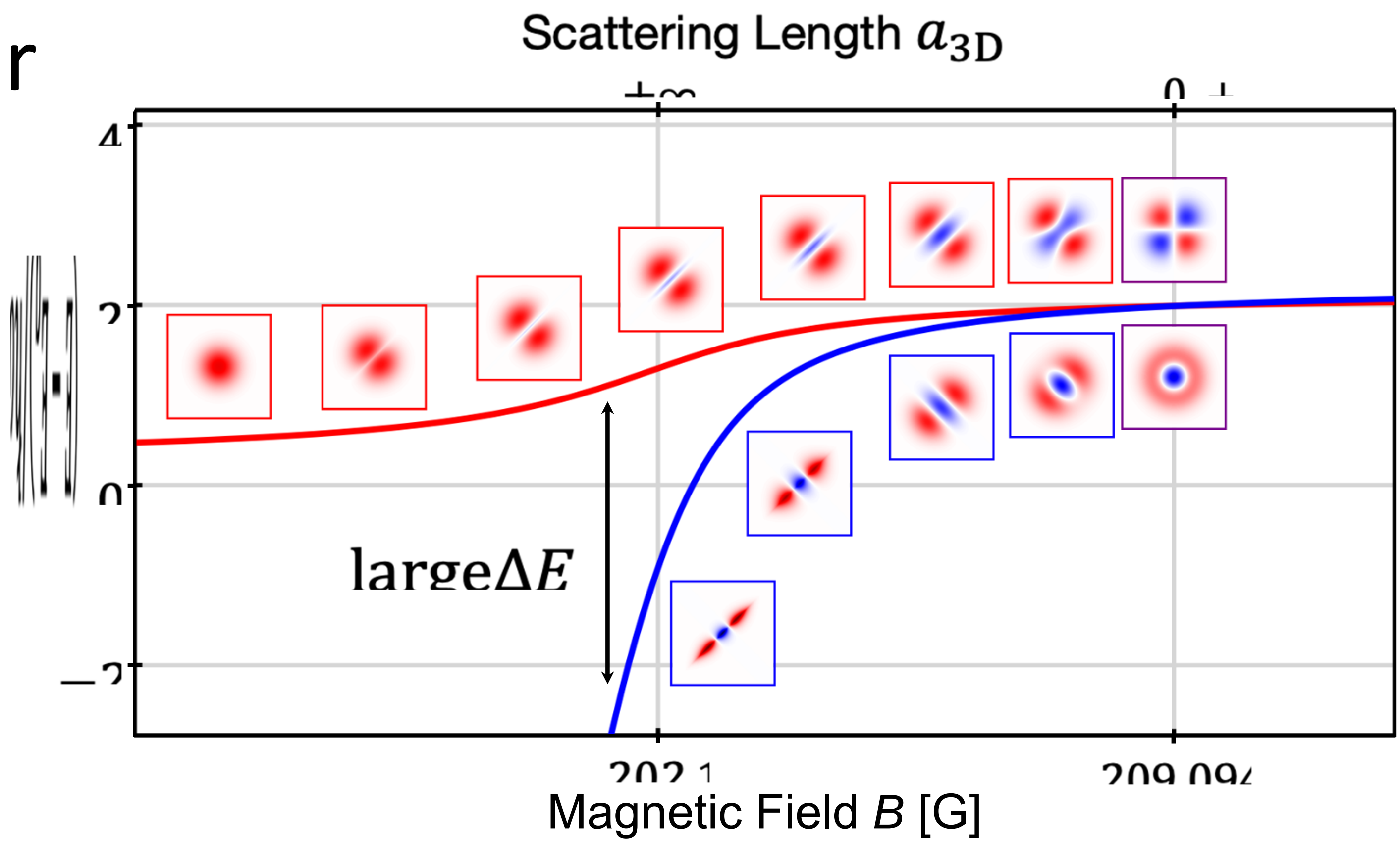


Molecular Crossover

Feshbach Scattering Resonance

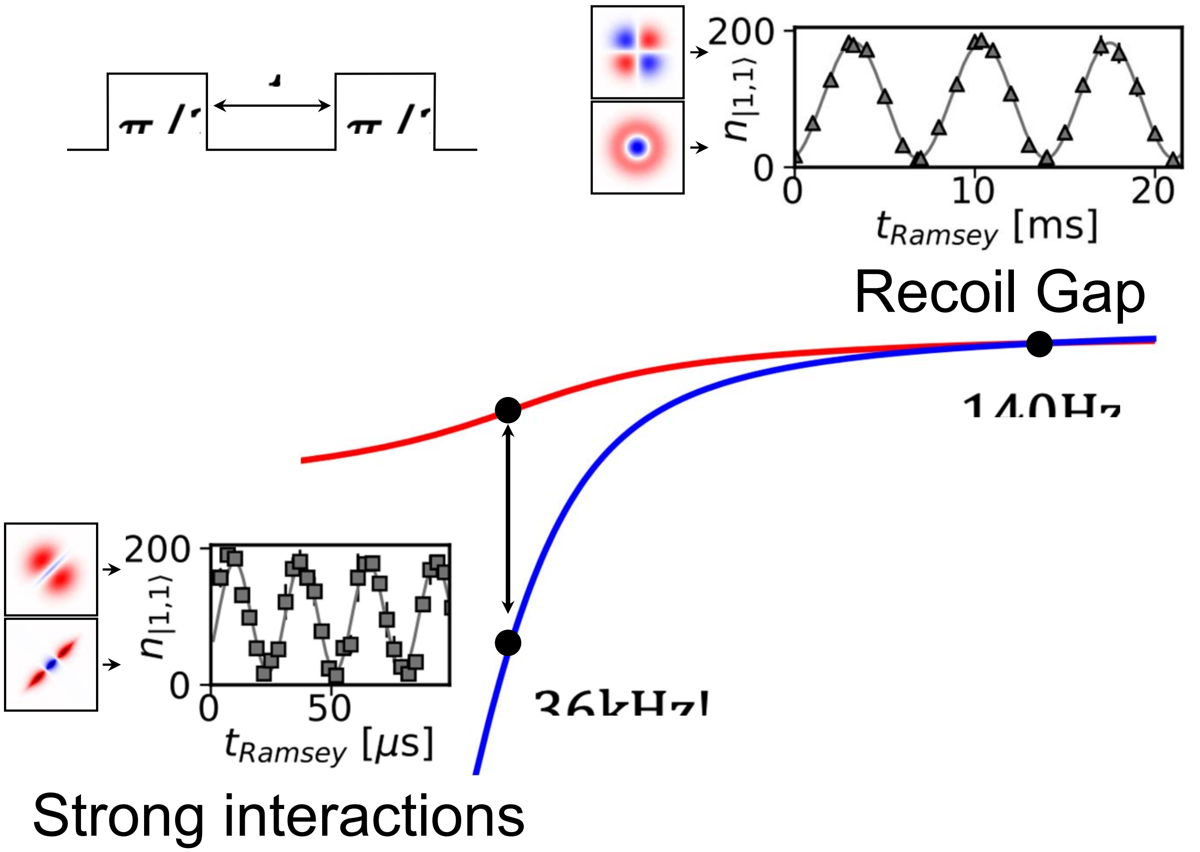
Coherent conversion to molecule

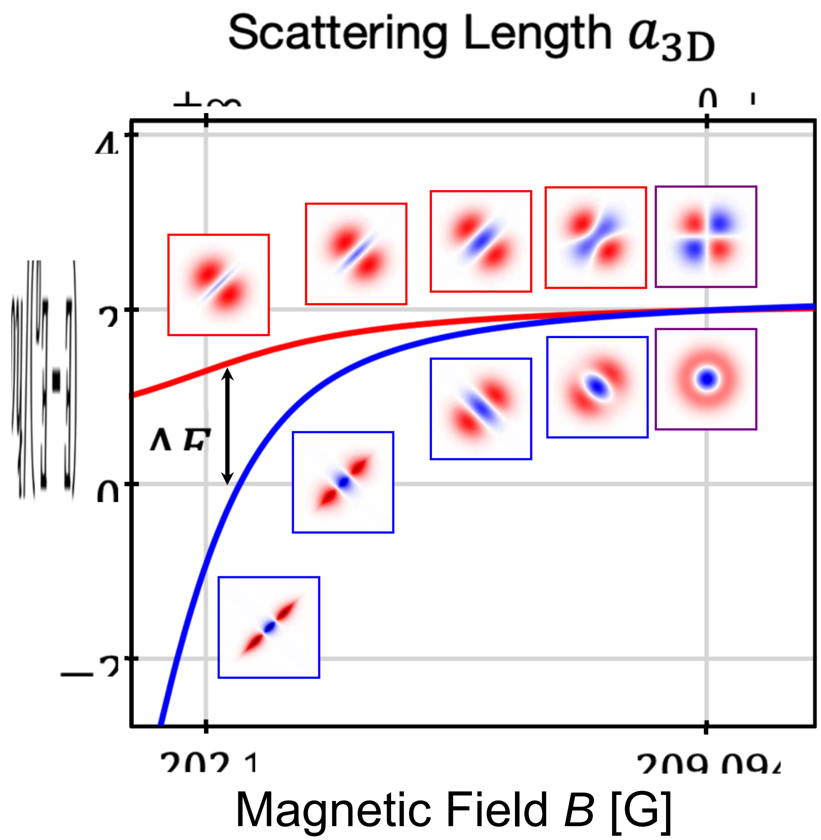




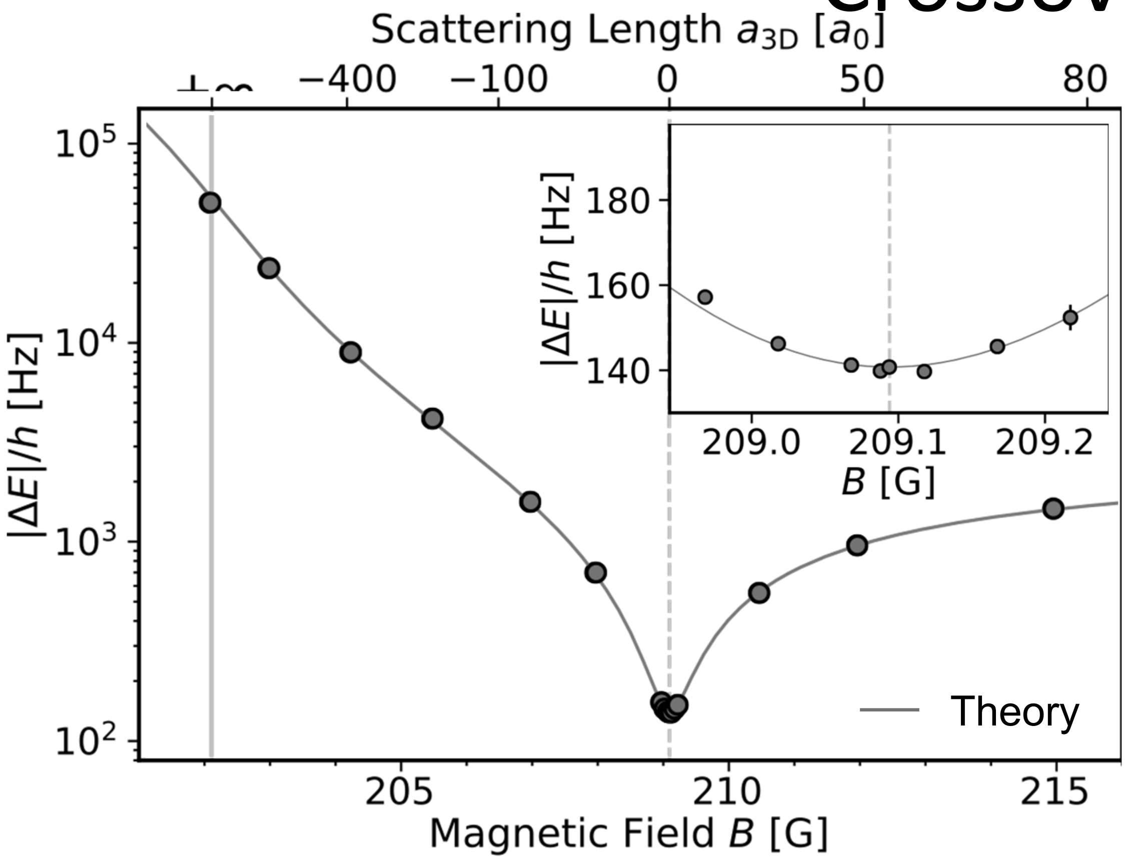
Zurn et. al., … S. Jochim, Phys. Rev. Lett. 108, 075303 (2012).
Sala et. al., … S. Jochim, and A. Saenz, PRL 110, 203202 (2013).

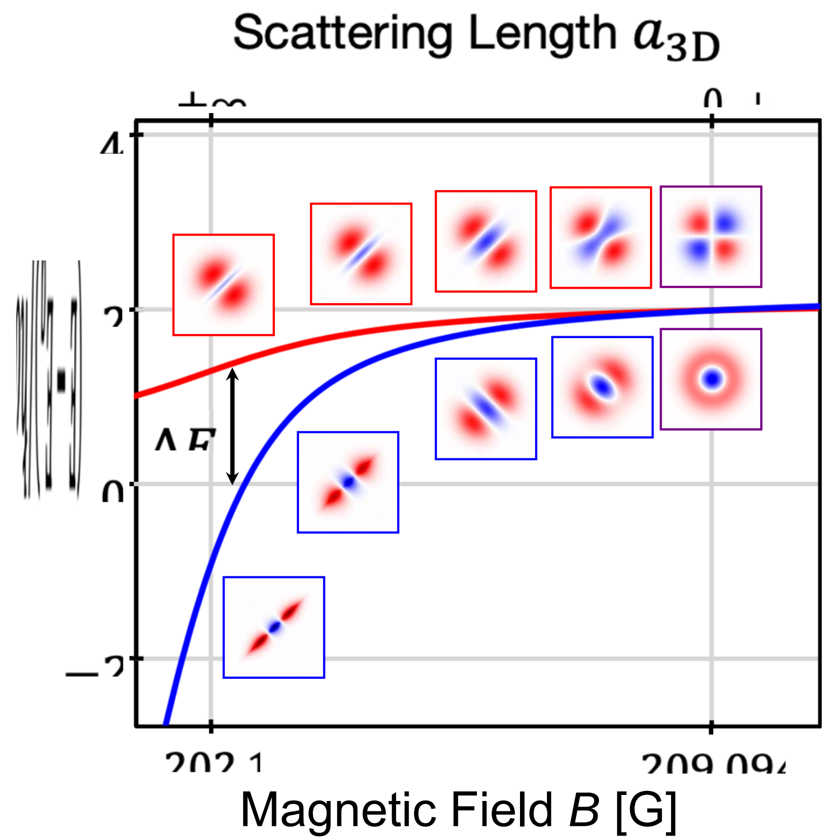
Ramsey Spectroscopy of the Molecular Crossover



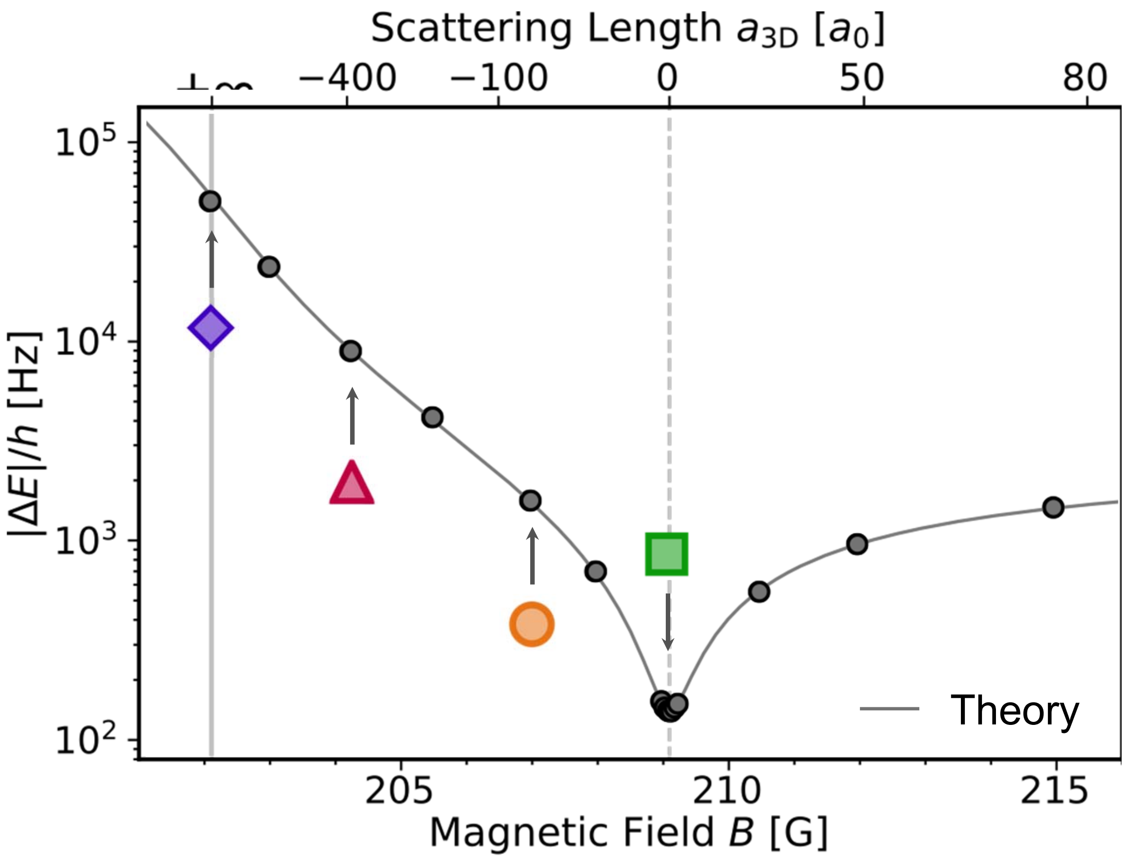


Ramsey Spectroscopy of the Molecular Crossover

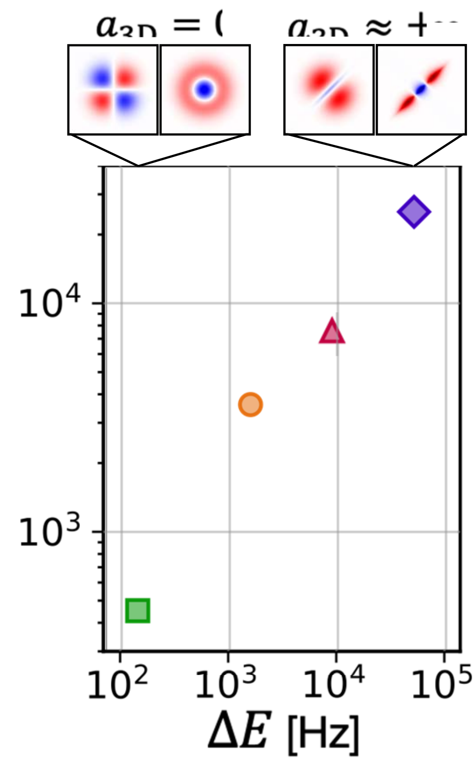




Coherence in the Molecular Crossover



Quality Factor = $f_{\text{Qubit}}\tau_{\text{Ech}}$



Molecule-Repulsive pair:

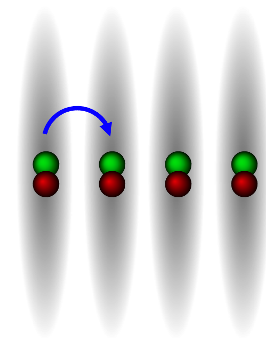
25,000 coherent oscillations during $\tau_{\text{Echo}} \approx 0.5\text{s}$

Future Work

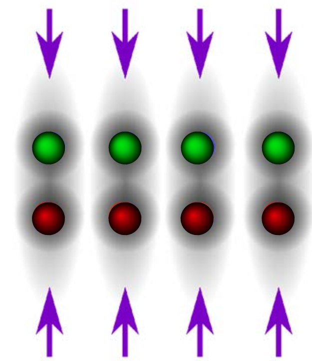
- Two Qubit gates
- Many-body physics

Tunneling

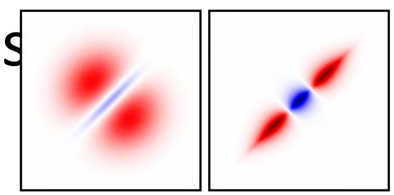
Between sites



Bilayer



- Coherent atom pair-molecular superpos
  - Molecular clocks
  - Molecule detection



Recoil Energy $E_R = \frac{\hbar^2\pi^2}{2ma_z^2}$

- Metrology of kinetic mass

Bosons and Fermions

Bosons and Fermions

BEC 1/Fermi3

Fermionic Superfluids

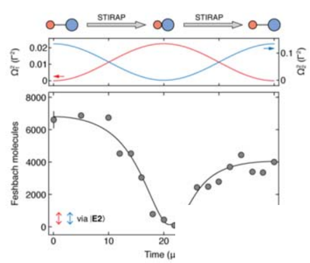
Biswaroop Mukherjee
Parth Patel
Zhenjie Yan
Dr. Richard Fletcher
Visiting Professors:
Zoran Hadzibabic
Chris Vale
Former Members:
Ariel Sommer
Mark Ku
Dr. Tarik Yefsah
(→ CNRS, ENS Paris)
Dr. Julian Struck
(→ ENS Paris)

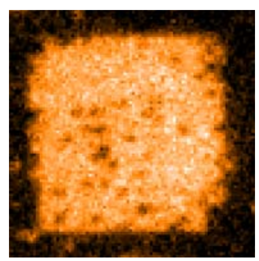
Fermi 1

NaK Dipolar Molecules

Yiqi Ni
Alex Yu Chuang
Eric Wolf
Dr. Carsten Robens

Former Members:
Zoe Yan
Jee Woo Park (→ SNU Korea)
Dr. Sebastian Will
(→Prof., Columbia U.)
Cheng-Hsun Wu (→ Google X)
Dr. Huanqian Loh (→ Singap.)





Fermi 2

Fermi Gas Microscope

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Fermi3

Rotating Superfluids

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