ÉCOLE DE PHYSIQUE
des HOUCHES

Predoc School on
Ultracold Fermions

Fermions in Optical Lattices

8-9 October 2018
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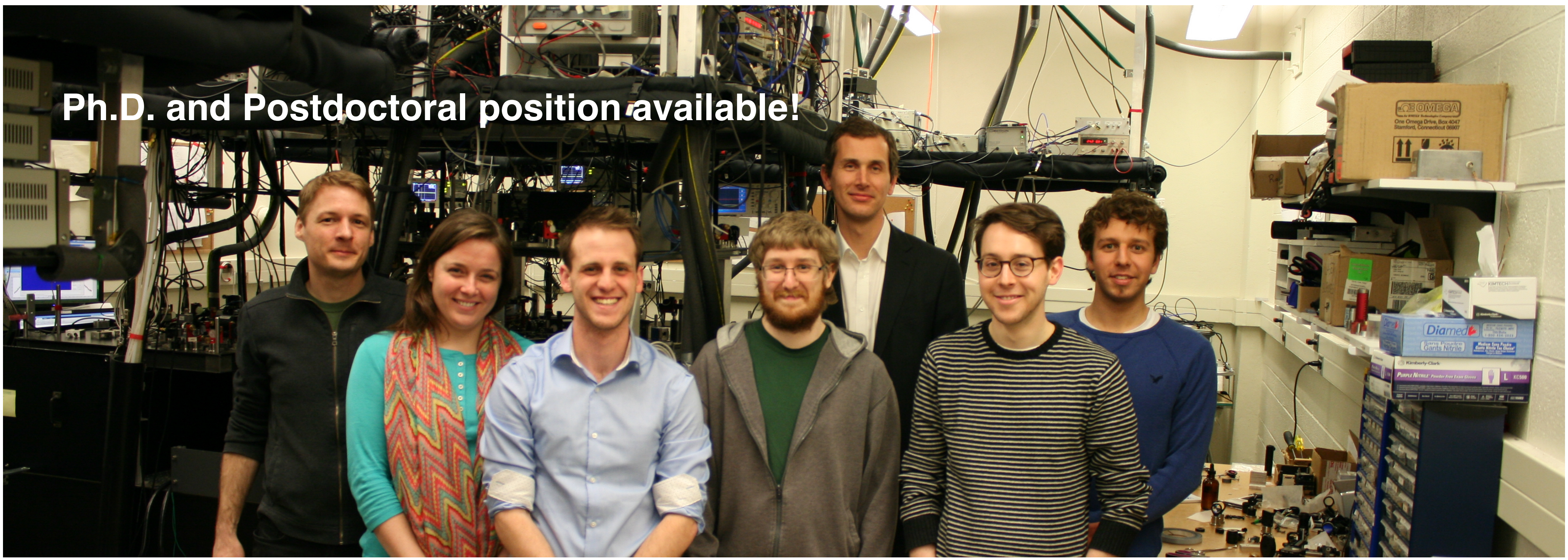

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University of Toronto

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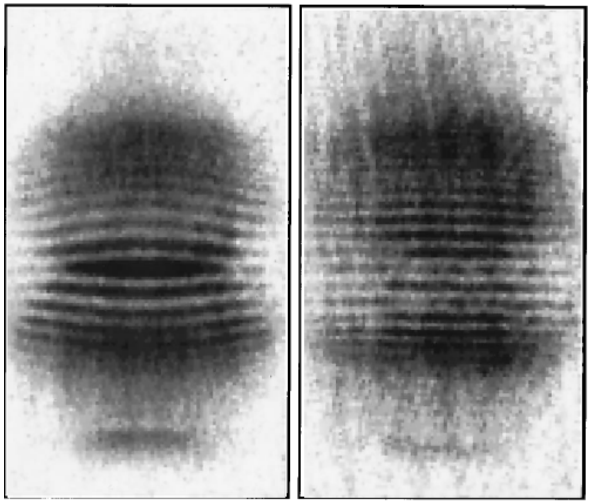
Introduction

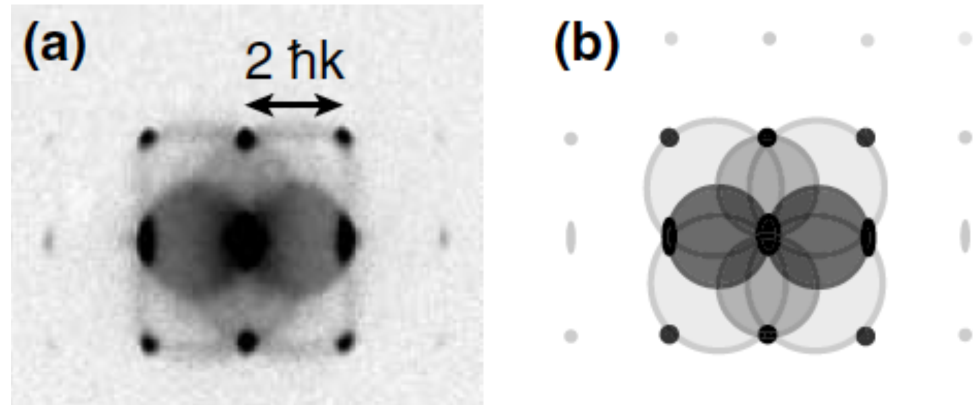
Matter waves in free flight

Interference



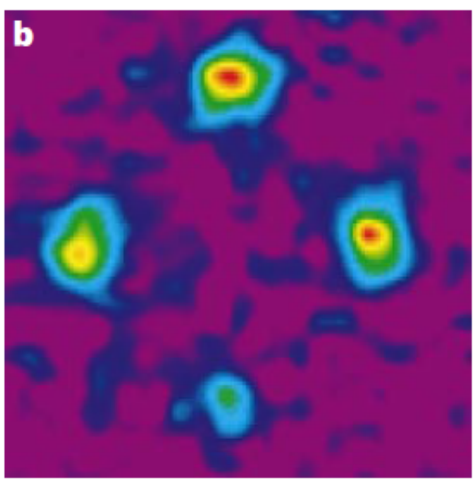
Ketterle, *Science* (1997)

Diffraction



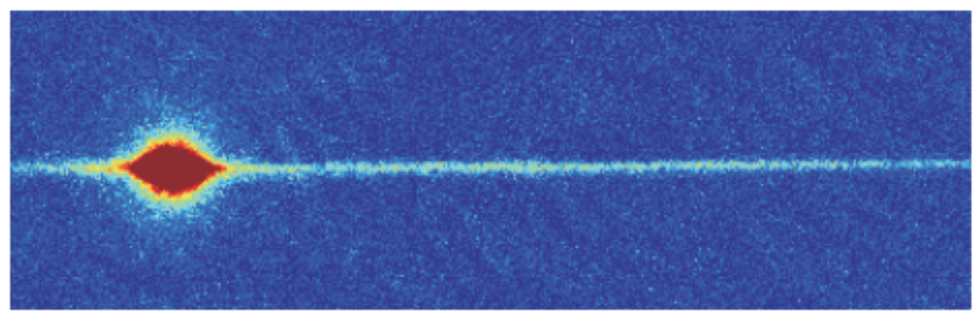
Hansch/Esslinger, *PRL* (2001)

4-wave mixing



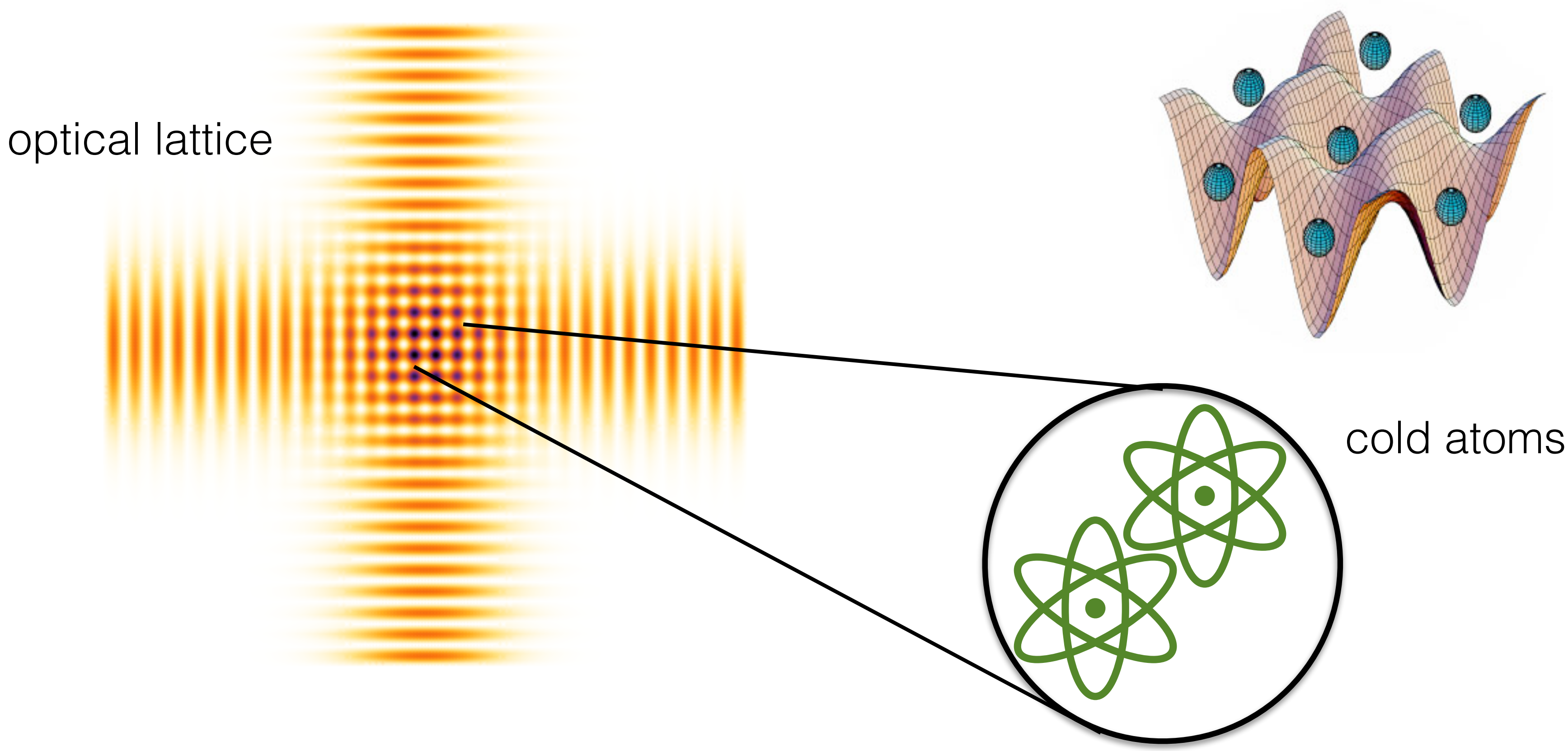
Rolston / Phillips, *Nature* (1999)

Atom laser



Bouyer / Aspect, *PRL* (2006)

Matter waves trapped in an optical lattice



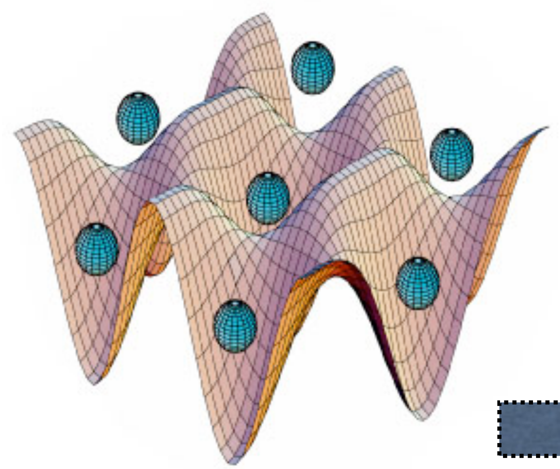
Waves trapped by waves

or: particles trapped by waves

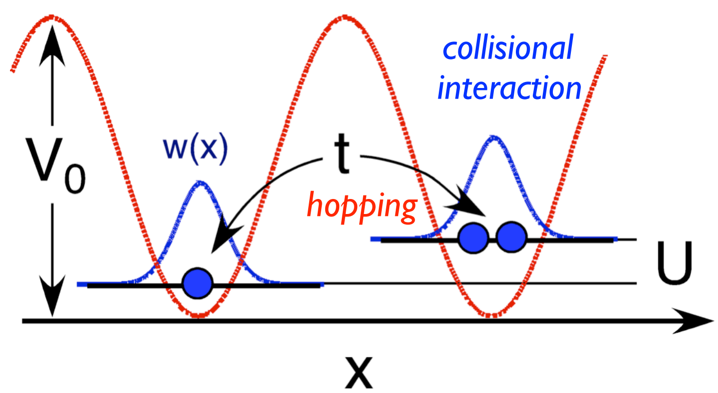
or: particles trapped by particles

The Hubbard model

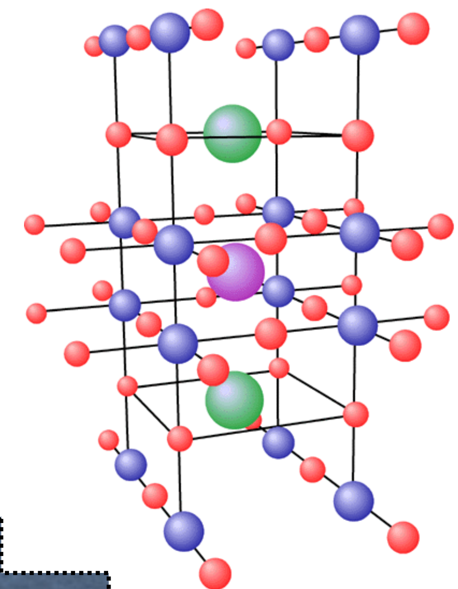
$$\hat{H} = \sum_{q,\sigma} \mathcal{E}_q \hat{n}_{q,\sigma} + U \sum_{\ell} n_{\ell\uparrow}\hat{n}_{\ell\downarrow}$$



Atoms: counter-propagating laser beams produce a sinusoidal potential



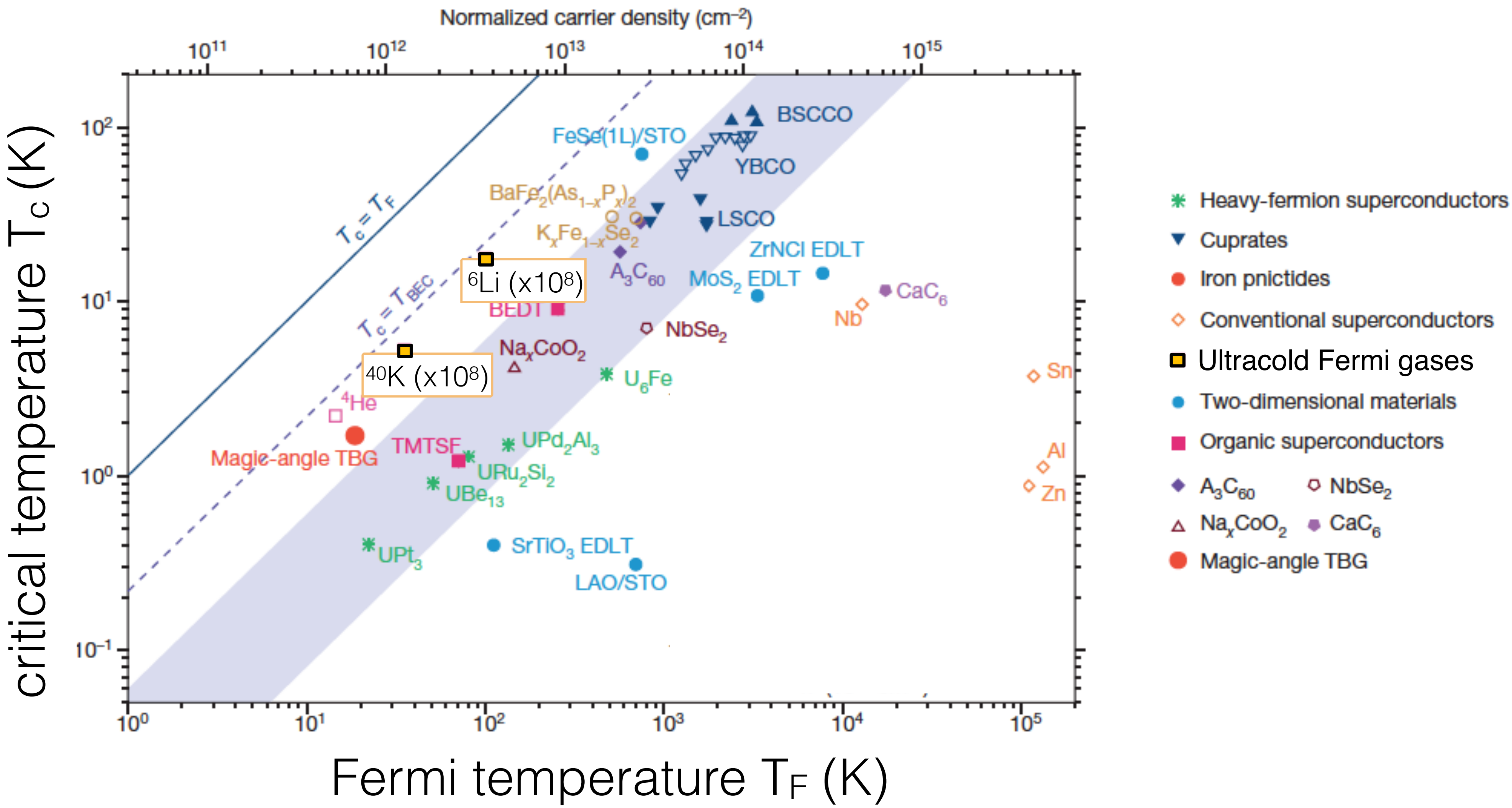
Interplay of tunnelling and on-site interaction



Electrons: ionic lattice

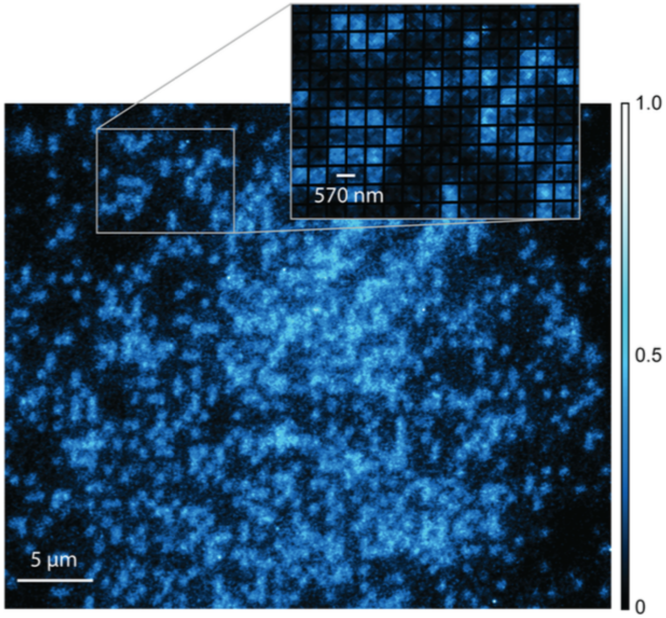
Dominant paradigm for strongly correlated lattice fermions

Strongly coupled matter

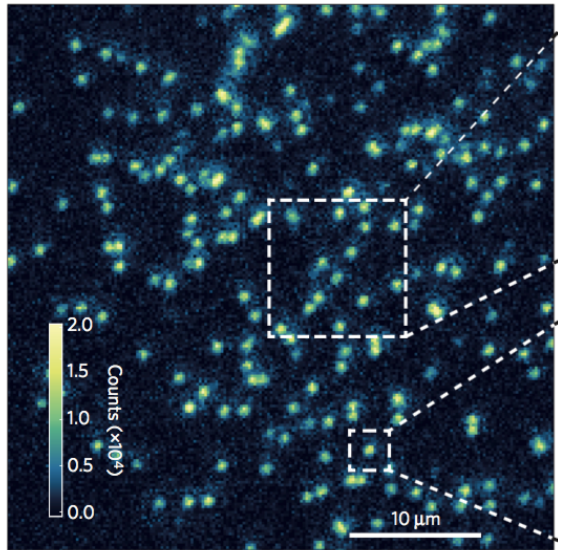


[adapted from Y. Cao… P. Jarillo-Herrero, Nature **556**, 43 (2018)]

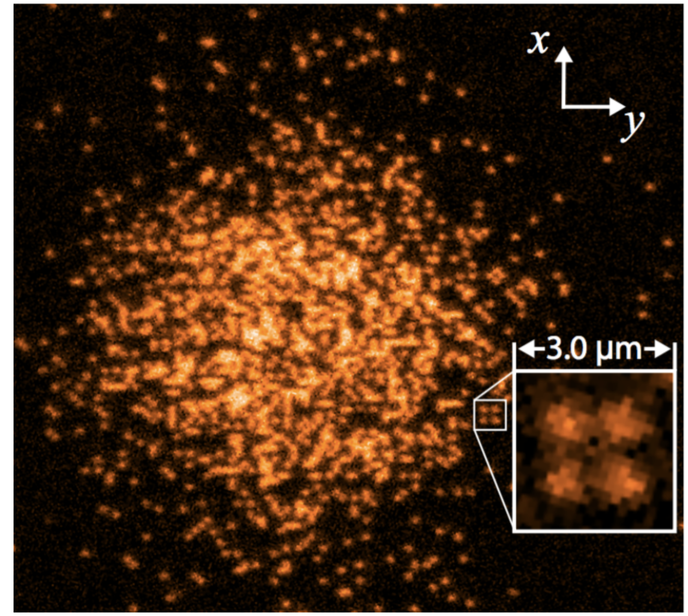
Fermion lattice microscopes



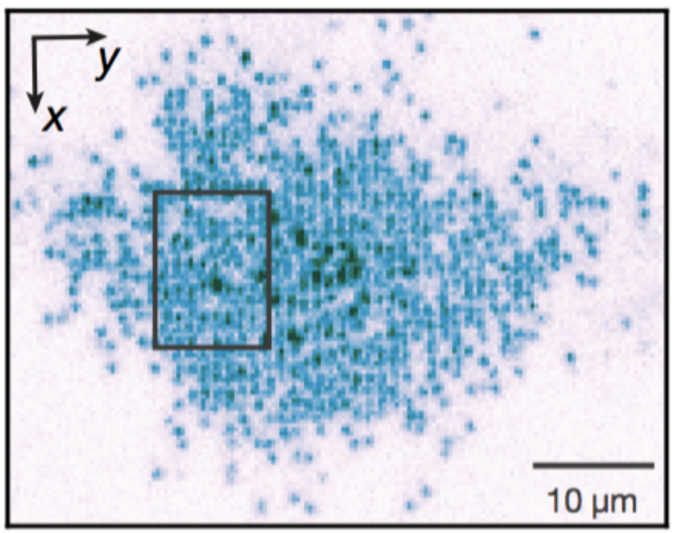
Harvard (2015)



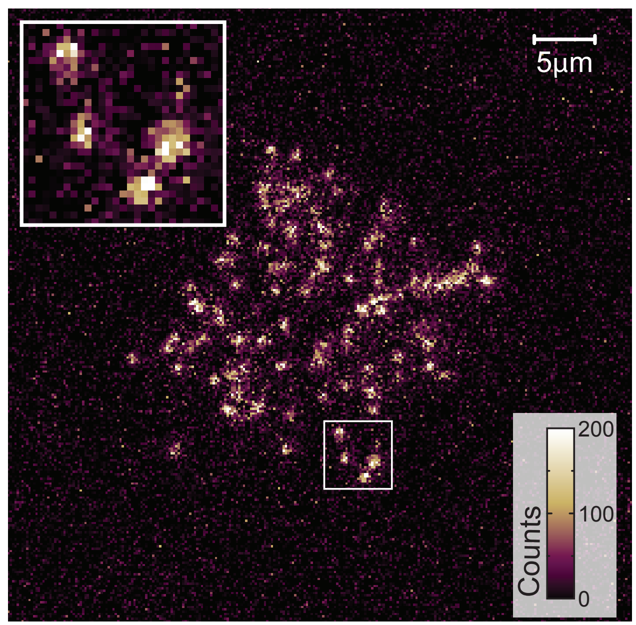
Strathclyde (2015)



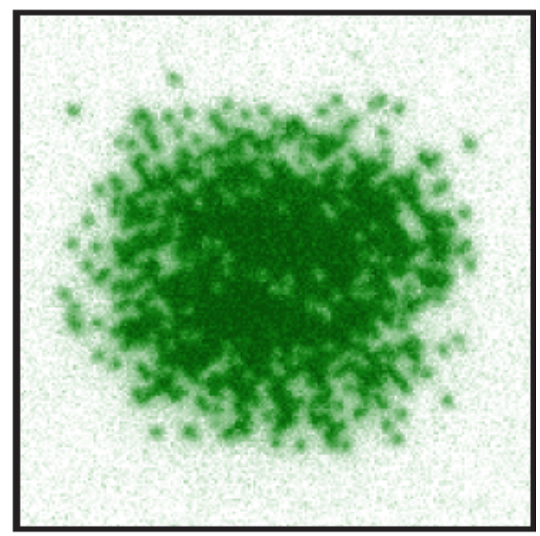
MIT (2015)



MPQ (2015)

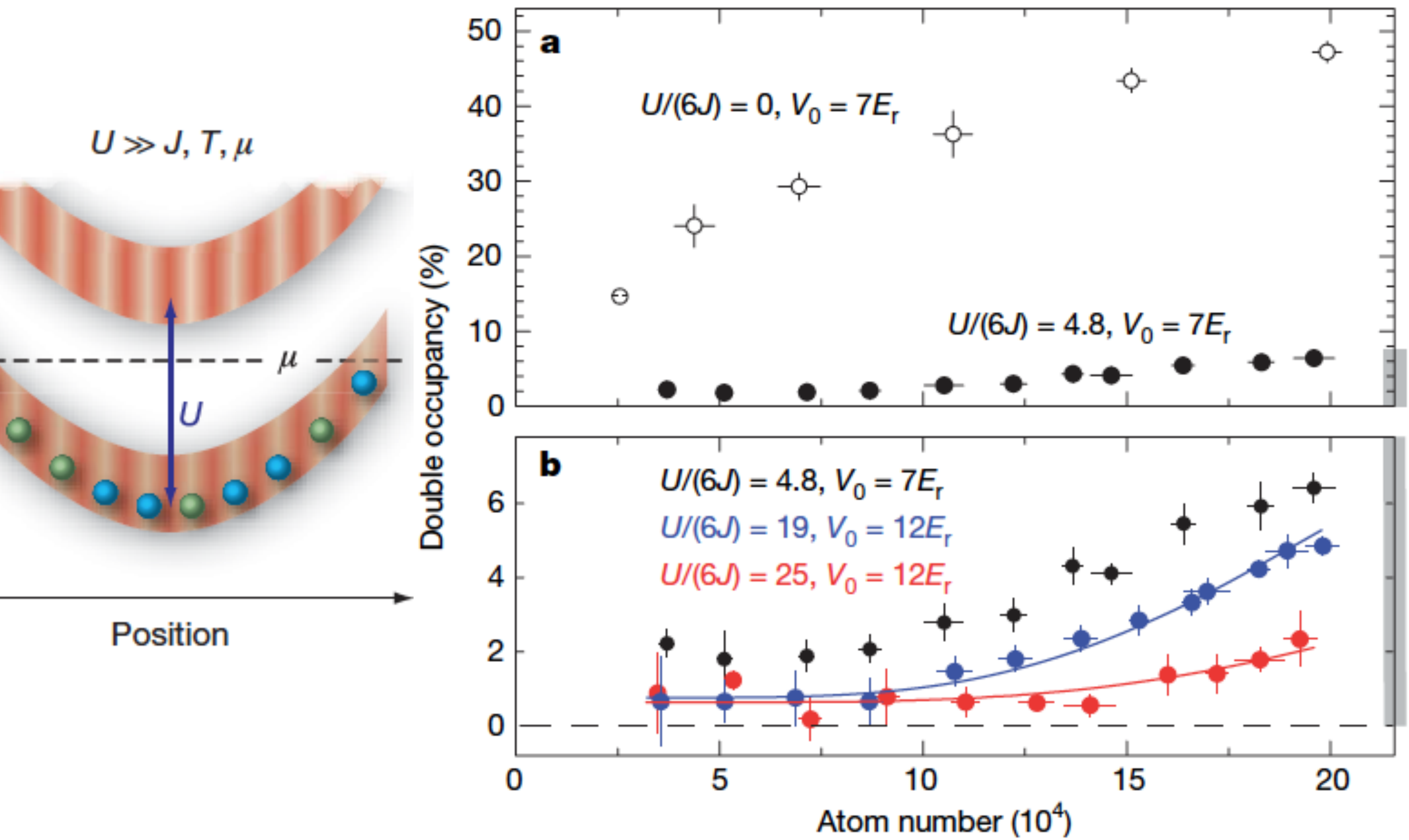


Toronto (2015)



Princeton (2016)

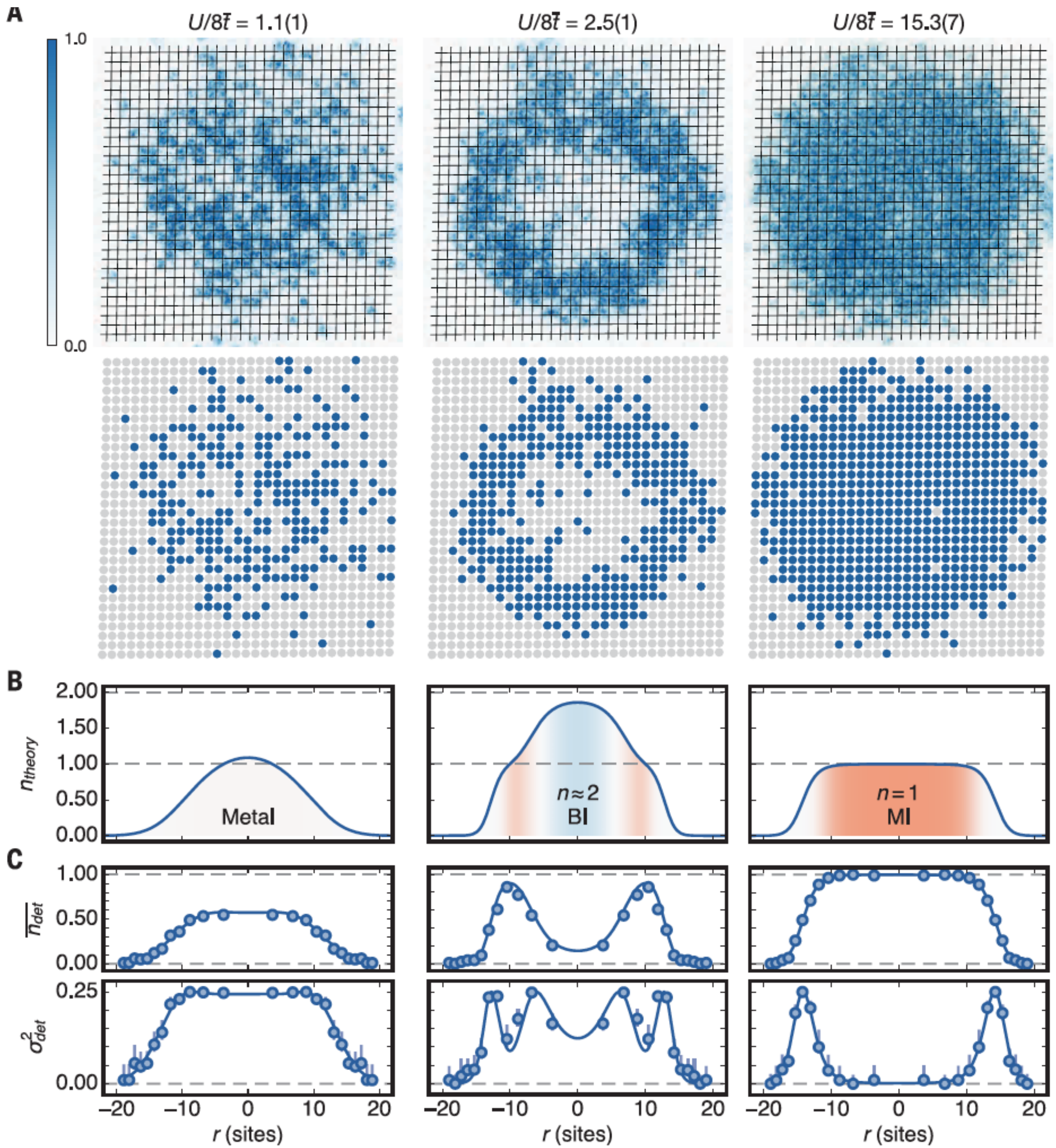
Mott Insulator in fermions



ETHZ (2008)

Fermion Mott Insulator experiments:
ETHZ, Munich, Harvard, MIT, Bonn, Princeton …

In-situ observation of band insulator and Mott Insulator



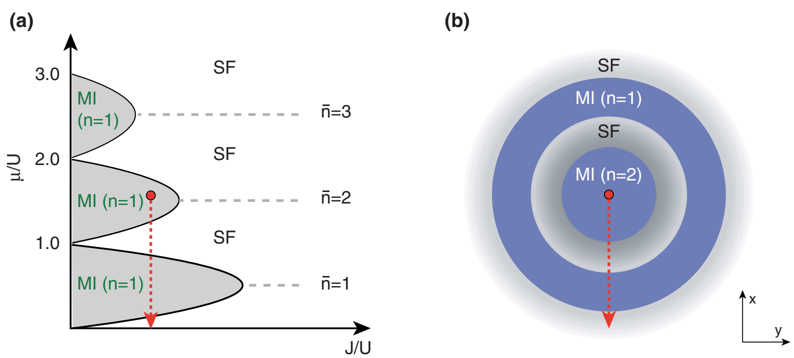
Harvard (2016)

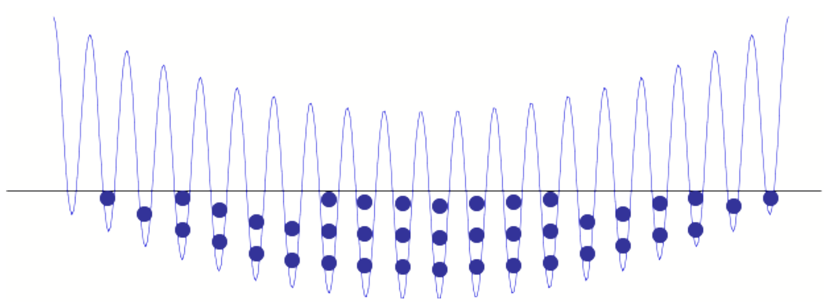
concurrent work at
Munich, Harvard, MIT

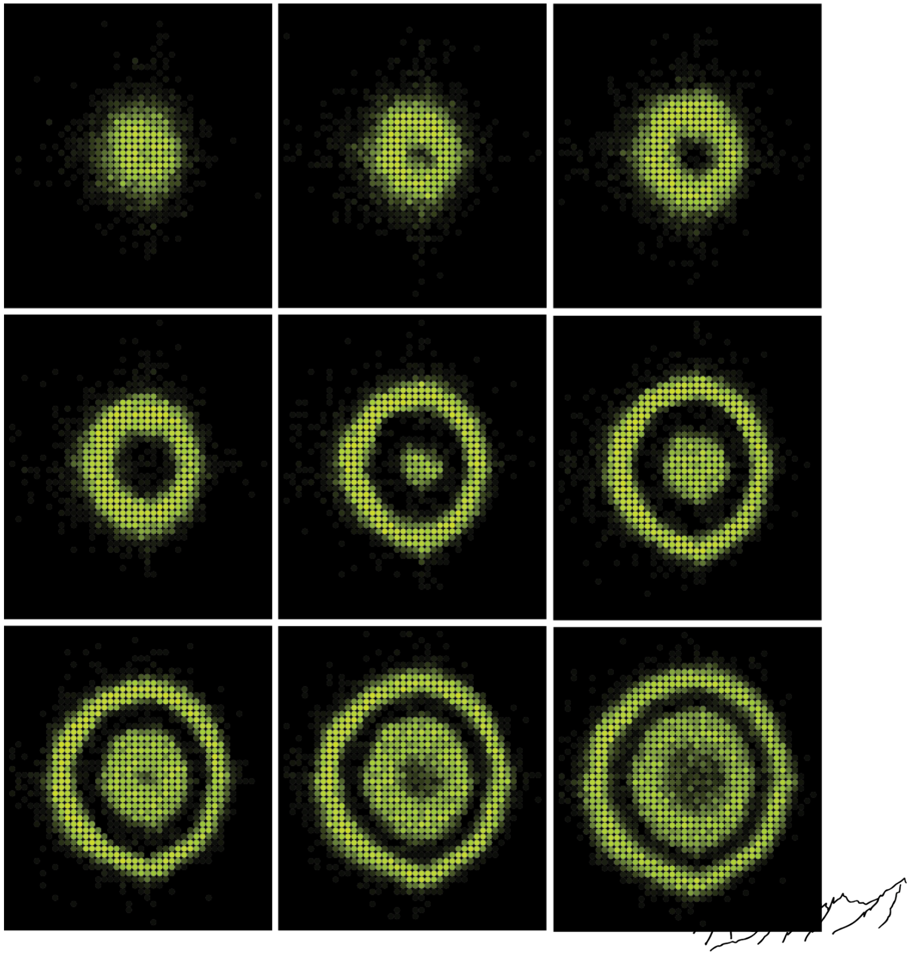
Mott transition

↳ in bosons

Mott shells in a lattice + harmonic trap (Greiner/Bloch 2011)







What’s new with ultracold lattice Fermions?

What's new with ultracold lattice Fermions?

cf. bosons —

- **Fermi statistics in equilibrium**: band fills up to Fermi surface, new states such as band insulator, superfluidity requires pairing (at lower temperature)
- **Many-body exchange statistics**: anti-bunching, blocking, exchange interaction, singlet states
- **Spinful mixtures** — necessary for contact interactions, a new degree of freedom, magnetic phases / correlations, spin currents
- **Transport paradigm**: emergent behaviour that is the signature of electronics

What's new with ultracold lattice Fermions?

cf. bosons —

- **Fermi statistics in equilibrium**
- **Many-body exchange statistics**
- **Spinful mixtures**
- **Transport paradigm**

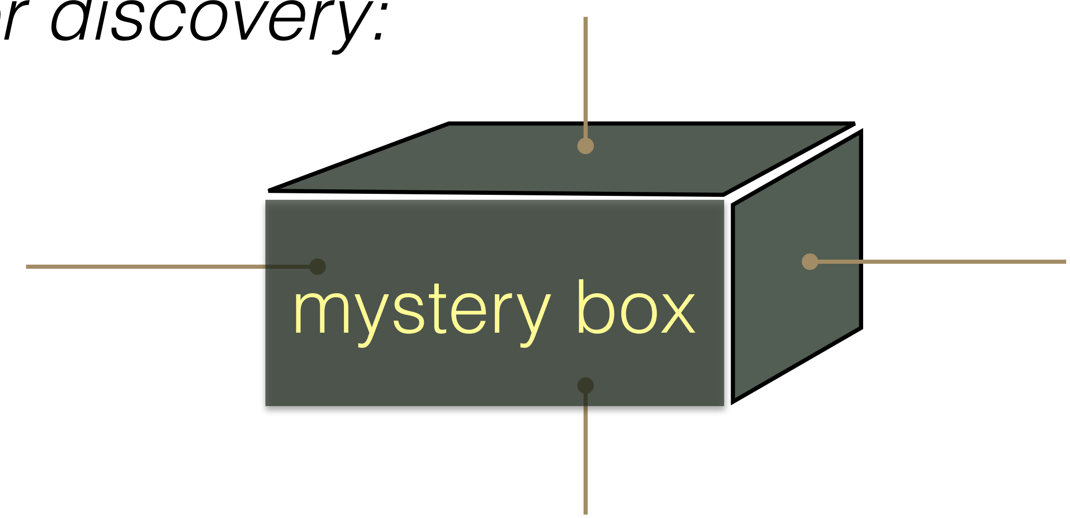
cf. electrons —

- **New observables**: time-of-flight, direct imaging, complex correlators, interferometric sensitivity
- **Optical lattice**: no phonons, known disorder (which can be small), dynamic control, non-bravais lattices
- **Non-equilibrium** — preparation, manipulation, and evolution far from thermal equilibrium…but T high!
- **Small sample** trapped sample, $<10^2$ sites per edge

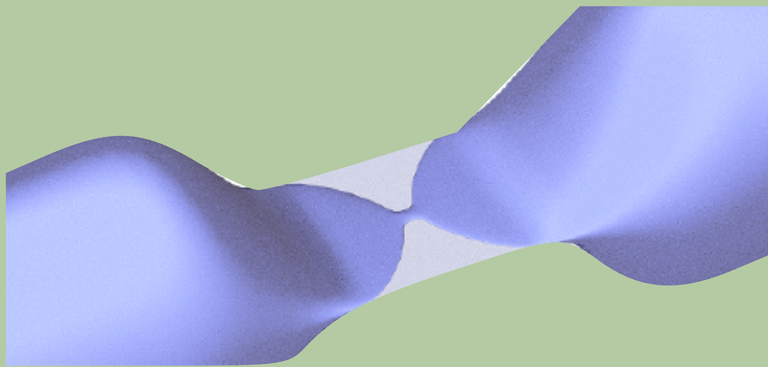
Transport phenomenology

- Metal
- Superconductor
- Insulator
- Quantum Hall State
- …

A tool for discovery:



channel

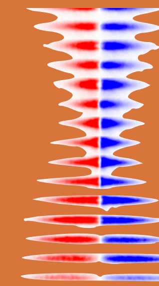


eg: EHTZ; EPFL; NIST/JQI

see review by Brantut, Esslinger, et al.
J Phys. Condens. Mat. (2017)

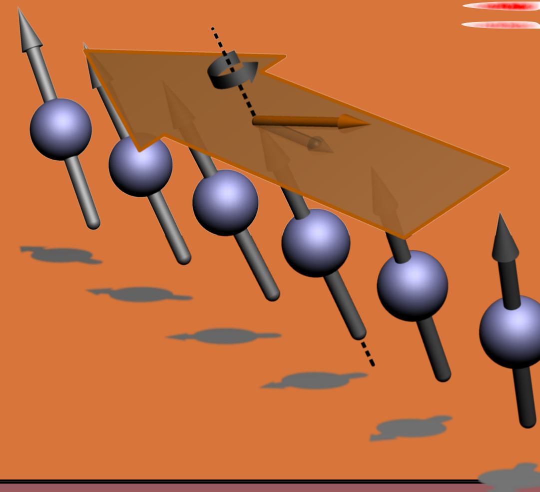
trap

(especially: spin transport)



Roati, Zwierlein *et al.*

MIT
Cambridge
Rice
Toronto
LENS
LKB
....



Trotzky, JHT *et al.*

disorder

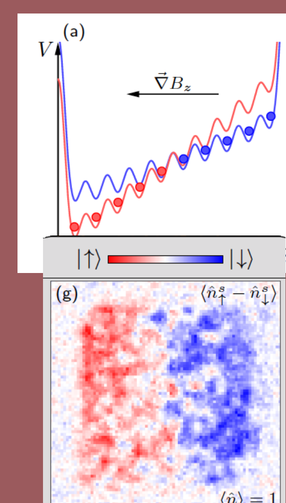
Palaiseau
LENS
UIUC
Munich
...

eg: MBL

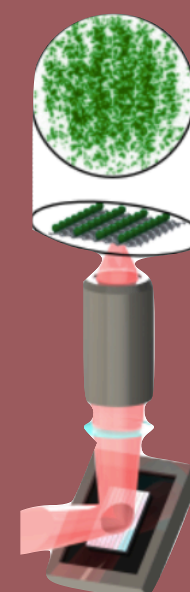
Gross, Bloch, *et al.*

lattice

LENS
ETHZ
UIUC
Munich
MIT
Princeton
Toronto
....

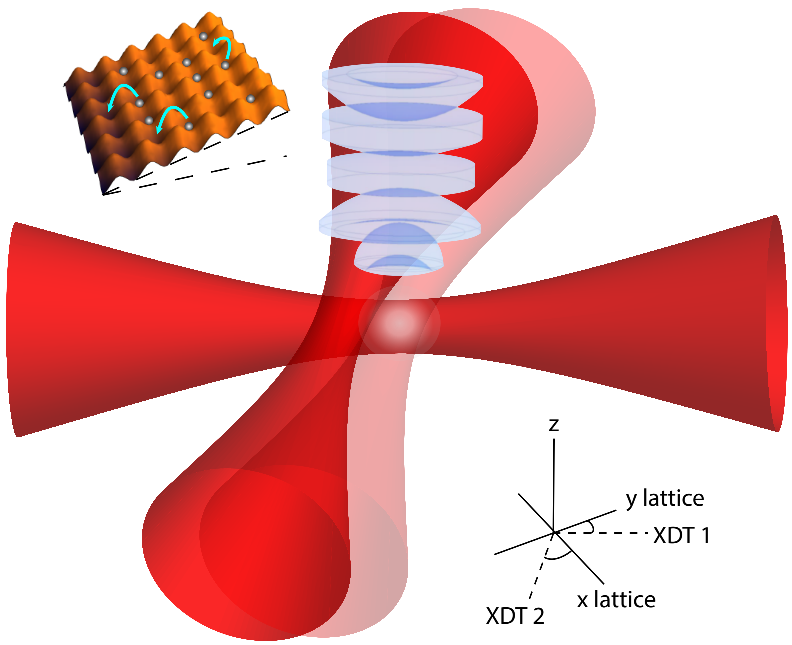


Zwierlein *et al.*

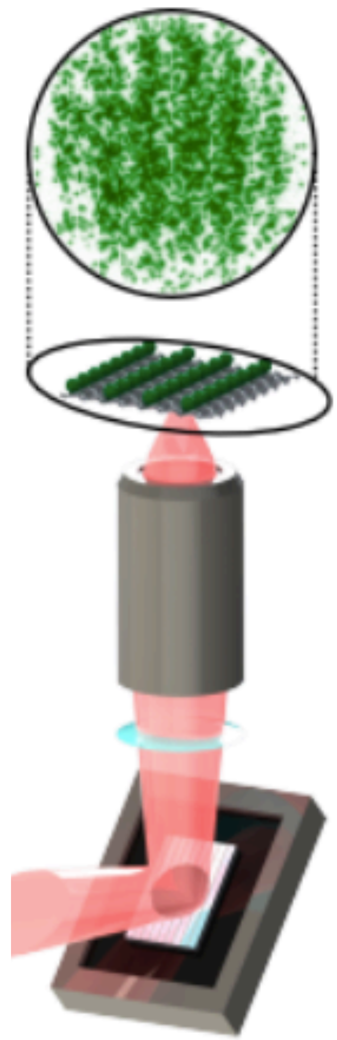


Schauss, Bakr *et al.*

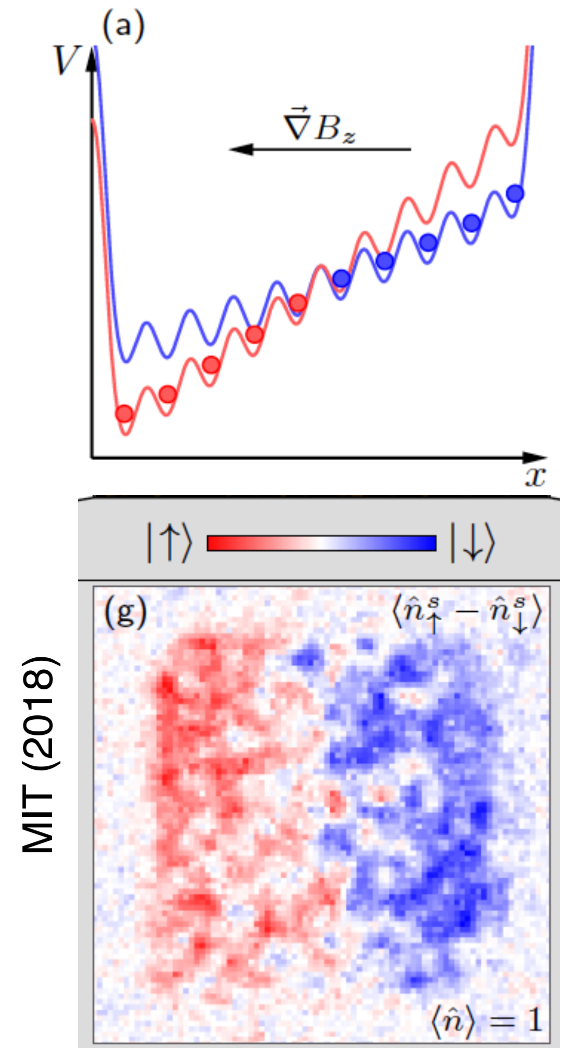
Transport under the microscope



Toronto
arxiv:1712.09965



Princeton
arxiv:1802.09456



MIT
arxiv:1802.10018

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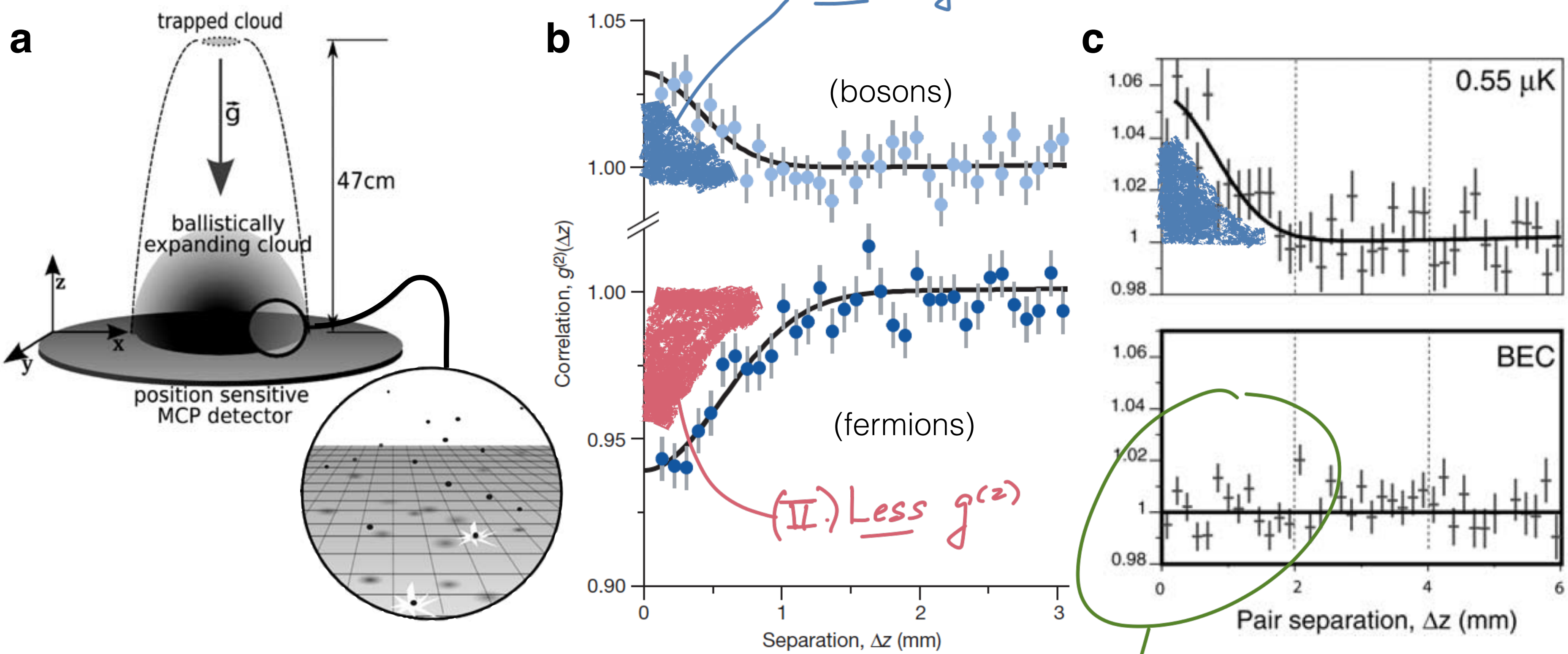
Fermions in Optical Lattices

- Introduction
- Fermions, statistics, & exchange
- Matter waves in crystals of light
- The Hubbard model
- Transport

Antisymmetry, Pauli, Fermi-Dirac

2-body correlations in bosonic $^4He^*$ and fermioic $^3He^*$

(I.) Thermal bosons: additional $g^{(2)}$

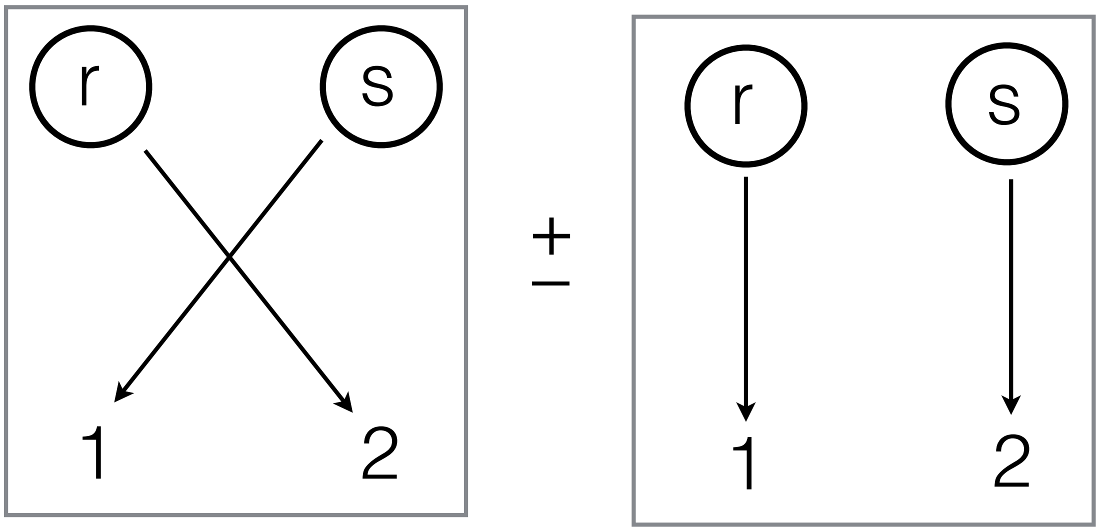


(II.) Less $g^{(2)}$

(III.) BEC: no bunching!

[Westbrook & Aspect, (2005 & 2007)

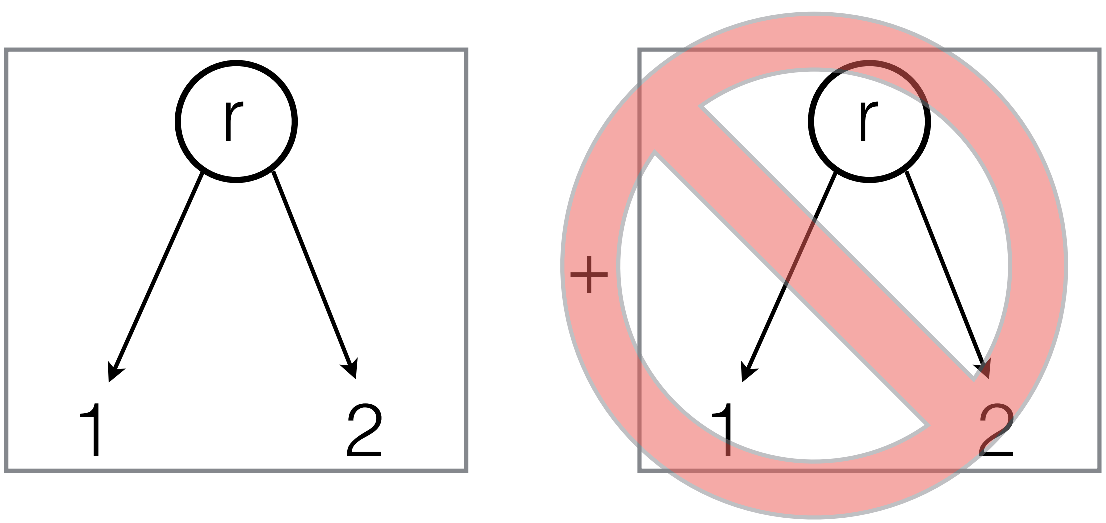
identical particles in **distinct** modes

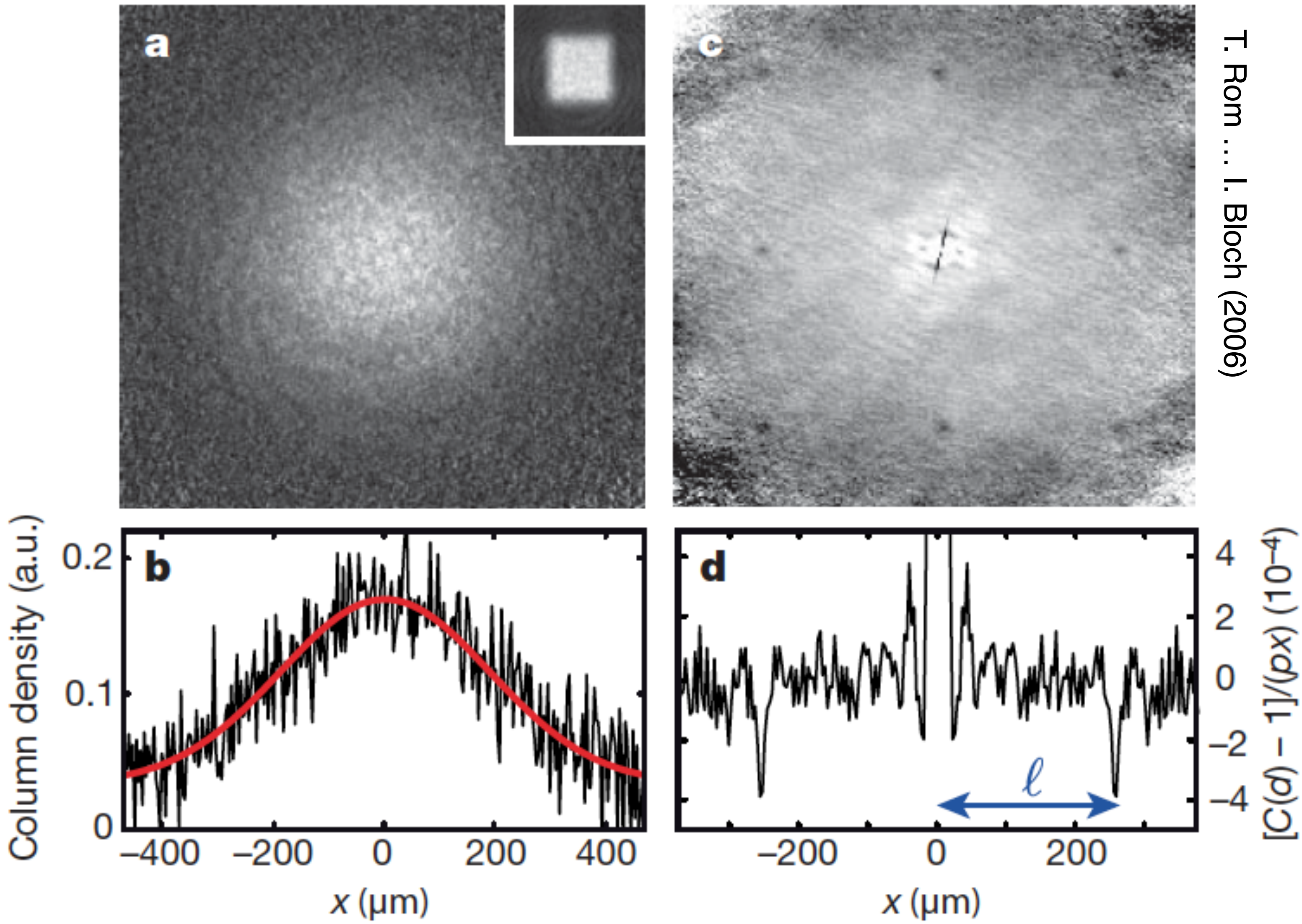


fermions: - sign
suppression
“anti-bunching”

bosons: + sign
enhancement
“bunching”

identical particles in **a single** mode (BEC)





T. Rom … I. Bloch (2006)

Summary, Topic 1

- Anticommutation relations of creation and anihilation operators lead to all fermionic properties
- Fermi blocking is just as fundamental as Fermi-Dirac statistics
- Anti-symmetrization of wave function gives anti-bunching of two-body correlations
- Interactions are correlation detectors, and suppressed by the "exchange interaction" for identical fermions
- Observations: g(2) function on a microchannel plate (Hanbury-Brown-Twiss like effect for fermions); reduced interactions; reduced density fluctuations

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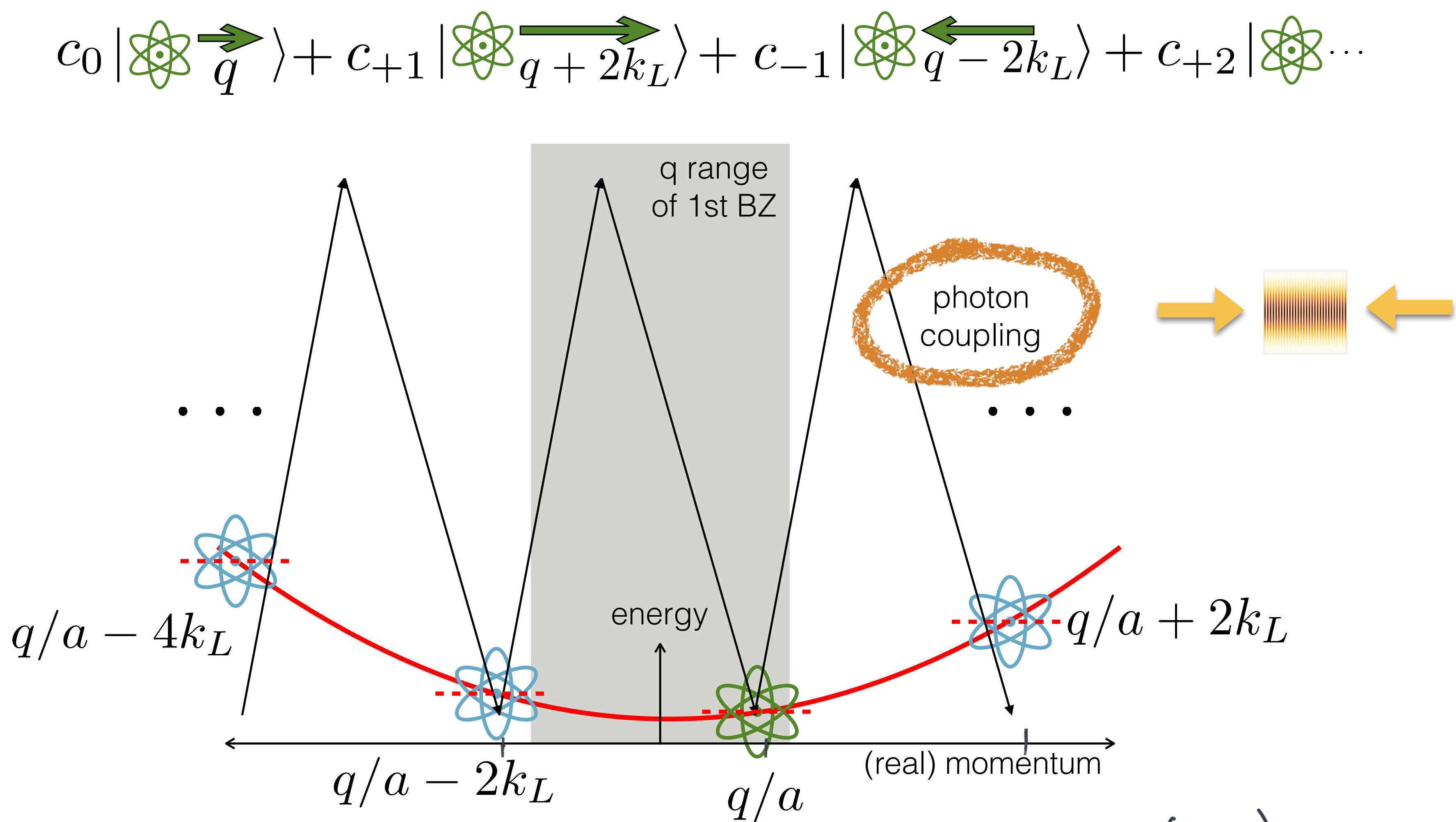
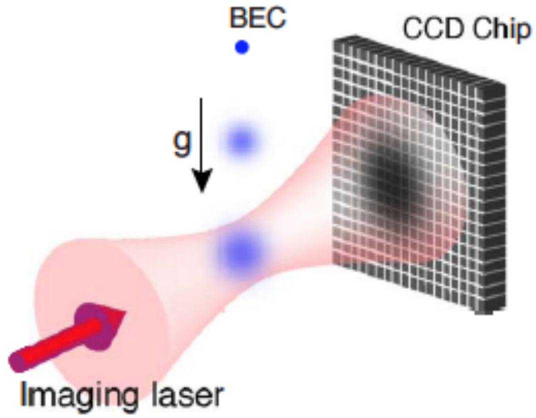
Matter waves in crystals of light

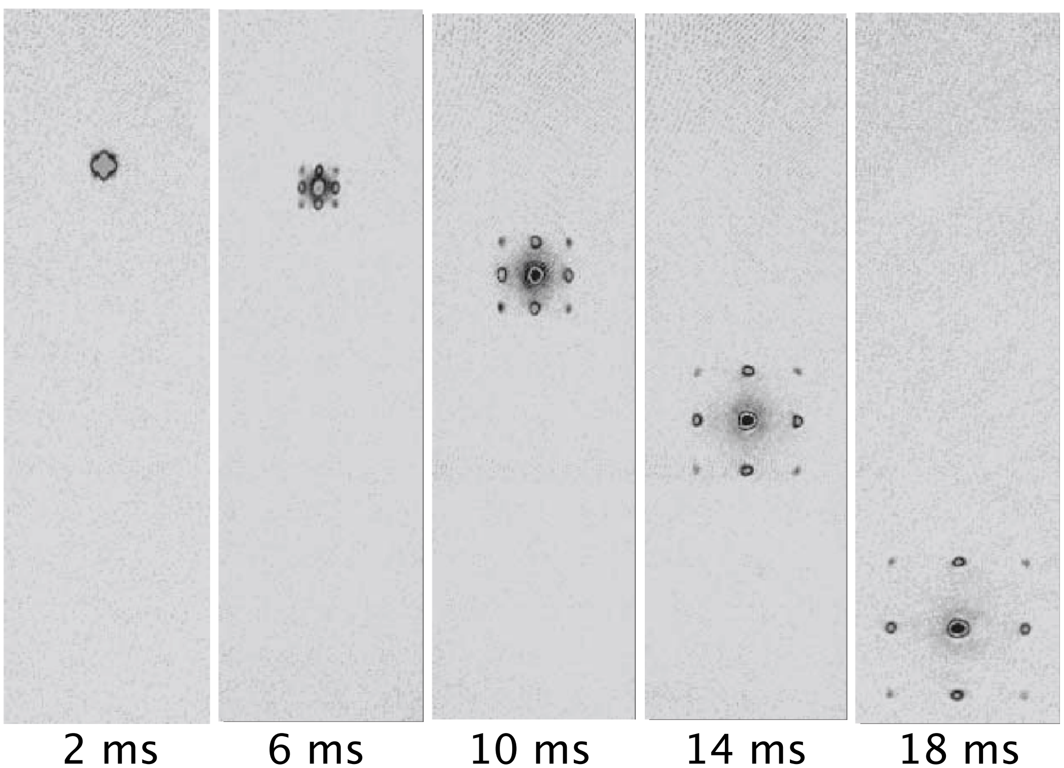
What is quasi-momentum q?

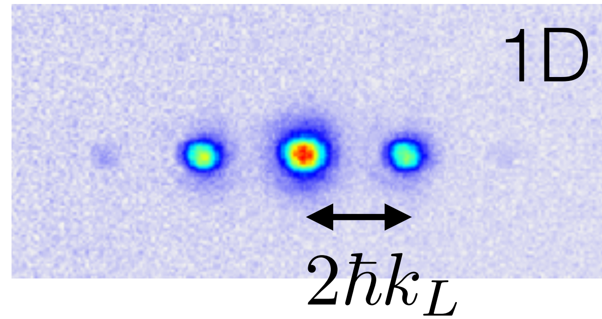


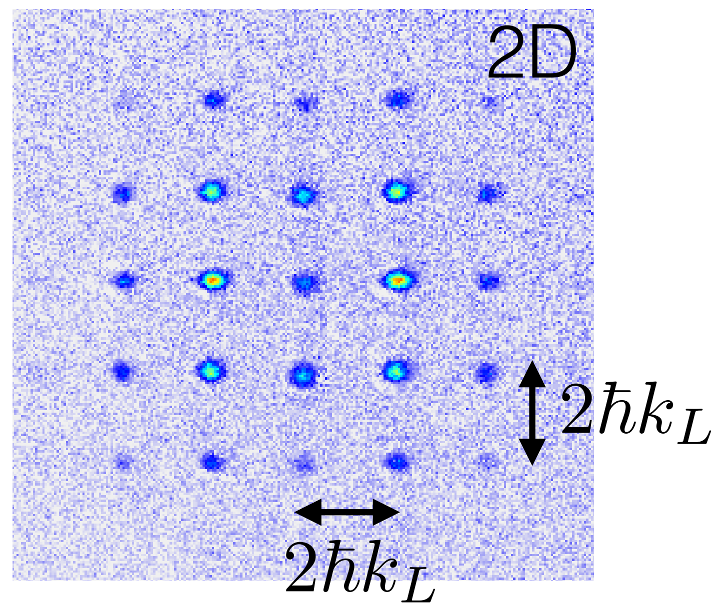
Atom in Bloch state does not have a well defined (true) momentum.

Matter-wave diffraction from standing wave









Two-photon spacings show Bragg coupling between momentum states by the lattice

Alternate perspective on quasi-momentum:

$$c_0 \left| q \right\rangle + c_{+1} \left| q + 2k_L \;\; \text{2 photons} \right\rangle + c_{-1} \left| q - 2k_L \;\; \text{2 photons} \right\rangle + c_{+2} \left| \;\; 4 \right\rangle \ldots$$

Quasi-momentum is total momentum of matter + light