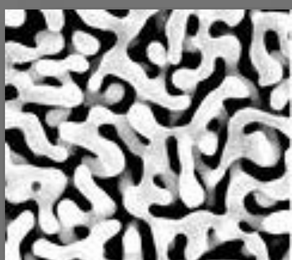
Many-Body Localization and Relaxation in Optical Lattices

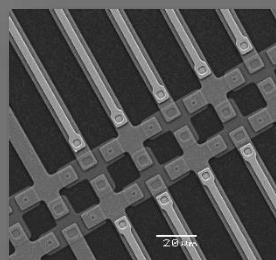
Brian DeMarco
University of Illinois

Disorder and Interactions

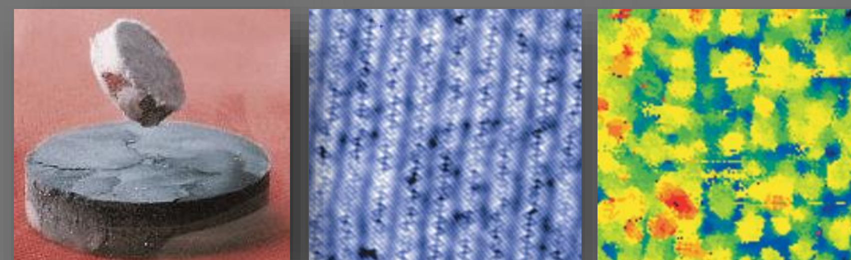
What is the fate of interacting disordered quantum particles?



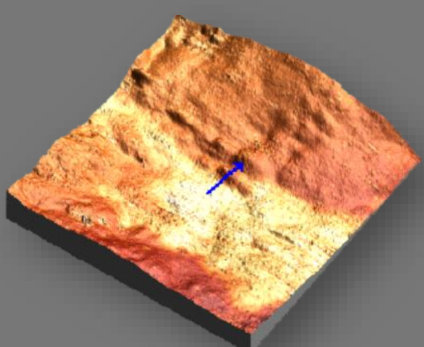
SF in porous media



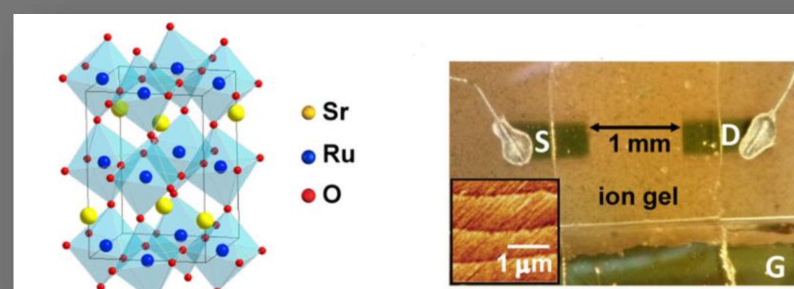
JJ arrays



High T_c SCs (Davis)



SC films
(Institut Nanosciences et Cryogénie)

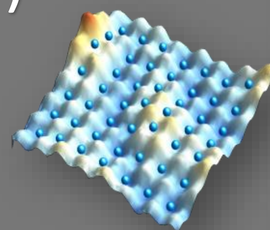


Transition metal oxides ($SrRuO_3$, Podzorov)

Strongly Correlated Disordered Physics

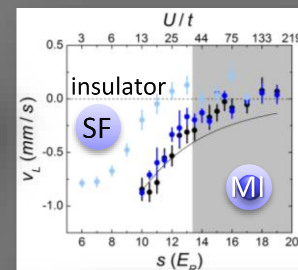
Highlights from our group

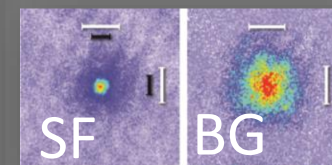
Disordered bosons (^{87}Rb)



SF-BG transition

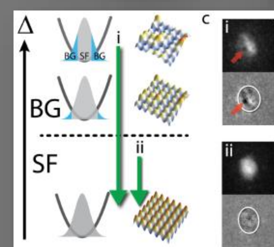
Nat. Phys. **6**, 677 (2010)

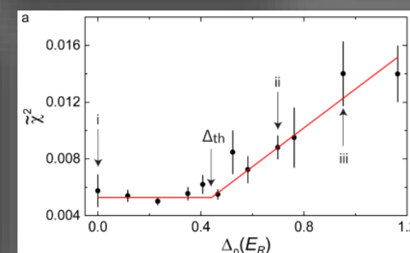


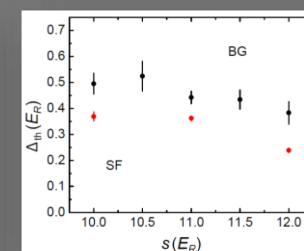


BG-SF disorder quench

arXiv: 1502.02333 (2015)





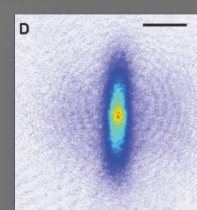


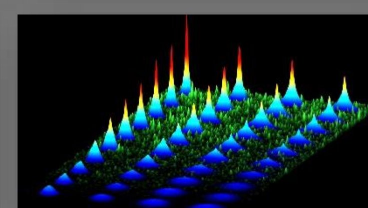
Disordered fermions (^{40}K)

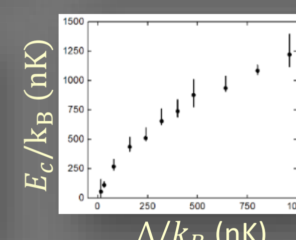
3D Anderson localization

Science **334**, 66 (2011)

Phys. Rev. Lett. **111**, 145303 (2013)

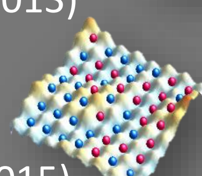


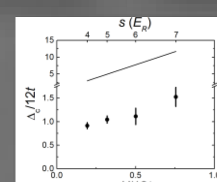


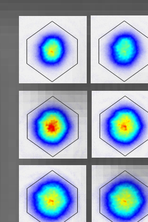


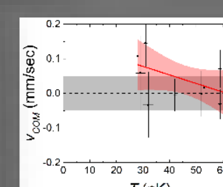
Evidence for MBL

Phys. Rev. Lett. **114**, 083002 (2015)







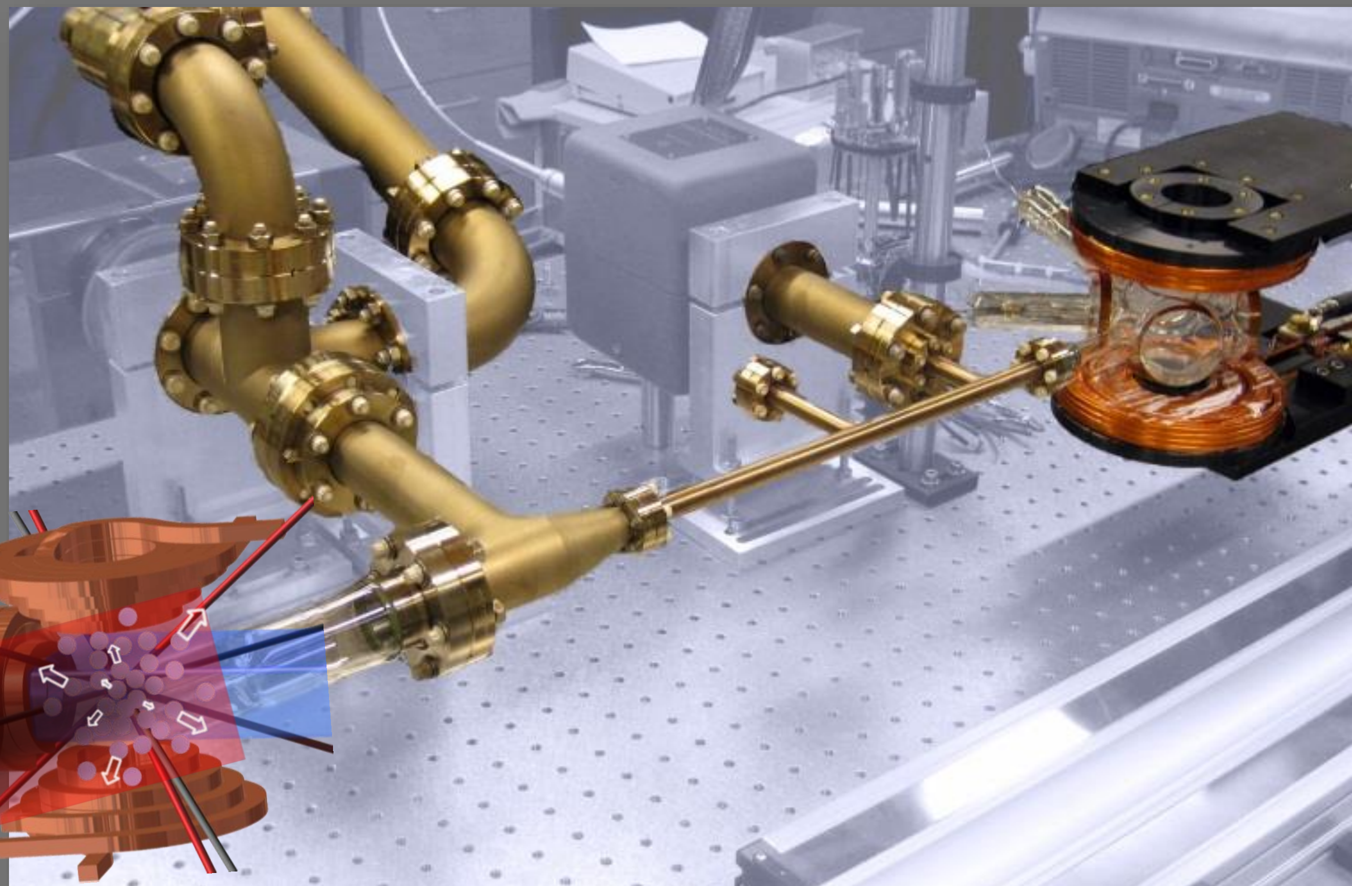


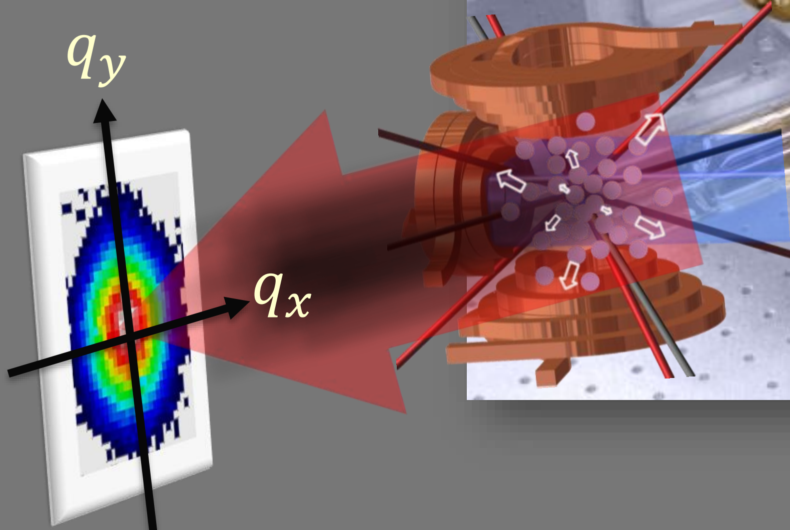
Outline

- How we make quantum gases
- Disordered 3D optical lattices
- Evidence for MBL
- Current / future experiments:
  - Spatially local excitations & relaxation

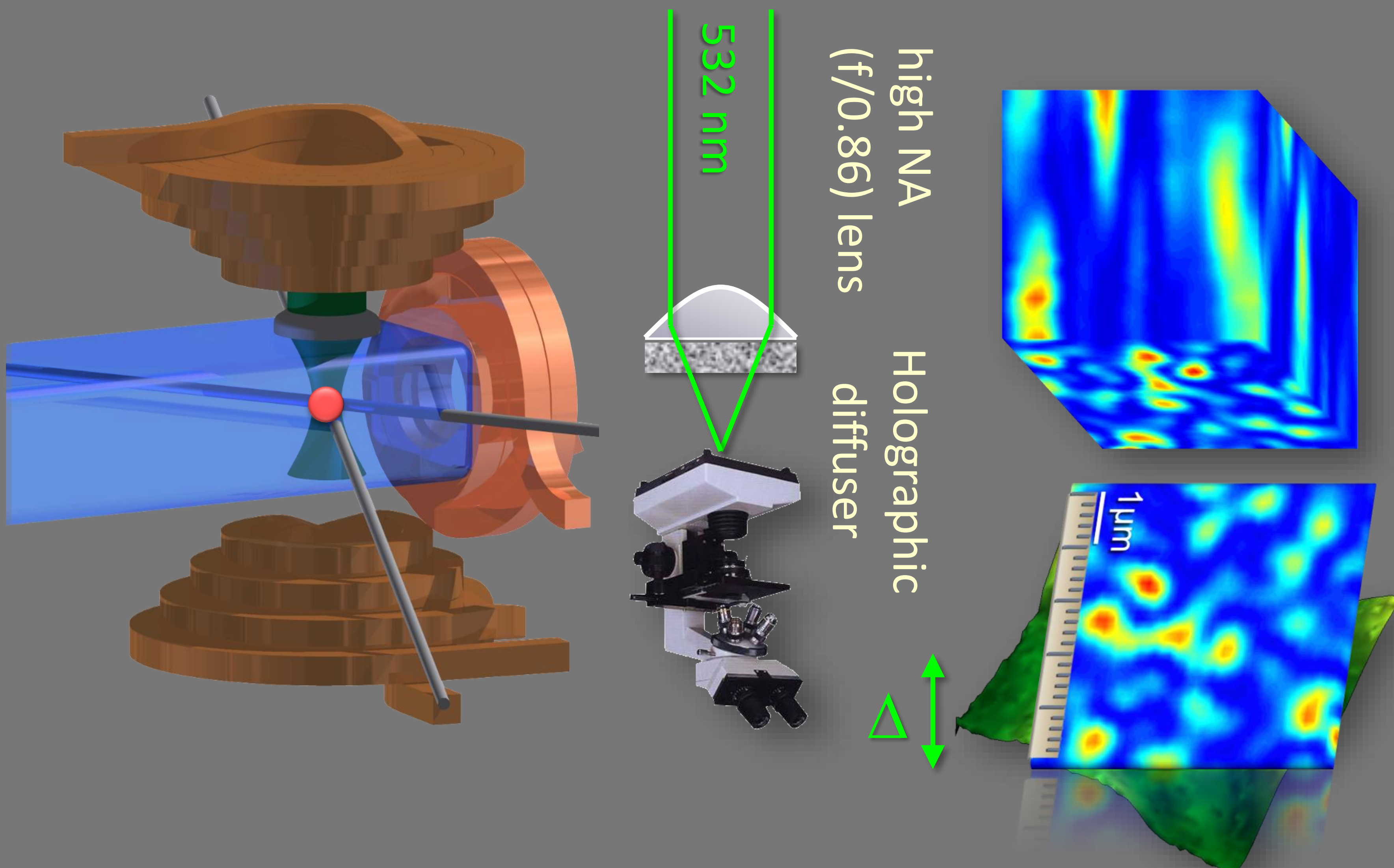
Ultracold Quantum Gases

- Fermi gas of ^{40}K atoms in 1064 nm crossed dipole trap
- $T/T_F \geq 0.15$



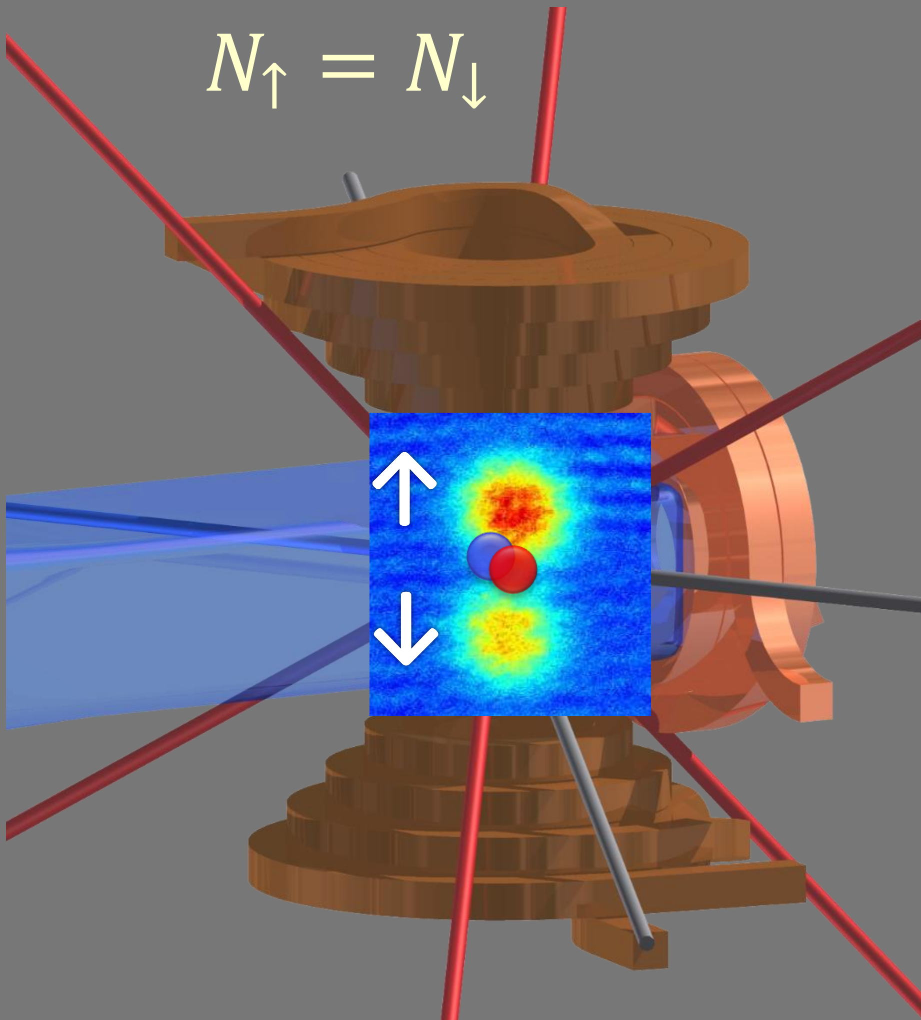


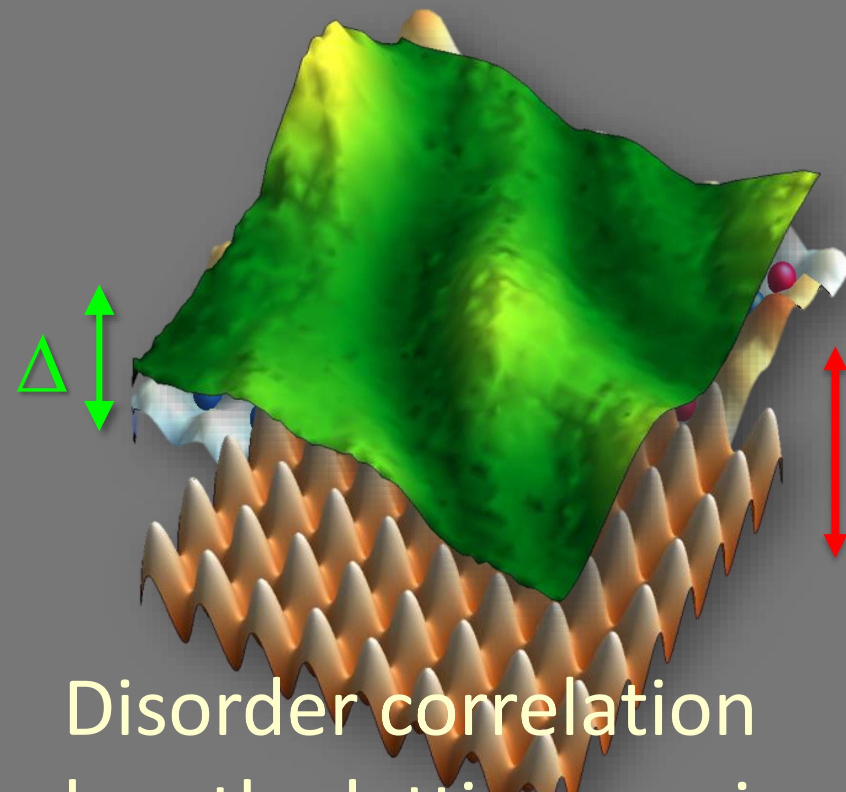
Disorder



Disordered Hubbard Model

3D, cubic optical lattice induces strong interactions



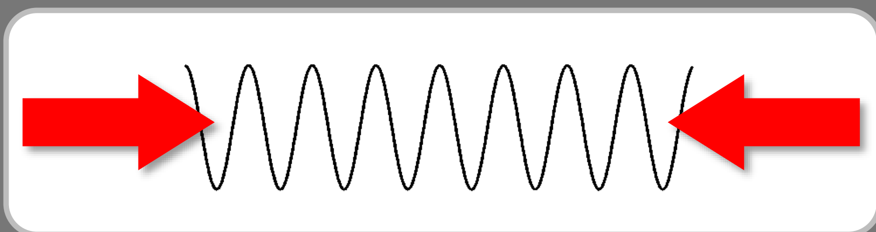


Disorder correlation length~lattice spacing

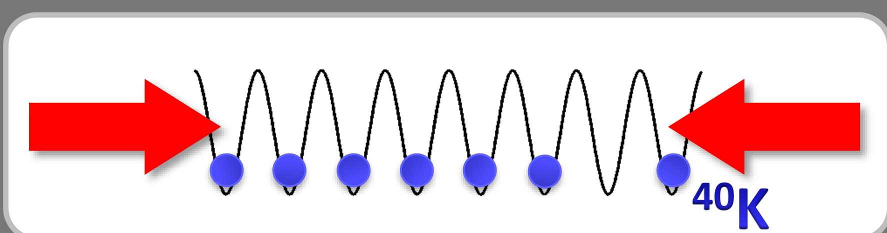
Exactly realizes Hubbard model

Our approach: An Artificial Material

Our experiment

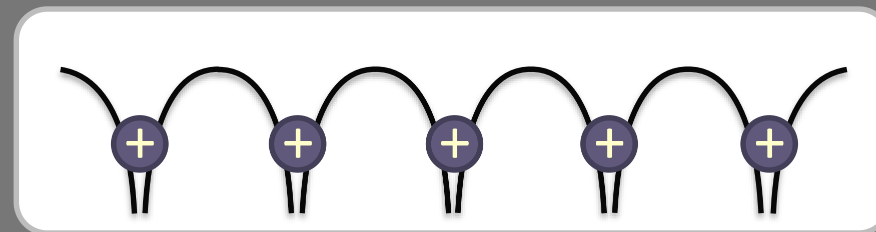


Optical lattice potential

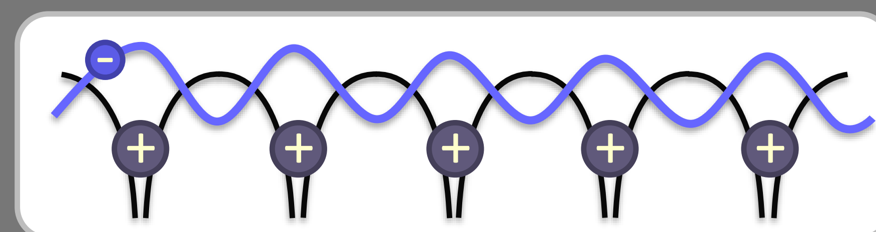


Atoms

Solids

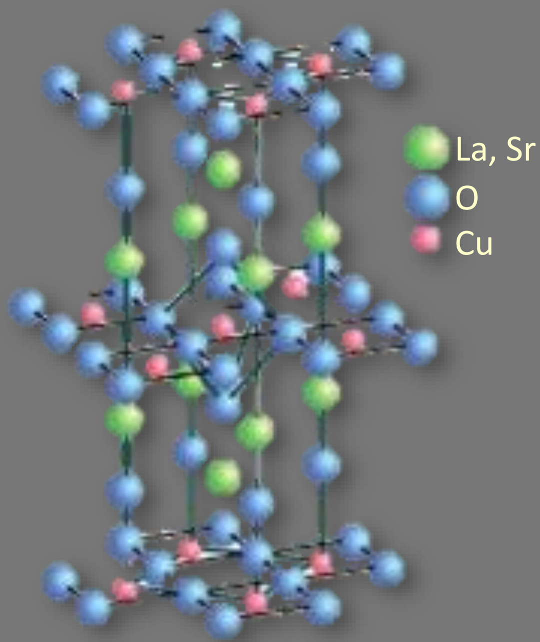


Ionic / Covalent crystal



Electrons

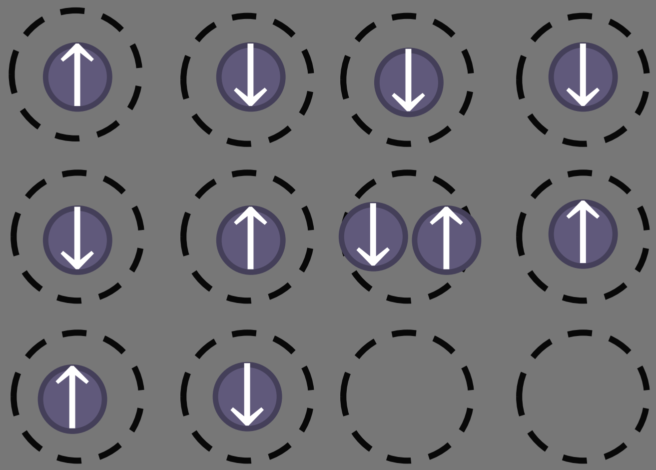
Hubbard Models

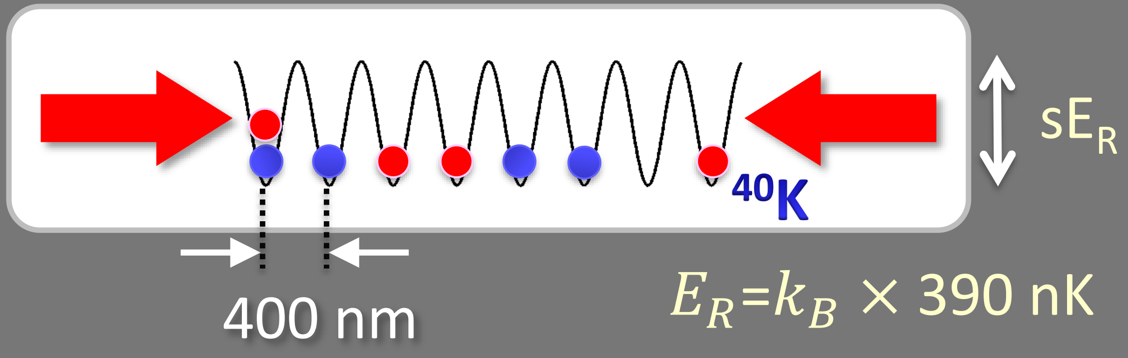


Minimal model

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

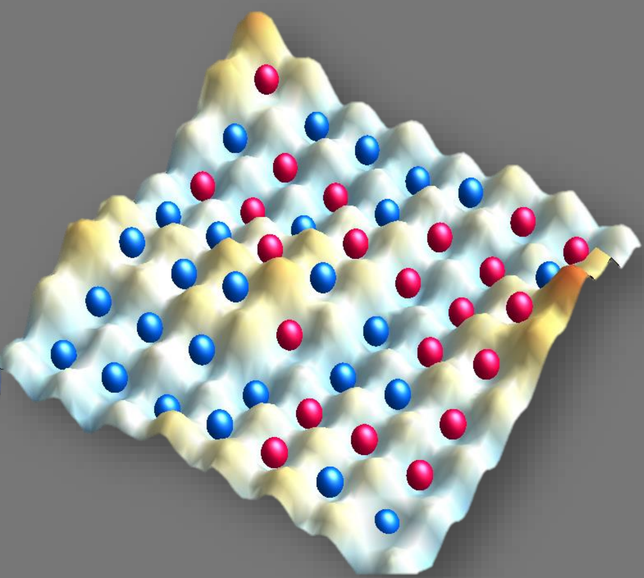
tunneling interactions

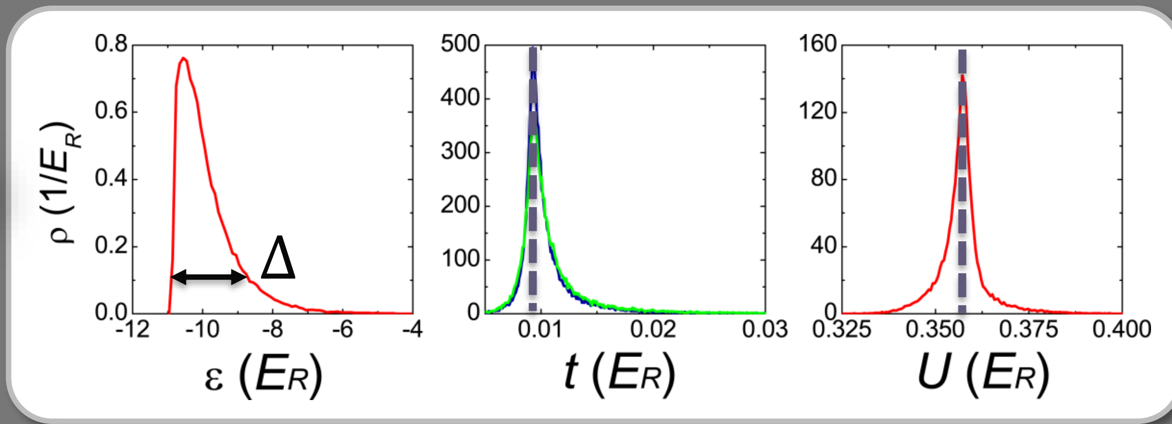




$E_R = k_B \times 390$ nK

Disordered FH model



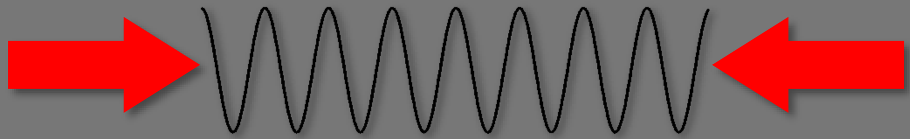


PRL **102**, 055301 (2009)

$$H = \sum_{i,\sigma} n_{i,\sigma}\varepsilon_i - \sum_{\langle ij\rangle} t_{ij} c_i^{\dagger} c_j + \sum_i U_i n_{i,\downarrow} n_{i,\uparrow}$$

Differences with an electronic solid

No phonons



No variable range hopping

No heat bath

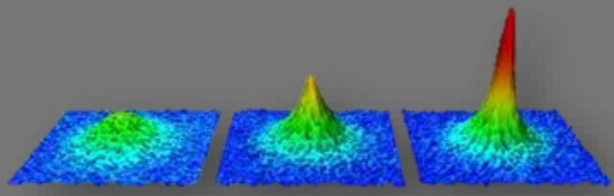
Closed quantum system

Coherence length larger than system size

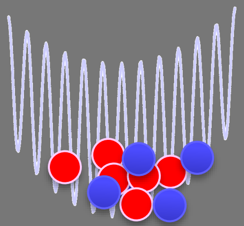
Particles are manifestly quantum

Interact only with each other

Scattering from disorder purely elastic



Trap

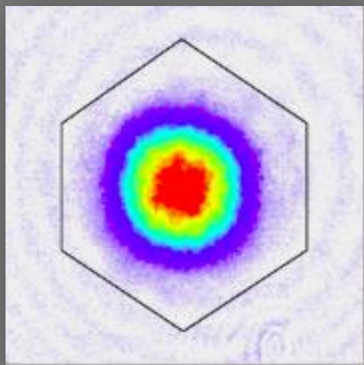


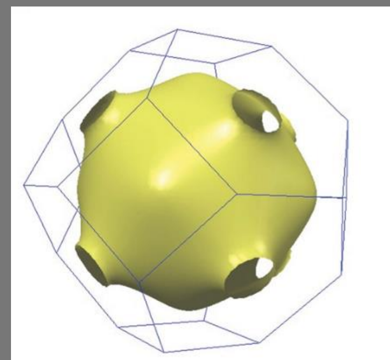
Inhomogeneous density profile

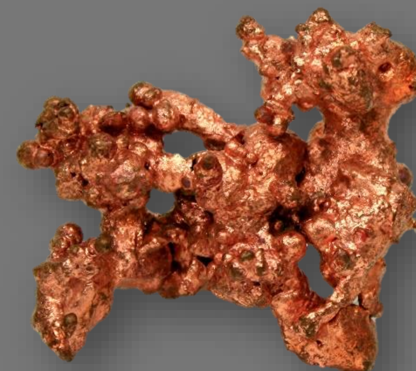
Momentum profile not sharp at $T = 0$

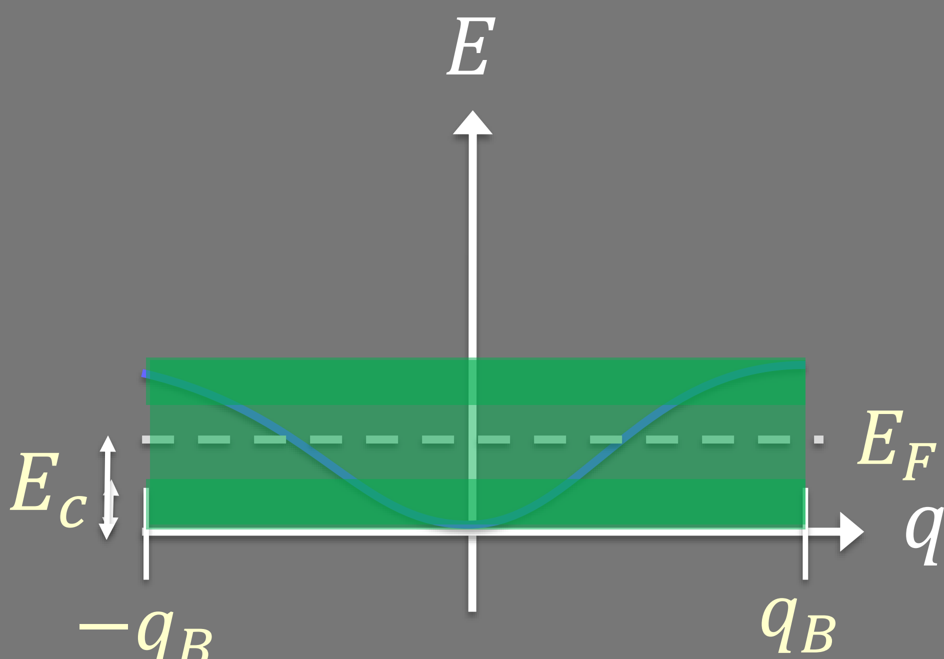
The dirty metal

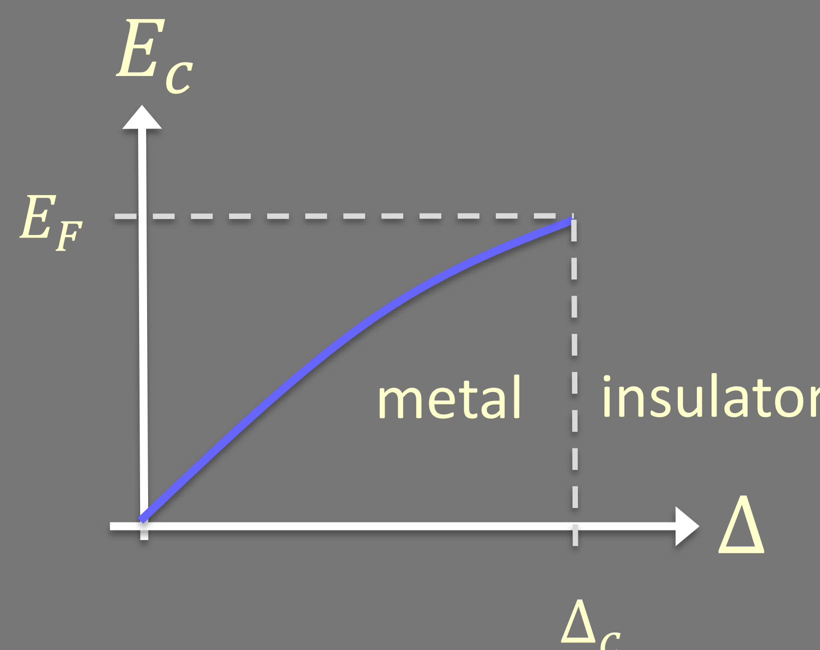
A Dirty (Non-interacting) Metal









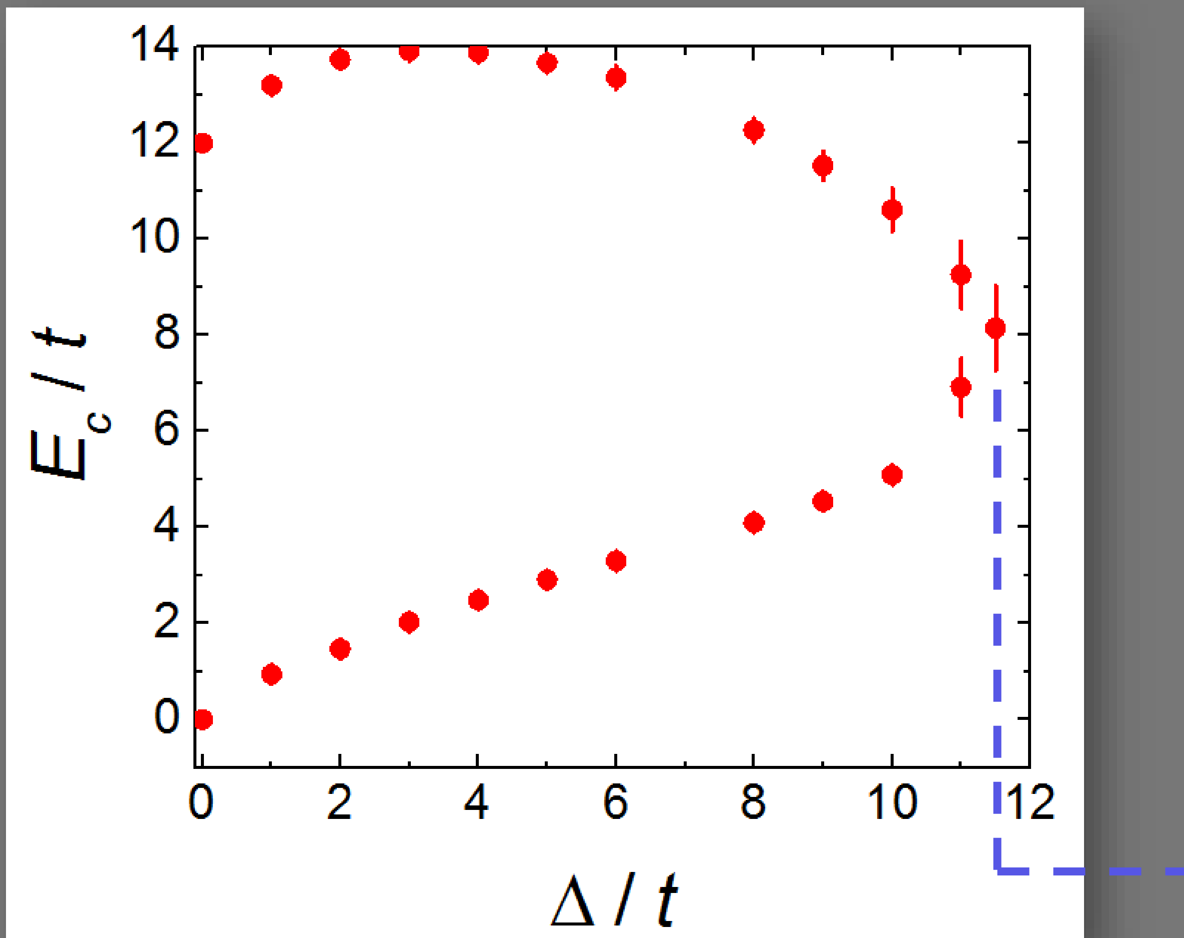


Single-particle mobility Edge: now known!

Anderson localization in optical lattices with correlated disorder

E. Fratini and S. Pilati[1]
[1] *The Abdus Salam International Centre for Theoretical Physics, 34151 Trieste, Italy*

arXiv: 1510.0512

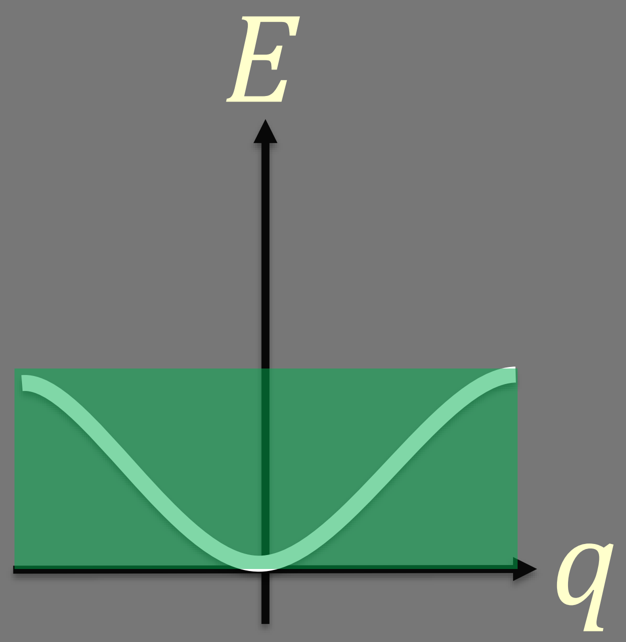


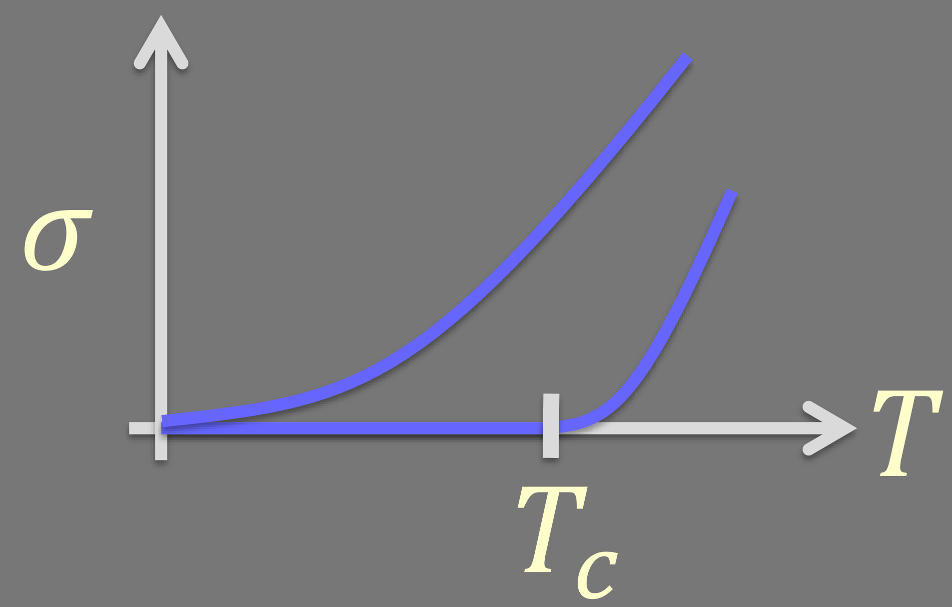
Consistent with onset of localization for $U = 0$ and weakest interaction strength

Many-body localization

Many-body localization

Basko, Aleiner, Altshuler (2006)





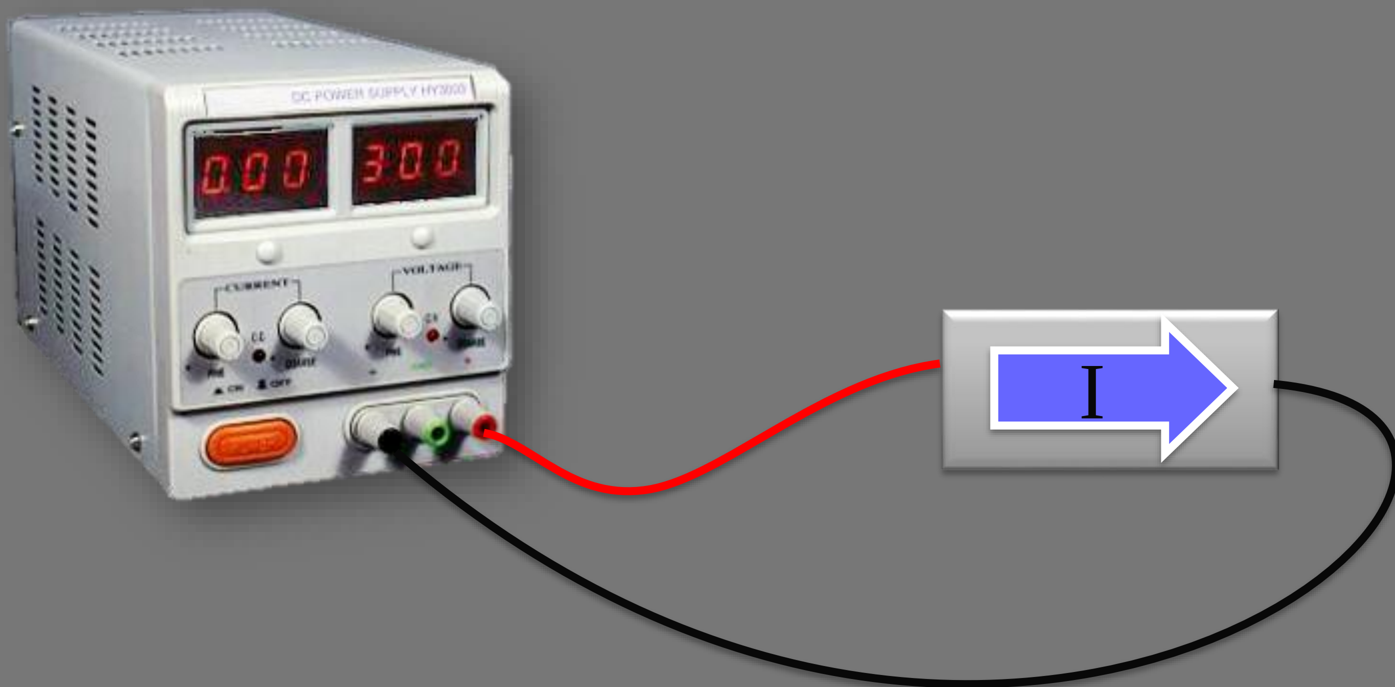
Many-particle, interacting states are localized

Untested! Difficult / Impossible in solids…

MBL predictions

- Localization at $T > 0$
- Interaction-induced delocalization
- Localization across a range of T

Transport Measurements

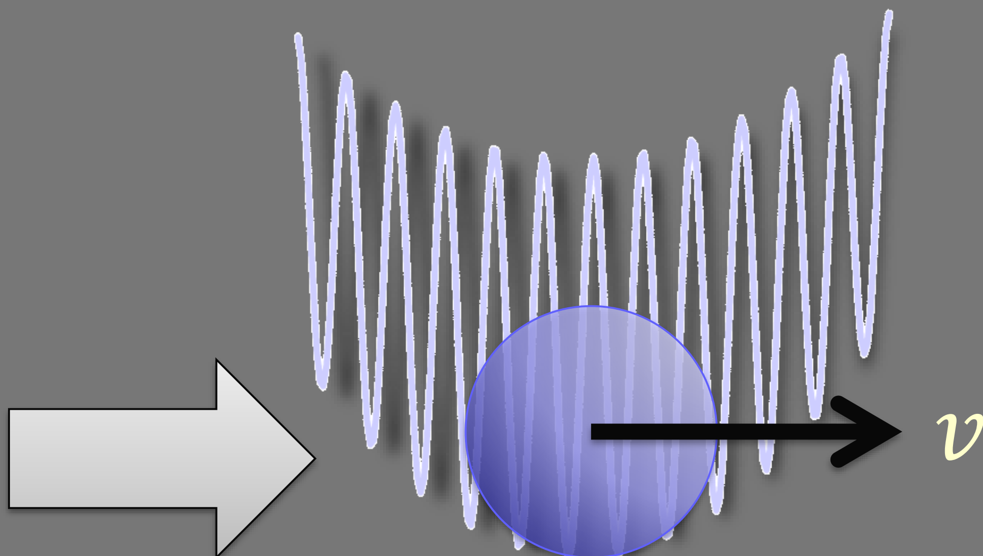


resistivity $\rho \propto \frac{V}{I}$

Look for transition to insulator

Impulse method to identify insulator

Nature Physics **6**, 677 (2010)



Measure v immediately after impulse

$v = 0$: insulator

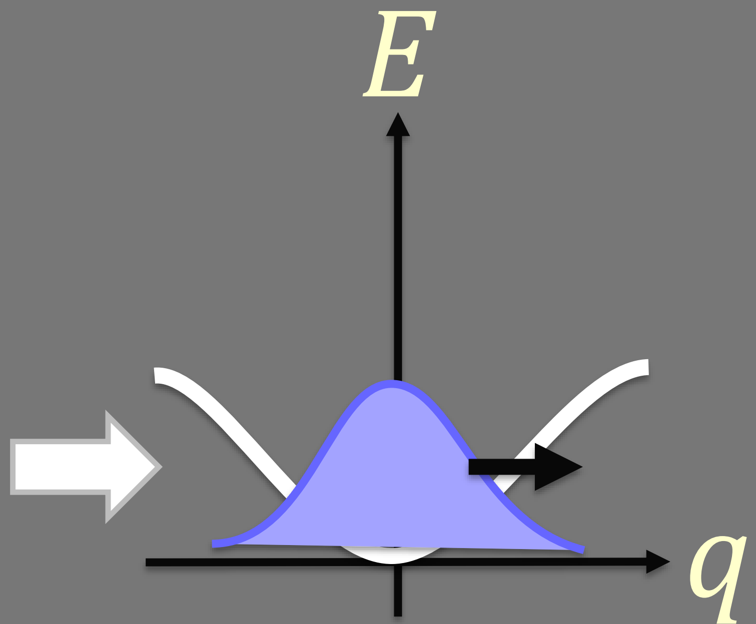
All states localized

$v > 0$: not insulator

Transport

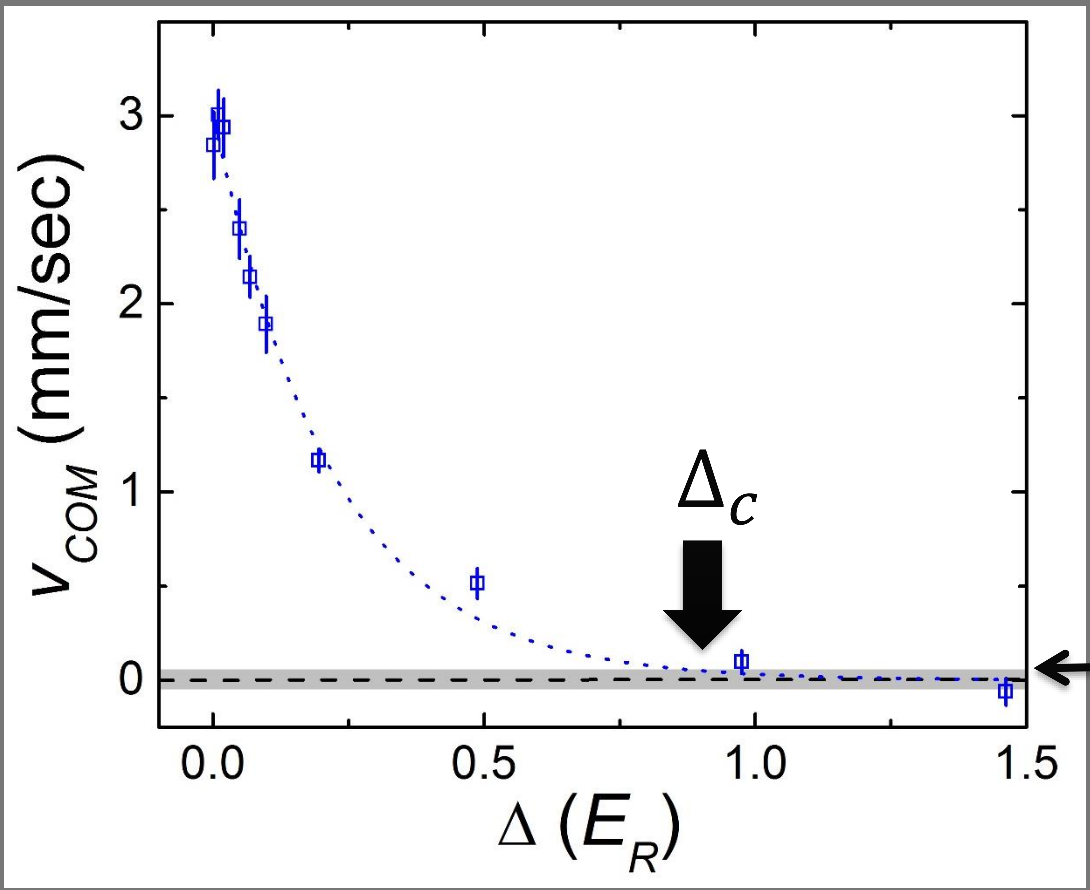
All atoms can participate in transport

Not just the particles near E_F

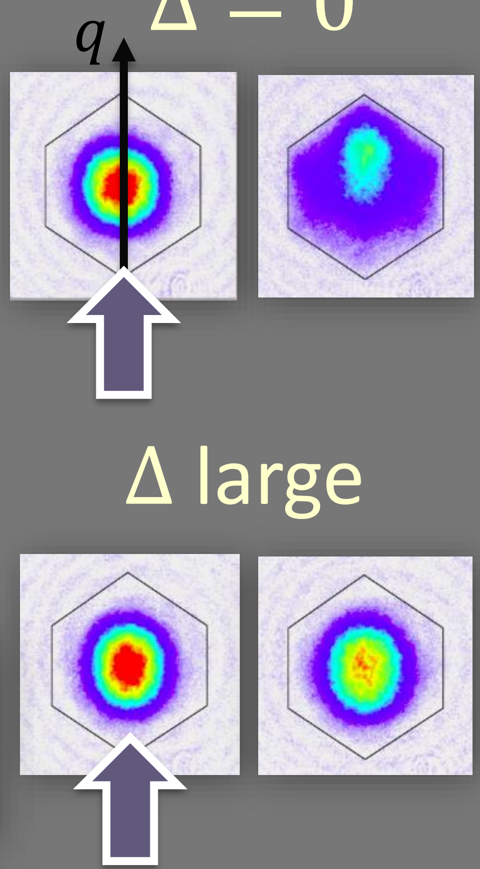


Metal-IN transitions

Fixed lattice: $U = 4t$

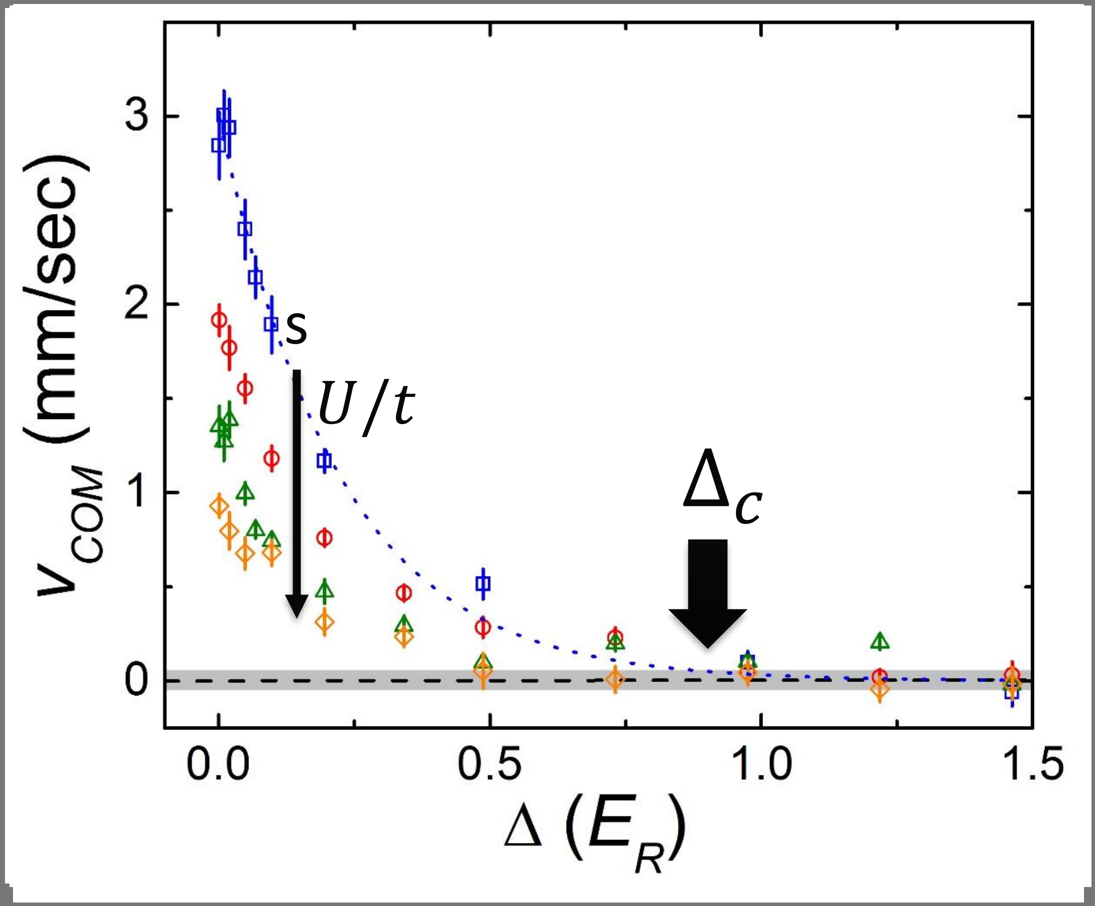


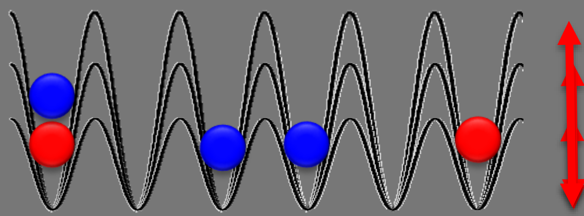
10 pK



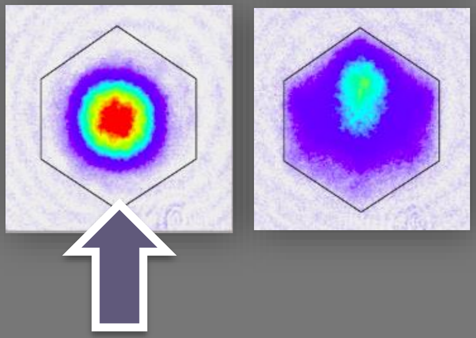
Measurement of Δ required to localize states @ ppt level

Metal-IN transitions

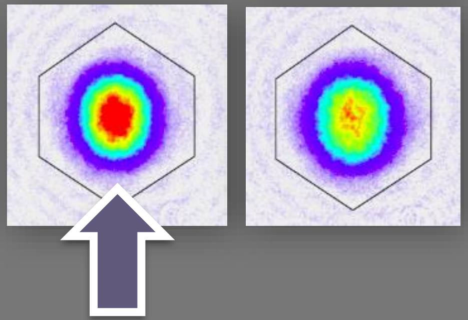




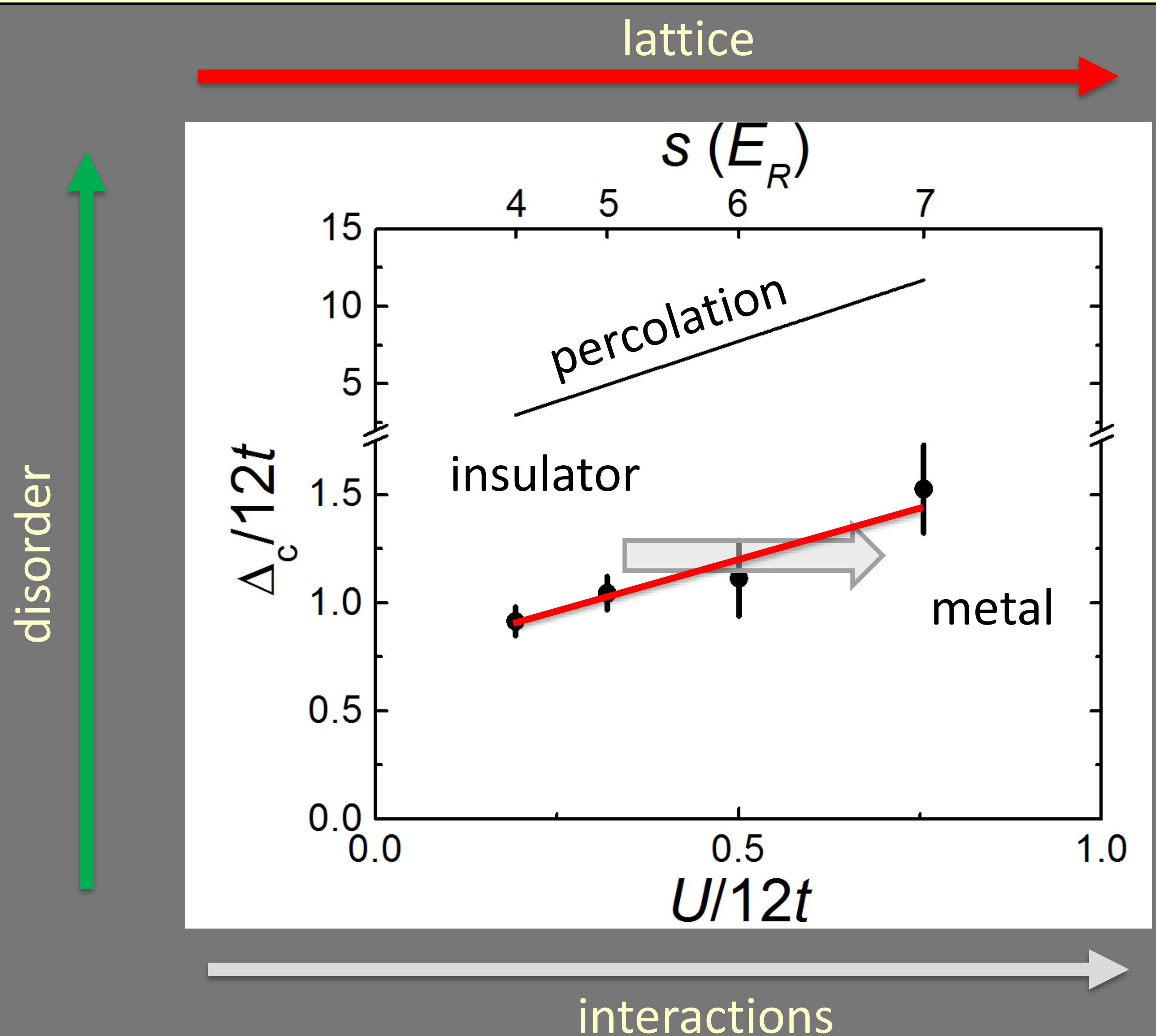
$\Delta = 0$



Δ large

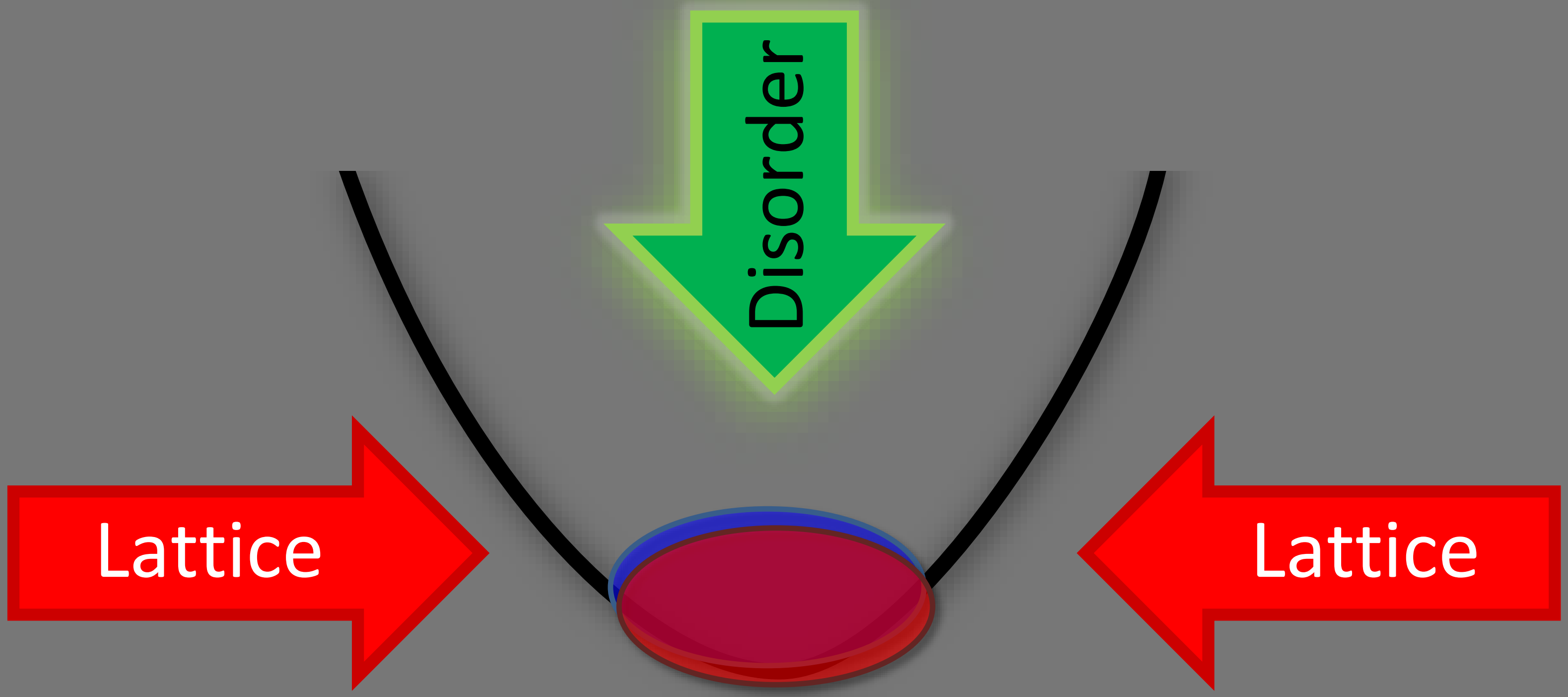


Low-Temperature Phase Diagram



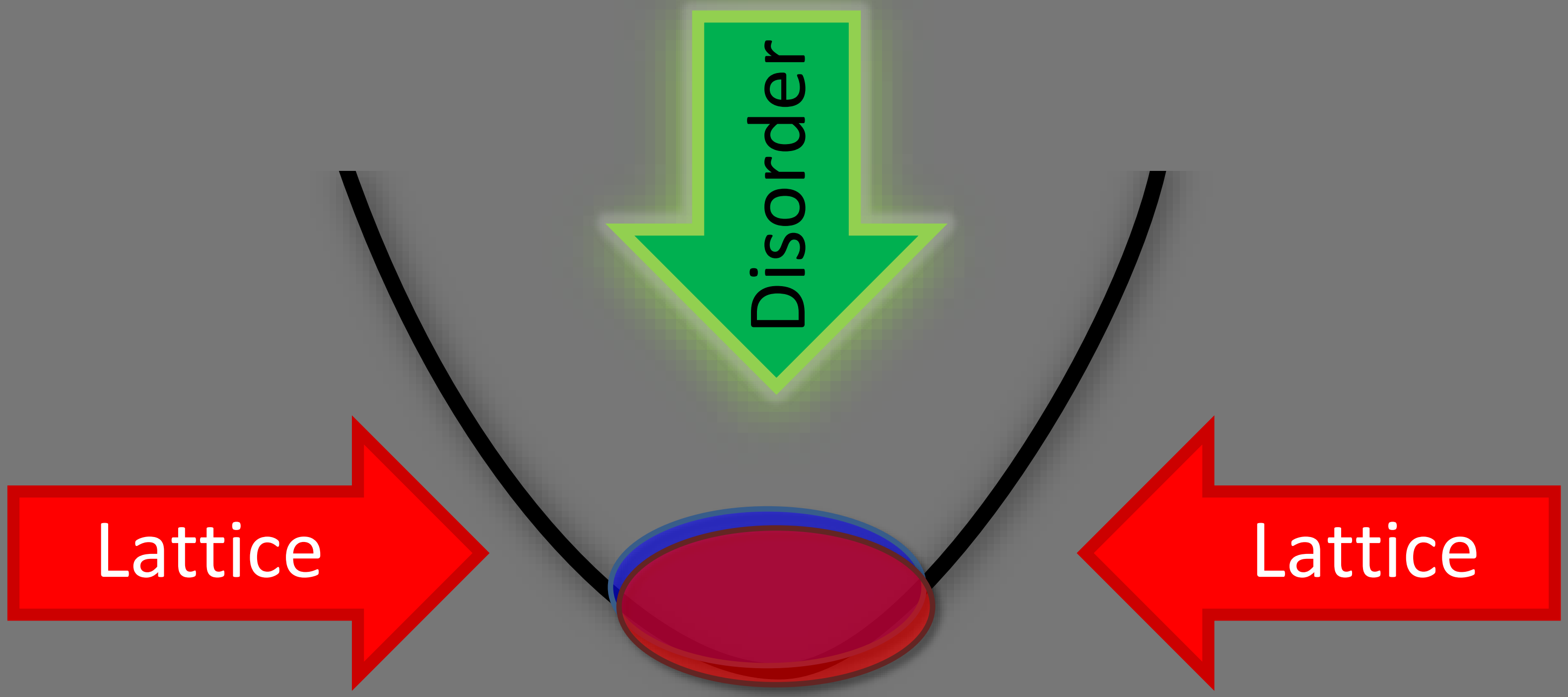
Varying energy density

Vary temperature *before* turning on the lattice



Varying energy density

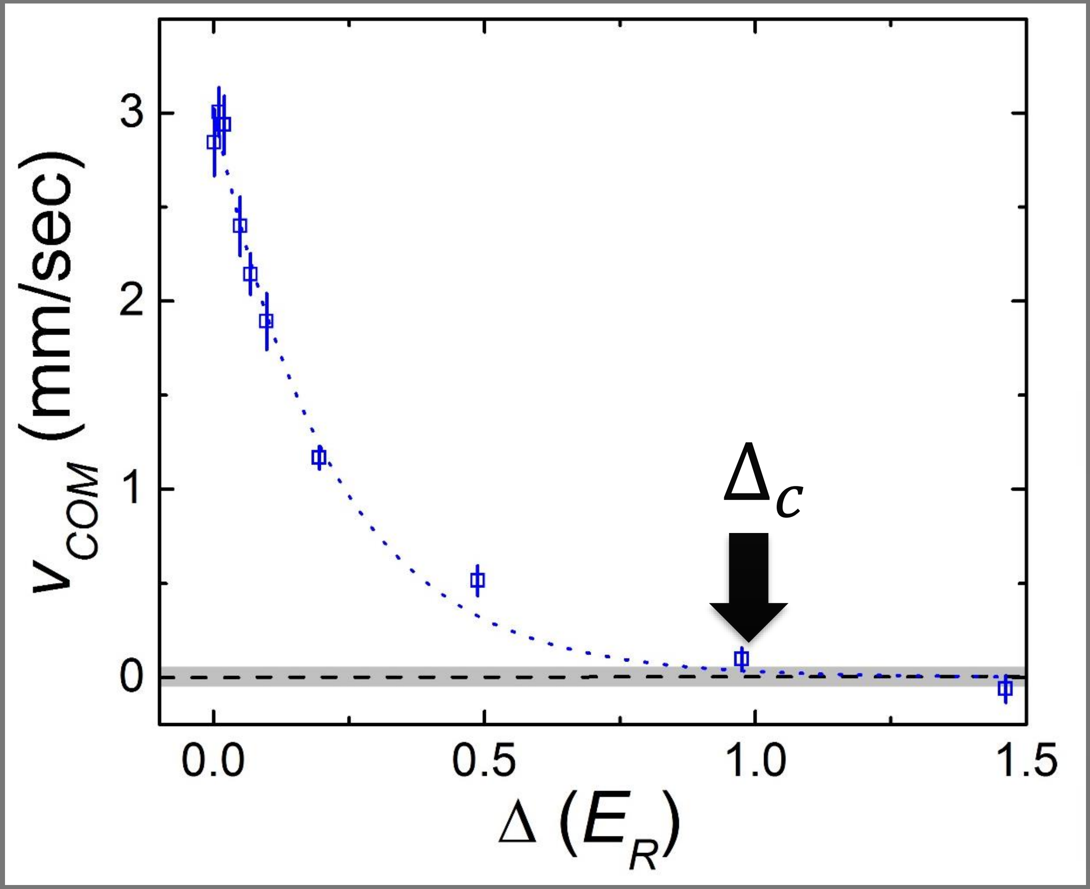
Vary temperature *before* turning on the lattice

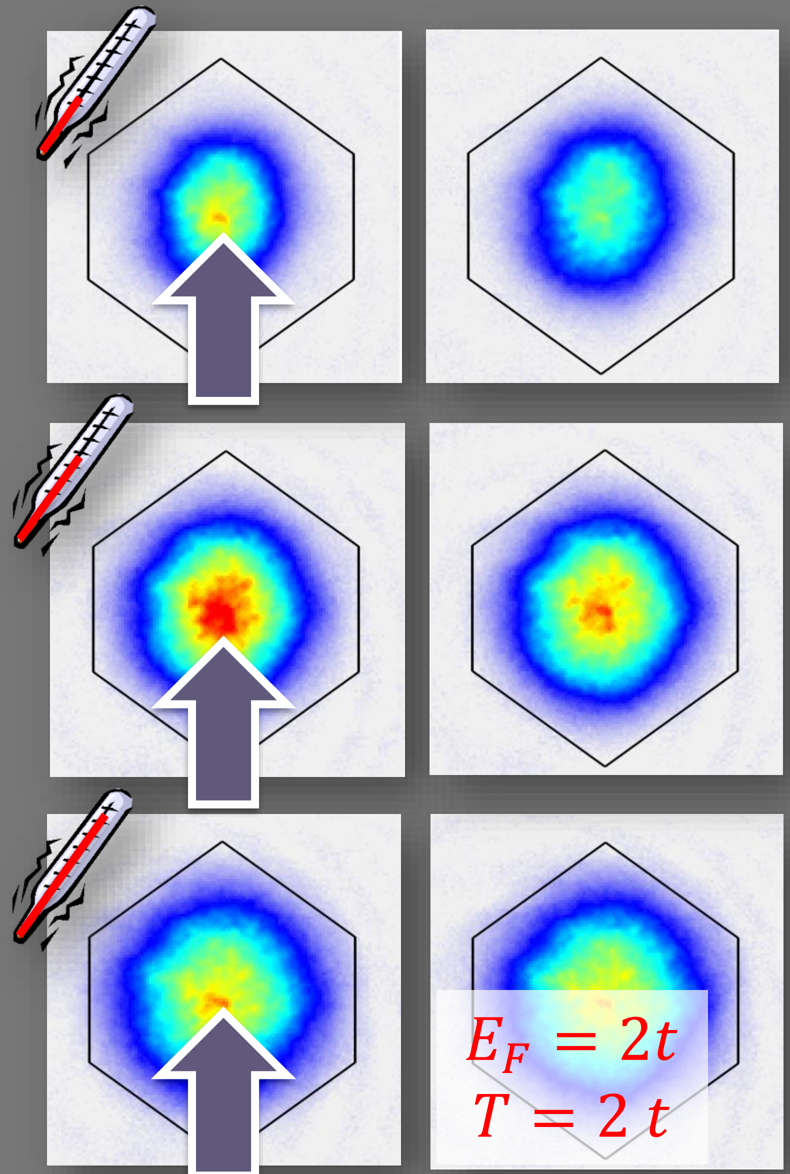


T/T_F sets S/N, energy density

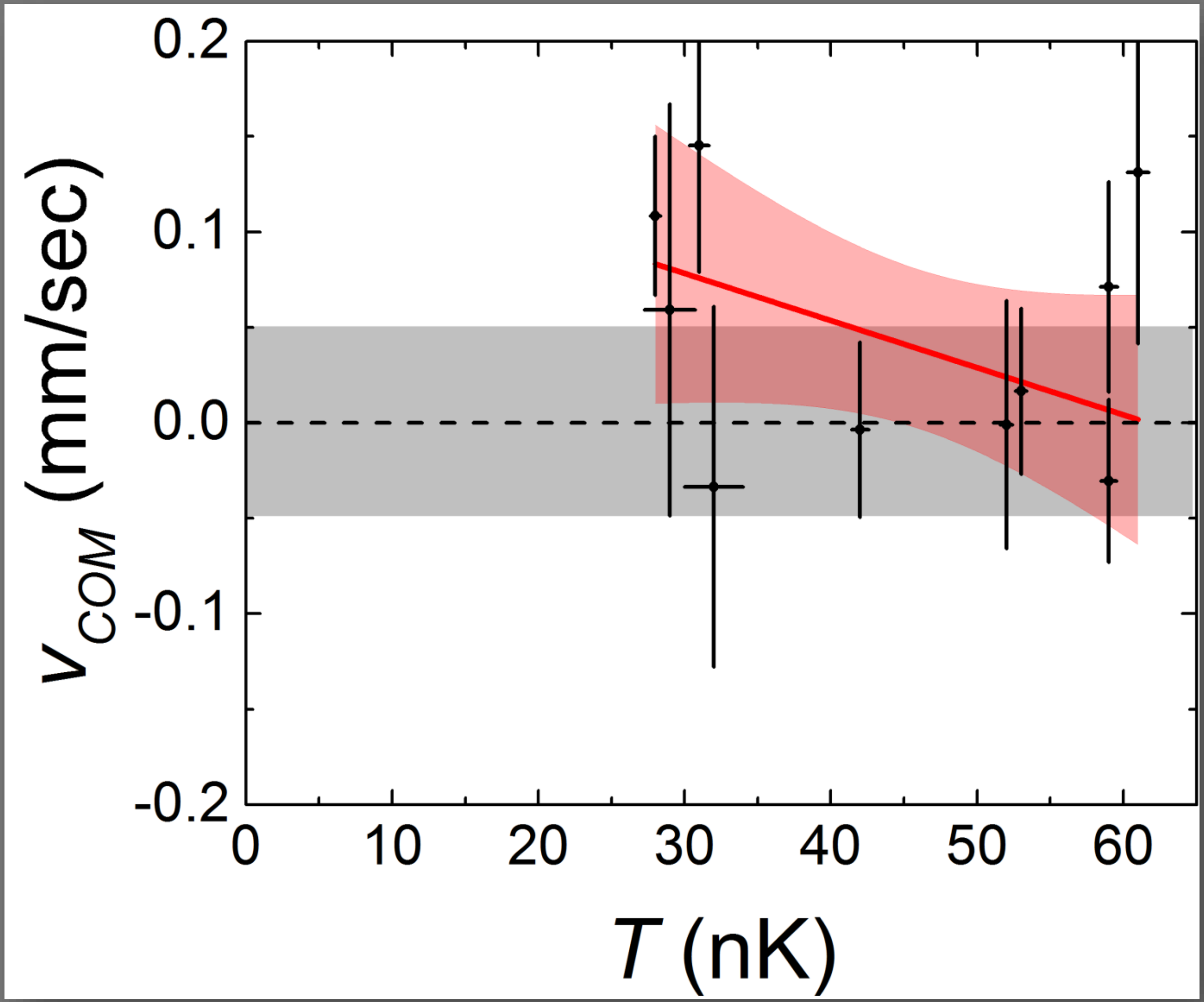
Temperature dependence

Fix $\Delta = \Delta_c, U = 4t$





Temperature dependence



An interacting insulator at $T > 0$!

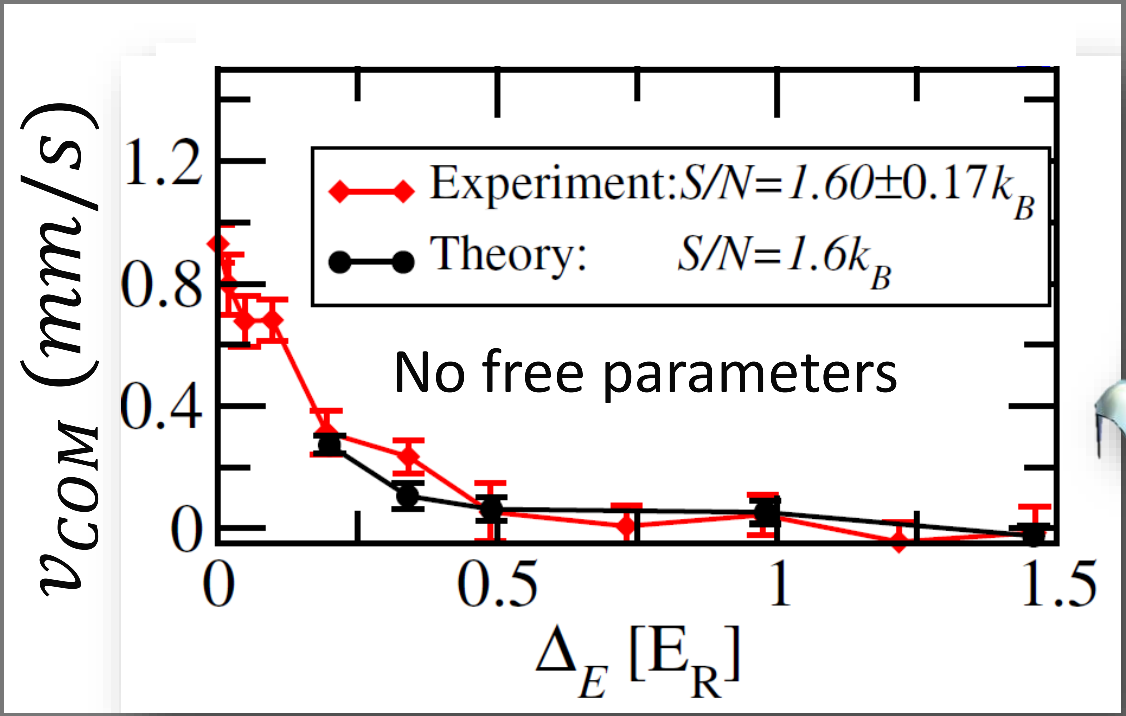
MBL predictions

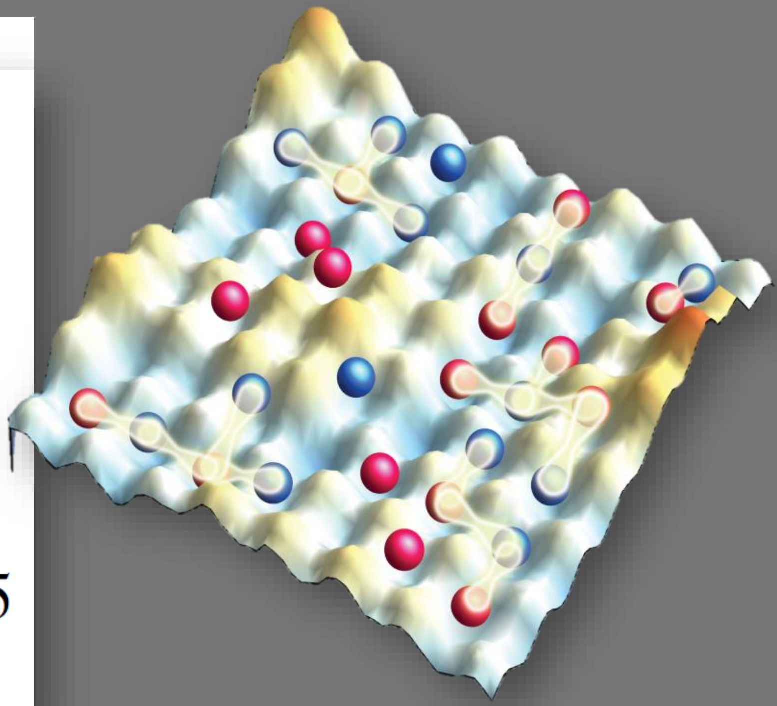
- Localization at $T > 0$
- Interaction-induced delocalization
- Localization across range of T

Phys. Rev. Lett. **114**, 083002 (2015)

Another recent theory development

Numerics from Vito Scarola (Virginia Tech)





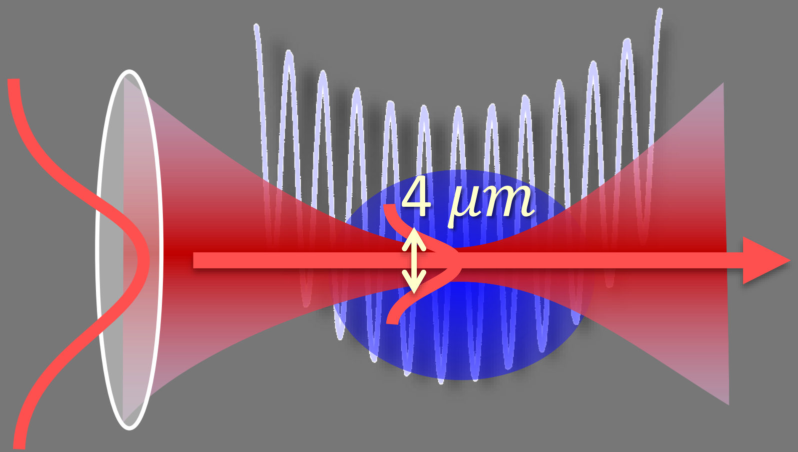
Anderson localization of Hubbard quasiparticles

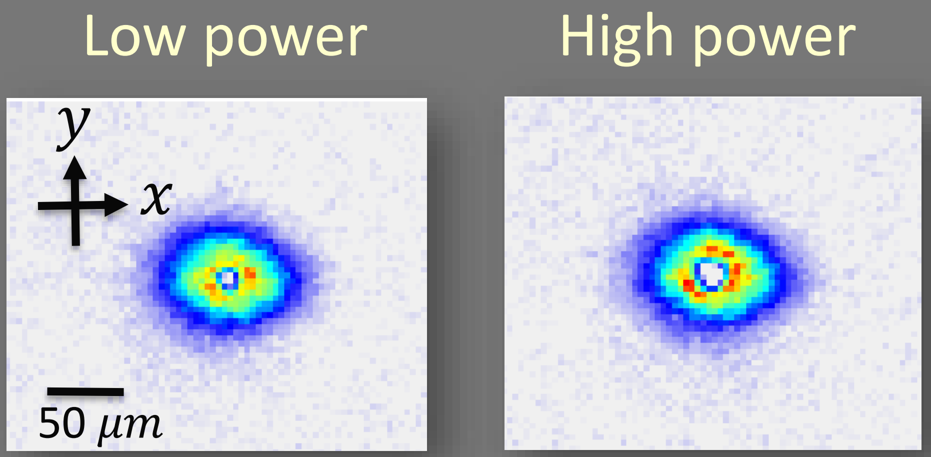
arXiv: 1503.07195 (2015)

(Local) Relaxation Dynamics

Density profile relaxation

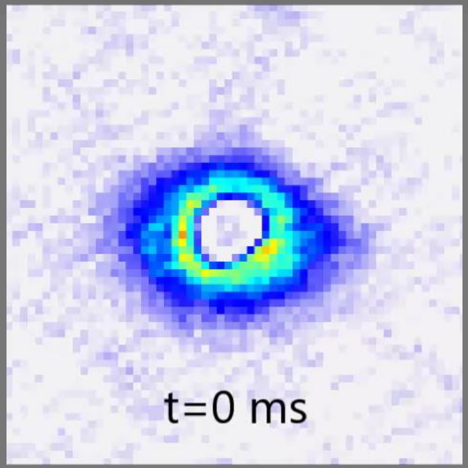
Create hole in gas



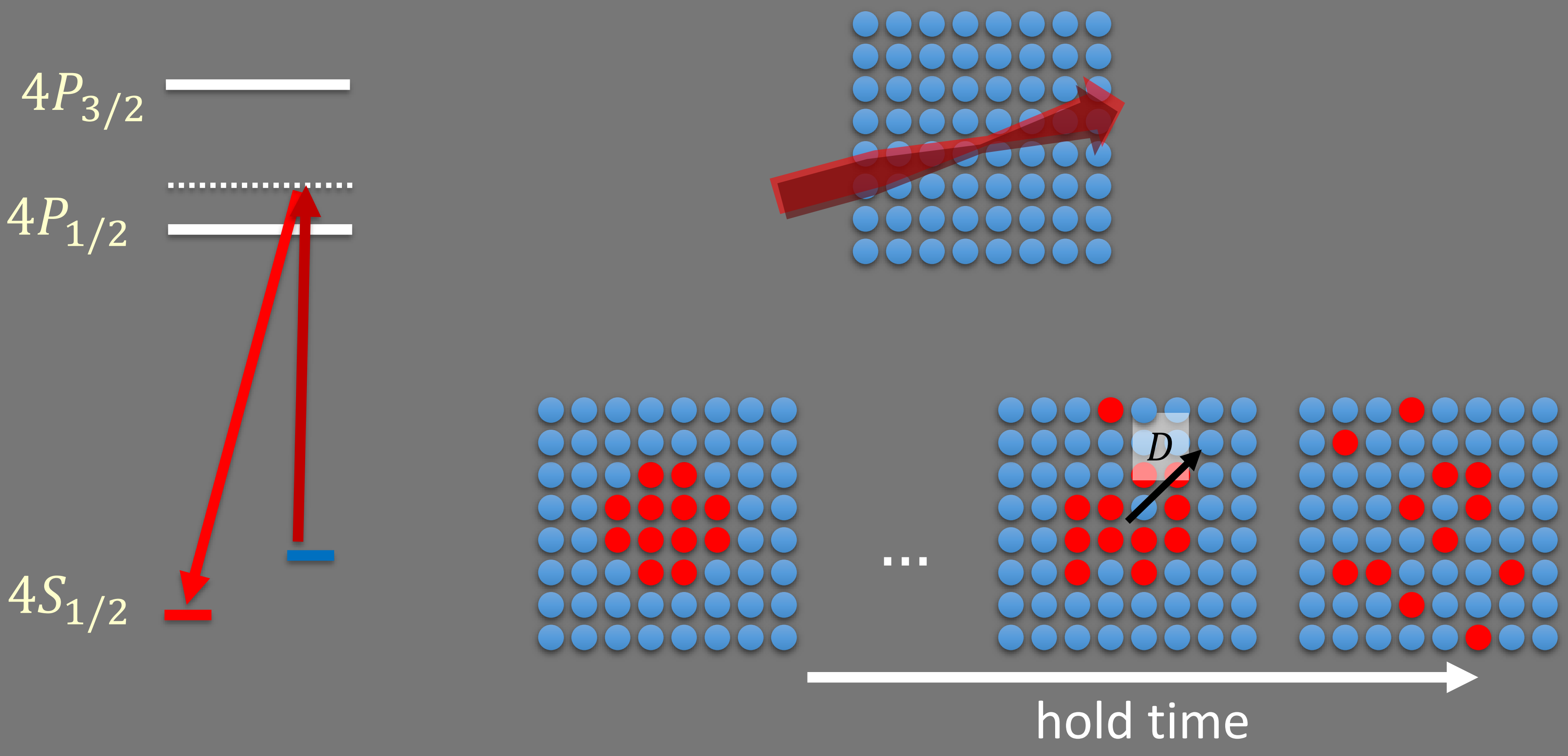


Watch dynamics of hole filling

Potential can also be attractive [Khemani]

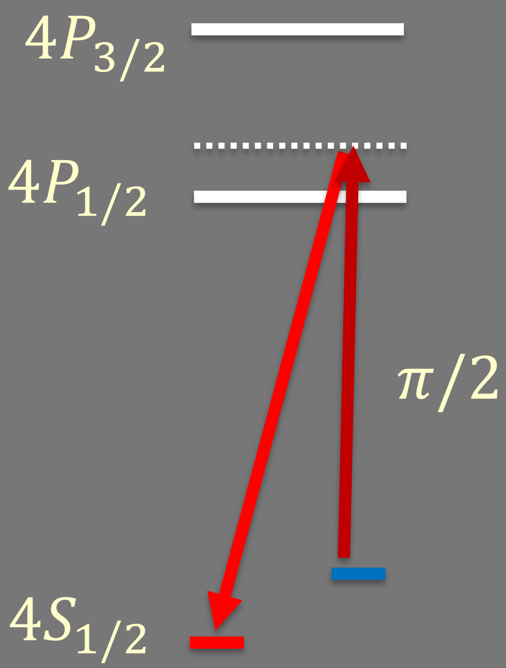


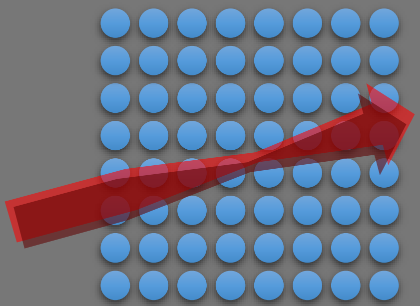
Spin relaxation & diffusion

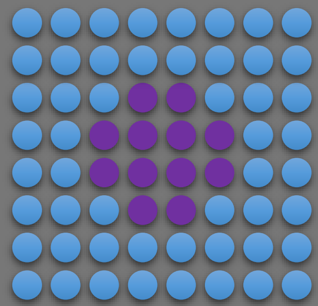


Add disorder…MBL apparent in this measure?

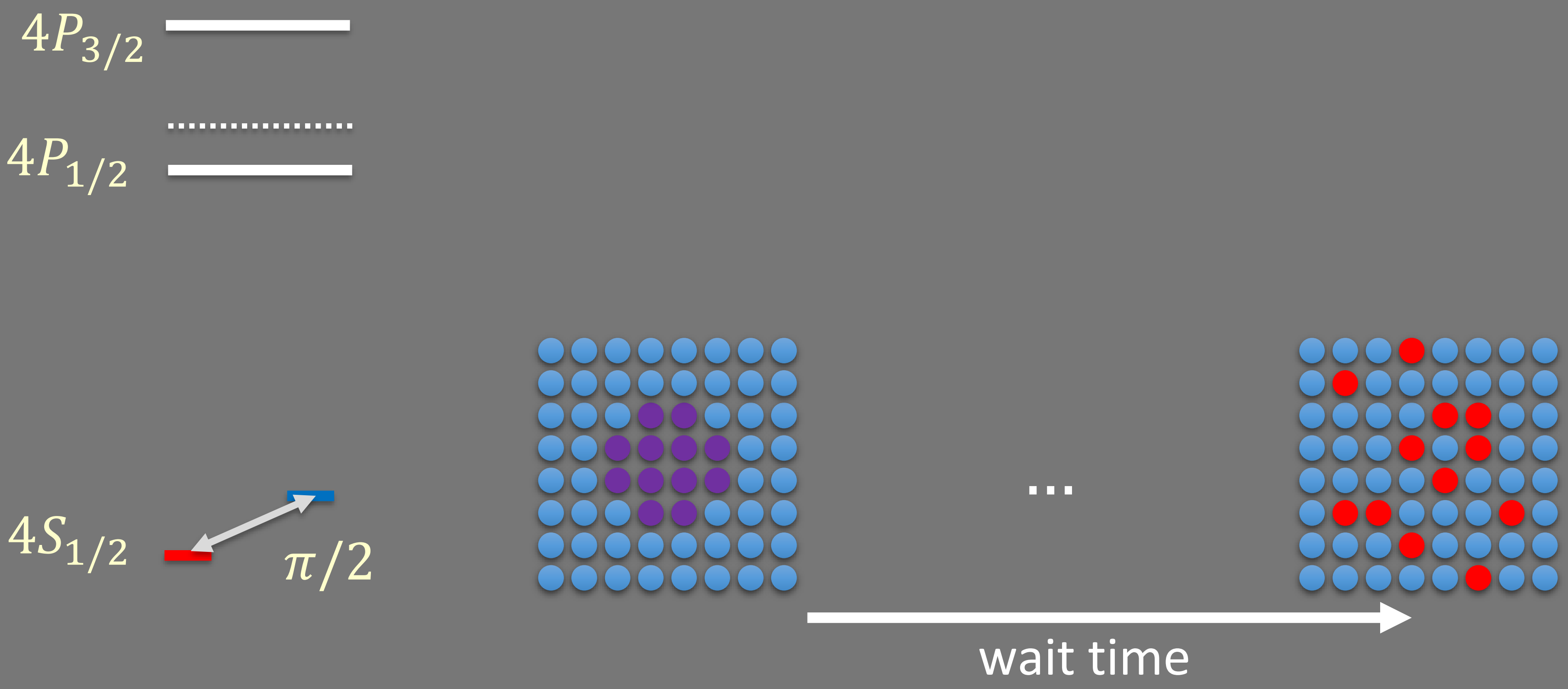
Local Ramsey experiment







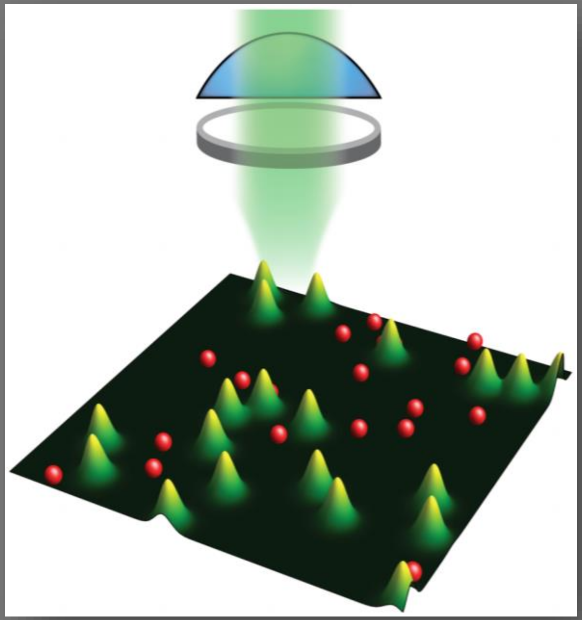
Local Ramsey / spectroscopy experiment



Add disorder…MBL apparent in this measure?

2D Localization: proposal

Phys. Rev. A 92, 023625 (2015)

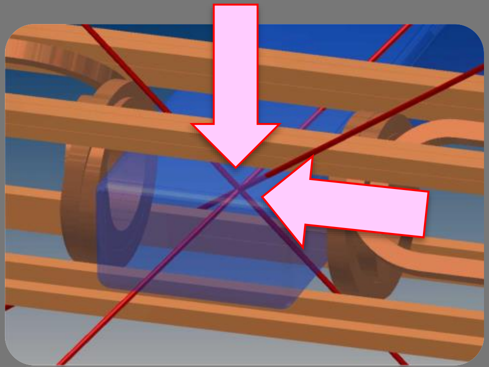


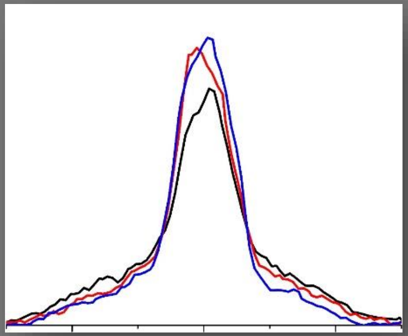
Point-like disorder:

- Avoid classical trapping
- Observable localization lengths

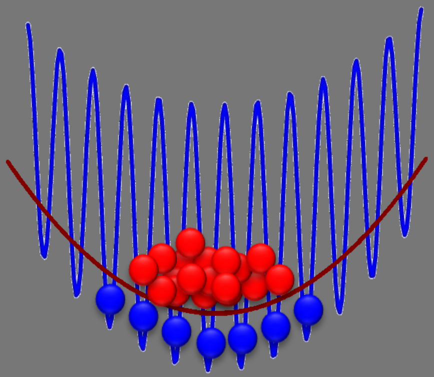
Renovated lab space; need equipment money

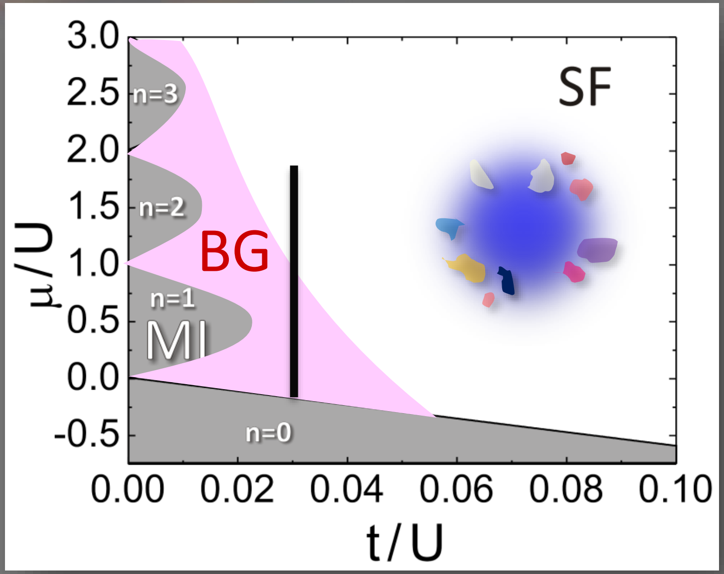
Other activities



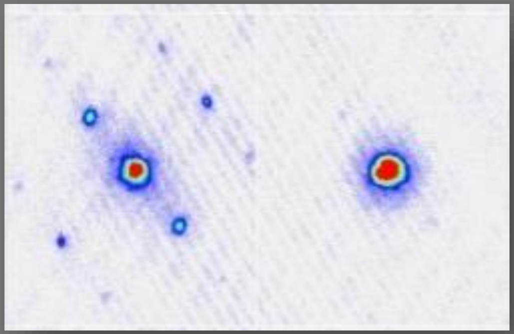


arXiv: 1503.07606 (2015)





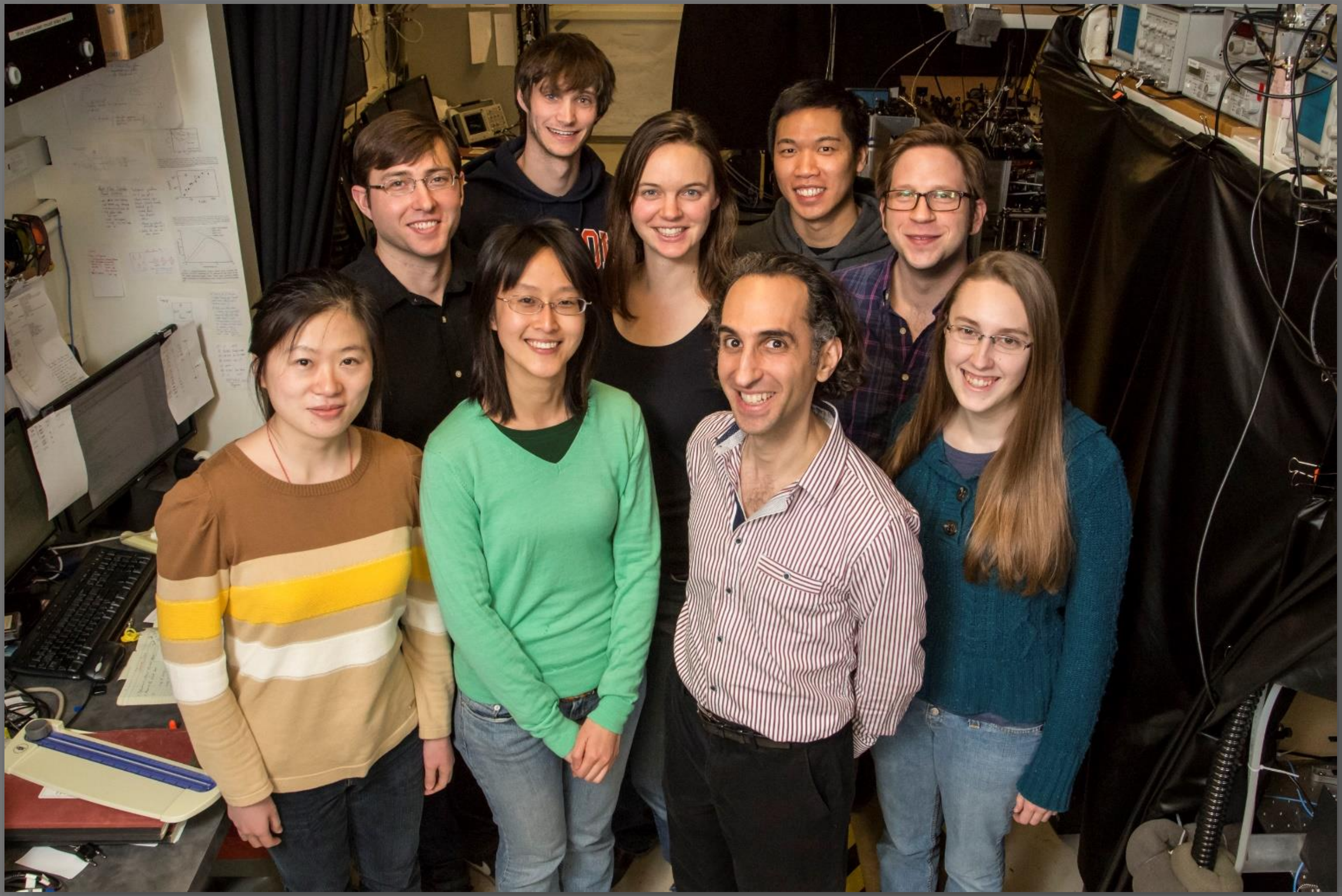
arXiv: 1502.02333 (2015)



PRL **111**, 063002 (2013);
PRA **90**, 0136012 (2014);
PRA **91**, 023625 (2015).

Cooling, Thermalization, Quantum Quenches, …

DeMarco group



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