The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1859-34

Summer School on Novel Quantum Phases and Non-Equilibrium Phenomena in Cold Atomic Gases

27 August - 7 September, 2007

Experiments on transport and disorder in the Bose-Hubbard model

Brian DeMarco

University of Illinois at Urbana-Champaign

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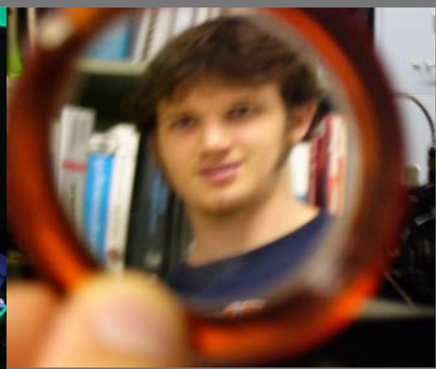
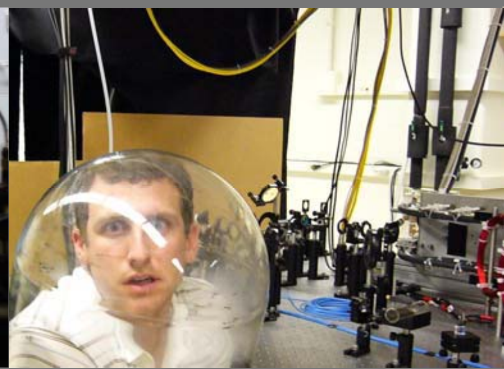
Matt White



David McKay



Matt Pasienski

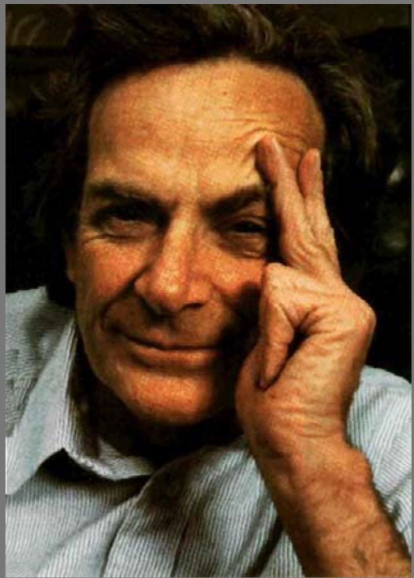
Lauren Aycock

Urbana-Champaign, IL

Outline

- Optical lattices for studying the Bose-Hubbard (BH) model
- Transport in the BH model
- Disorder in the BH model

Quantum simulation



"I want to talk about the possibility that there is to be an exact simulation, that the computer will do exactly the same as nature."

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

4. QUANTUM COMPUTERS—UNIVERSAL QUANTUM SIMULATORS

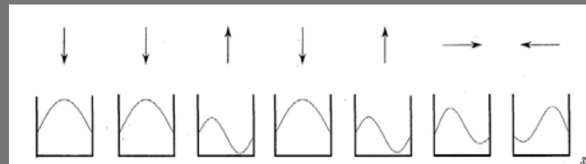
The first branch, one you might call a side-remark, is, Can you do it with a new kind of computer—a quantum computer? (I'll come back to the other branch in a moment.) Now it turns out, as far as I can tell, that you can simulate this with a quantum system, with quantum computer elements. It's not a Turing machine, but a machine of a different kind. If we disregard the continuity of space and make it discrete, and so on, as an approximation (the same way as we allowed ourselves in the classical case), it does seem to

RESEARCH ARTICLES

Universal Quantum Simulators

Seth Lloyd

Feynman's 1982 conjecture, that quantum computers can be programmed to simulate any local quantum system, is shown to be correct.



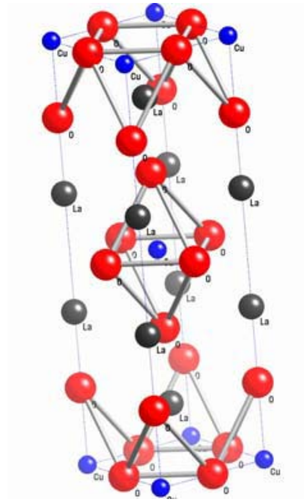
Make a quantum system that you can control and probe perfectly behave like one that you want to study

Our goal

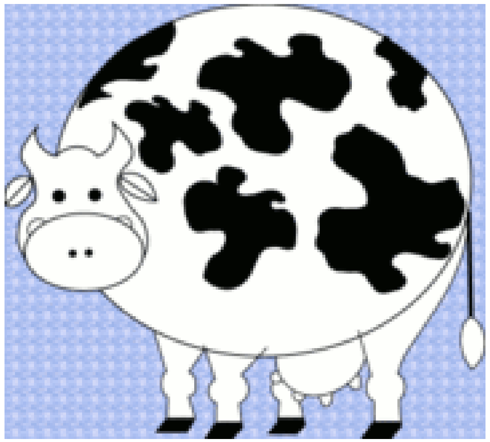
Realize quantum simulation for ~100,000 strongly interacting quantum particles (spins, bosons, fermions...)

Models

Cow

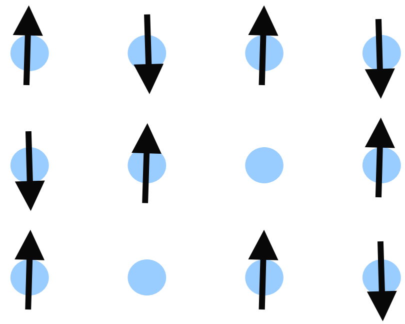


High-T_c superconducting cuprates



Spherical cow

Phenomenology



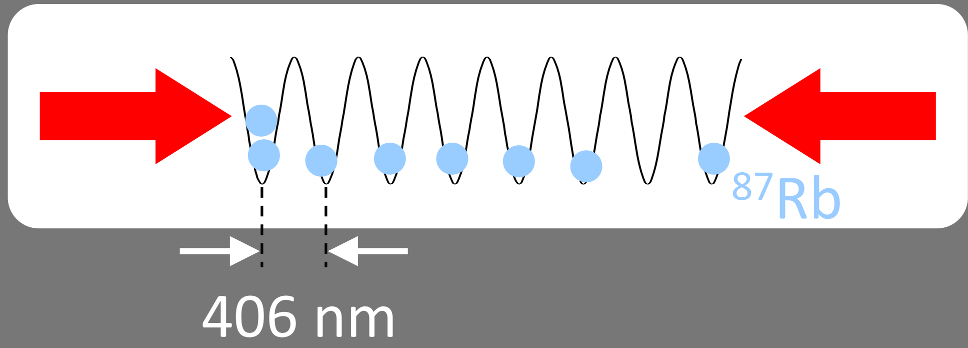
Hubbard model

milk / day / cow?

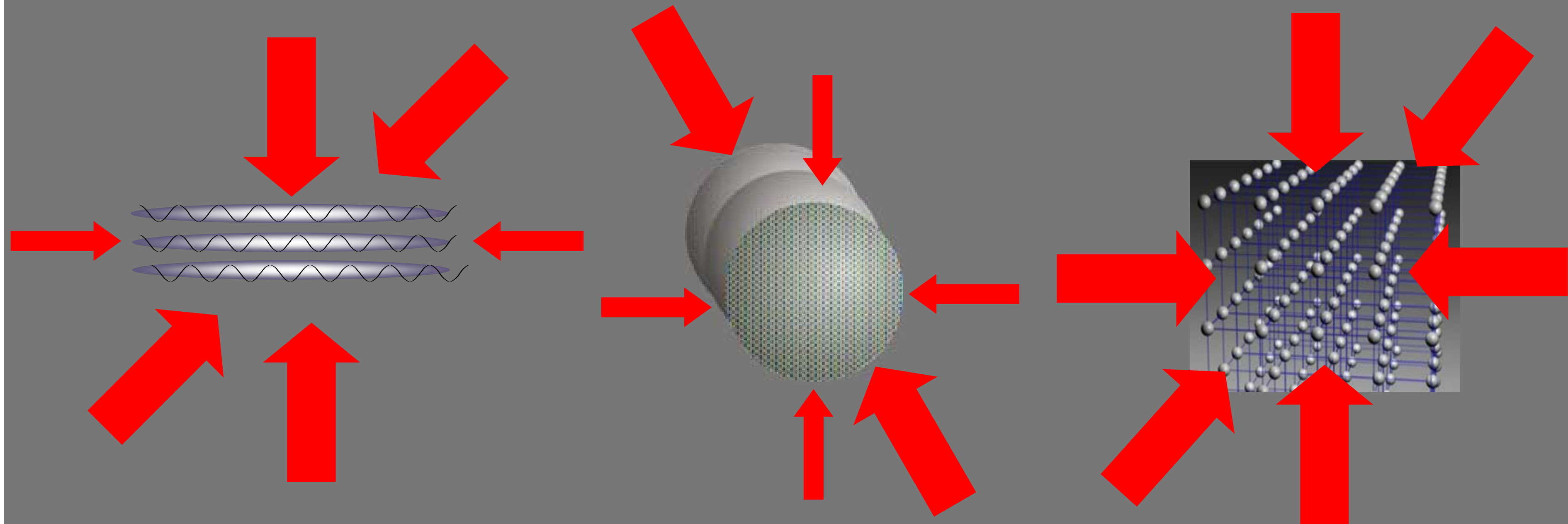
d-wave superconductivity?

Optical lattices

Atoms confined by periodic potential arising from intensity and/or polarization gradients

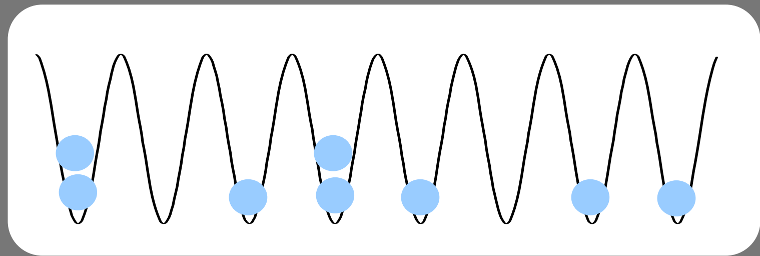


Tunneling and interaction energy controlled by lattice depth



Bose-Hubbard (BH) model

- Bosons (^{87}Rb, ^{4}He…) in a periodic potential….



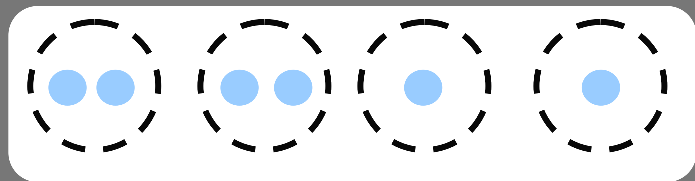
$V_0 = sE_R$

$E_R = 170$ nK

$$V_0\left[\cos^2\left(\pi \,{}^{x}\!/_{d}\right) + \cos^2\left(\pi \,{}^{y}\!/_{d}\right) + \cos^2\left(\pi \,{}^{z}\!/_{d}\right)\right]$$

- …in the tight binding limit
  (n-n tunneling and on-site interactions only)… $s \gtrsim 4$

- …are *one* realization of the BH model

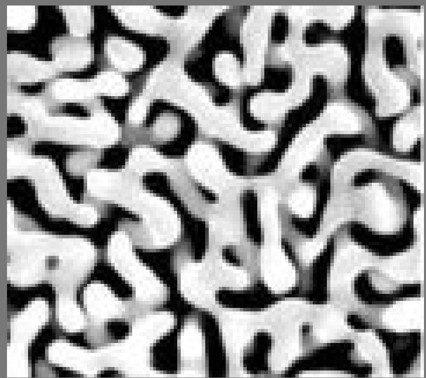


$$H = -t\sum_{\langle ij\rangle}\left(b_i^\dagger b_j + b_j^\dagger b_i\right) + U\sum_i n_i\left(n_i - 1\right)$$

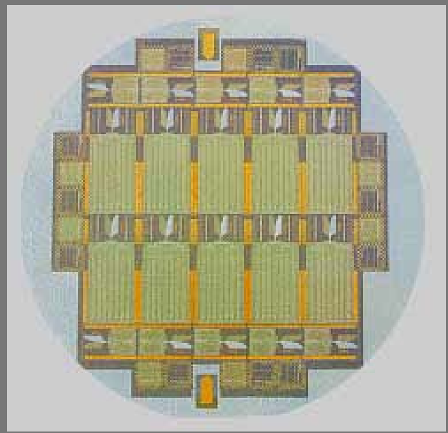
tunneling (kinetic + potential) | interaction

BH model applications

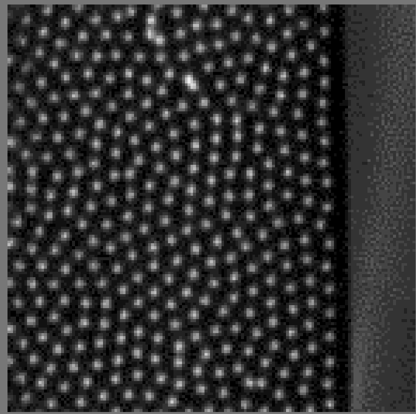
Supersolids (?)



Superfluids
in porous media



Josephson-
junction arrays



Thin “super-
conducting”
films

And many other physical systems…

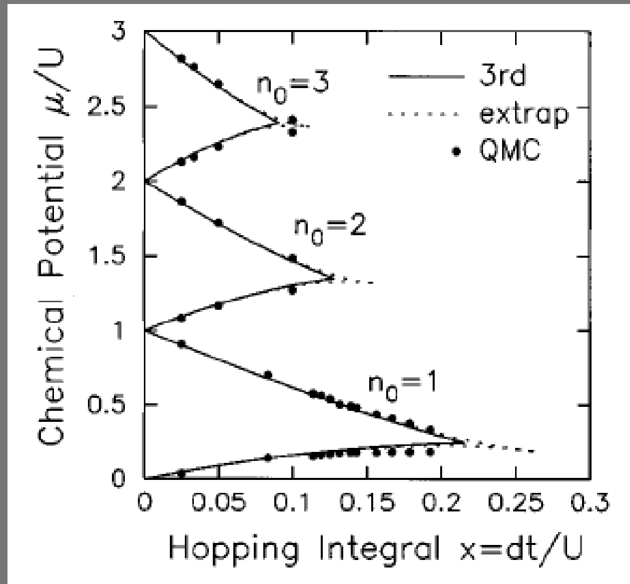
Known and unknown BH model physics

Full properties of BH model not exactly solvable using any known method (theory, digital simulation)

Ground state phase diagram for "pure" model well understood

Freericks & Monien, PRB **53**, 2691 (1996)

more recent numerical work: PRA **70**, 053615 (2004)

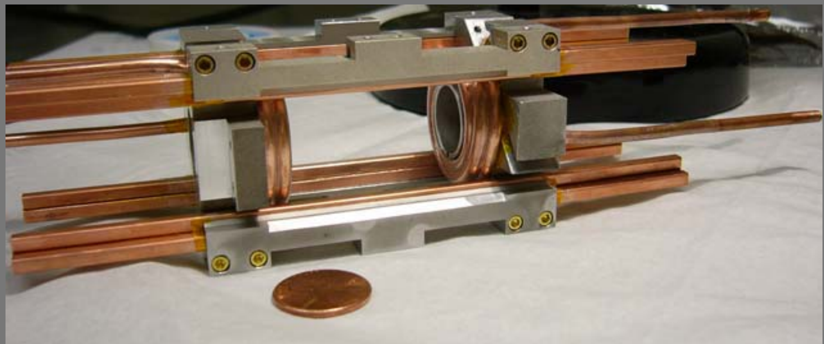


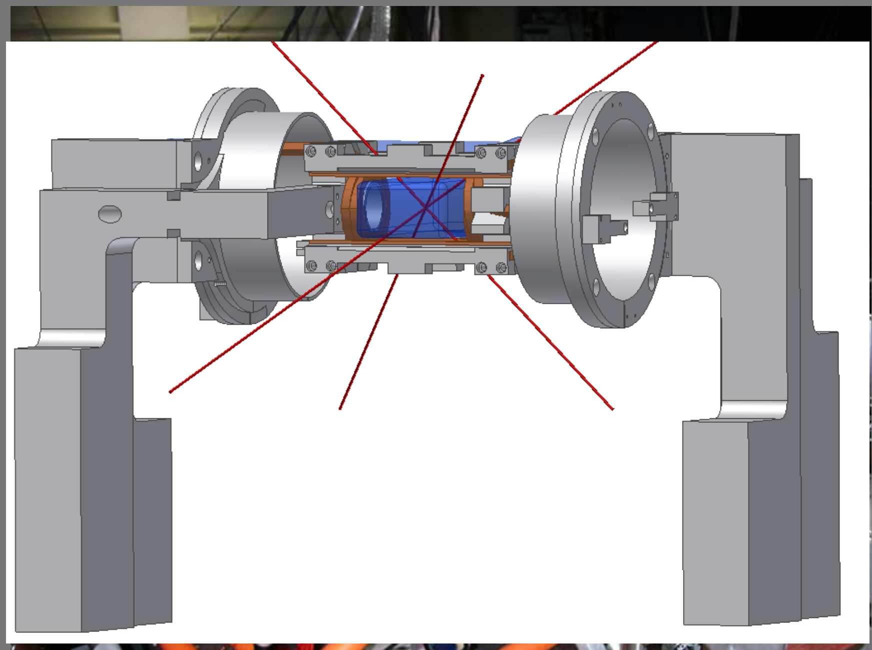
Lack of consensus on:

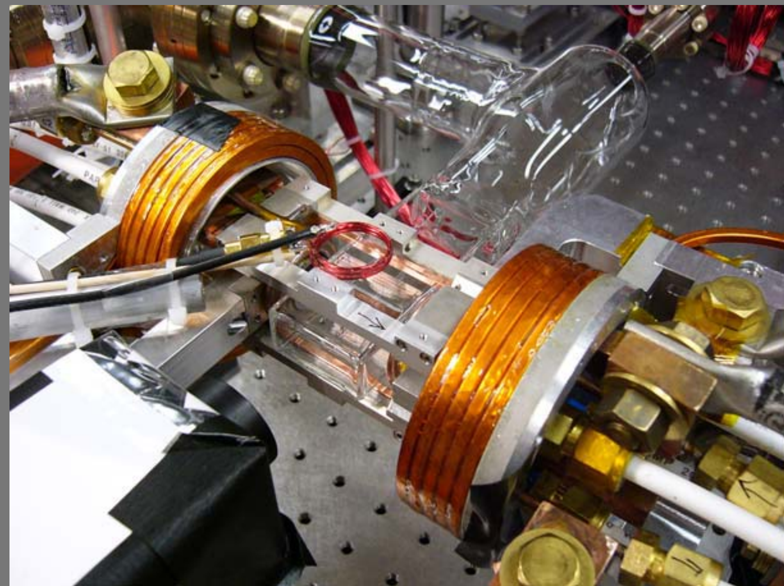
- transport properties of pure and disordered models
- ground state phase diagram of disordered model

Our experiment

Better than f/1 optical access along 5 directions



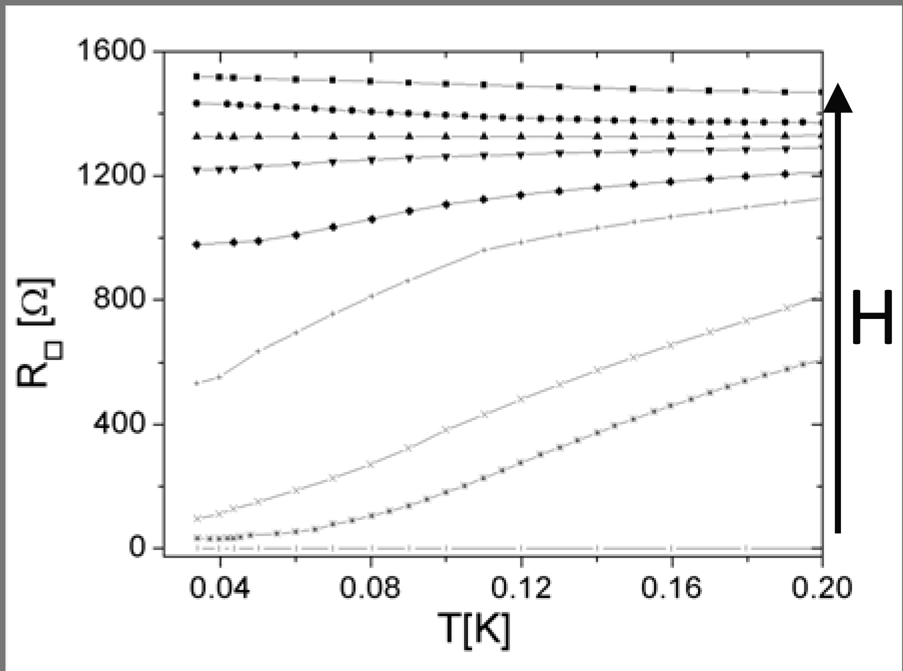




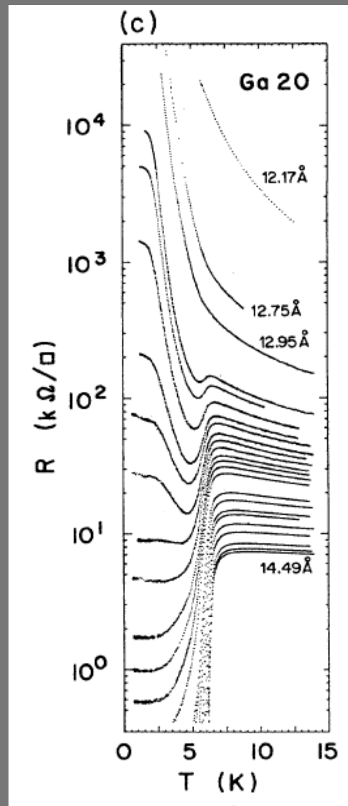
Transport measurements

Measurements in solids: linear response

$$R \propto \frac{V}{I}$$



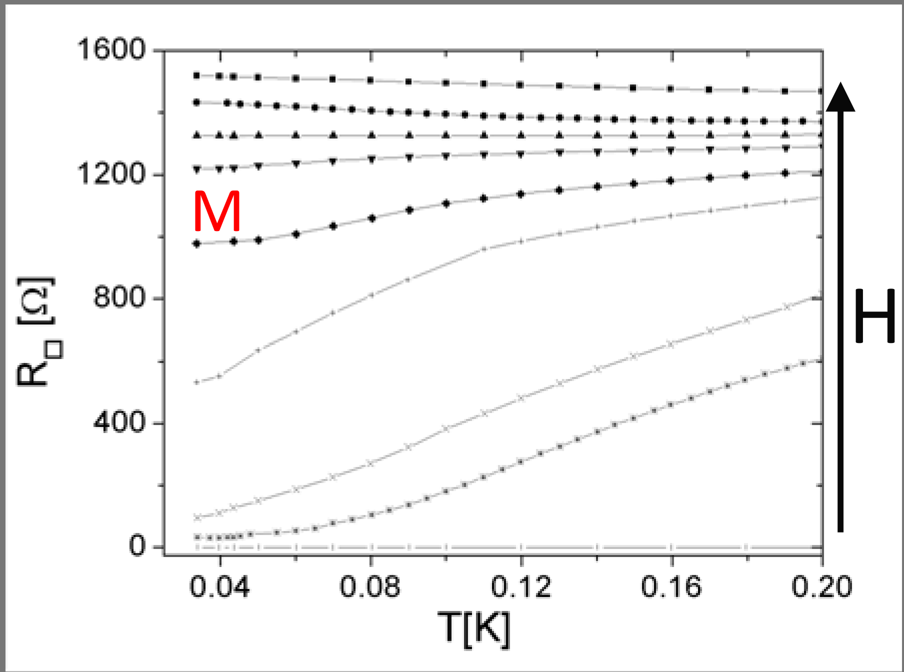
MoGe films



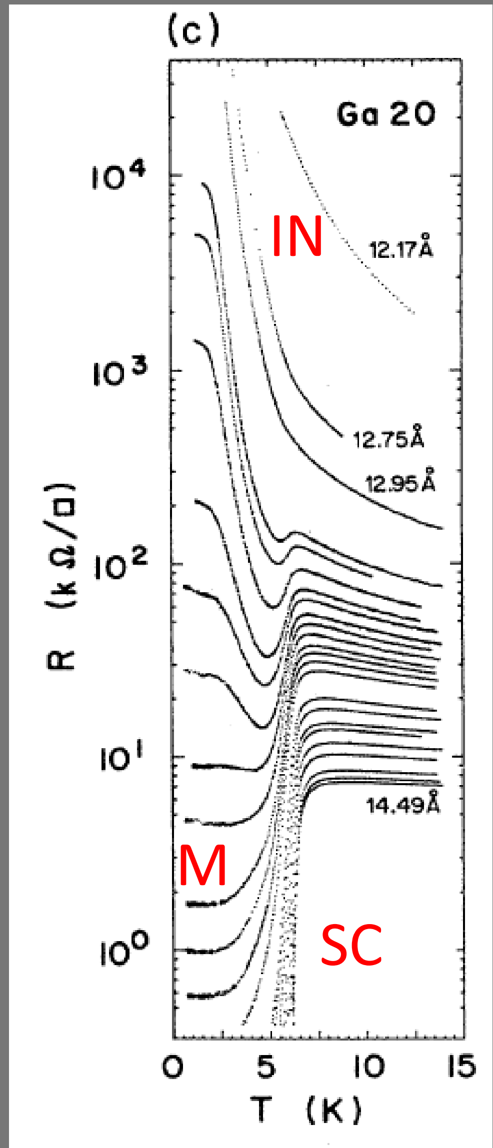
thickness

sputtered Ga films

Transport measurements



MoGe films



thickness

sputtered Ga films

SC: superconductor $R \to 0, T \to 0$

M: metal $R \to (0, \infty), T \to 0$

IN: insulator $R \to \infty, T \to 0$

How to explain "Bose-metal?"

Controversy…useful reviews:

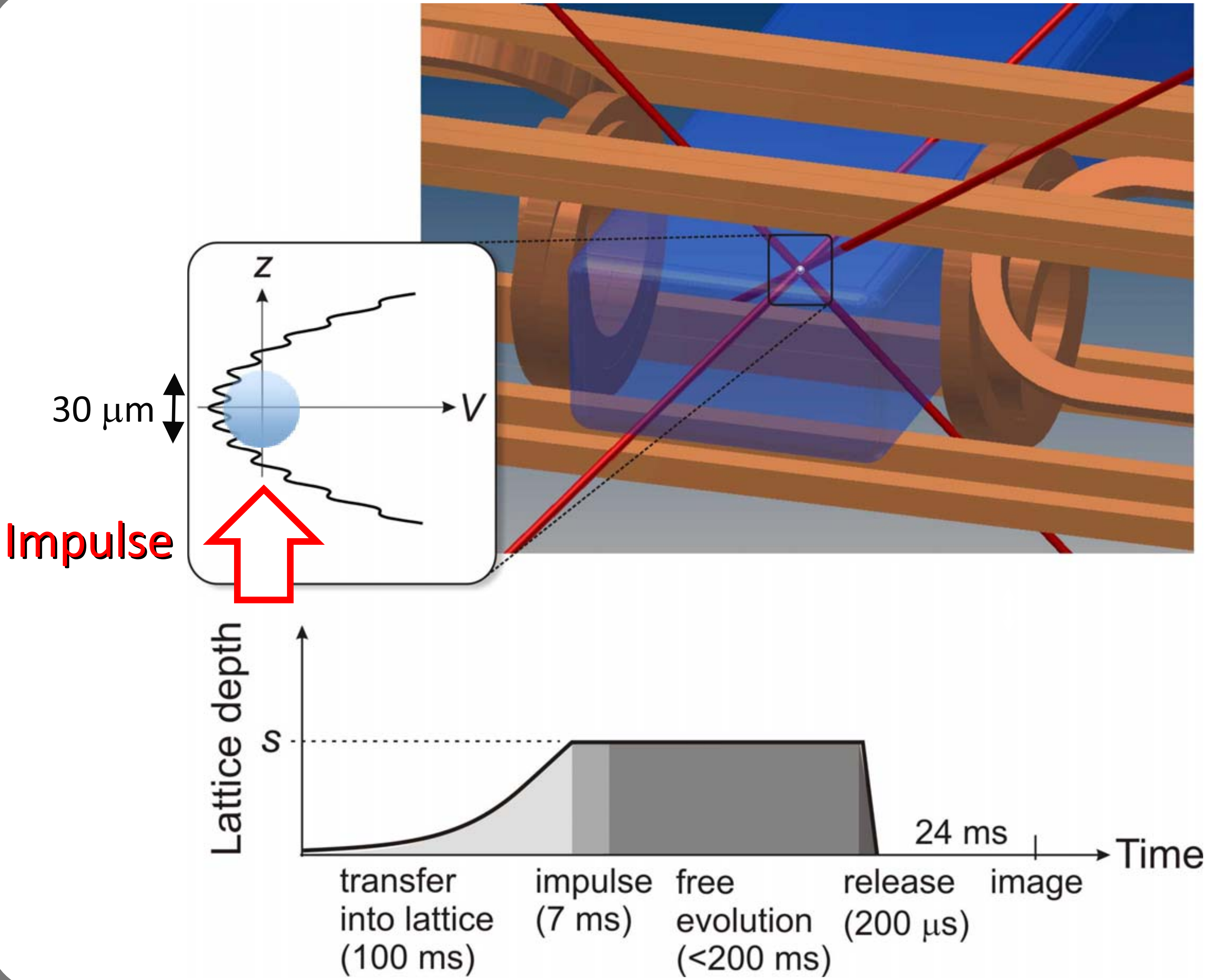
- Mason, *Superconductor-Metal-Insulator Transitions in Two Dimensions*, Ph.D. dissertation, 2001.
- Goldman, *Superconductor-insulator transitions in the two-dimensional limit,* Physica E **18**, 1-6 (2003).
- Phillips and Dalidovich, *The elusive Bose metal.* Science, **302**, 243-247 (2003).
- Goldman and Markovic, *Superconductor-Insulator Transitions in the Two-Dimensional Limit.* Physics Today, Nov., 39-44 (1998).

Belief: pairs are unbroken in metallic state

theory using variants of BH model!

- Does BH phenomenology agree with data?
- Is disorder required (i.e, universal conductance not always right)?
- Does BH model include intrinsic dissipation / Bose-metal?

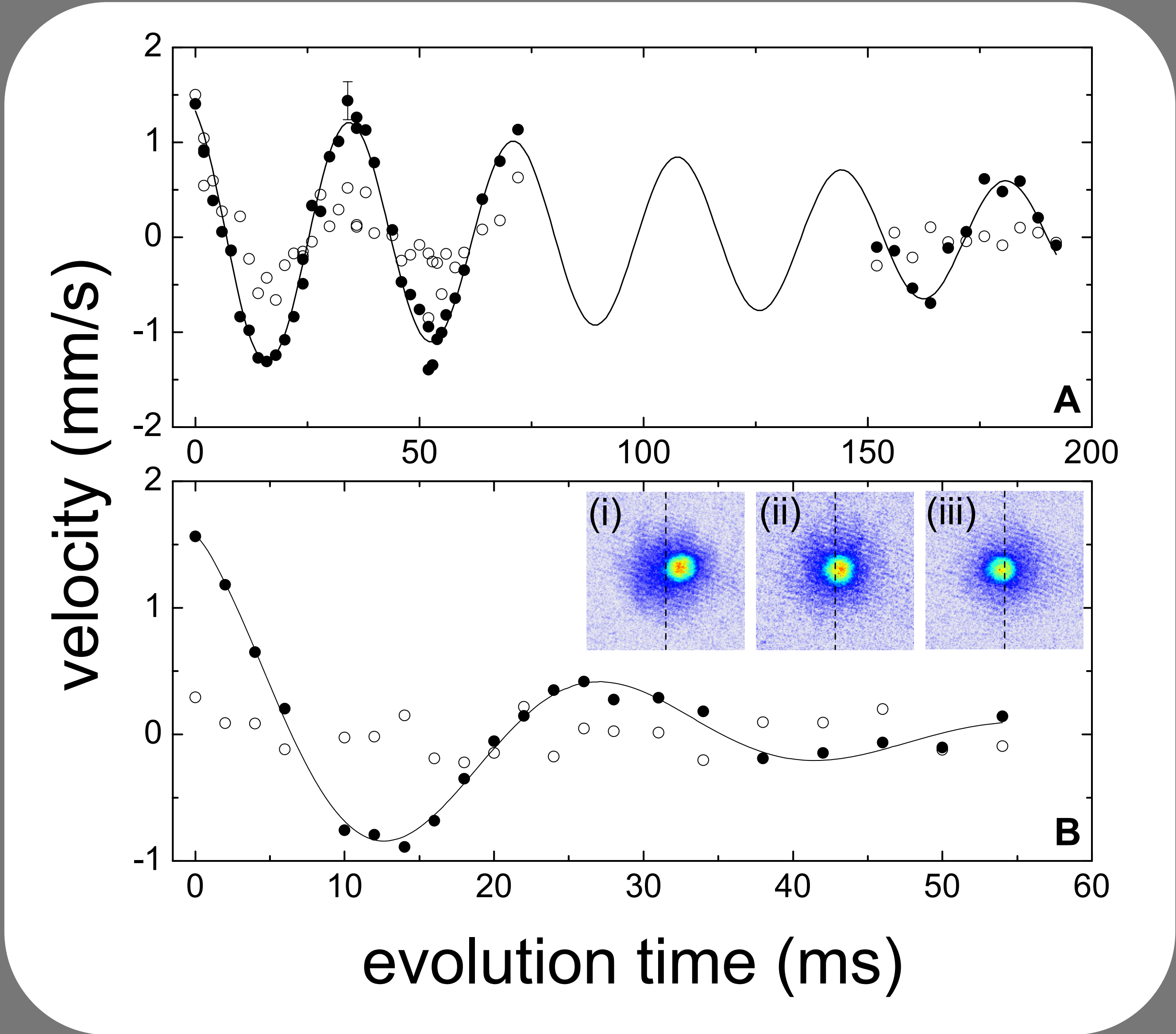
Transport in 3D



Motion

Quasi-momentum distribution

Observable: velocity



2 E_R
T/T_c=0.85(2)
N_0=8(1) × 10^5

6 E_R
T/T_c=0.93(1)
N_0=2.7(6) × 10^5

What are we seeing?

This is not the dynamic or Landau instability!

- no excitations reminiscent of LENS data
- no significant change in BEC fraction
- low velocity ($v \lesssim 1.5$ mm/s; inflection point=2.6 mm/s) / linear response

Previous work: BH transport in 1D (NIST), BH dynamical instability in 1,2,3D (Ketterle), no systematic study of temperature

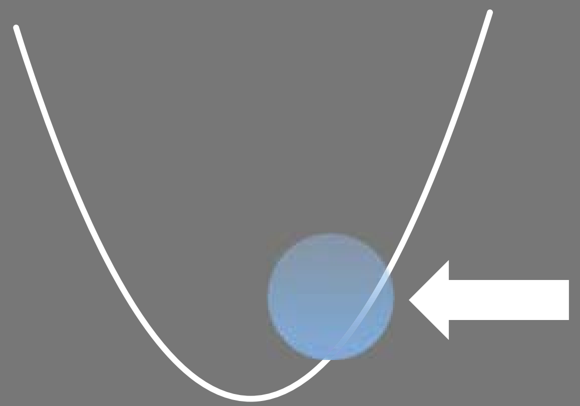
Damped harmonic oscillator

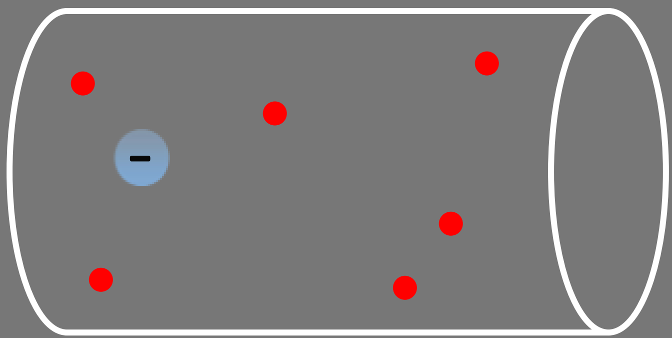
Treat as damped harmonic oscillator

$$m^{*}\ddot{z} = -2m^{*}\gamma\dot{z} - kz$$

Restoring force

Friction force





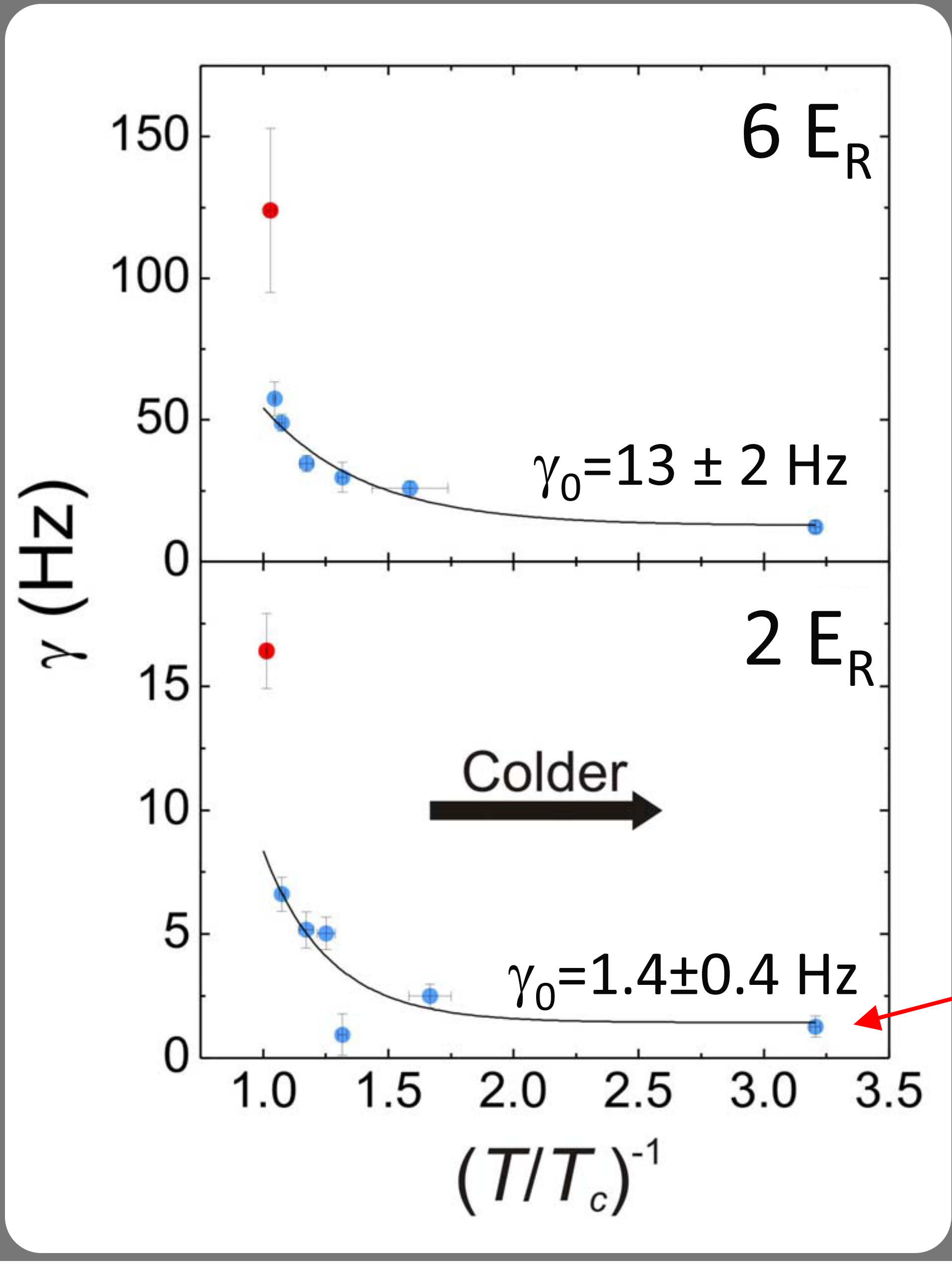
$$F = -kz$$

Just like the Drude model…

$$F = \frac{\Delta p}{\Delta t} = \frac{mv}{\tau} = -ne^{2}\rho\dot{z}$$

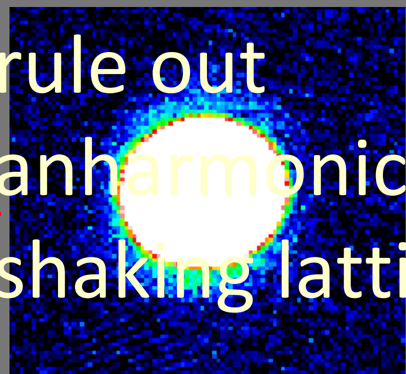
…of electrical resistance

Temperature dependence



Fit to model of thermally-activated damping:

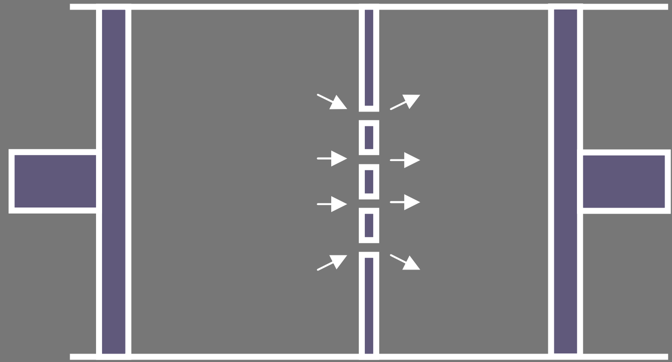
$$\gamma = \gamma_0 + \gamma_\infty e^{-\Delta E/(T/T_c)}$$



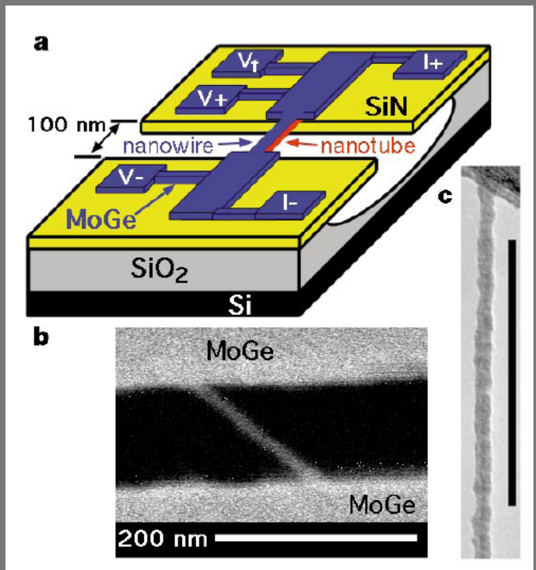
rule out anharmonicity, shaking lattice, …

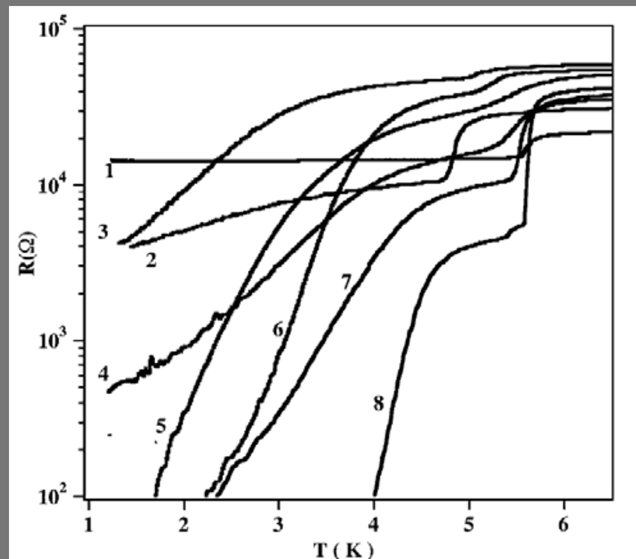
Phase slips

Packard group Helium whistle

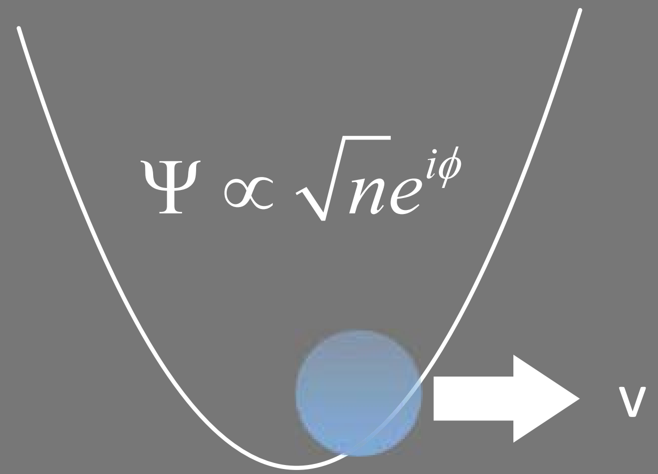


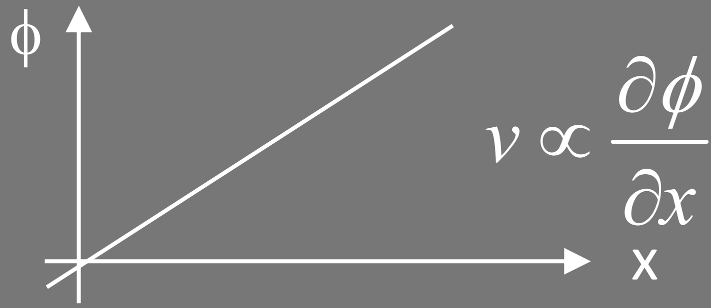
Bezryadin / Tinkham group nanowires





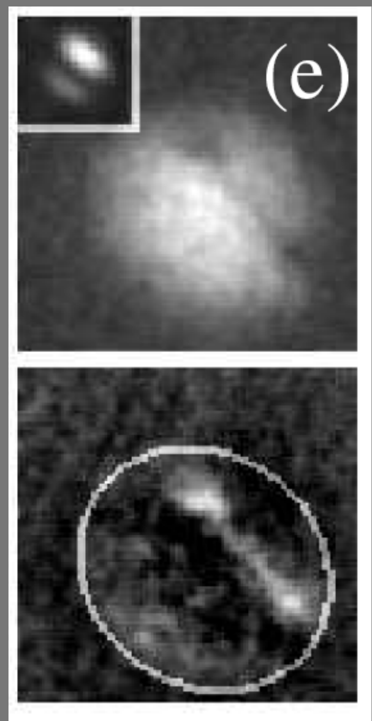
Phase slips: Langer and Fisher, 1967



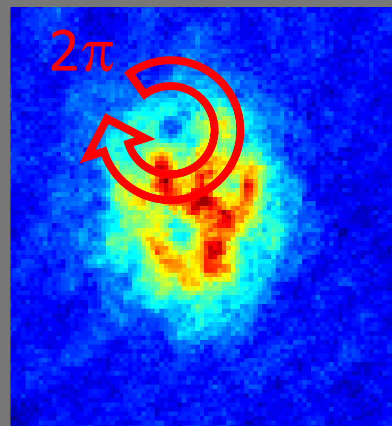


courtesy of Goldbart group

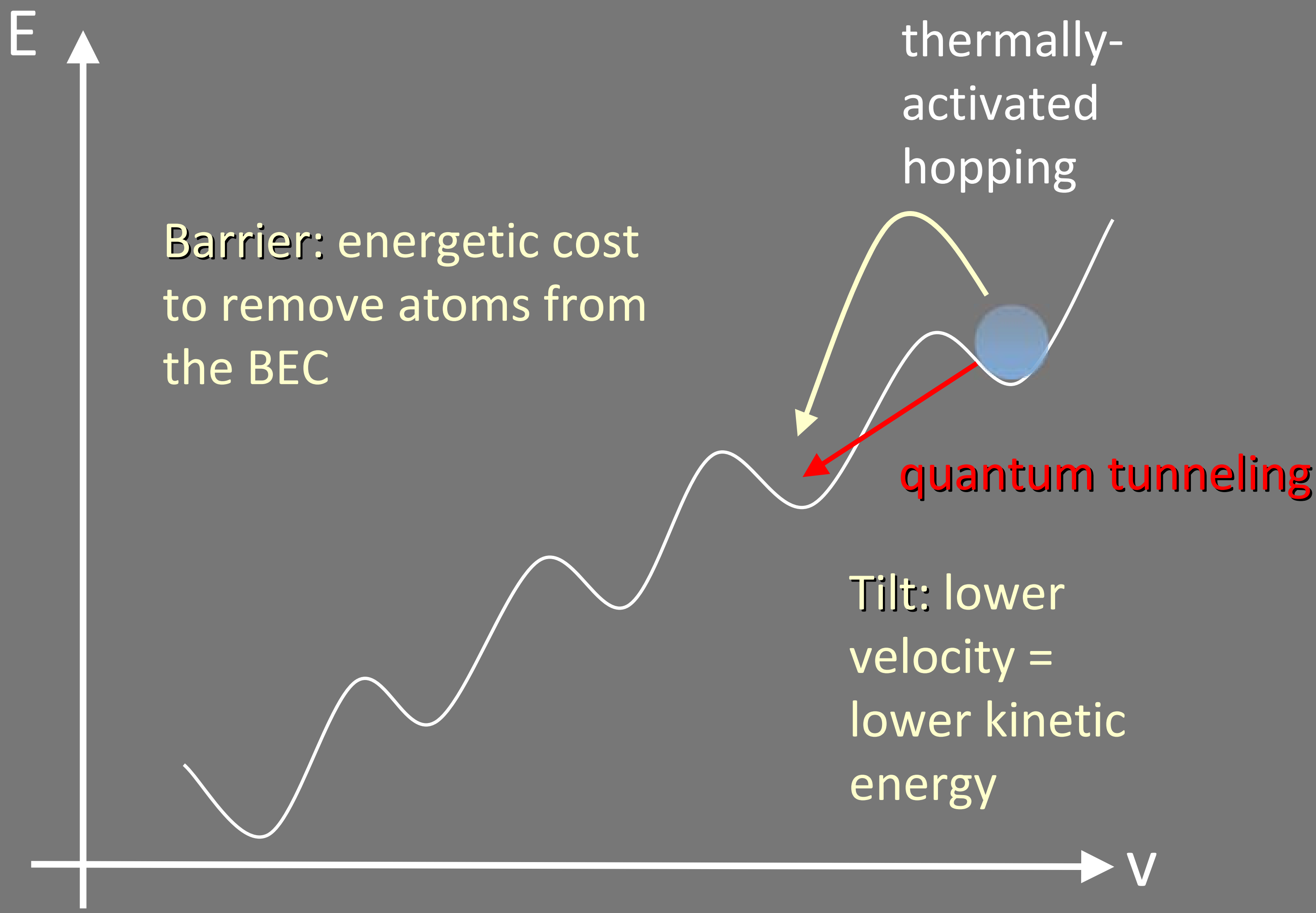
What if a vortex or vortex ring nucleates and moves across the BEC?



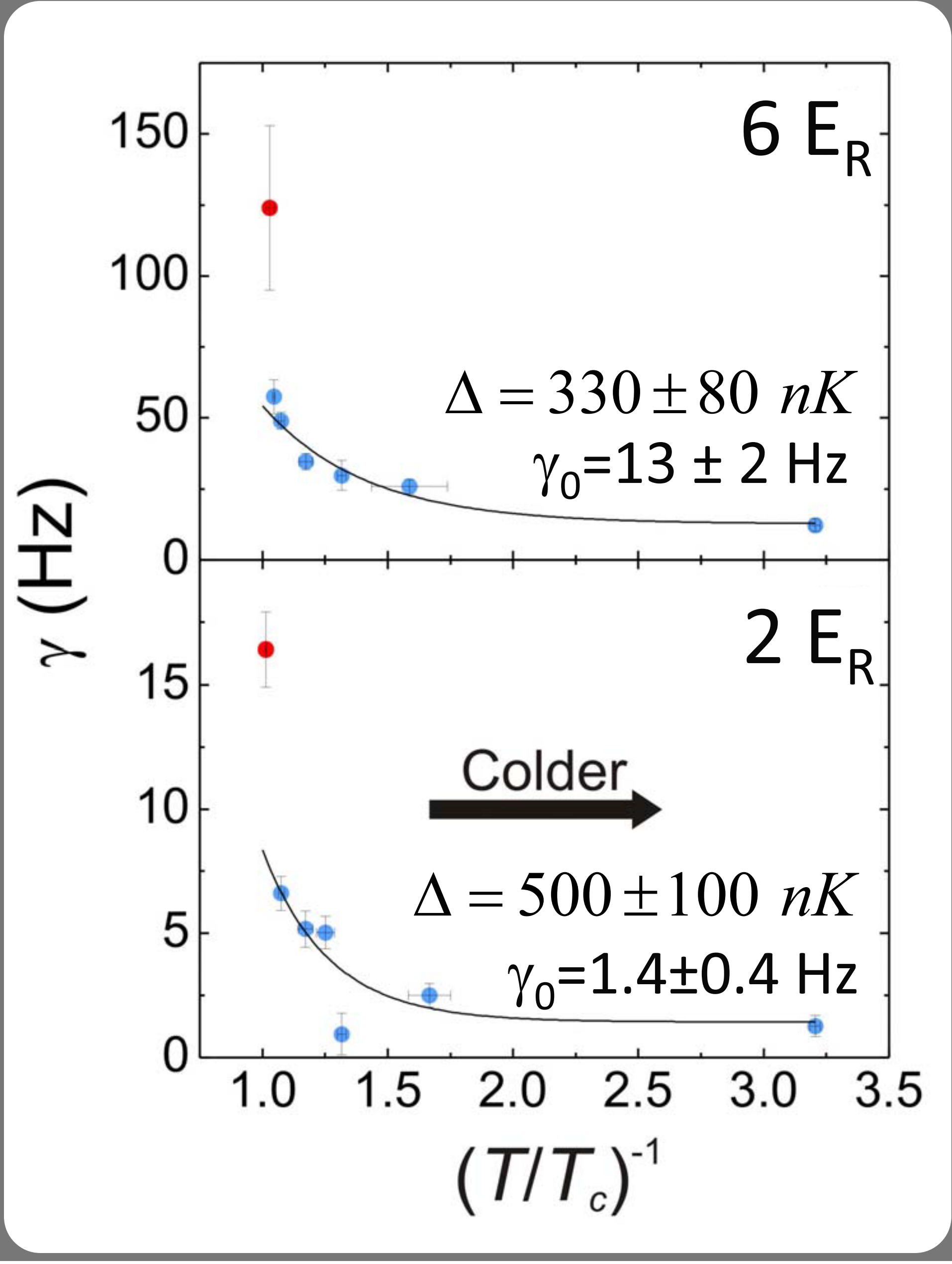
Cornell group



Free energy surface



Temperature dependence



Fit to model of thermally-activated damping:

$$\gamma = \gamma_0 + \gamma_\infty e^{-\Delta E/(T/T_c)}$$

Theoretical predictions

Langer & Ambegaokar, Phys. Rev. **164**, 498 (1967)
McCumber & Halperin, PRB **1**, 1054 (1970)
Caldeira & Leggett, PRL **46**, 211 (1981)
Zaikin *et al.*, PRL **78**, 1552 (1997)

Quantum phase slip rate: $\Gamma \propto e^{-S}$

Calculation of action for BH model:

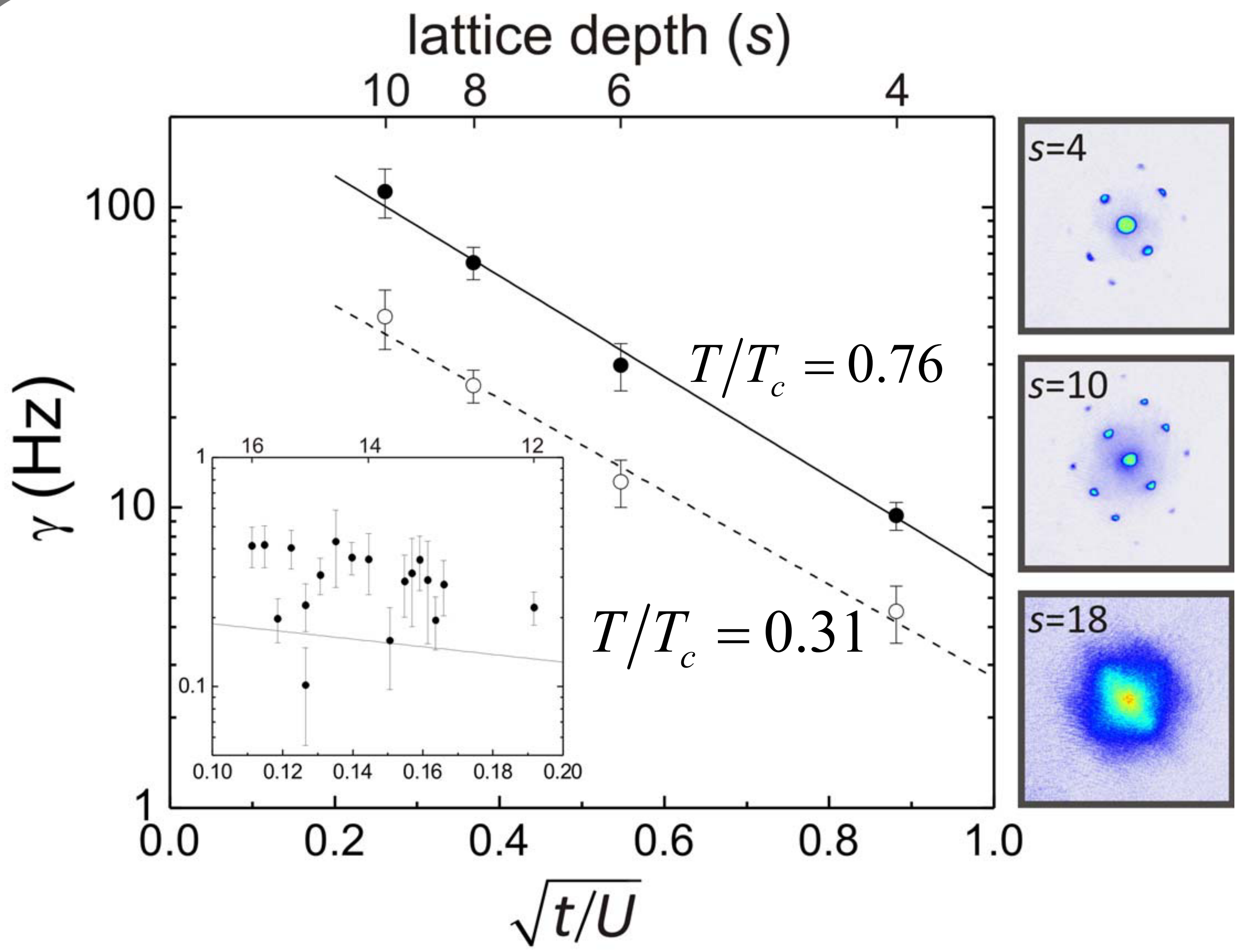
PHYSICAL REVIEW A **71**, 063613 (2005)

Decay of superfluid currents in a moving system of strongly interacting bosons

A. Polkovnikov, E. Altman, E. Demler, B. Halperin, and M. D. Lukin
Physics Department, Harvard University, Cambridge, Massachusetts 02138, USA
(Received 20 December 2004; published 23 June 2005)

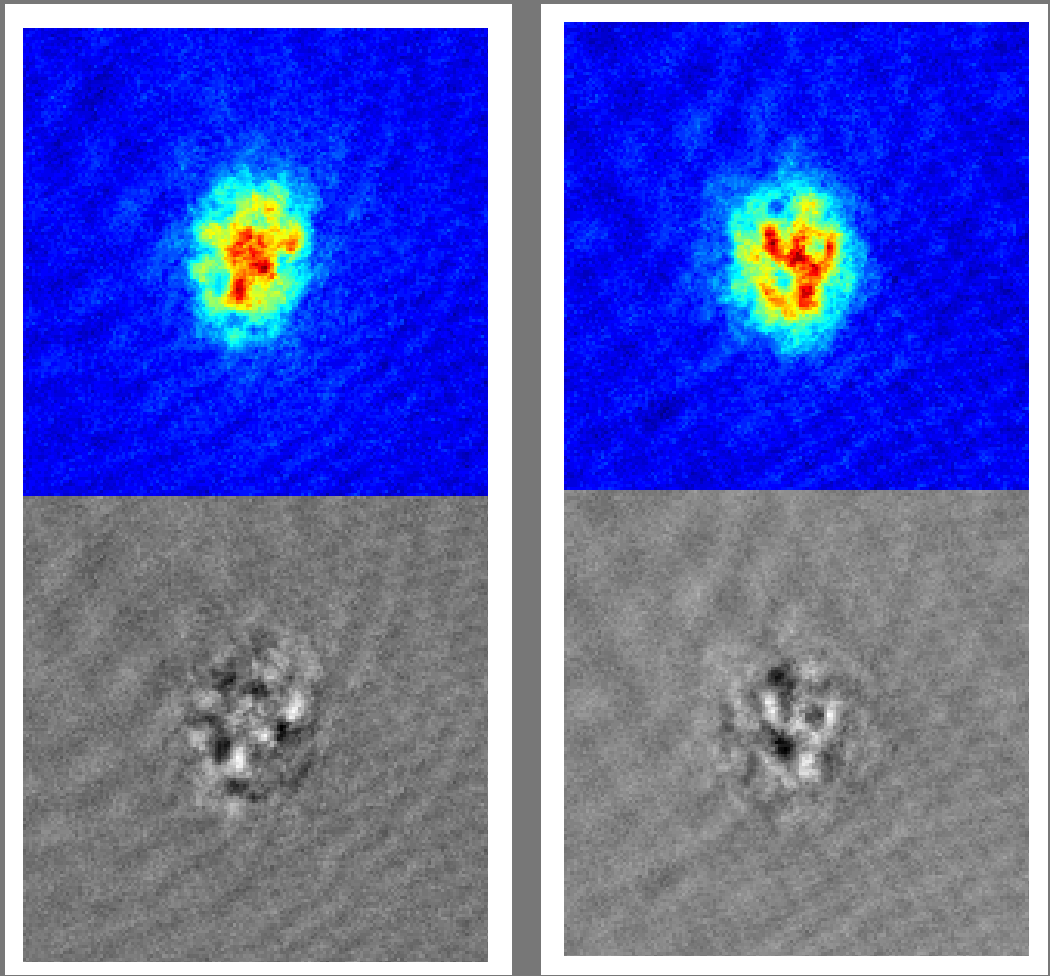
$$S \propto -\sqrt{t/U} \rightarrow \Gamma \propto e^{-\sqrt{t/U}}$$

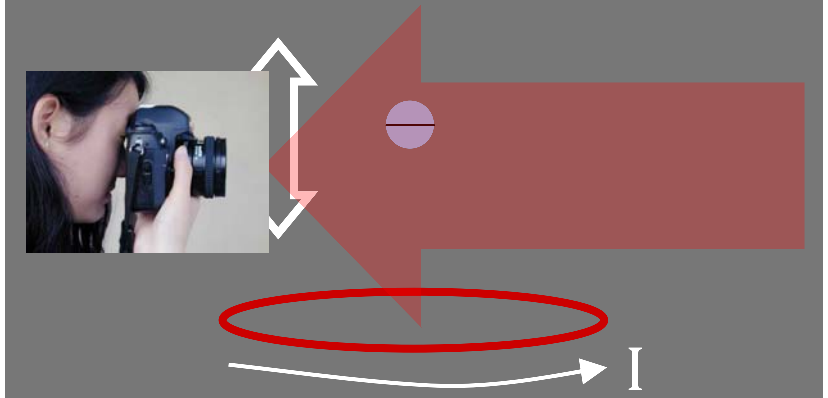
Scaling with BH model parameters



Direct observation of phase slips

raw image





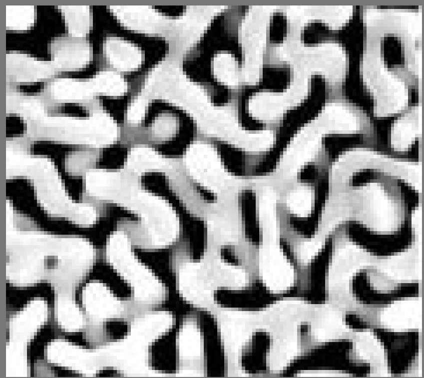
TF profile subtracted

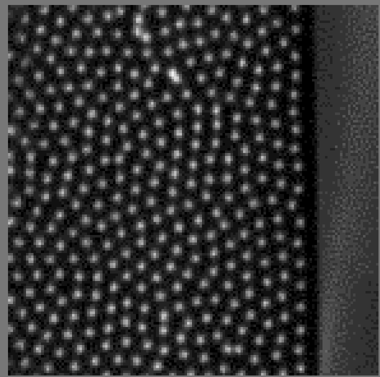
Punchline

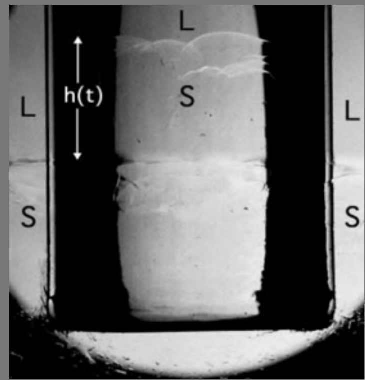
- Data for Bose-Hubbard model with external confinement consistent with metallic ground state
  - does finite size suppress vortex binding dominant for bulk? (Kosterlitz & Thouless, J. Phys. C 1972, 1973; Nelson and Halperin PRB 1978, 1989; liquid drop MC: arxiv/0706.2125)
  - what is the timescale for vortices to leave the BEC? Are they nucleated only at high velocity? (See Anderson, PRL 98, 110402)
  - What is the role of finite frequency?
- Consistency with phase-slip model & *intrinsic dissipation*
  - temperature dependence
  - scaling law
  - direct observation of phase slips
- http://arxiv.org/abs/0708.3074

Disordered BH model

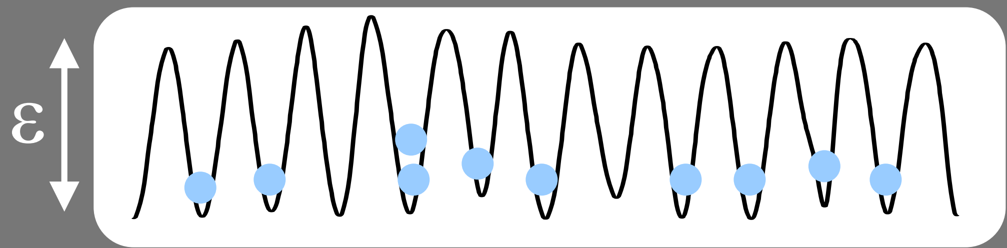
Disorder is everywhere

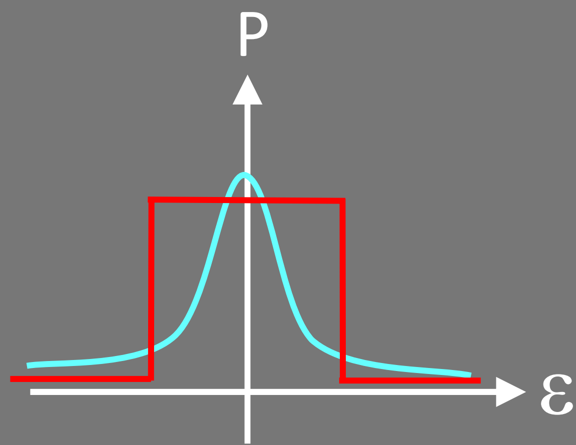






disordered Bose-Hubbard model



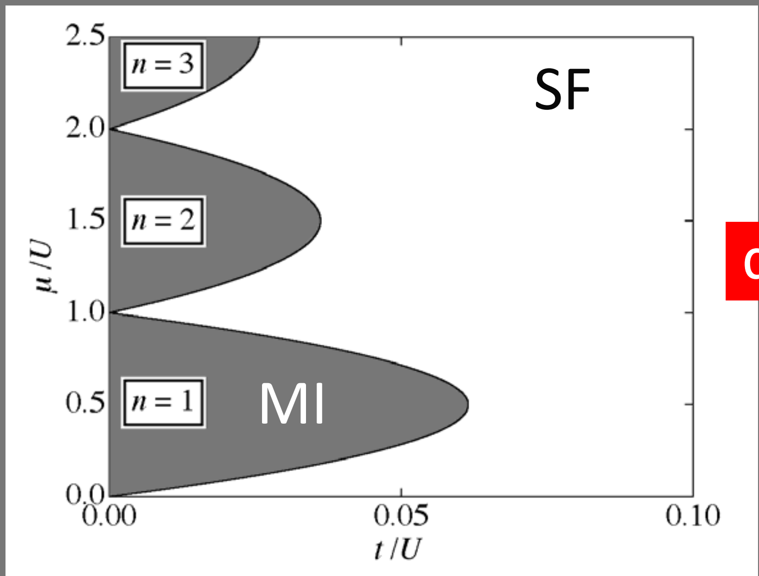


$$H = \sum_i \varepsilon_i - \sum_{\langle ij \rangle} t_{ij} \left(b_i^\dagger b_j + b_j^\dagger b_i \right) + \sum_i U_i n_i \left(n_i - 1 \right)$$

ε_i: “diagonal” disorder $\quad$ t_{ij}: “off-diagonal” disorder

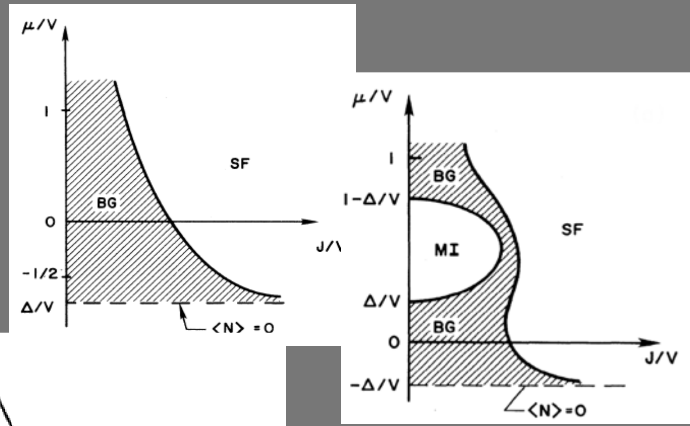
Disordered BH model

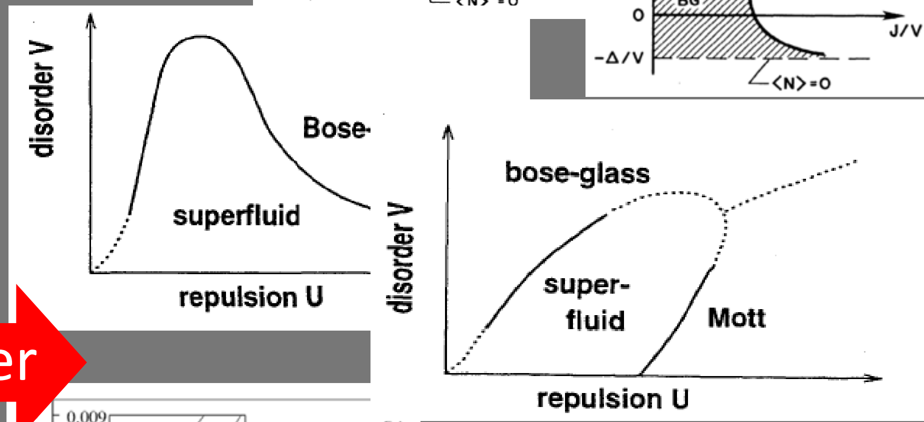
start by understanding
ground state phase diagram

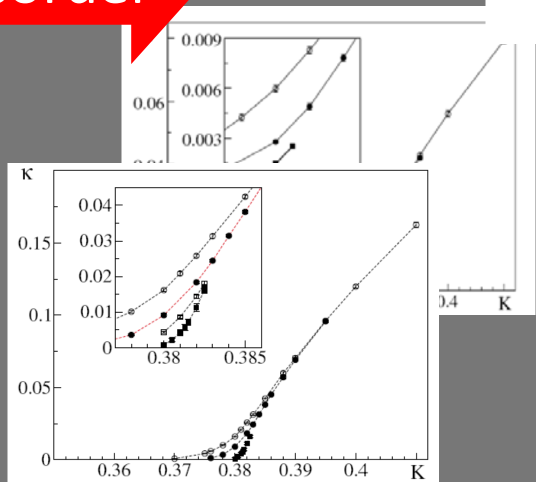


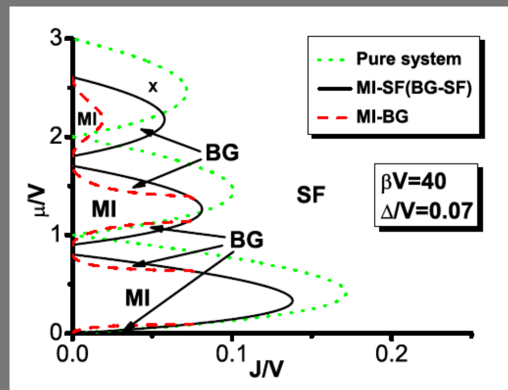
increasing lattice depth

disorder

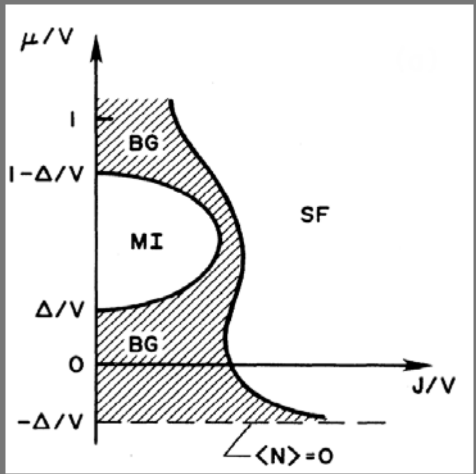


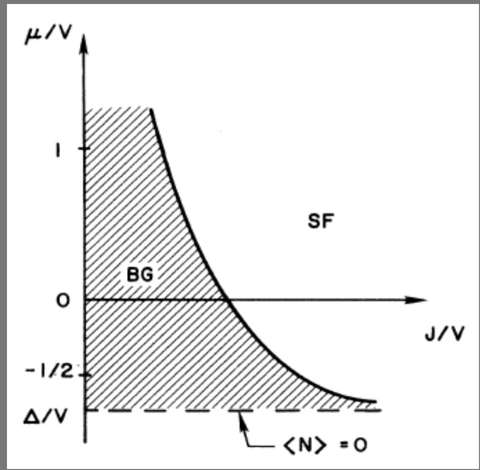






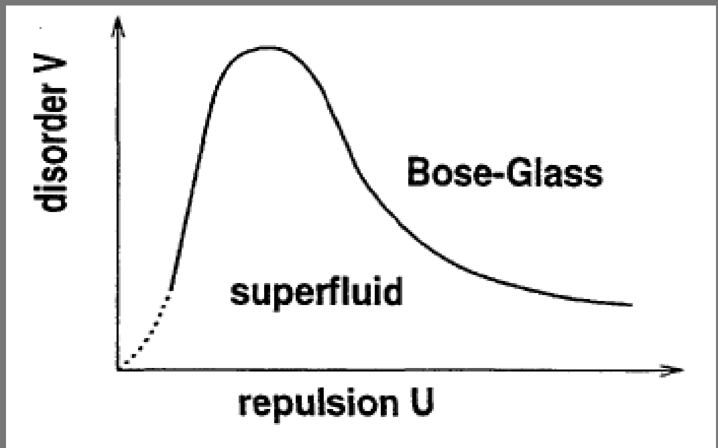
Disordered BH predictions

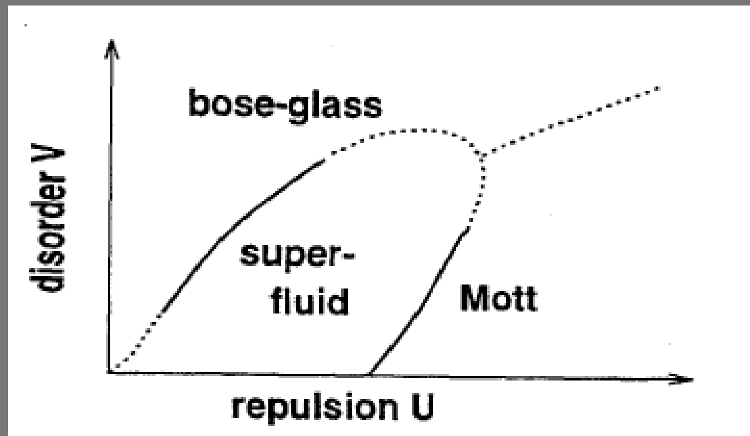




SF: superfluid
BG: Bose-glass
(gapless, compressible)
MI: Mott-insulator
(gapless, incompressible)

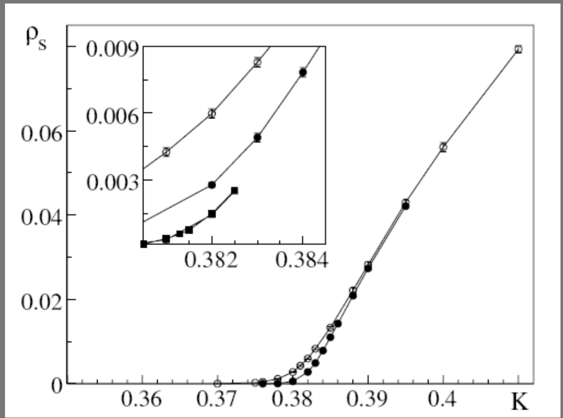
Fisher *et al.*, PRB **40**, 546 (1989)

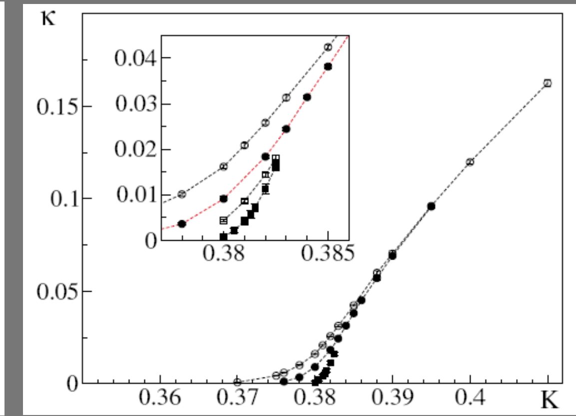




QMC / Trivedi: review: *Quantum Phase Transition in Disordered Systems: What are the Issues*, in *Proceedings of the 20th International Workshop on Condensed Matter Theories* **12**, 141 (1997)

Disordered BH predictions

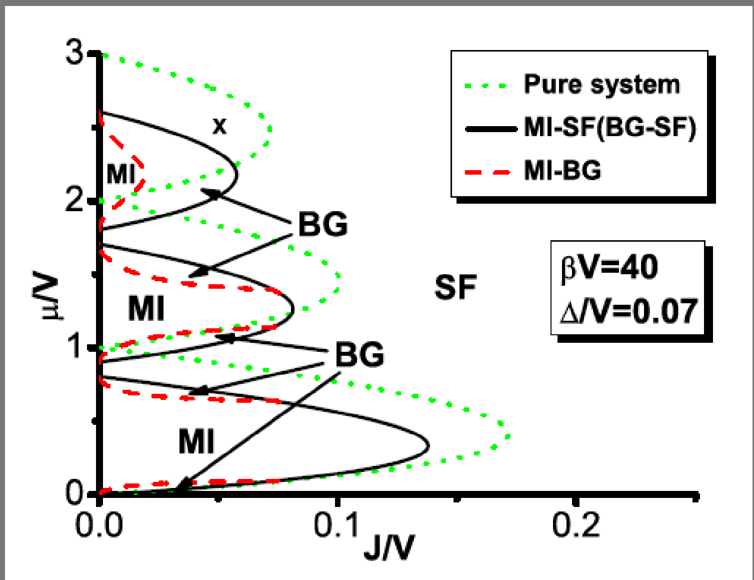


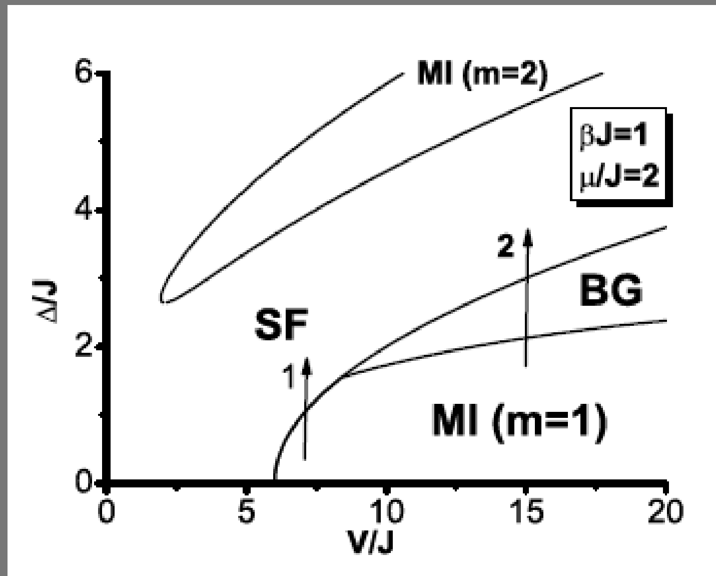


Prokov'ef & Svistunov, PRL **92**, 015703 (2004)

off-diagonal disorder in 2D:

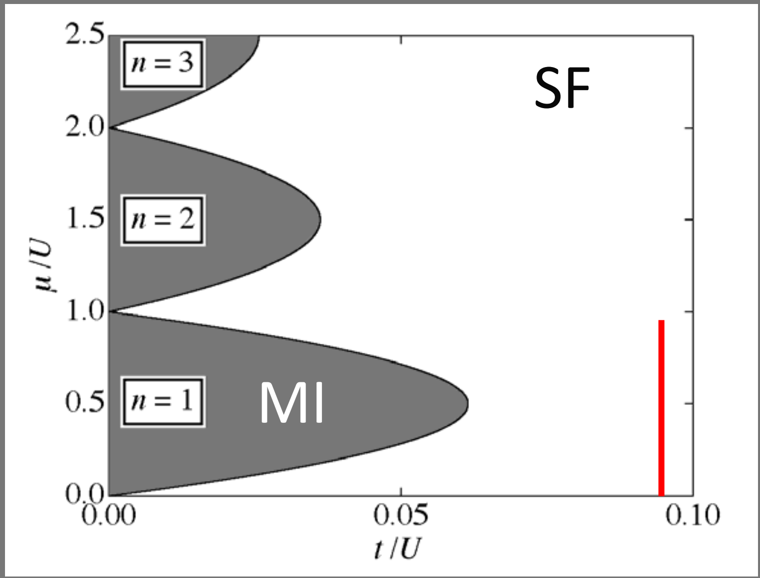
SF-MG (Mott-glass, gapless & incompressible)



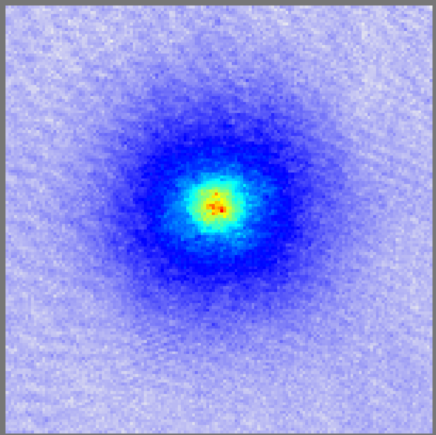


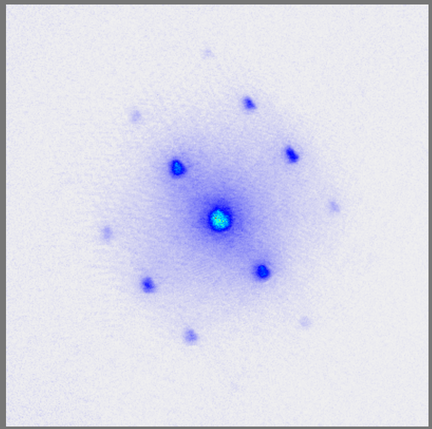
Phillips, cond-mat/0612505

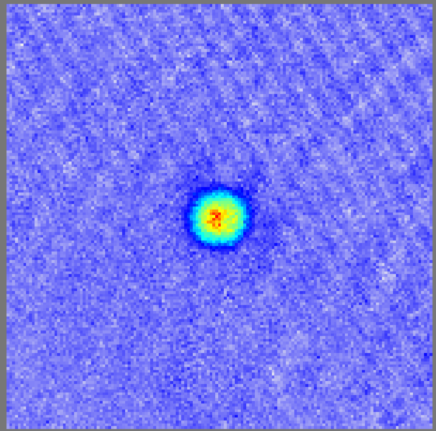
Discriminate using condensate fraction?



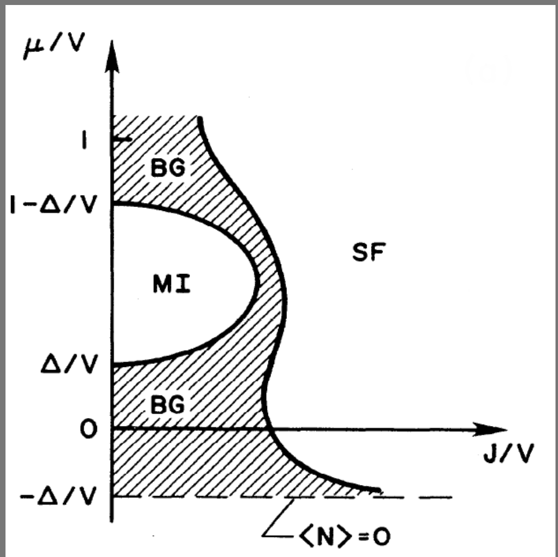
increasing lattice depth

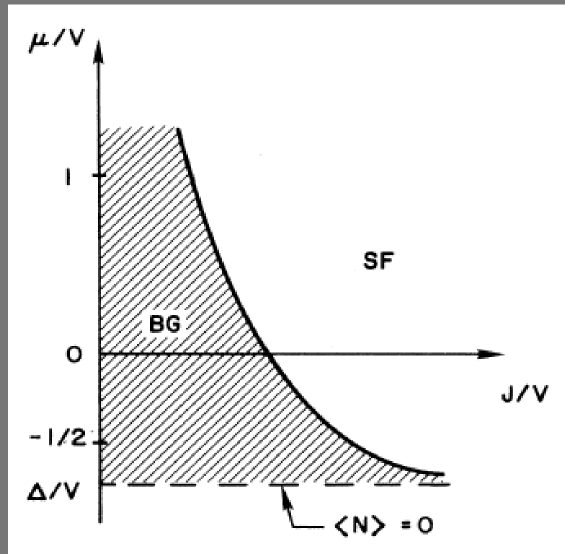


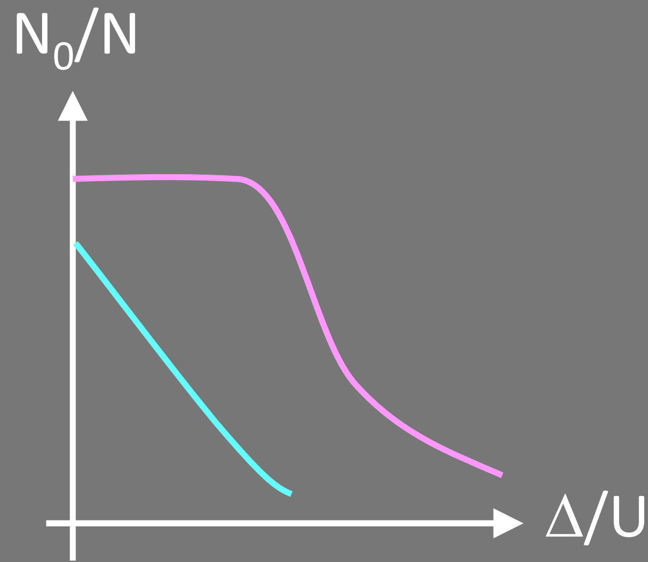


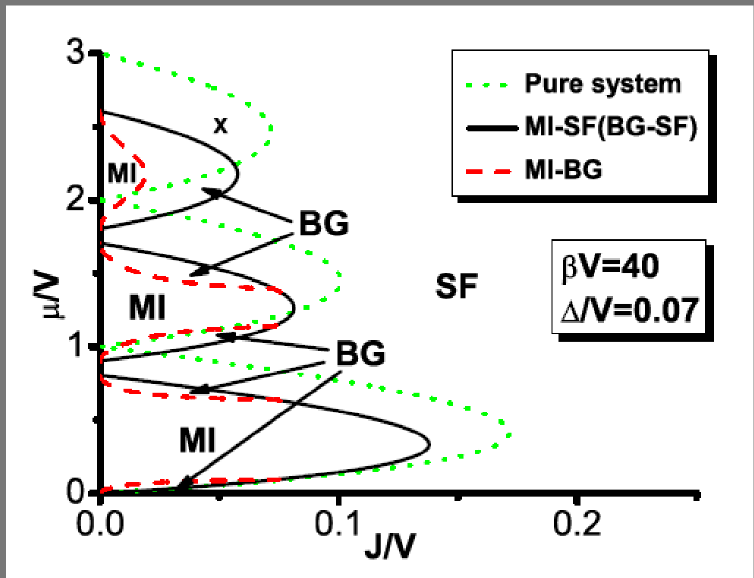


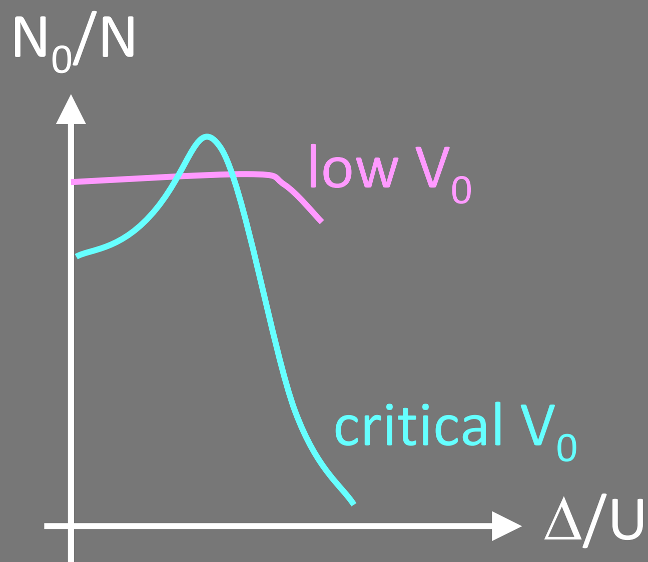
What should we expect?



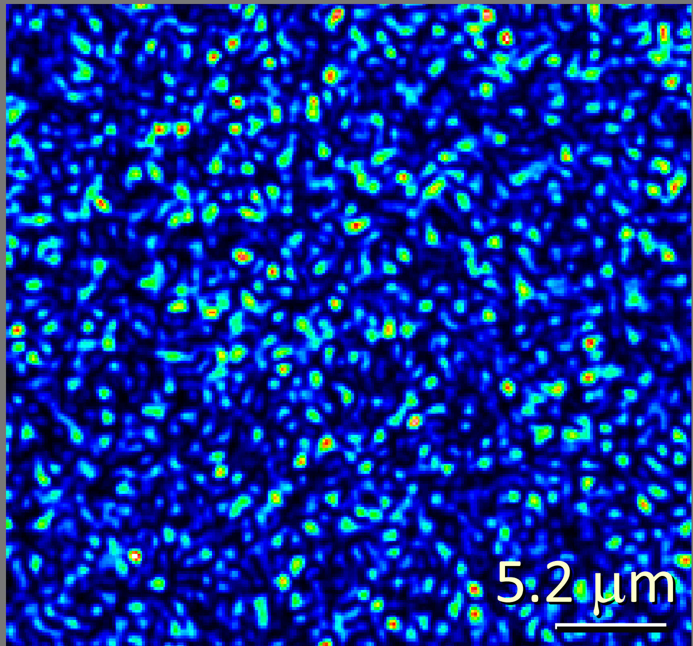


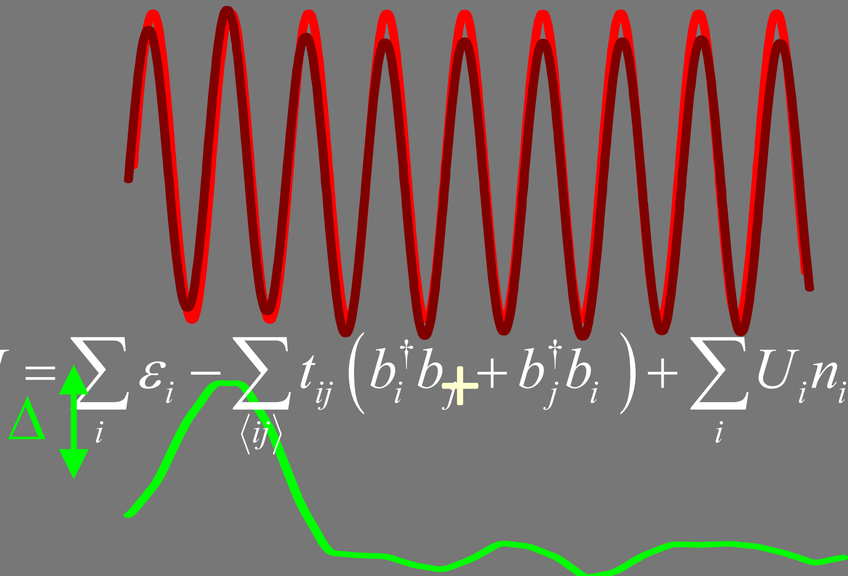




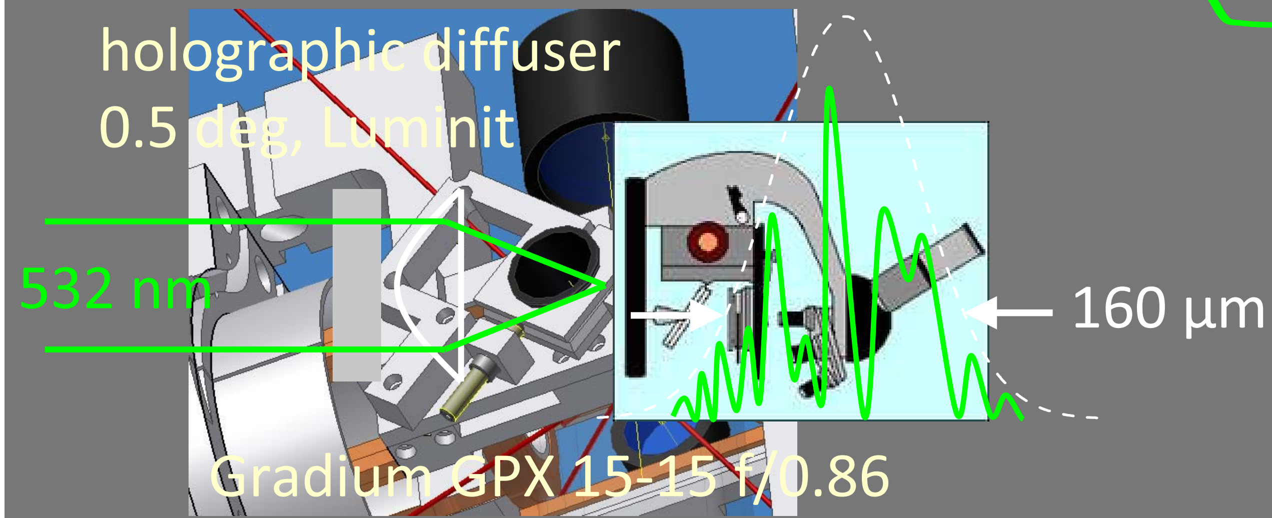


Speckle





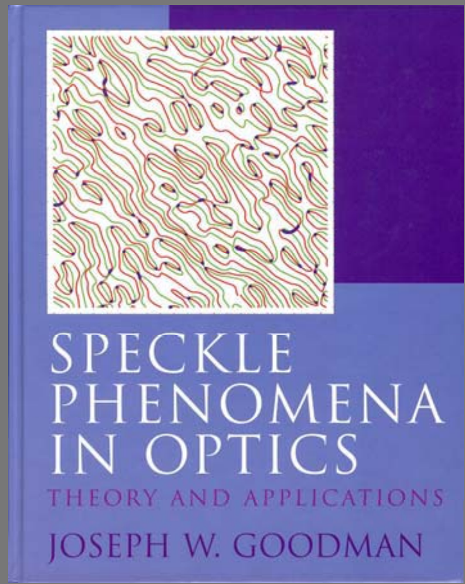
$$H = \sum_i \varepsilon_i - \sum_{\langle ij \rangle} t_{ij} \left(b_i^\dagger b_j + b_j^\dagger b_i \right) + \sum_i U_i n_i \left(n_i - 1 \right)$$



The theory of optical speckle

What is the speckle "size?"

Most theories assume no site-to-site correlations

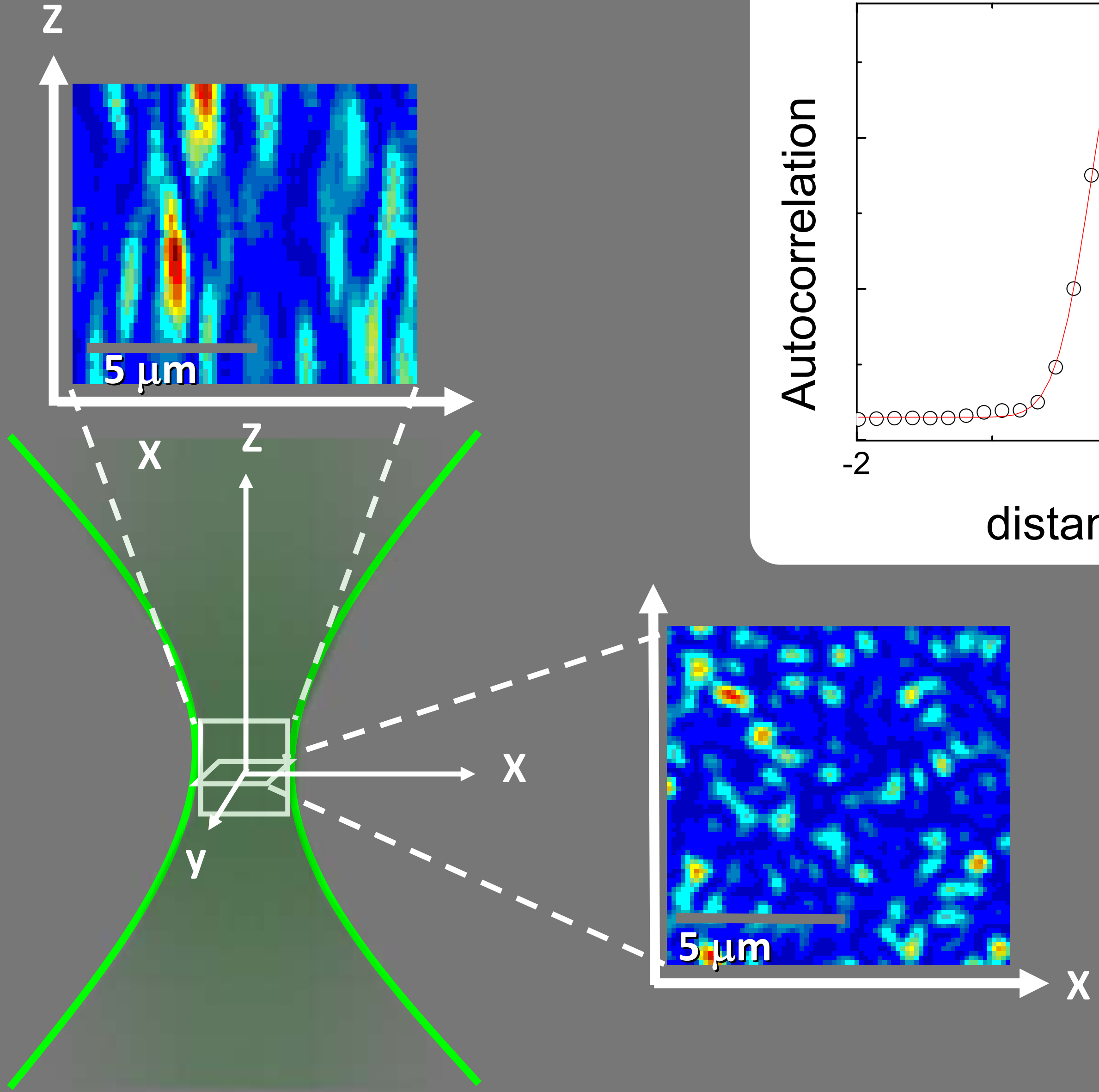


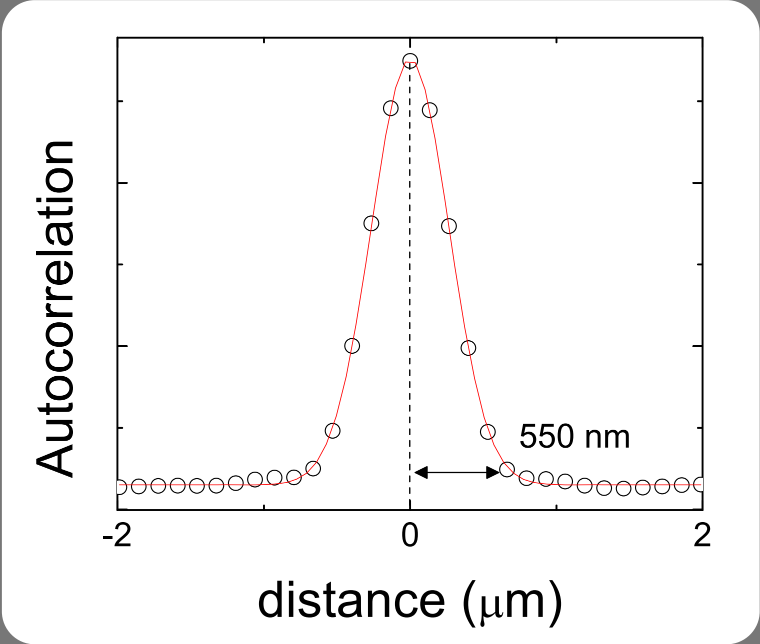
Autocorrelation width

$$\mu \propto \langle I(\vec{x})I(\vec{x}+\vec{d})\rangle$$ Intensity autocorrelation

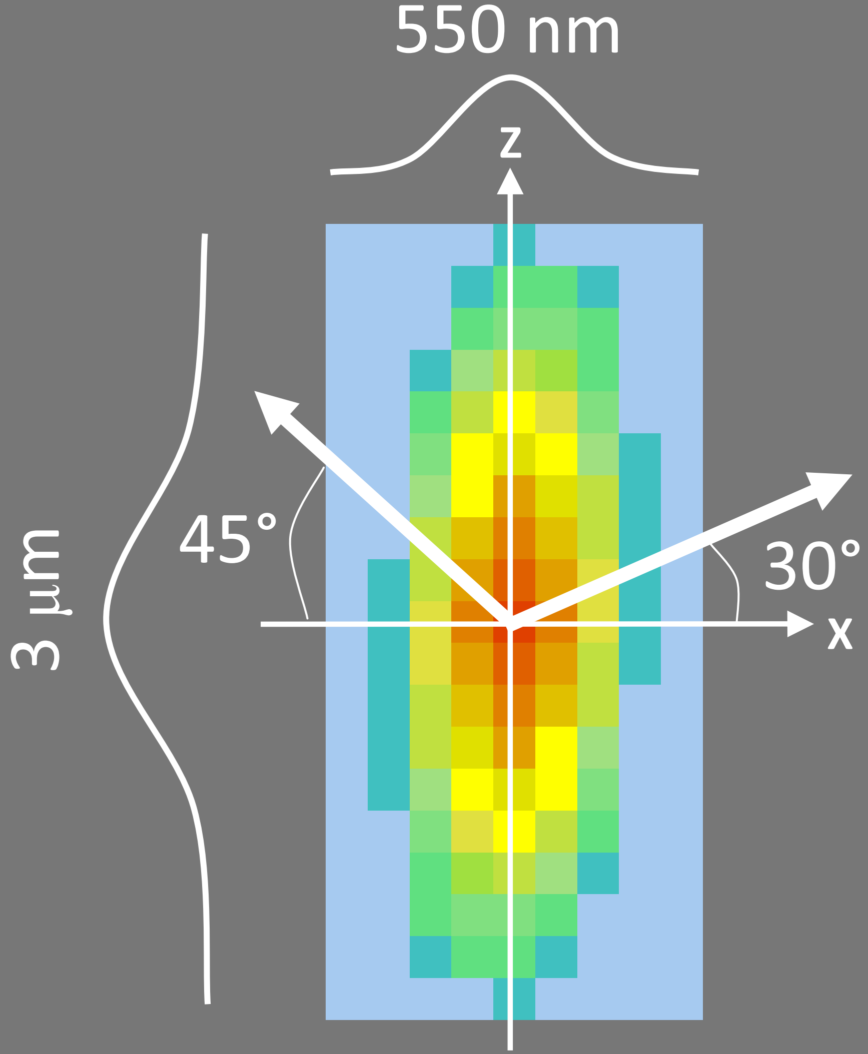
$$\left(\Delta z\right)_{1/2} = 6.7\lambda\left(f/D\right)^2 \qquad \left(\Delta r\right)_{1/2} = 1.4\lambda\left(f/D\right)$$

Autocorrelation measurement

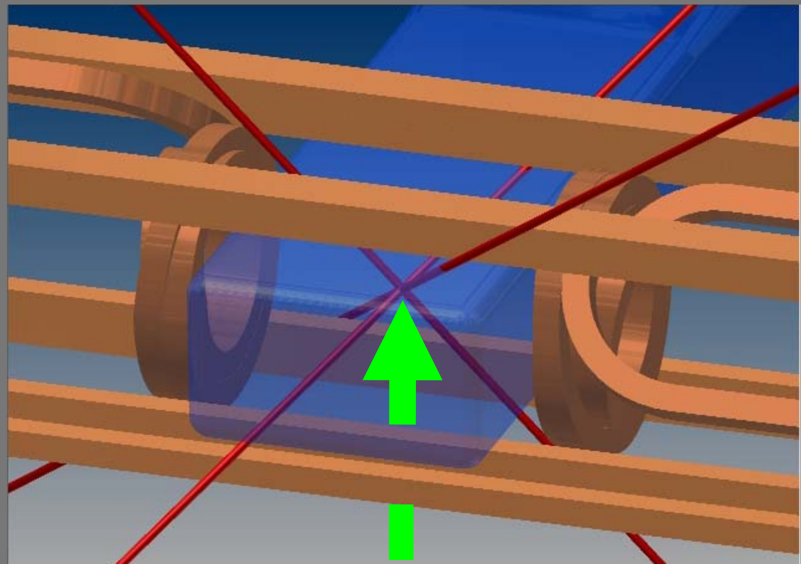




Fine-grain 3D disorder



3D AC measurement

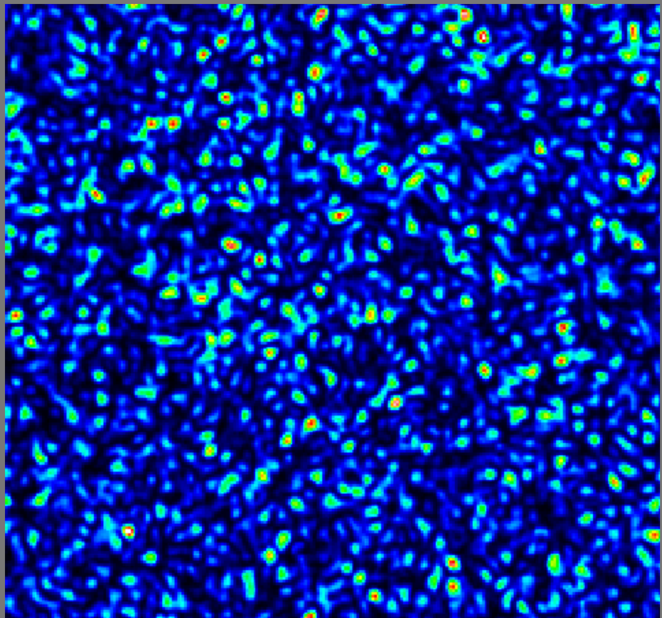


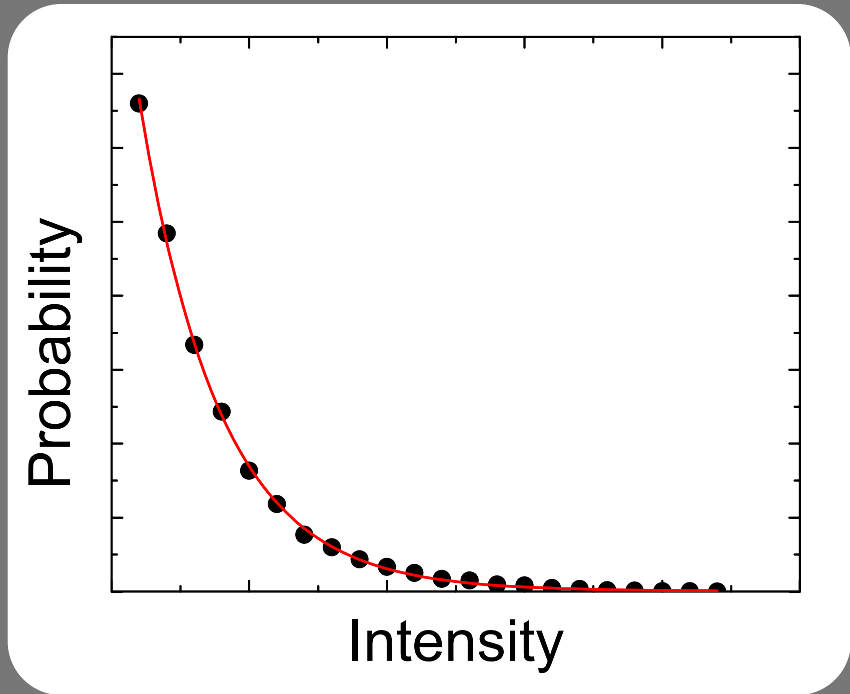
30° beams ⇨ 650 nm

45° beam ⇨ 790 nm

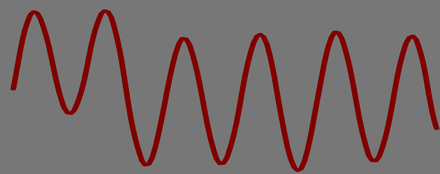
Lattice Spacing = 406 nm

Speckle distribution





Exponential distribution: $P(I) \propto e^{-I/\bar{I}}$

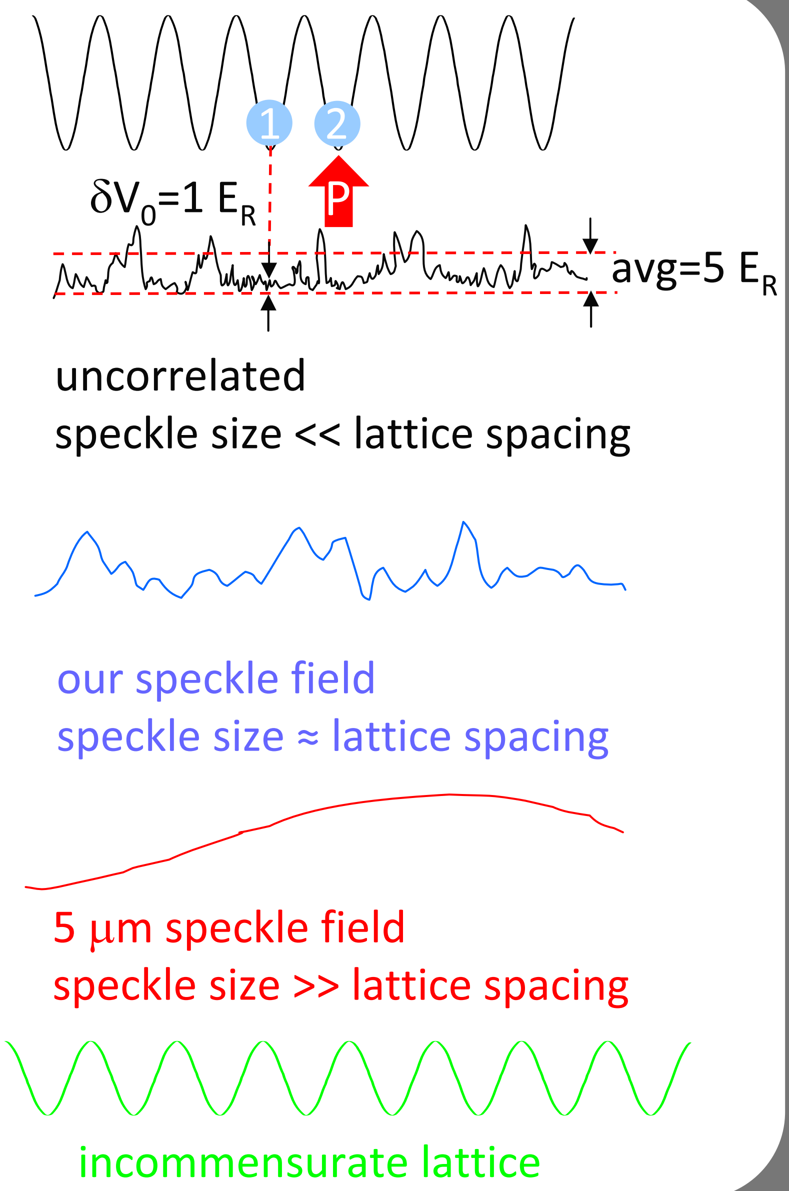


Disorder in all BH parameters:

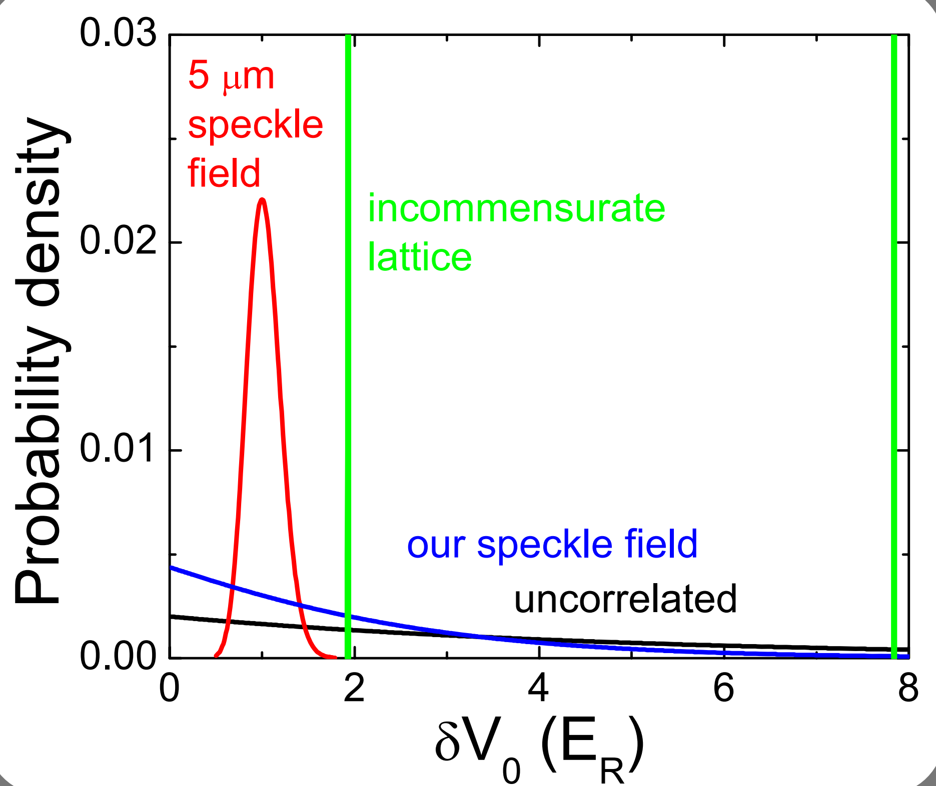
$$H = \sum_i \varepsilon_i - \sum_{\langle ij \rangle} t_{ij}\left(b_i^\dagger b_j + b_j^\dagger b_i\right) + \sum_i U_i n_i \left(n_i - 1\right)$$

Working with Ceperley to determine distributions

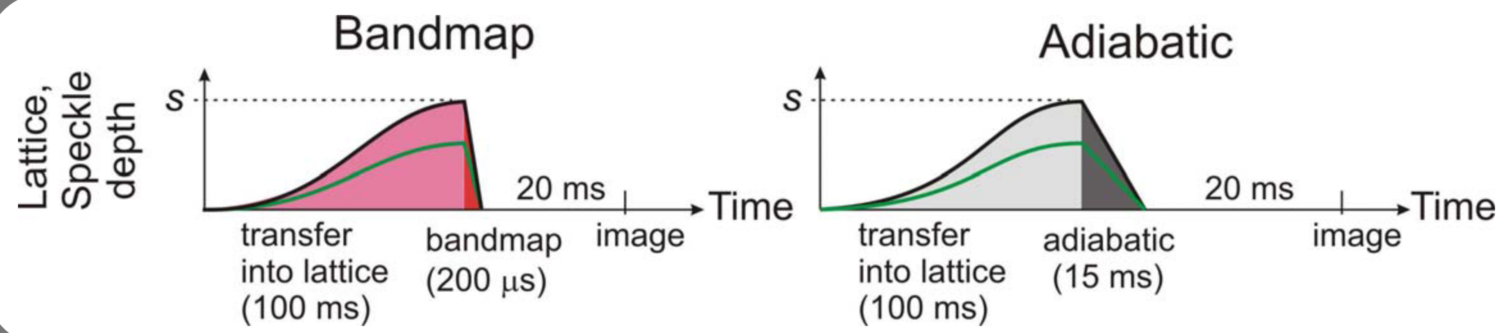
Disorder comparison

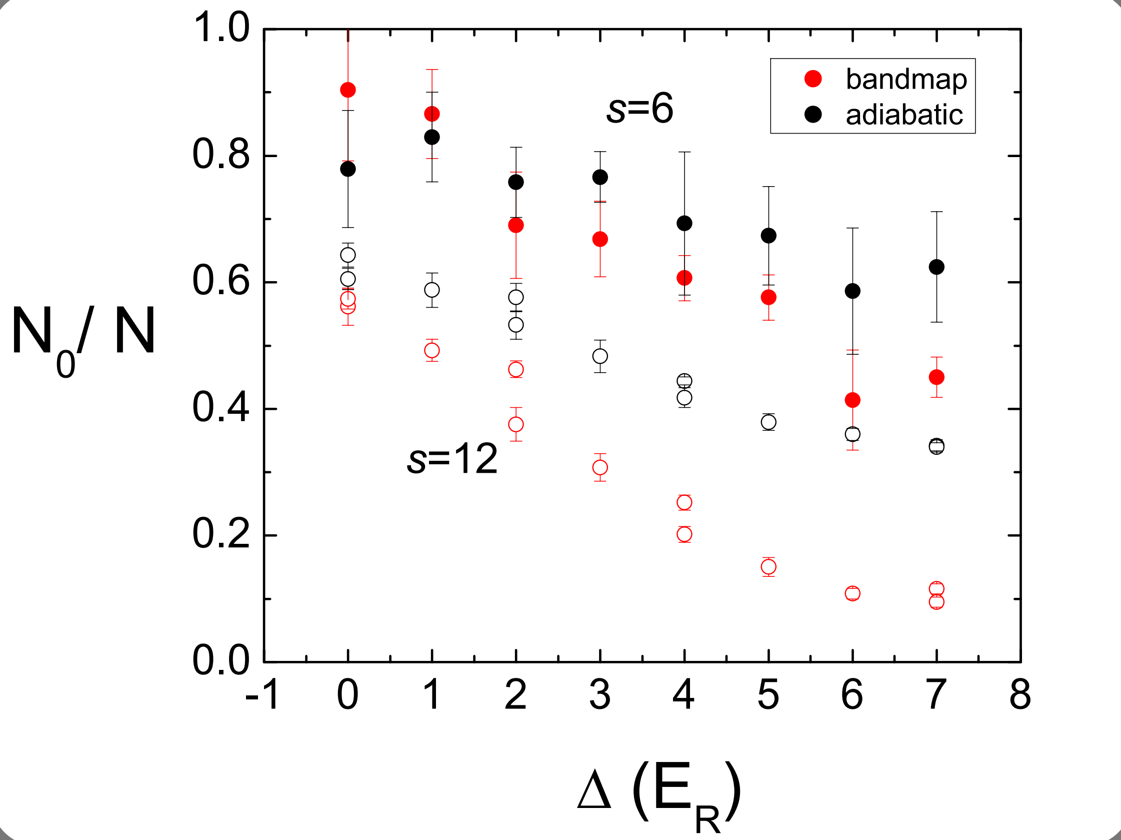


Joint probability ($\Delta\varepsilon_1$=1 E_R|P_2)



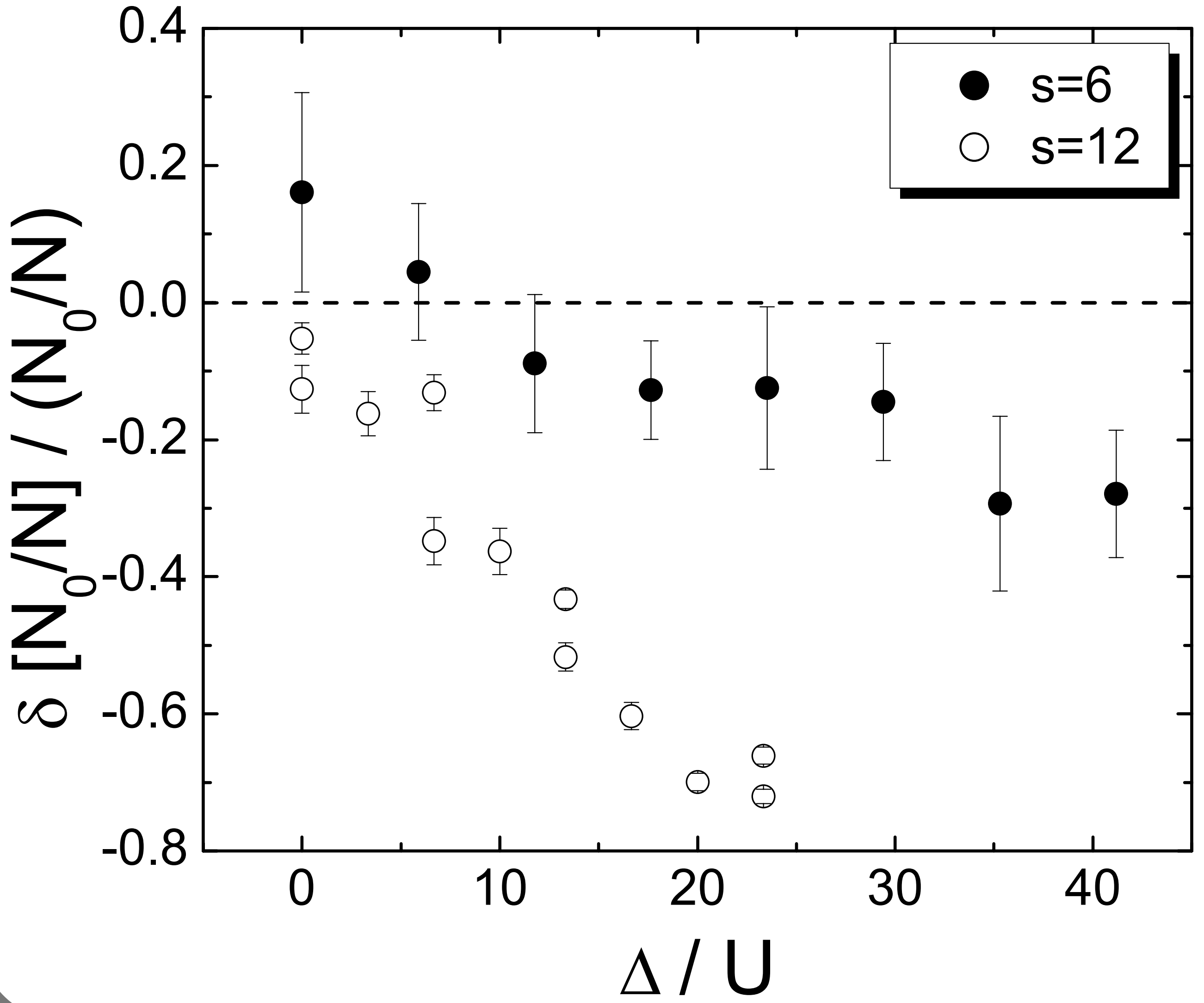
Condensate fraction: results





n=3 in
center of lattice

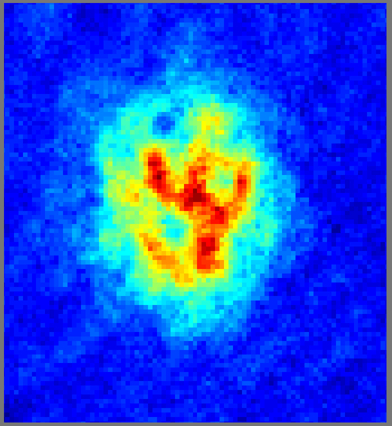
Speckle effect on condensate fraction



Conclusion

Transport measurements:

- linear response, low velocity, temperature-dependence
- dissipation observed consistent with phase slips
- vortices nucleated by linear motion observed



Disordered BH model

- fine-grained disorder created using speckle
- initial measurements of N_0 / N : STAY TUNED!
- other measurements needed (local gap, correlations, …)
- engineered speckle: how much does physics depend on disorder details?