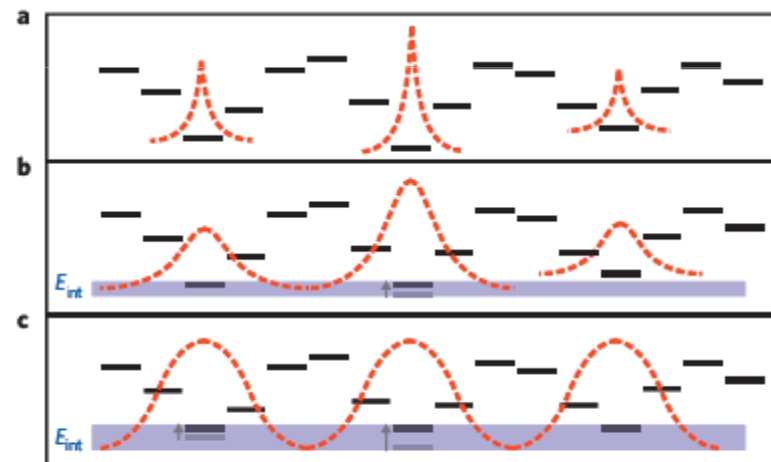


# Delocalization of a disordered bosonic system by repulsive interactions

B. Deissler<sup>1\*</sup>, M. Zaccanti<sup>1</sup>, G. Roati<sup>1</sup>, C. D'Errico<sup>1</sup>, M. Fattori<sup>1,2</sup>, M. Modugno<sup>1</sup>, G. Modugno<sup>1</sup> and M. Inguscio<sup>1</sup>

Clarifying the interplay of interactions and disorder is fundamental to the understanding of many quantum systems, including superfluid helium in porous media<sup>1</sup>, granular and thin-film superconductors<sup>2-5</sup> and light propagating in disordered media<sup>6-8</sup>. One central aspect for bosonic systems<sup>9-11</sup> is the competition between disorder, which tends to localize particles, and weak repulsive interactions, which instead have a delocalizing effect. As the required degree of independent control of disorder and of interactions is not easily achievable in most available physical systems, a systematic experimental investigation of this competition has not so far been possible. Here we use a degenerate Bose gas with tunable repulsive interactions in a quasiperiodic lattice potential to study this interplay in detail. We characterize the entire delocalization crossover through the study of the average local shape of the wavefunction, the spatial correlations and the phase coherence. Three different regimes are identified and

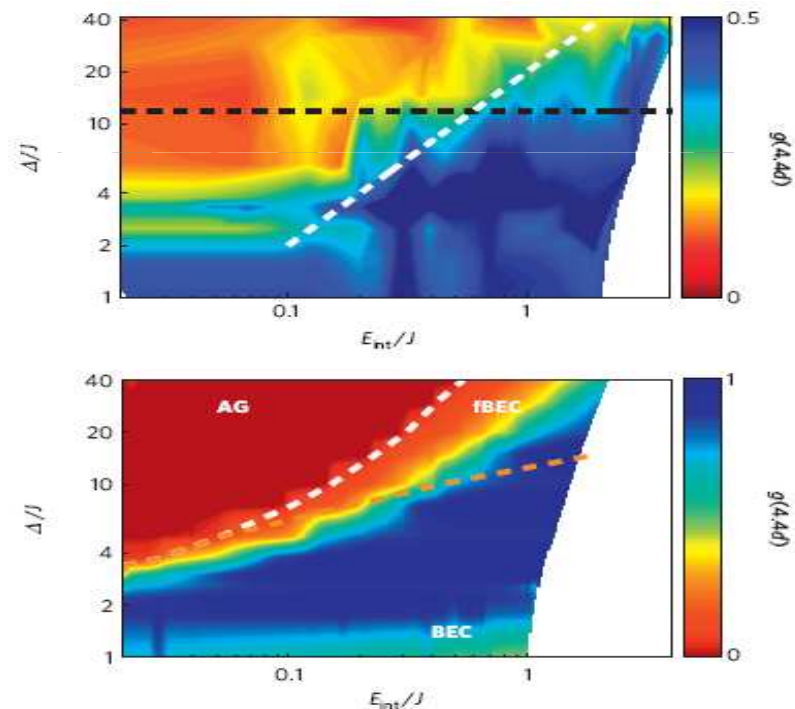


**Figure 1 | Delocalization in a quasiperiodic potential.** Schematic of the interaction-induced delocalization. **a**, In a very weakly interacting system

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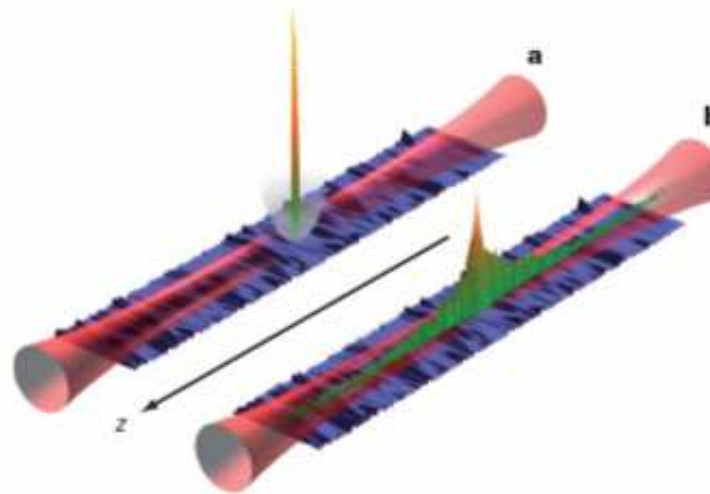
# Full disclosure...

Vol 453 | 12 June 2008 | doi:10.1038/nature07000

nature

## Direct observation of Anderson localization of matter waves in a controlled disorder

Juliette Billy<sup>1</sup>, Vincent Josse<sup>1</sup>, Zhanchun Zuo<sup>1</sup>, Alain Bernard<sup>1</sup>, Ben Hambrecht<sup>1</sup>, Pierre Lugan<sup>1</sup>, David Clément<sup>1</sup>, Laurent Sanchez-Palencia<sup>1</sup>, Philippe Bouyer<sup>1</sup> & Alain Aspect<sup>1</sup>



Rockson Chang Group meeting Jan 28<sup>th</sup>, 2009



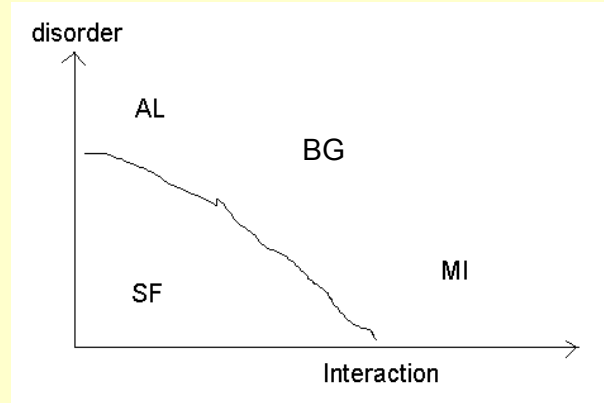
- Review of Anderson localization in an ultracold system
- AL in a 1D quasi-periodic lattice
- New experimental results:
  - phase diagram - disorder vs interactions

# Anderson Localization

- Classical transport of particles through a material
  - scattering off impurities, mean free path, resistance
- But if meanfree path  $<$  de Broglie Wavelength, quantum effects can be important:
  - A wave phenomenon
  - Single particle interference between multiple scattering pathways
- Signature: suppression of diffusion and exponential localization
  
- Alternately: Bloch waves in a perfect lattice... disorder breaks translational symmetry leading to localization

# Anderson Localization

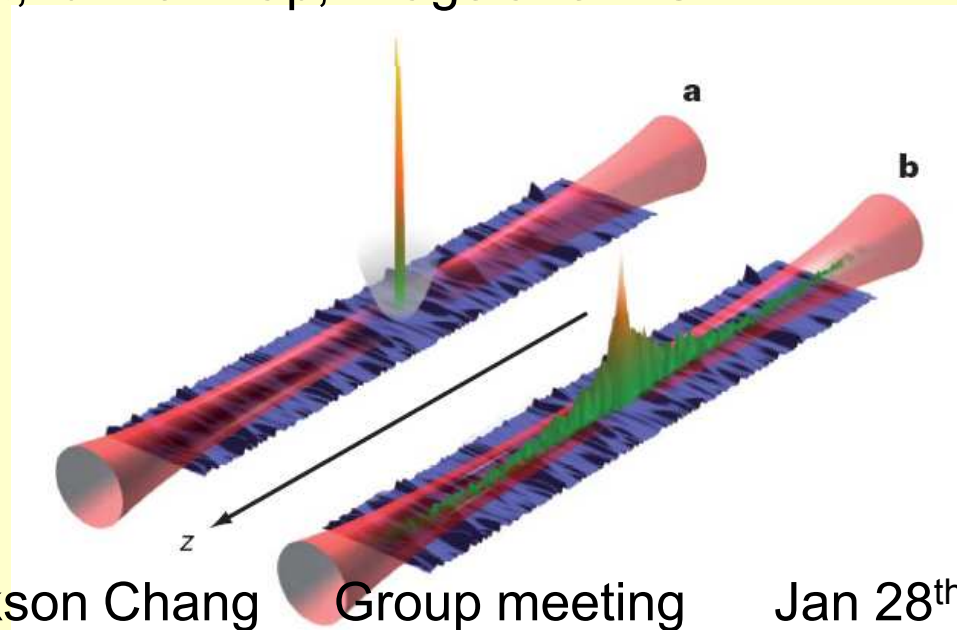
- Predicts a metal-to-insulator transition (delocalized to localized wavefunctions)
- Originally applied to non-interacting particles, but it is well known that interactions can play significant role
  - disorder potential, non-linear interaction, hopping
  - interesting phases: bose glass, anderson glass, Mott insulator ...



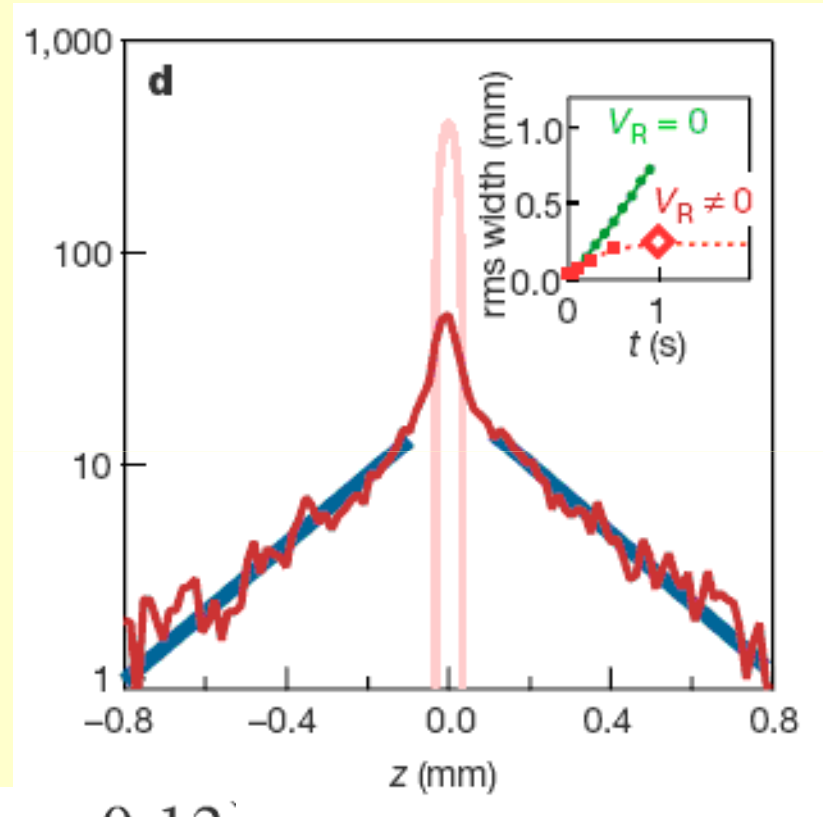
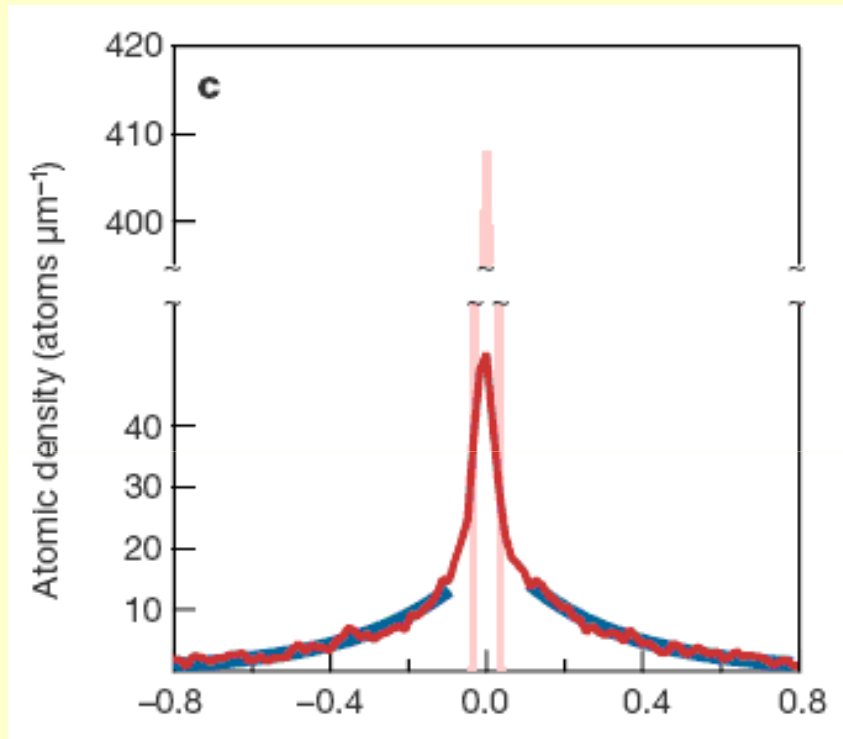
- This work: avoid interactions to unambiguously see AL

# Experimental setup

- 87-Rb BEC,  $1.7 \times 10^4$  atoms.
- opto-magnetic hybrid trap
  - transverse confinement (70 Hz) [optical waveguide]  $3 \mu\text{m}$
  - longitudinal confinement (5.4 Hz) [magnetic trap]  $35 \mu\text{m}$
- Turn on disorder potential
- Switch off magnetic confinement
- Weakly anti-trapping magnetic field compensates the residual longitudinal trapping of the optical waveguide, atoms expand freely over several millimetres.
- Wait for time  $t$ , turn off trap, image after TOF.



# Exponential localization



$$V_R/\mu_{\text{in}} = 0.12$$

# Summary

- First direct observation of exponentially localized matter waves in space, algebraic tails above the mobility edge.

# Outlook

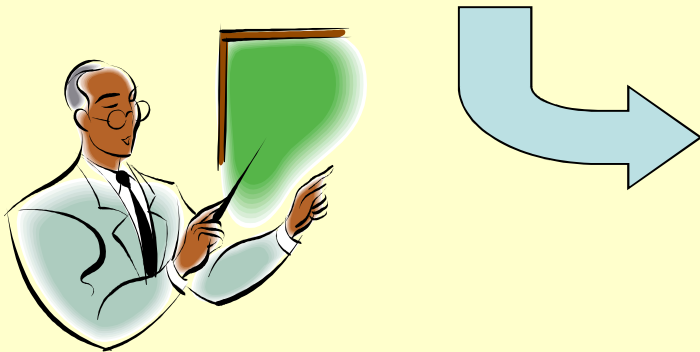
- Quantum simulation of Anderson localization in higher dimensions
- Add interactions: competition between interactions, disorder, and kinetic energy poorly understood

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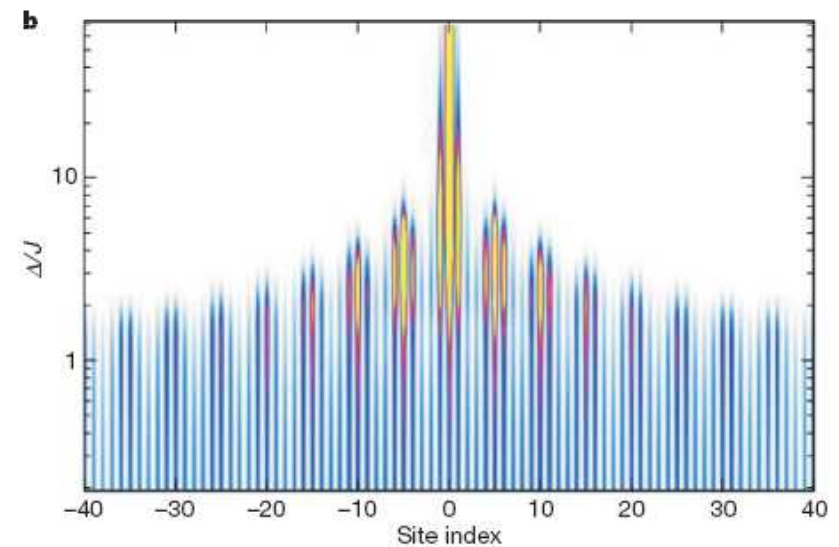
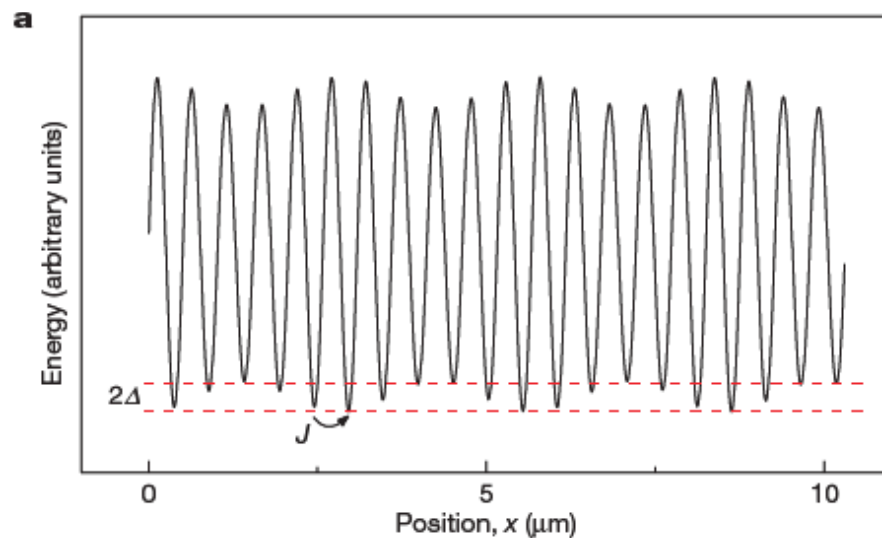
Rockson Chang

Group meeting

Jan 28<sup>th</sup>, 2009

# Anderson localization of a non-interacting Bose–Einstein condensate

Giacomo Roati<sup>1,2</sup>, Chiara D’Errico<sup>1,2</sup>, Leonardo Fallani<sup>1,2</sup>, Marco Fattori<sup>1,2,3</sup>, Chiara Fort<sup>1,2</sup>, Matteo Zaccanti<sup>1,2</sup>, Giovanni Modugno<sup>1,2</sup>, Michele Modugno<sup>1,4,5</sup> & Massimo Inguscio<sup>1,2</sup>



- $^{39}\text{K}$  1D quasiperiodic potential
- Primary lattice 1064.4 nm,  $10.5 E_{R1}$
- Secondary lattice 866.6 nm,  $1.7 E_{R2}$  max

$$E_R = \hbar^2 / (2M\lambda^2)$$

- Anderson-like localization at  $\Delta/J = 2$ .

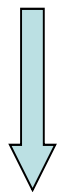
$$H = -\frac{\hbar^2}{2m} \nabla_x^2 + V_b(x), \quad V_b(x) = s_1 E_{R1} \sin^2(k_1 x) + s_2 E_{R2} \sin^2(k_2 x + \phi),$$

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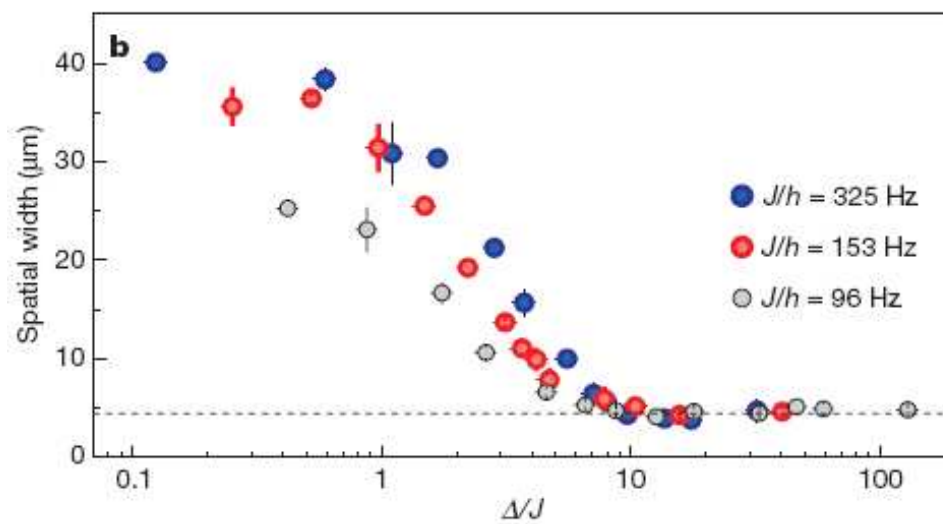
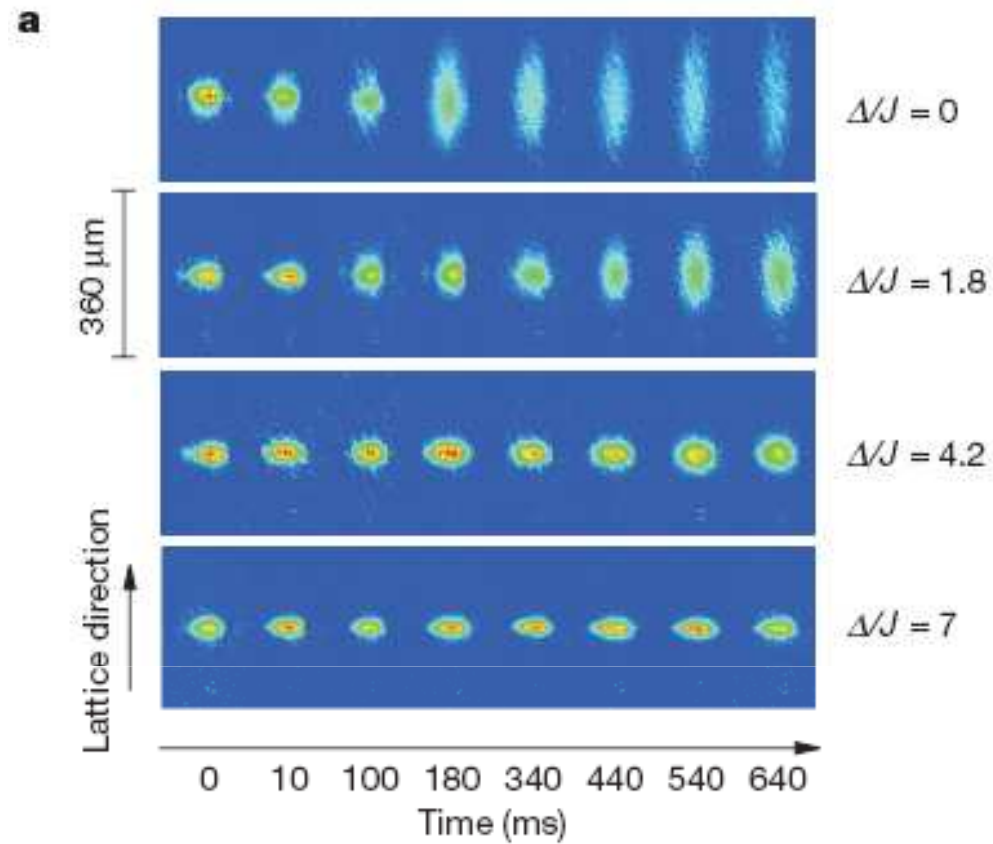
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Tight-binding approximation, expand in Wannier basis

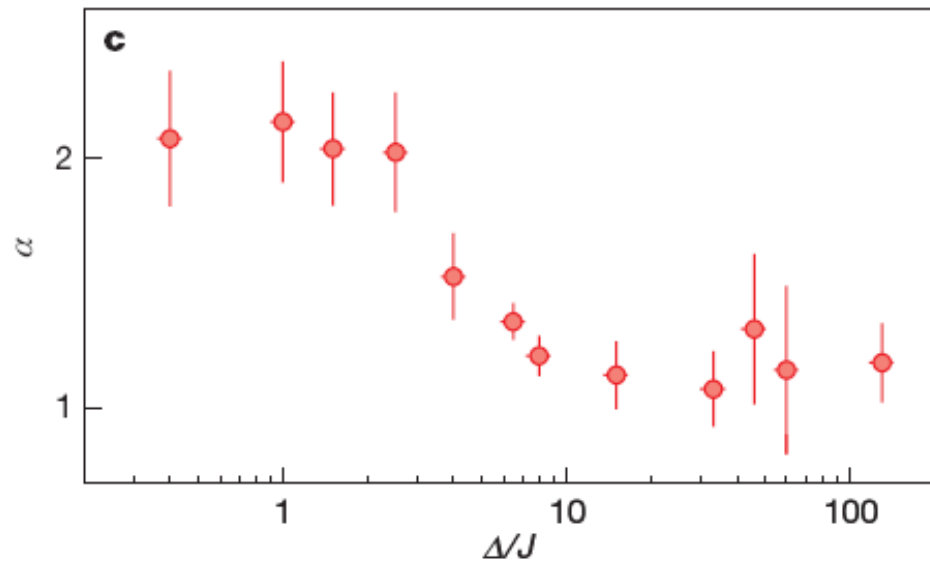
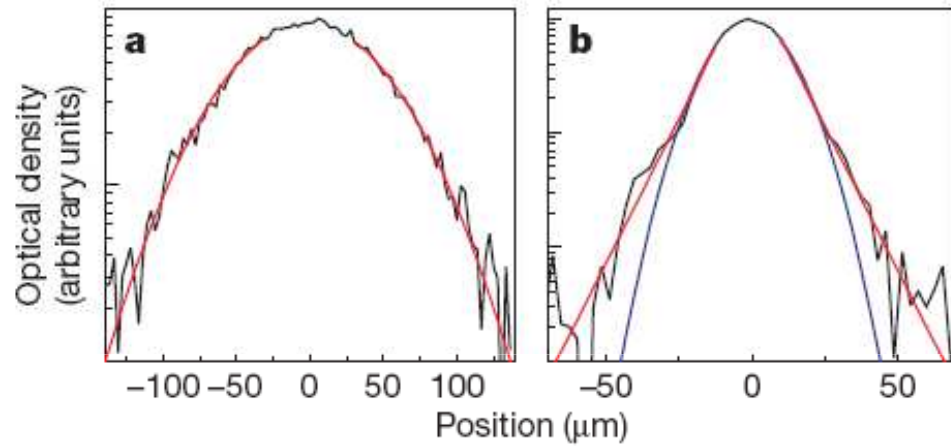
$$H = -J \sum_j (|w_j\rangle\langle w_{j+1}| + |w_{j+1}\rangle\langle w_j|) + \Delta \sum_j \cos(2\pi\beta j + \phi') |w_j\rangle\langle w_j|,$$

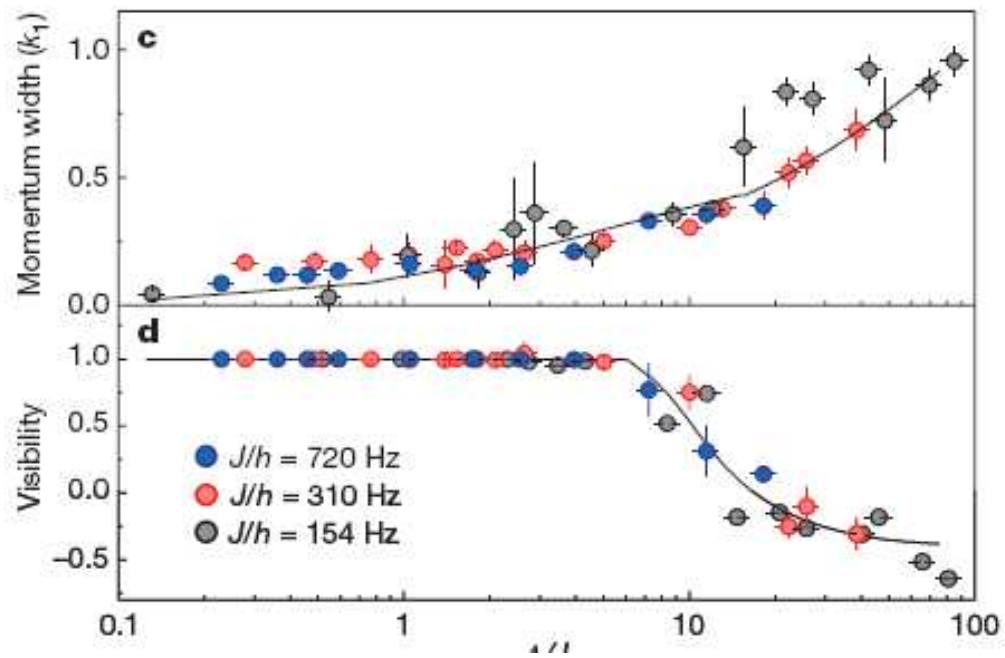
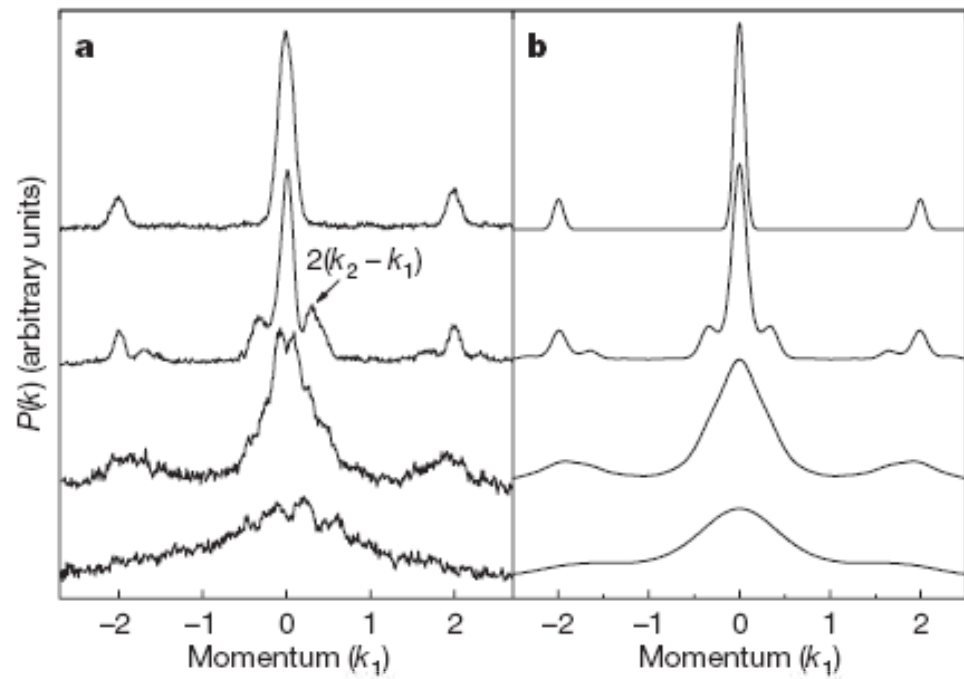
$$H = -J \sum_j (|w_j\rangle\langle w_{j+1}| + |w_{j+1}\rangle\langle w_j|) + \sum_j \epsilon_j |w_j\rangle\langle w_j|$$

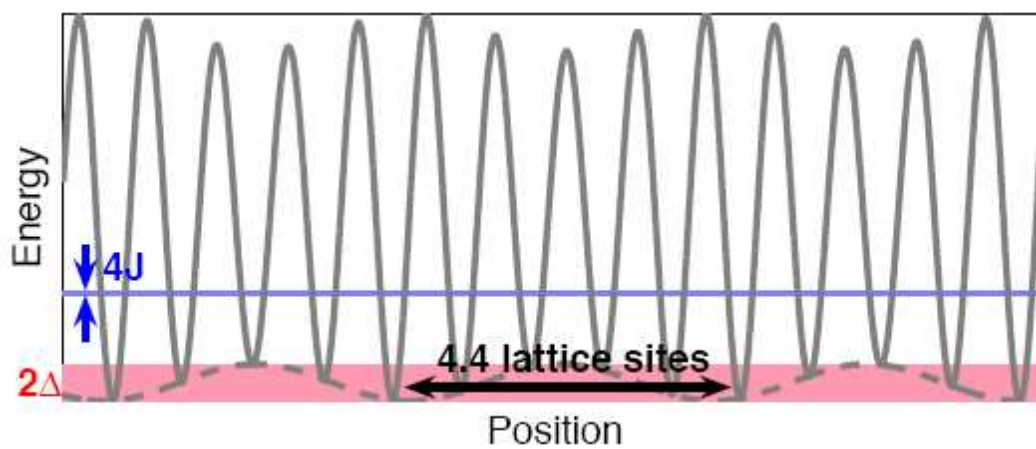
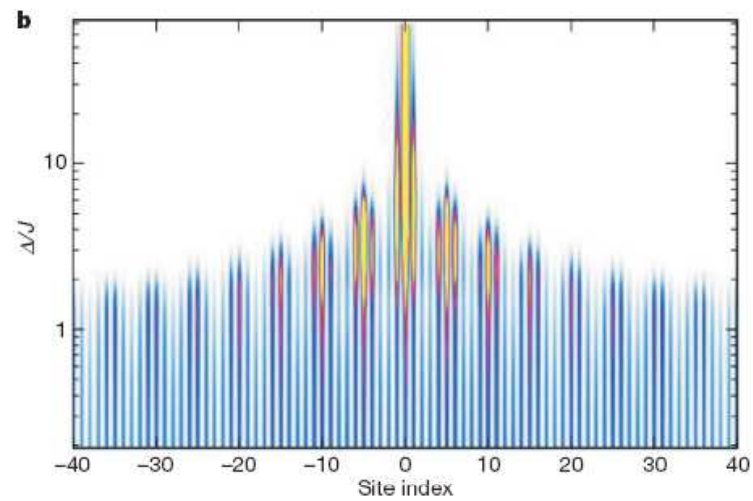
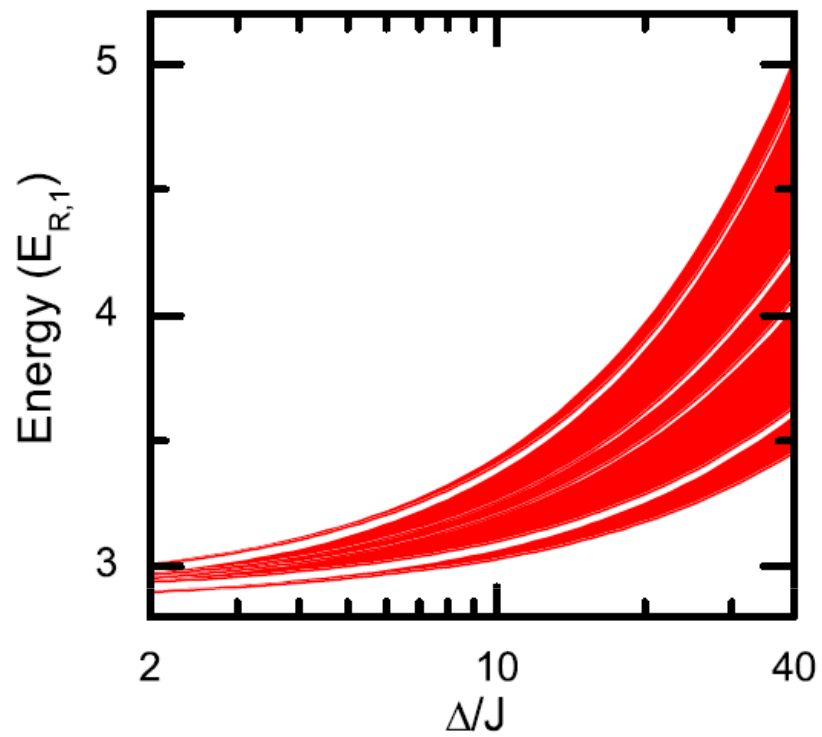


# Exponential localization

$$f_{\alpha}(x) = A \exp(-|(x - x_0)/l|^{\alpha})$$



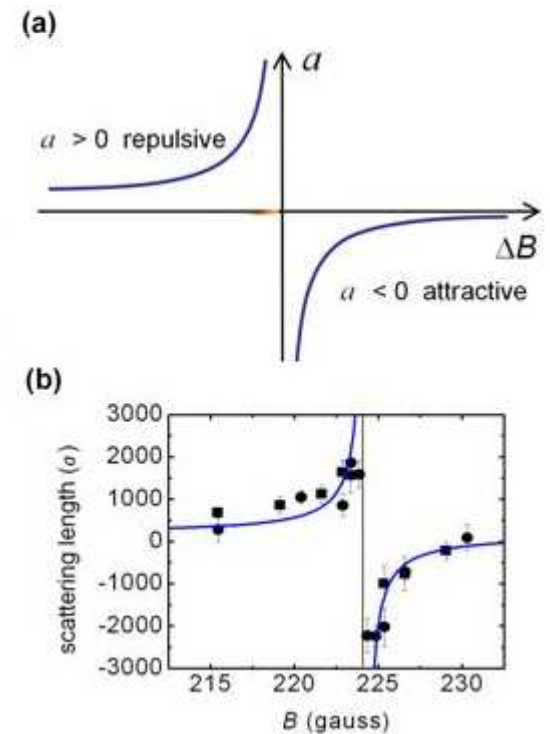
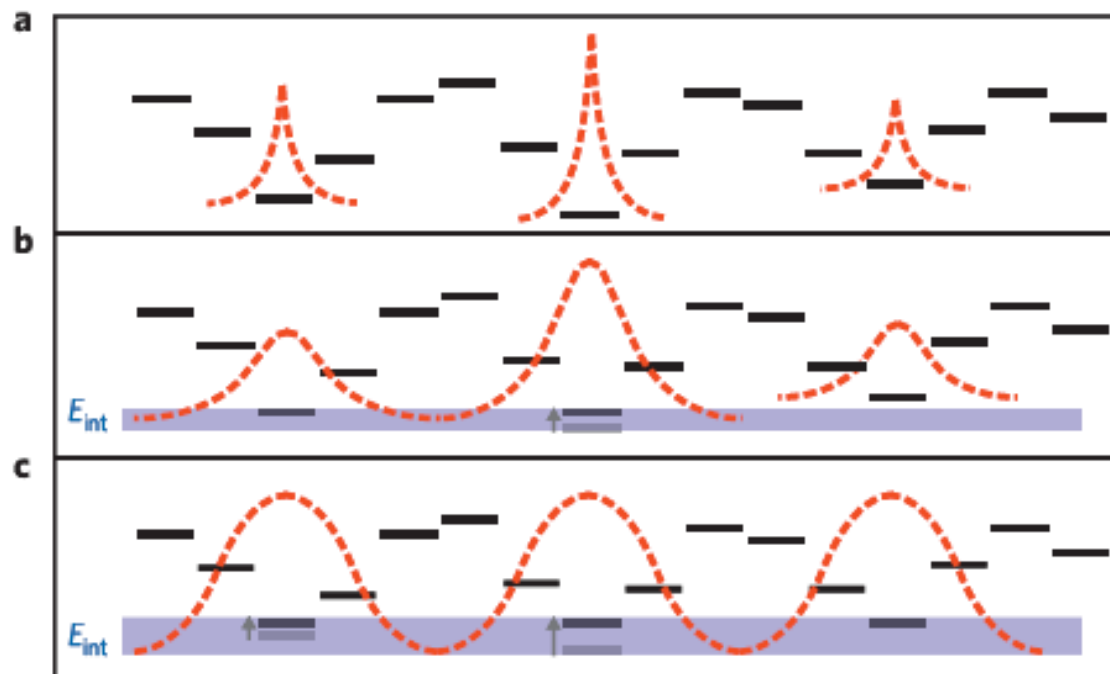


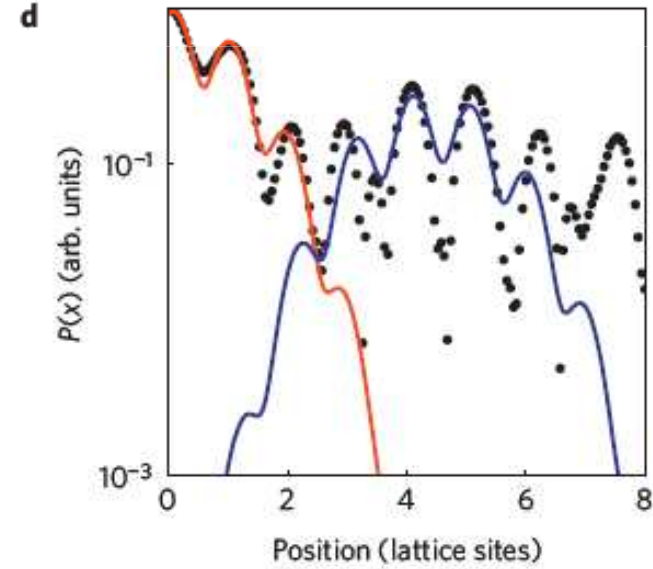
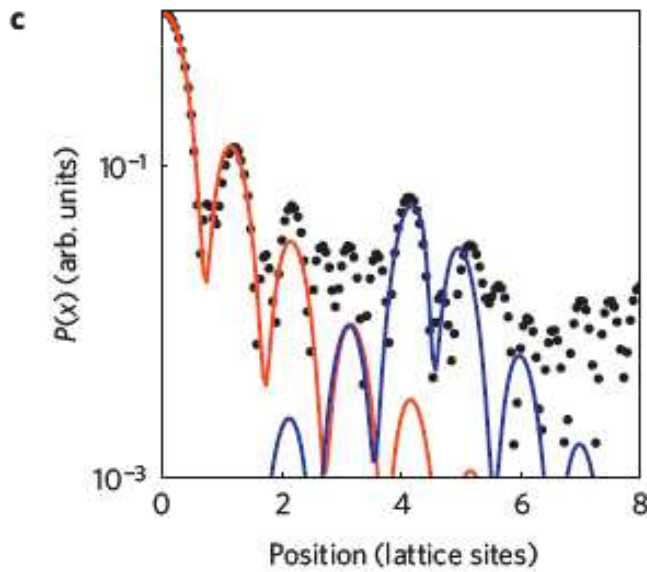
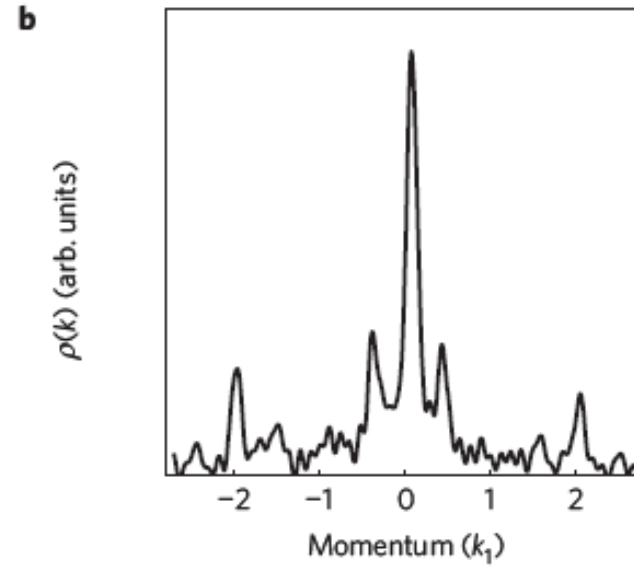
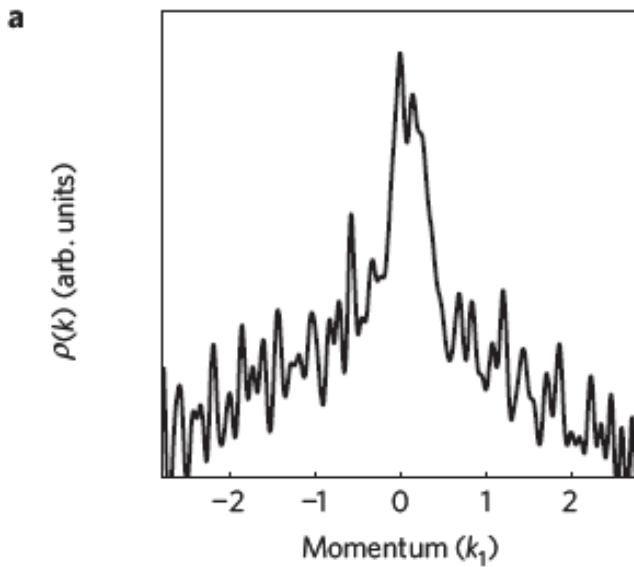


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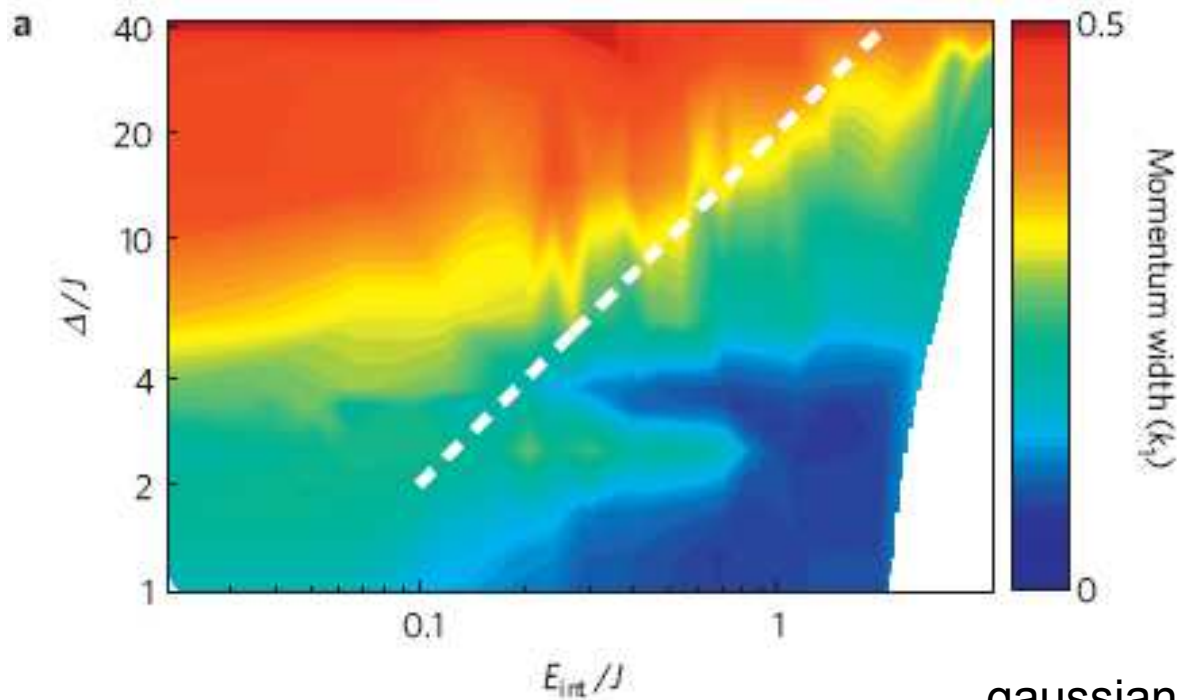
B. Deissler<sup>1\*</sup>, M. Zaccanti<sup>1</sup>, G. Roati<sup>1</sup>, C. D'Errico<sup>1</sup>, M. Fattori<sup>1,2</sup>, M. Modugno<sup>1</sup>, G. Modugno<sup>1</sup>  
and M. Inguscio<sup>1</sup>

- Disorder (localize) vs. Repulsive interactions (delocalize)



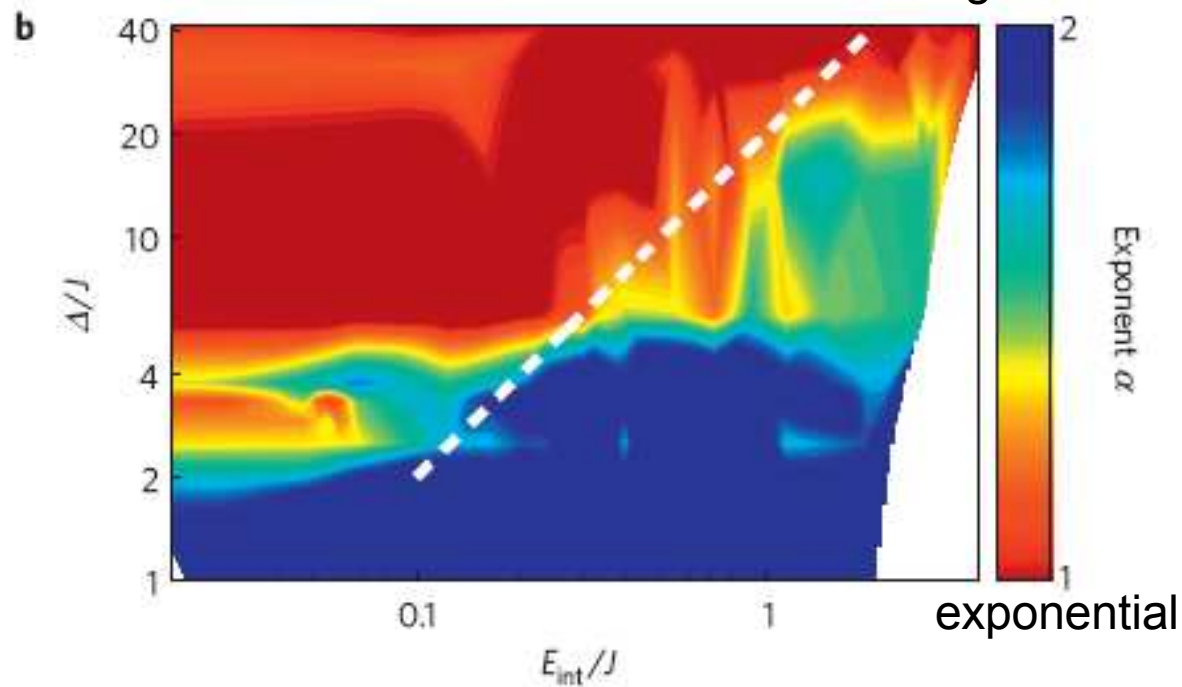


$$A \exp(-|(x - x_c)/L|^\alpha) \cdot [1 + B \cos(k_1(x - x_c) + \delta)],$$

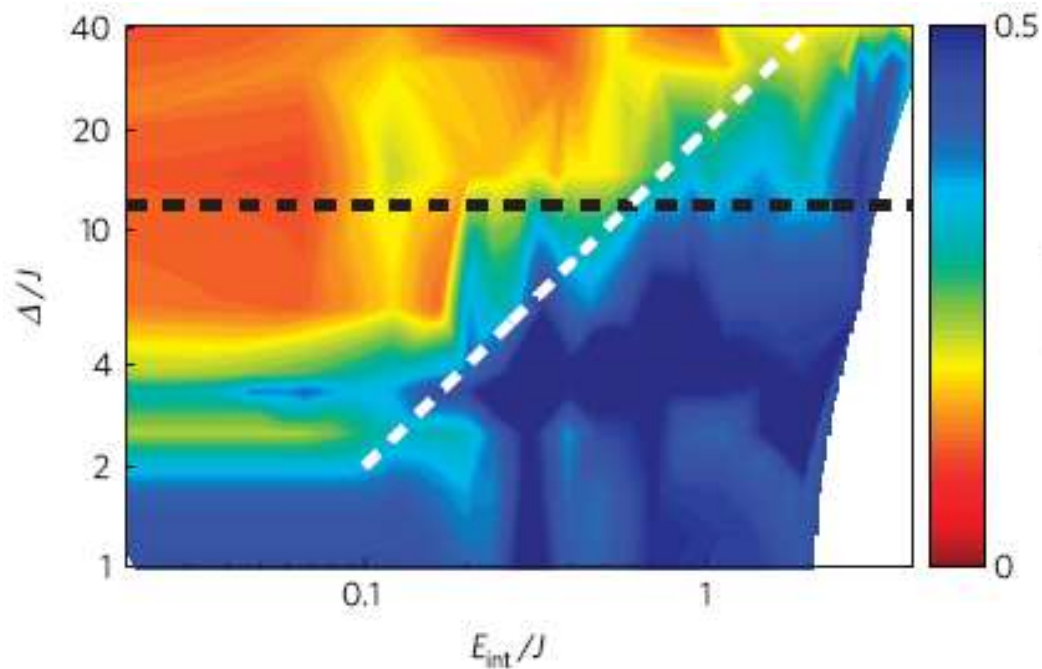


White line:  
screening argument.

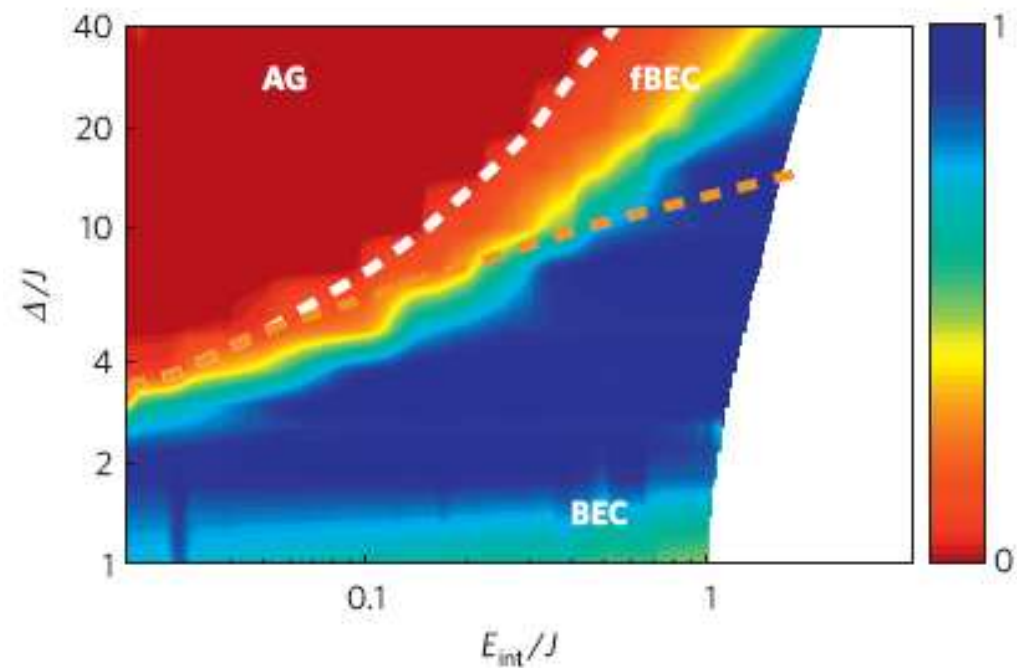
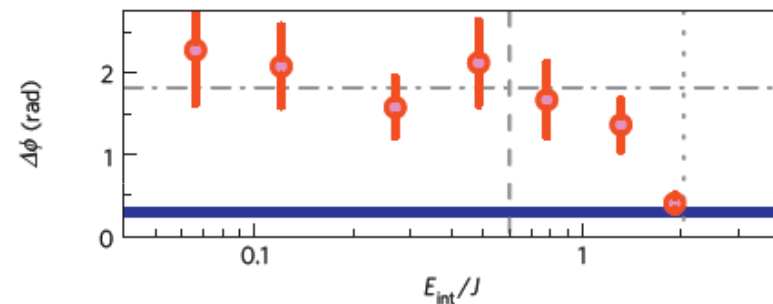
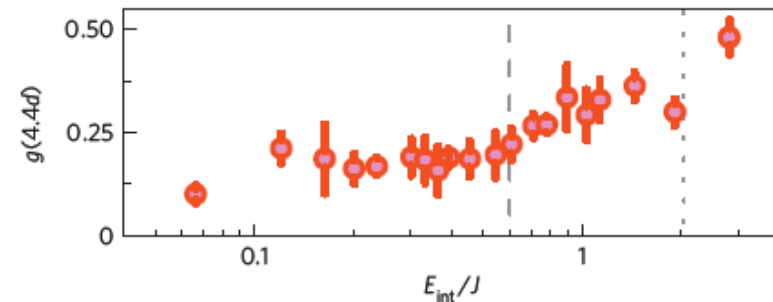
Crossover occurs when  
 $E_{\text{int}} \sim$  standard deviation  
of lowest mini-band of  
non-interacting  
spectrum.



$$E_{\text{int}} = 0.05\Delta$$



$g(4,4d)$



$g(4,4d)$

$$G(x', x+x') = \langle \hat{\Psi}^\dagger(x') \hat{\Psi}(x+x') \rangle$$

$$\rho(k) \propto \mathfrak{F}^{-1} \int G(x', x+x') dx'$$

$$g(x) = \int G(x', x+x') dx'$$

- Anderson localization in a quasi-periodic, 1D lattice
- Mapped out phase diagram, disorder versus interactions
- Observed AG, fBEC, BEC phases.
- Outlook: push to stronger interactions  $E_{\text{int}} \gg J$ ;

