The physics of disorder with a Bose-Einstein condensate

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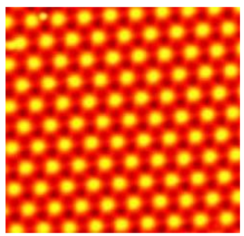
Disorder in quantum systems

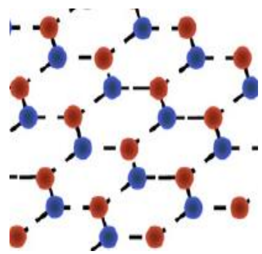
Disorder is ubiquitous in nature
and rules the behavior of many physical systems.

Fundamental phenomena: Anderson localization, interaction vs disorder, strongly-correlated spin glasses, etc.

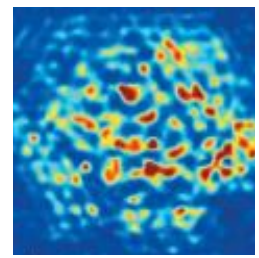
Superfluids
in porous media



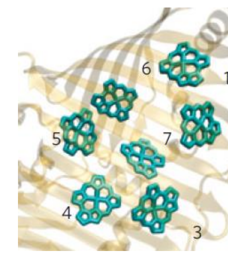
Superconductors



Graphene



Photonic media



Biological systems

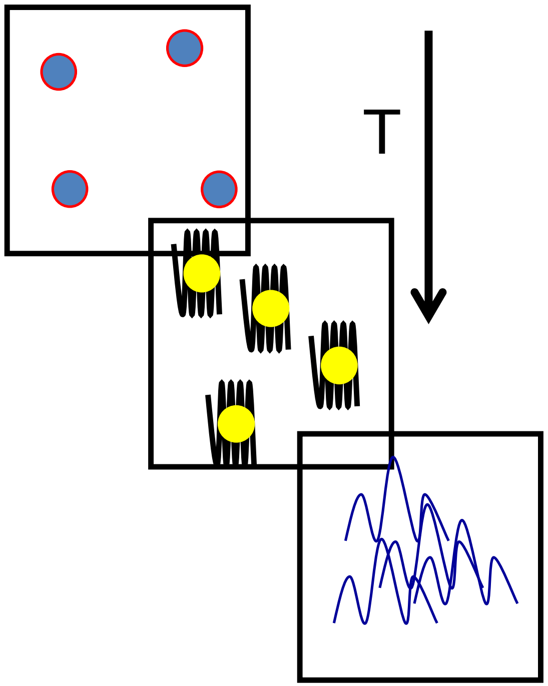
Applications: 2D superconductive films, graphene, photonic media, biological systems, etc.

Ultracold atoms

Quantum gas :

Atoms cooled down to quantum degeneracy

Matter wave with interaction -> superfluidity



Quantum gas experiment :
extremely versatile tool characterized by
good control and large tunability of the system parameters

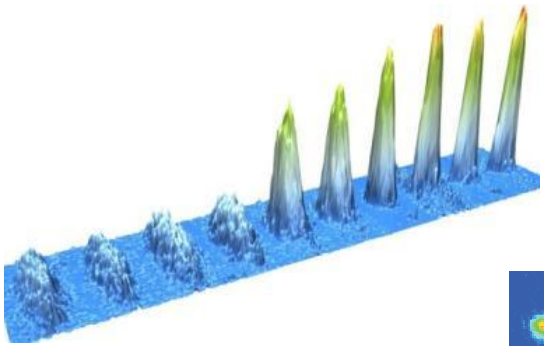
- Statistics (Bosons or fermions)
- Dimensionality (1D, 2D, 3D)
- Shaping of the potential (optical potentials)
- Control and tune of the interactions (attractive/repulsive, short/long range)

The physics of disorder with ultracold atoms

Disorder is hard to model in theory and to control and tune in both real and experimental systems.

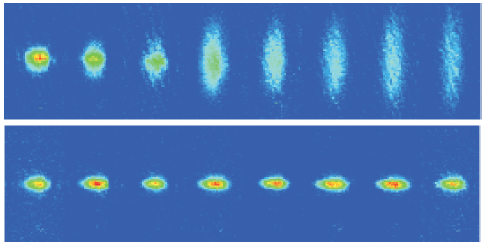
Paricularly challenging is the study of the combined effect of disorder and interactions.

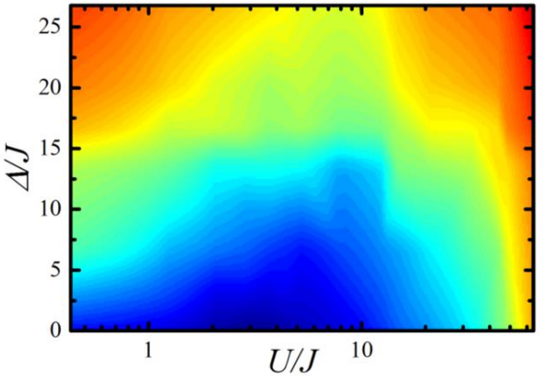
Disorder in Florence!



Anderson localization of matter waves

Transport in a disordered interacting system





Glassy phases of disordered interaction bosons

Reviews: A. Aspect and M. Inguscio, Physics Today 62, 30 (2009);
L. Sanchez-Palencia and M. Lewenstein, Nat. Phys. 6, 87 (2010); G. Modugno, Rep. Progr. Phys. 73, 102401 (2010).

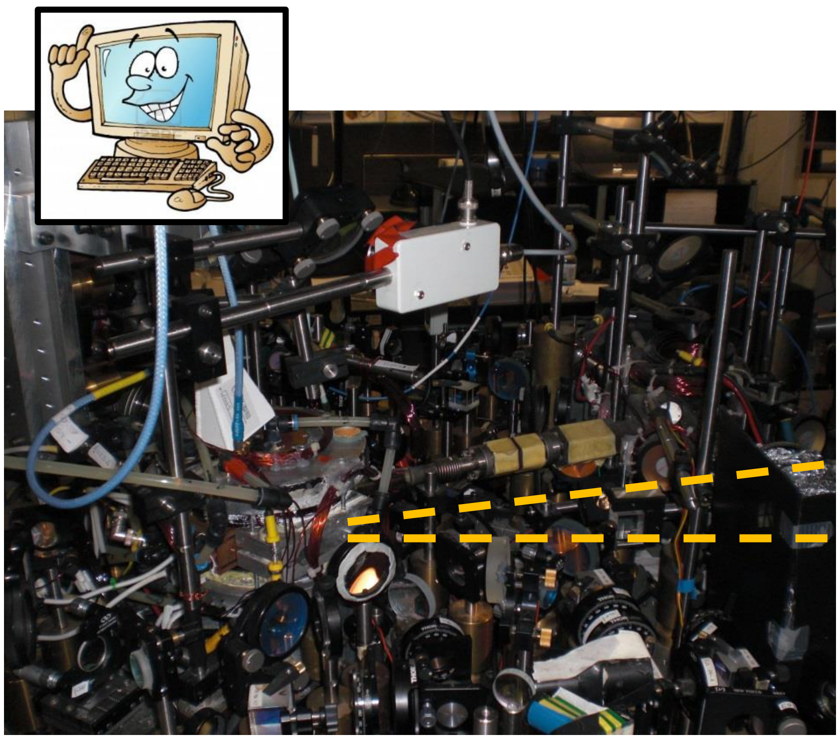
Quantum simulations with cold atoms

Solutions of Hamiltonians in the laboratory

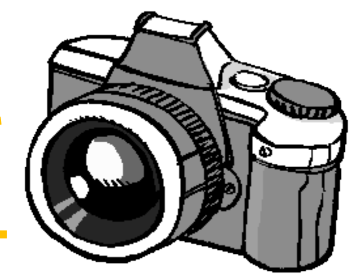
$$H\psi = E\psi$$

Ex: 1D Disordered Bose-Hubbard Hamiltonian

$$H = -J\sum_i \left(b_i^\dagger b_{i+1} + h.c.\right) + \Delta \sum_i \cos(2\pi\beta i)\, n_i + \frac{U}{2}\sum_i n_i(n_i - 1)$$



Direct access to the solutions
in both real and momentum space
and probing of the excitation spectrum

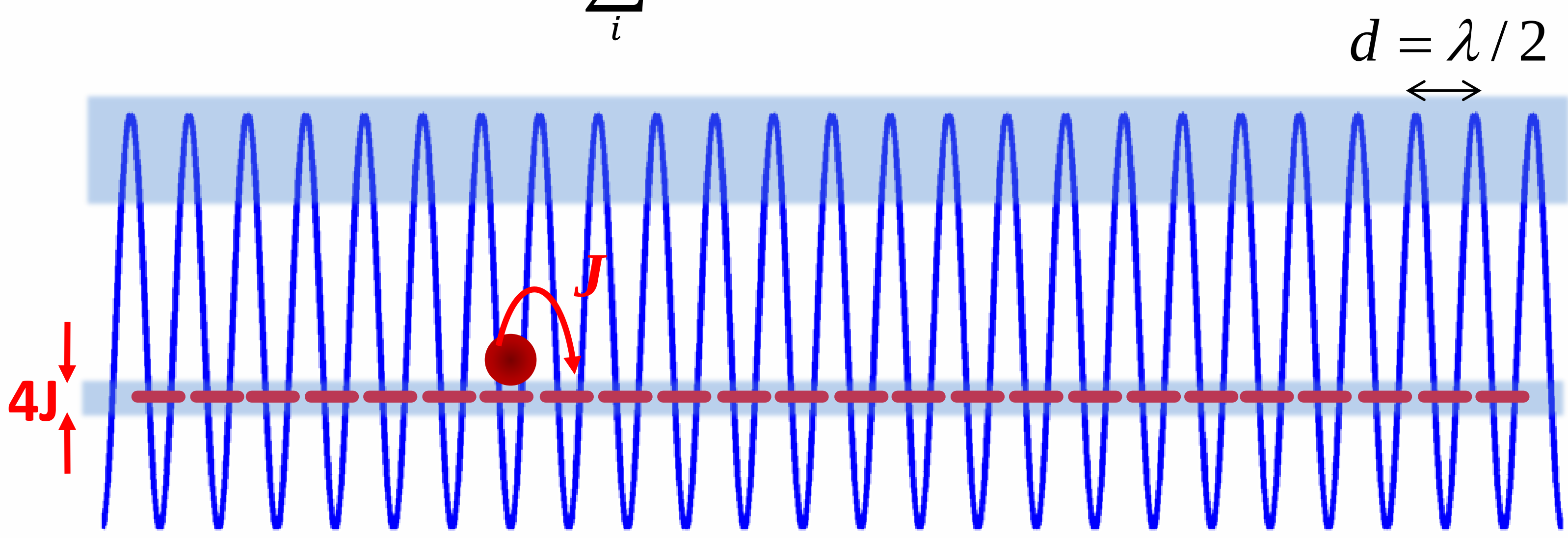


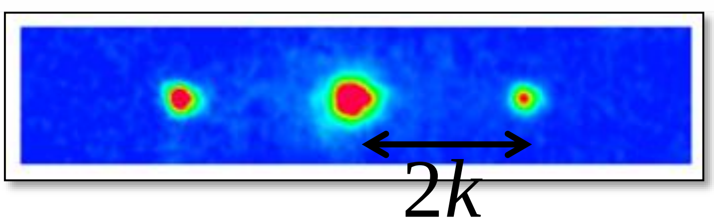
Optical lattice

Using laser light it is possible to shape conservative potentials for neutral atoms at will, exploiting the dipole interaction between the electromagnetic field and the induced atomic dipolar momentum:

A standing wave provides a perfect periodical potential

Tigth binding limit: $H = -J \sum_i (b_i^\dagger b_{i+1} + h.c.)$





$$k = \frac{2\pi}{\lambda}$$

Disordered Optical lattice

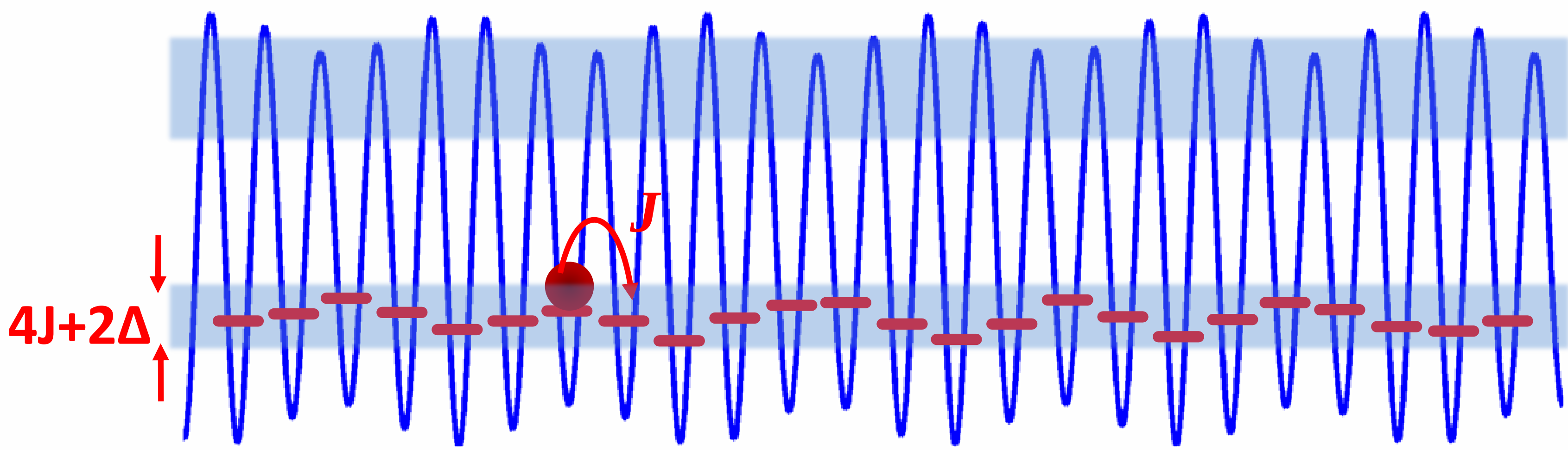
Quasiperiodic potential:
Aubry-André Hamiltomial

$$H = -J \sum_i \left(b_i^\dagger b_{i+1} + h.c.\right) + \Delta \sum_i \cos(2\pi\beta i)\, n_i$$

$$\beta = \frac{\lambda_1}{\lambda_2}$$

Set J by fixing the strenght of the primary lattice

Tune disorder by varying the strenght of the secondary lattice

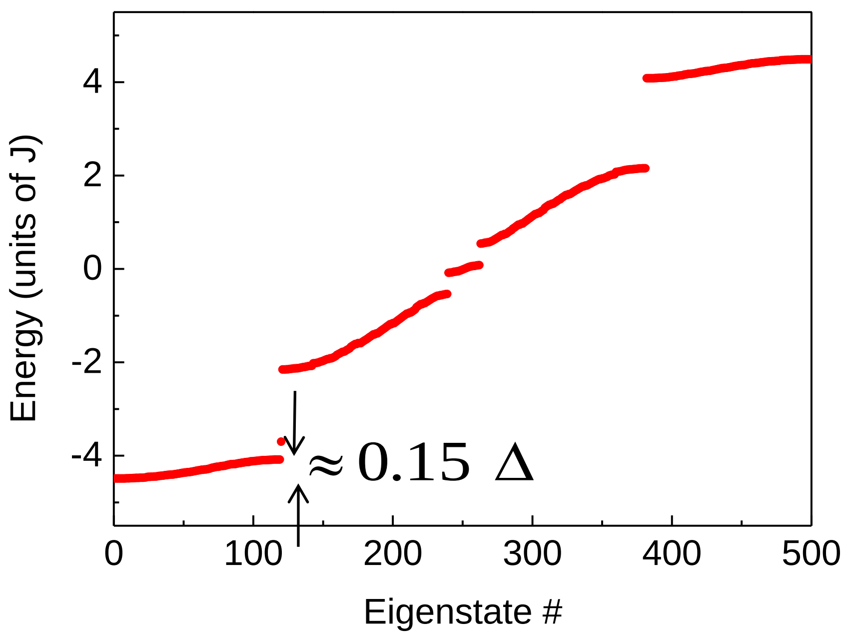


Anderson localization in the quasiperiodic potential

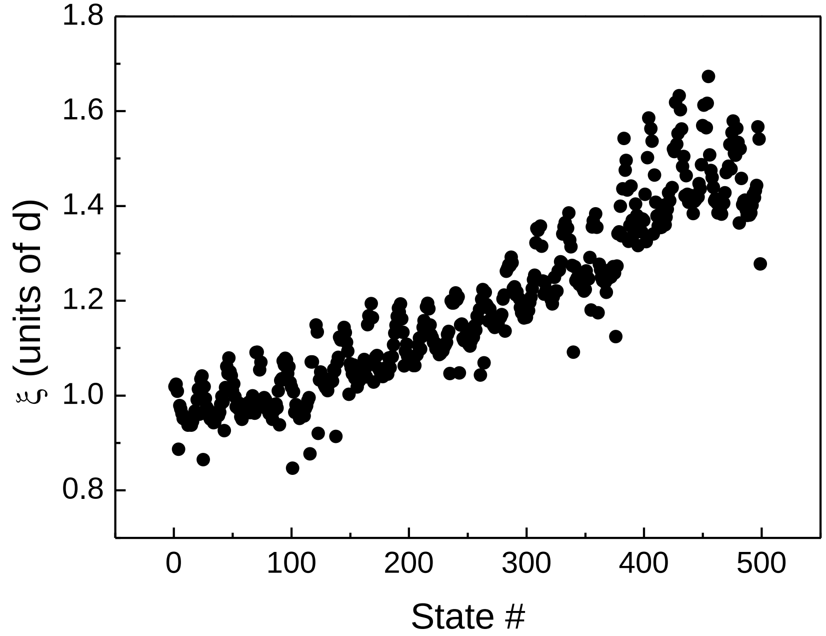
$$H = -J\sum_i \left(b_i^\dagger b_{i+1} + h.c.\right) + \Delta \sum_i \cos(2\pi\beta i)\, n_i$$

Quasiperiodic potential: localization transition at $\Delta = 2J$

Eigenvalues: miniband structure



Eigenfunction: exponential decay



Short, uniform localization length:

$$\xi \approx d / \log(\Delta / 2J)$$

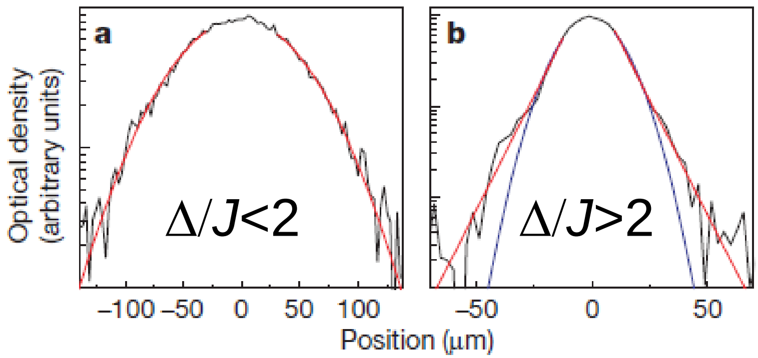
S. Aubry and G. André, Ann. Israel Phys. Soc. **3**, 133 (1980);
M. Modugno, New J. Phys. **11,** 033023 (2009)

Anderson localization in the quasiperiodic potential

$$H = -J\sum_i \left(b_i^\dagger b_{i+1} + h.c.\right) + \Delta \sum_i \cos(2\pi\beta i)\, n_i$$

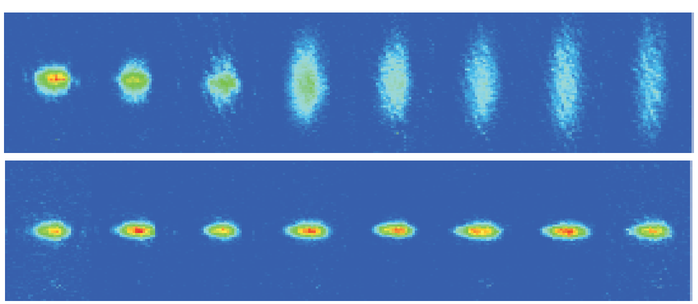
Quasiperiodic potential: localization transition at $\Delta = 2J$

$|\Psi(x)|^2$ Density distribution:

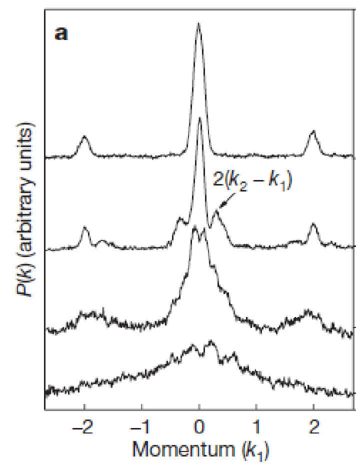


Δ/J<2

Δ/J>2

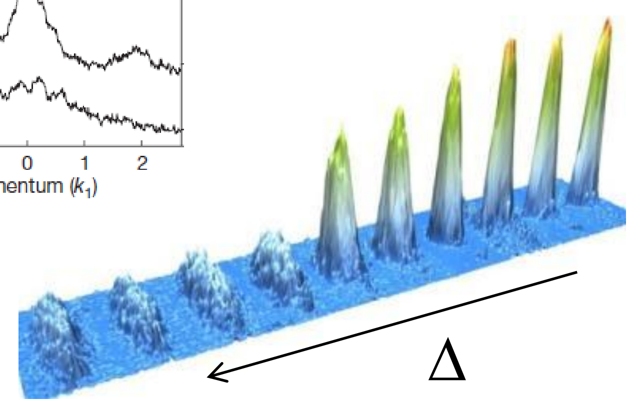


time



$|\Psi(k)|^2$

Momentum distribution



G.Roati et. al., Nature **453**, 895 (2008)

Anderson localization in the quasiperiodic potential

FT

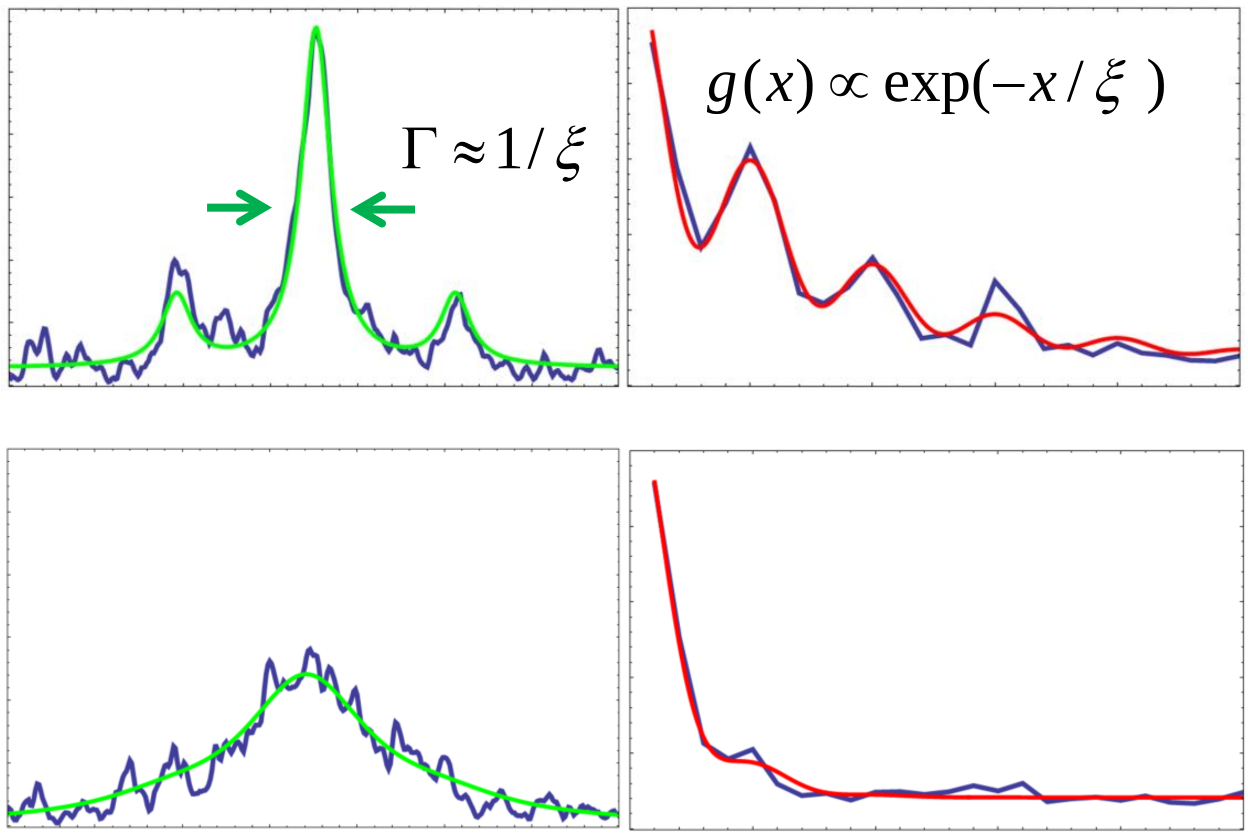
$$|\Psi(k)|^2 \qquad g(x)=\int dx'\left\langle \Psi^{+}(x)\Psi(x+x')\right\rangle$$

Momentum distribution

Spatially averaged correlation function

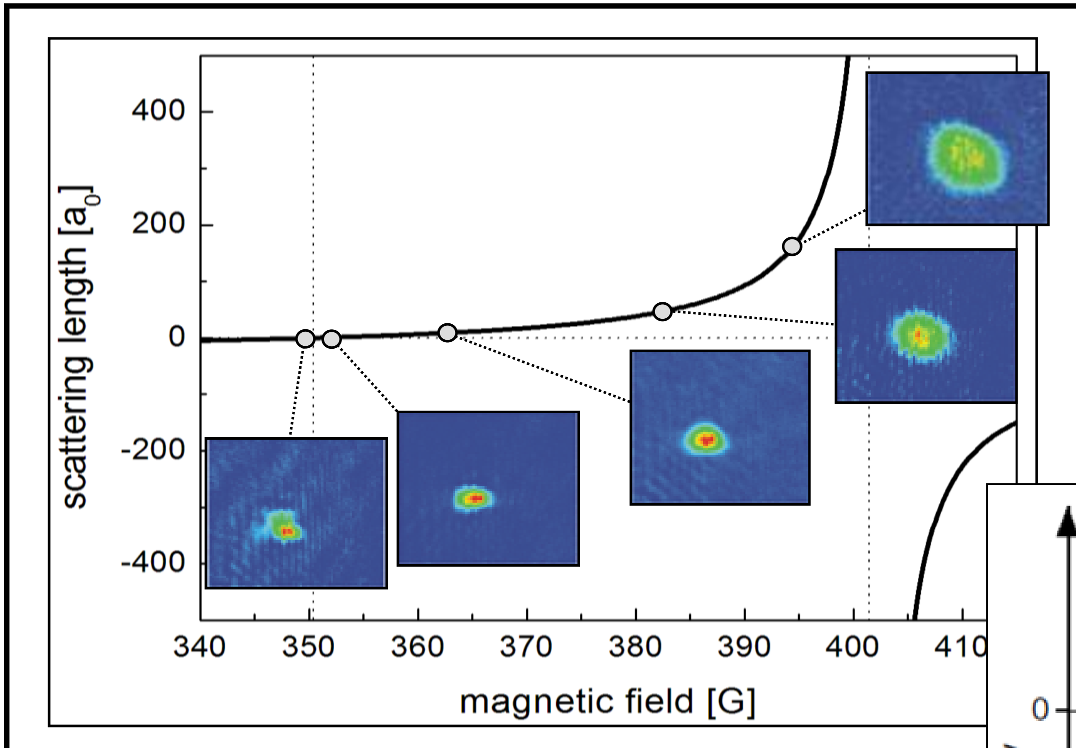
$\Delta<2J$
Coherent extended state

$\Delta>2J$
Incoherent localized state



G.Roati et. al., Nature **453**, 895 (2008)

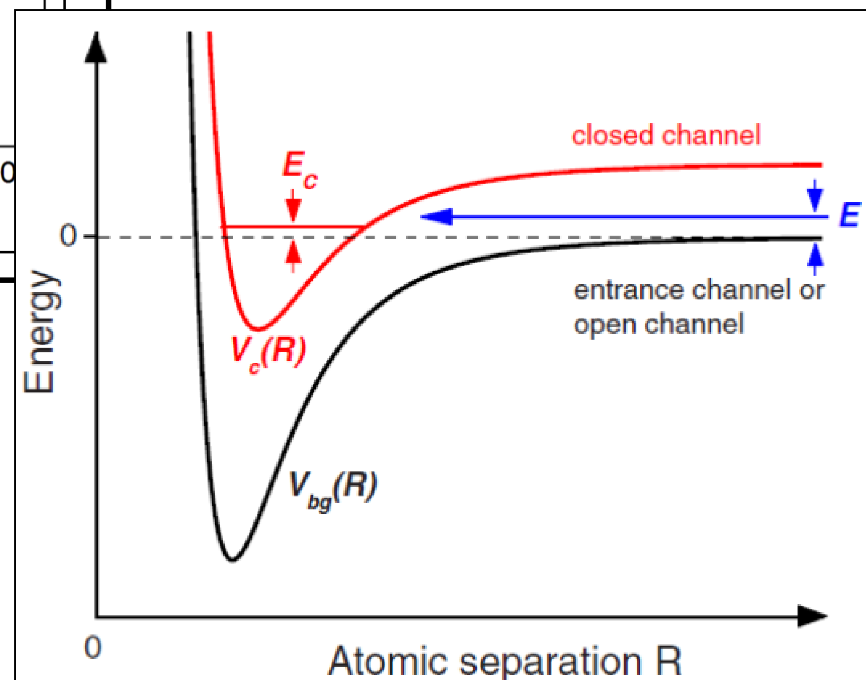
Interaction tuning: Feshbach resonance



Two-body interaction potential: contact interaction

$$v(r-r') = \frac{4\pi\hbar^2}{m} a\,\delta(r-r')$$

s-wave scattering length



^{39}K atoms:
broad magnetic Feshbach resonance

G. Roati *et al.*, Phys. Rev. Lett. **99**, 010403 (2007)

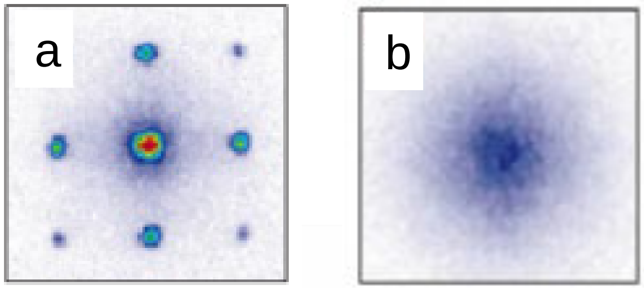
Interaction in the lattice

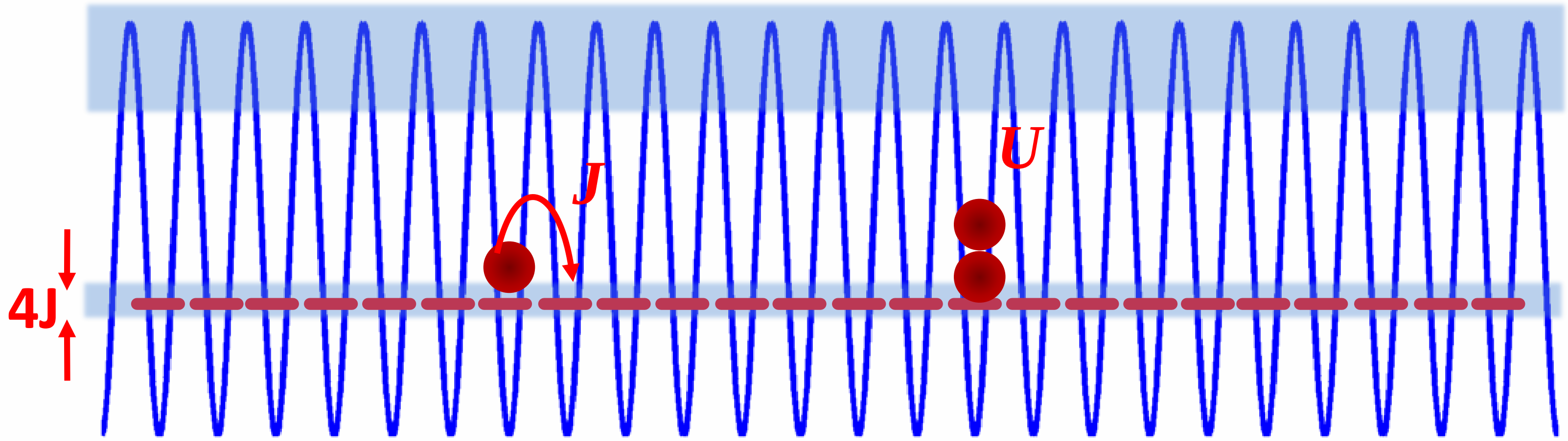
Bose-Hubbard Hamiltonian

$$H = -J\sum_i (b_i^\dagger b_{i+1} + h.c.) + \frac{U}{2}\sum_i n_i(n_i - 1)$$

$$U = \frac{4\pi\hbar^2}{m} a \int |\varphi(x)|^4 \, d^3x$$

Mott insulator transition





M. Greiner et al., Nature 415, 39 (2002)

Disordered Bose-Hubbard

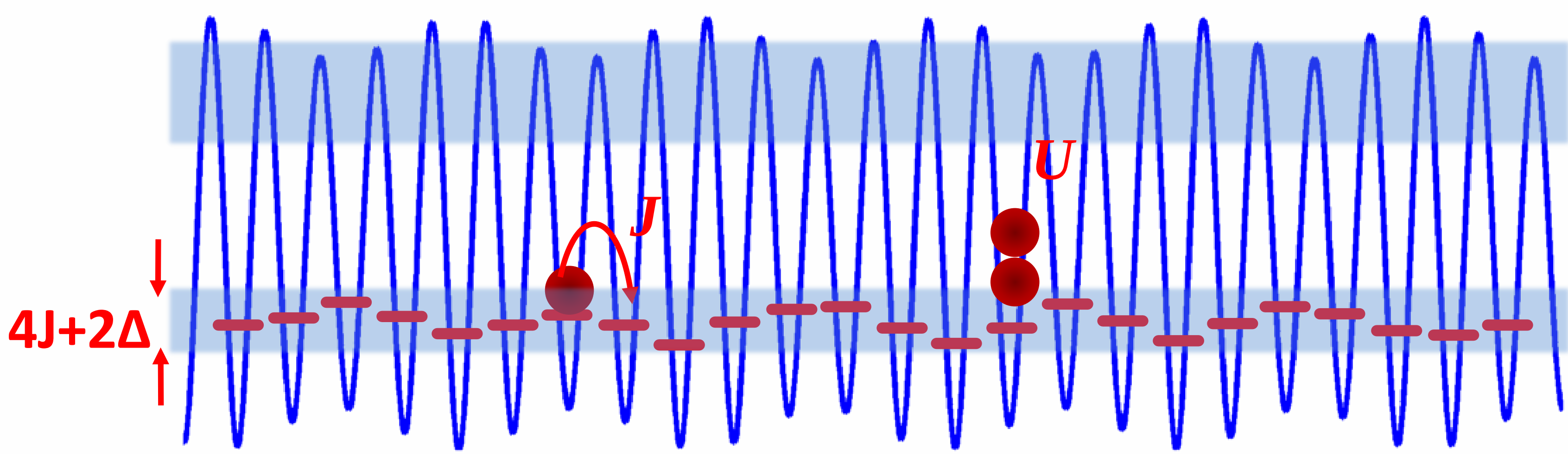
^{39}K bosonic atoms with controlled interaparticle repulsive interactions in a quasiperiodic lattice potential

$$H = -J\sum_i (b_i^\dagger b_{i+1} + h.c.) + \Delta \sum_i \cos(2\pi\beta i)\, n_i + \frac{U}{2}\sum_i n_i(n_i - 1)$$

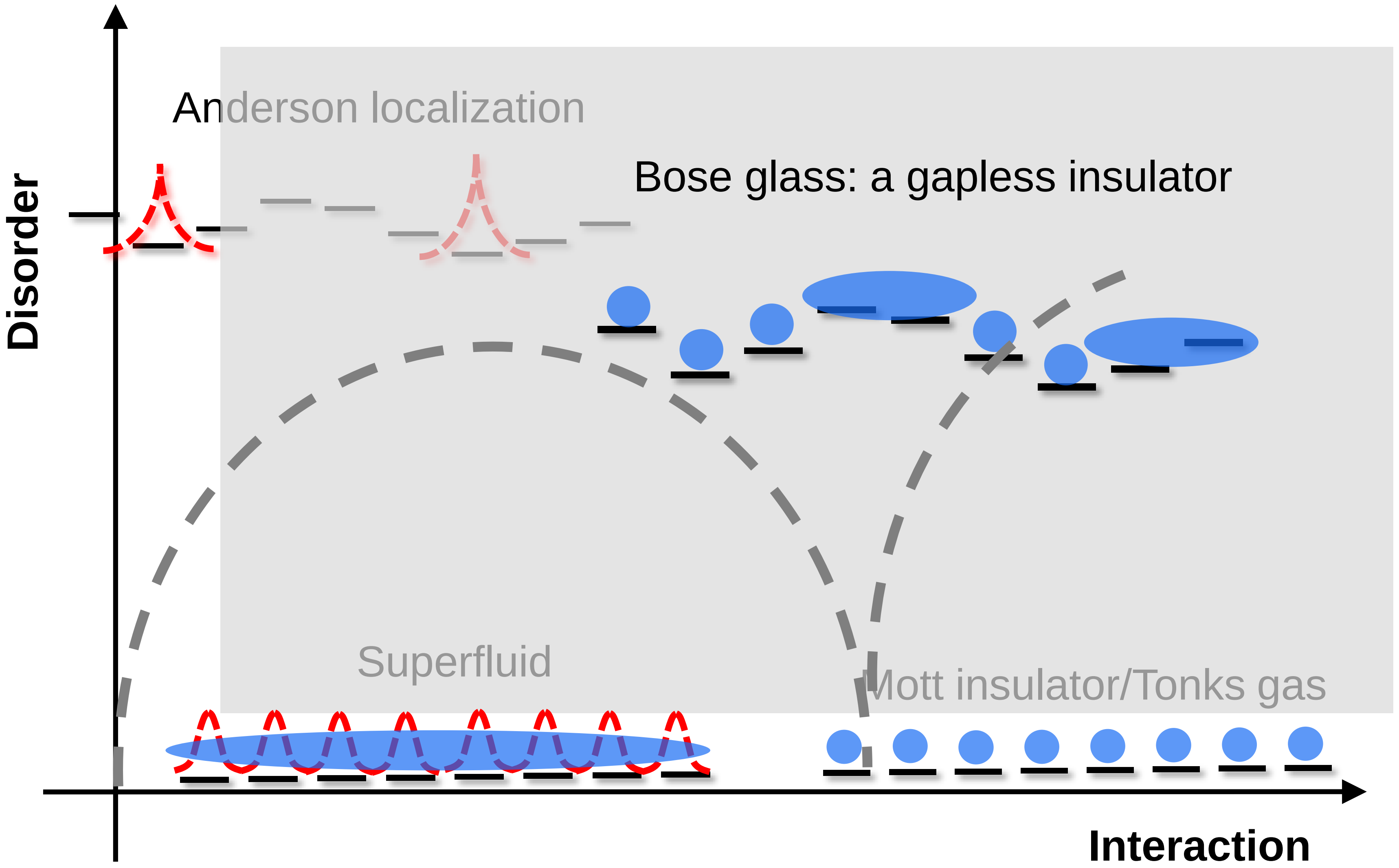
Set J by fixing the strenght of the primary lattice

Tune disorder by varying the strenght of the secondary lattice

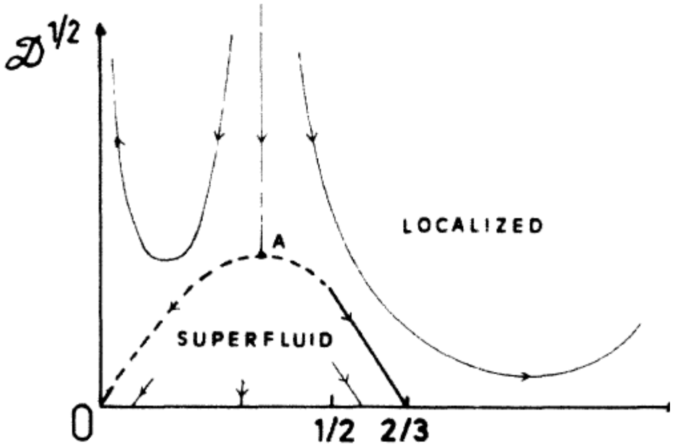
Tune interaction by varying the external magnetic field



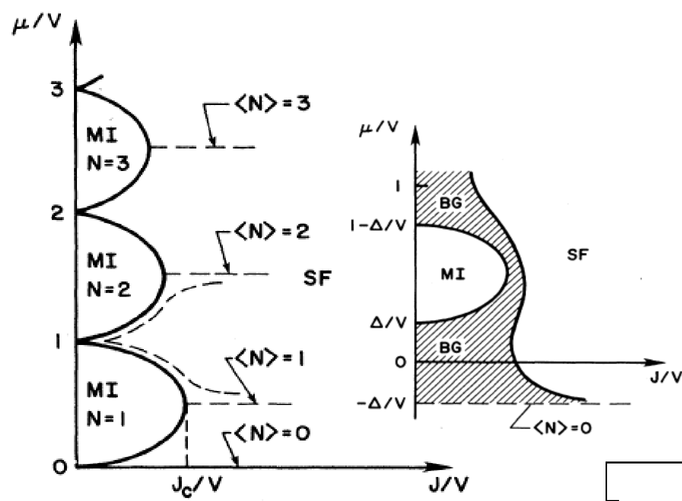
Quantum phases across the Δ-U diagram



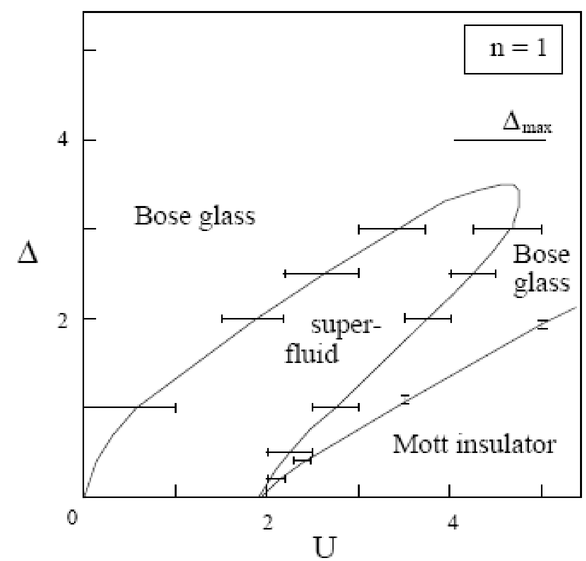
1D disordered interacting bosons



Giamarchi & Schultz,
PRB 37 325 (1988)



Fisher et al
PRB 40, 546 (1989)

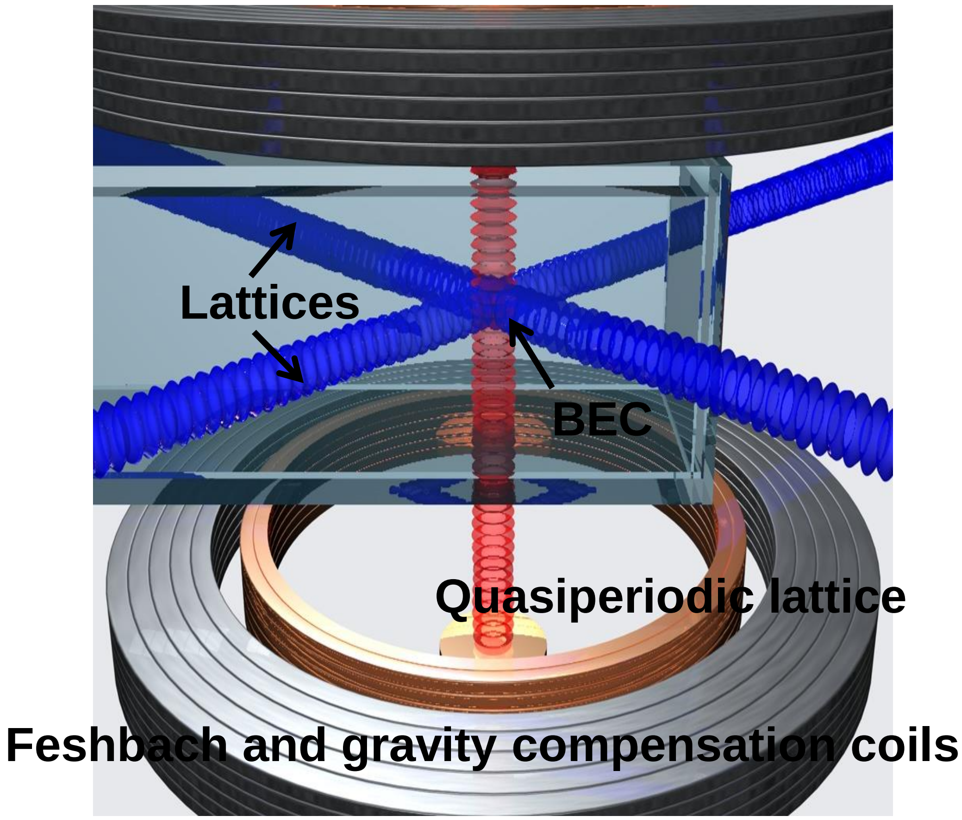


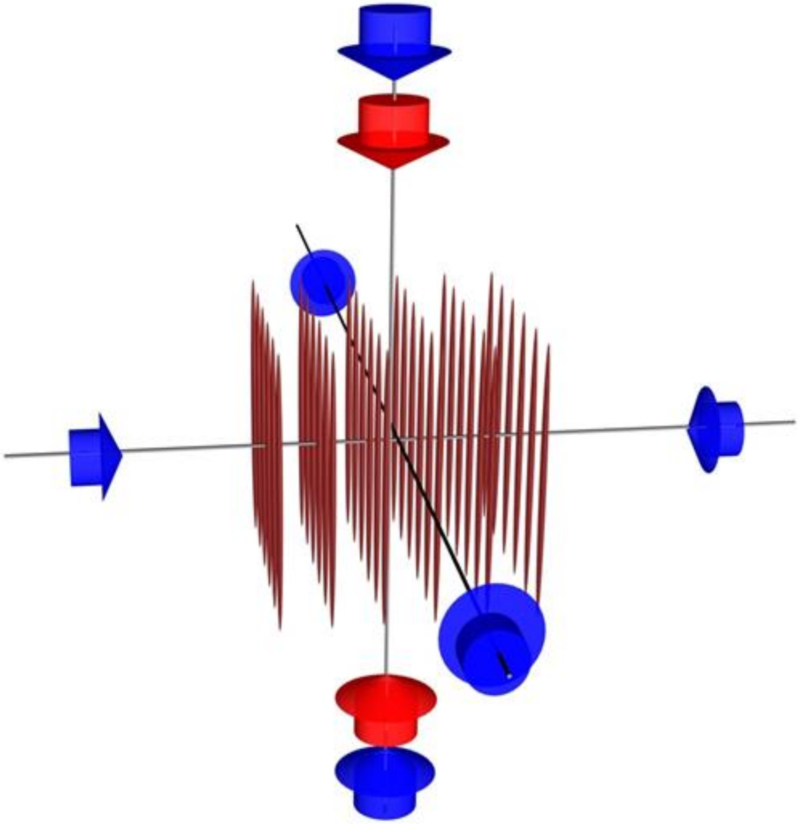
Rapsch, et al.EPL 46 559 (1999)

One dimensional bosons are the prototype disordered systems, with an established theoretical framework.

And many others (1988-2013)…

Experimental configuration: 1D systems





Radial energy much larger than any other energy: ν_r=50 kHz; J/h=100 Hz

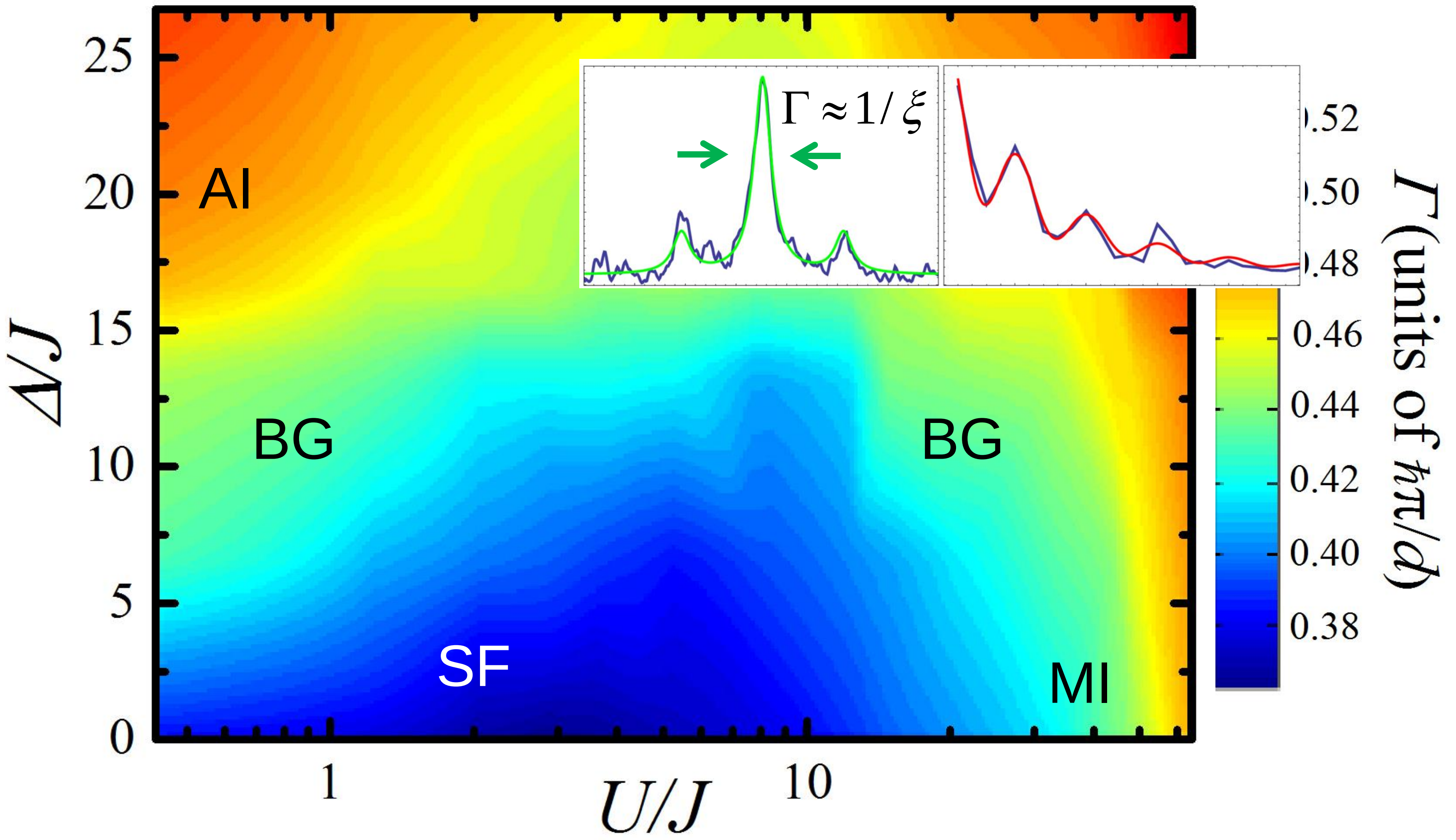
Experimental results

- Investigation of the Δ-U diagram
  and comparison with zero-temperature theory
  C. D'Errico, E. Lucioni et al., submitted

- Transport instability at the fluid-insulator transition
  L. Tanzi et al., Phys. Rev. Lett. (2013)

- Induced expansion dymanics in a disorder-localized system
  E. Lucioni et al., Phys. Rev. Lett. 106, 23 (2011)
  E. Lucioni et al., Phys. Rev. E 87, 042922 (2013)
  C. D'Errico et al., New J. Phys.15, 045007 (2013)

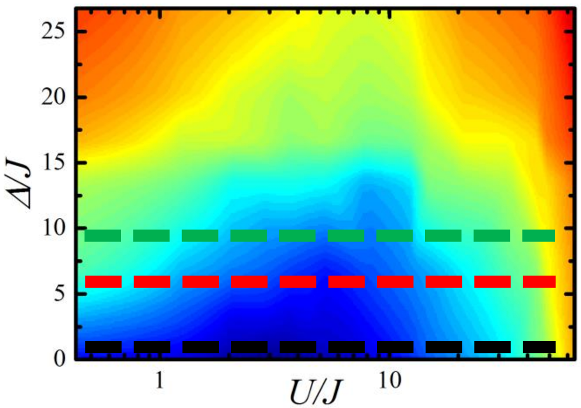
Δ-U diagram: coherence measurements

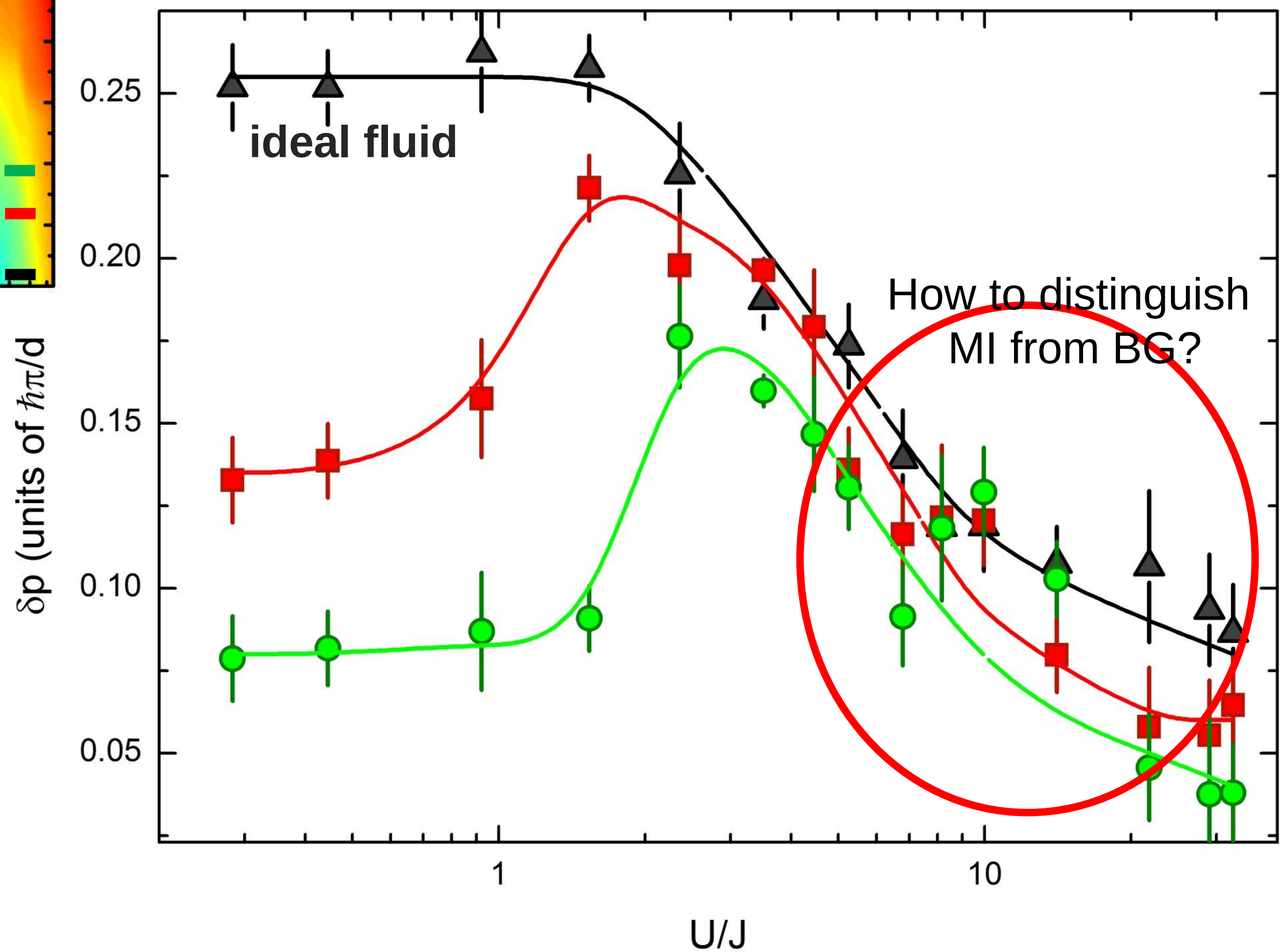


- Finite size systems
- Non-uniform density

Transitions → Crossovers

Incoherent phases are insulating: transport

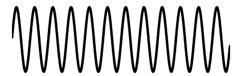




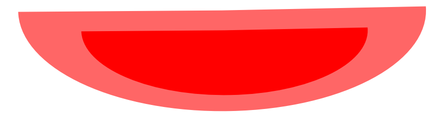
Evidence of a strongly correlate BG: spectra

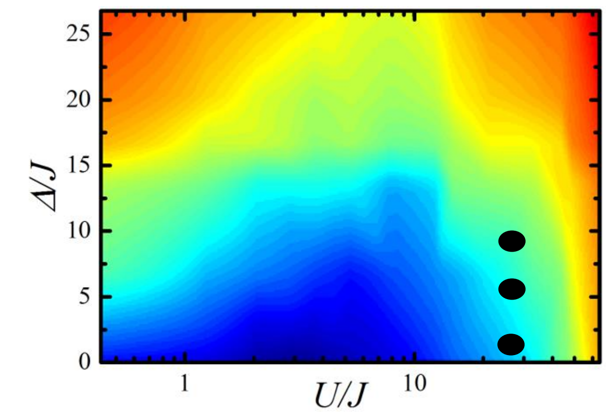
prepare in equilibrium

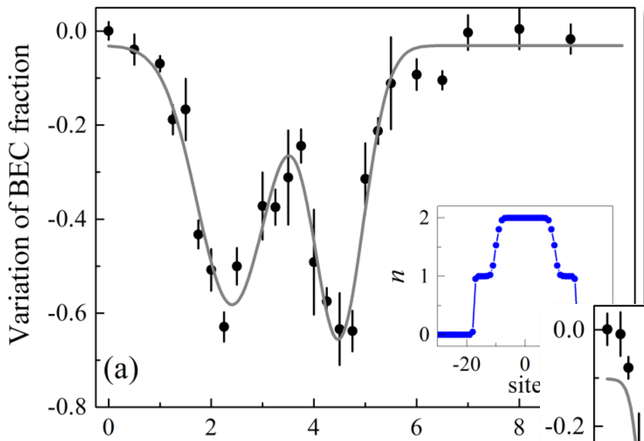
main lattice modulation
(15%, 200ms)

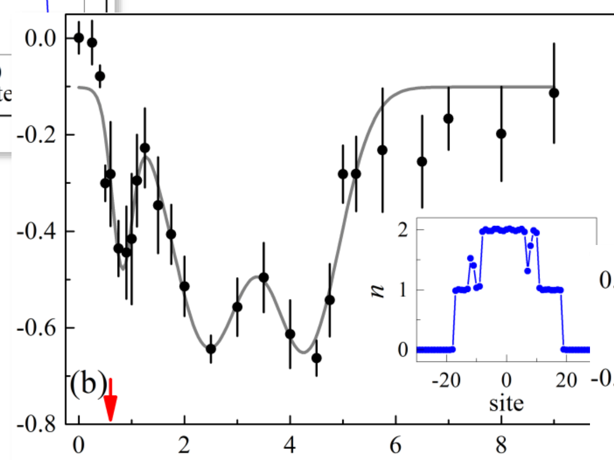


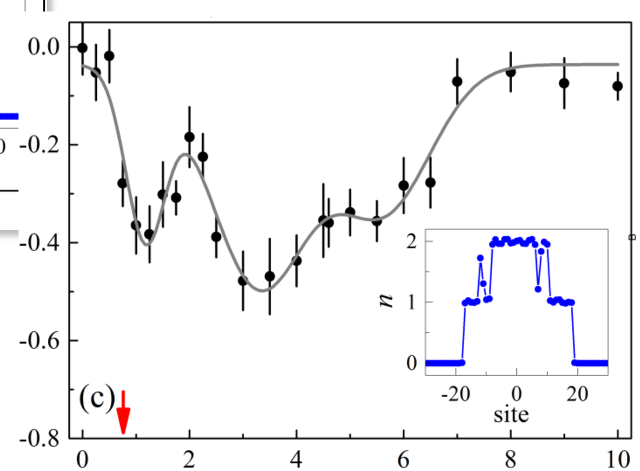
“energy” measurement











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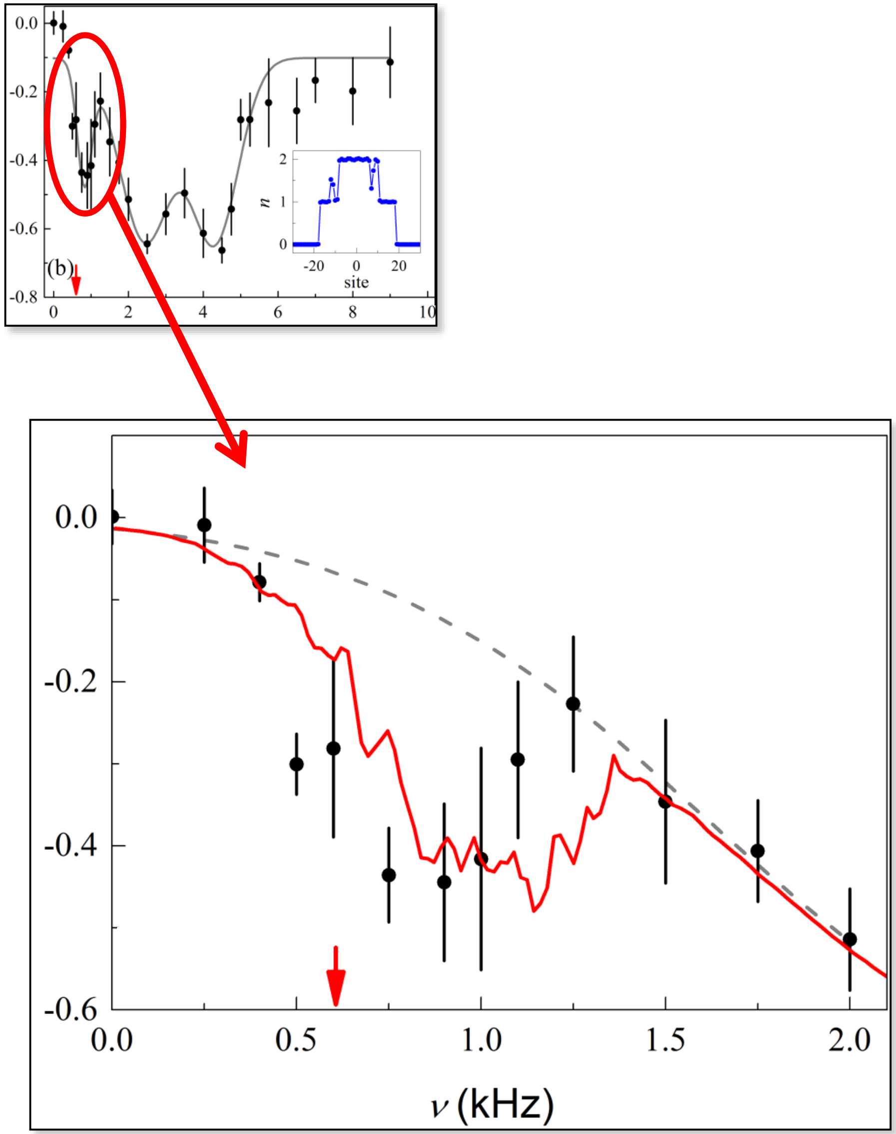
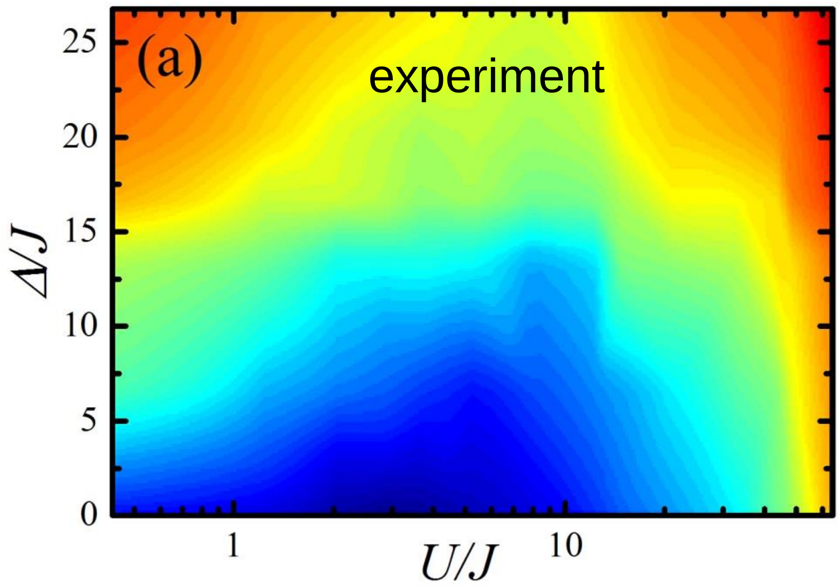


We calculate the energy absorption rate:

Response of non-interacting fermions: the strongly-correlated SF is Anderson-localized by disorder.

G. Orso *et al.*, Phys. Rev. A 80 033625 (2009)

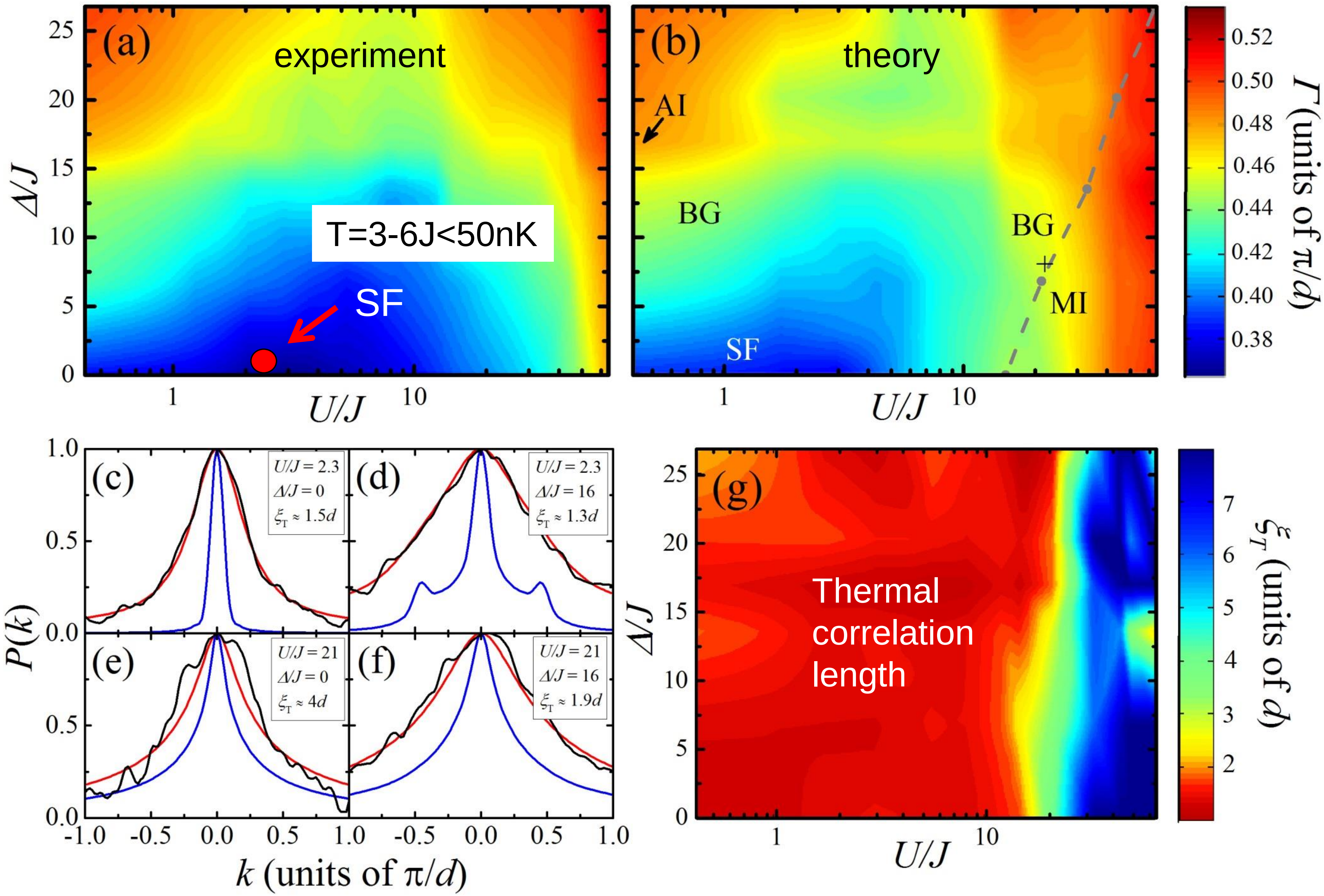
Connection between zero-T theory and experiment



We fit a thermal broadening of $P(k)$ that corresponds to an exponential decay of the correlation function $g(x)$ with thermal length ξ_T

$$g_T(x) \propto \exp(-x/\xi_T)$$

Connection between zero-T theory and experiment



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  C. D'Errico, E.Lucioni et al., submitted

  Reentrance of the Bose glass from coherence measurements
  Evidence of a strongly correlated BG from the excitation spectra
  Connection with zero-temperature phase diagram

- Transport instability at the fluid-insulator transition:

  L. Tanzi et al., Phys. Rev. Lett. (2013)

- Induced expansion dymanics in a disorder-localized system:

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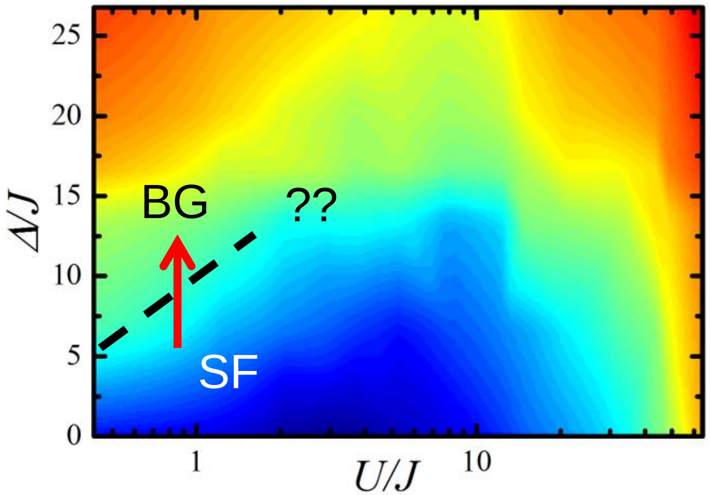
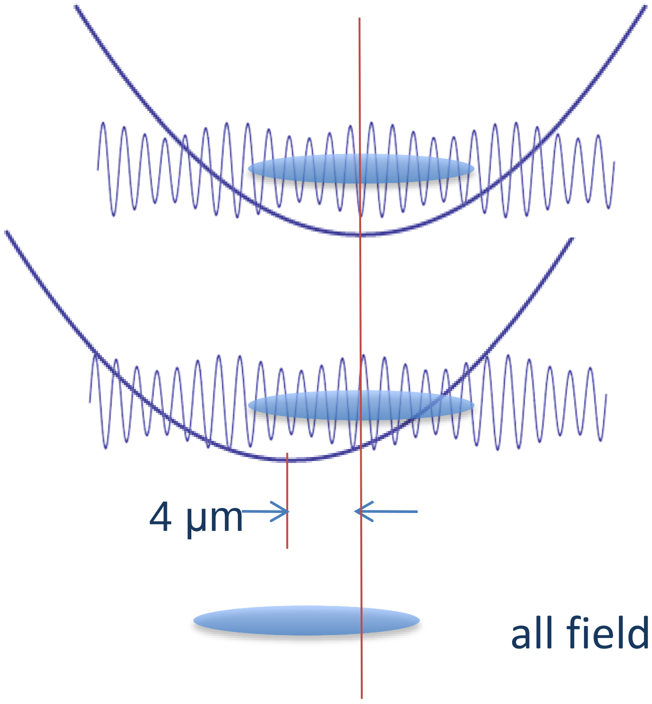
  C. D'Errico et al., New J. Phys.15, 045007 (2013)

Transport measurements at the SF-BG transition

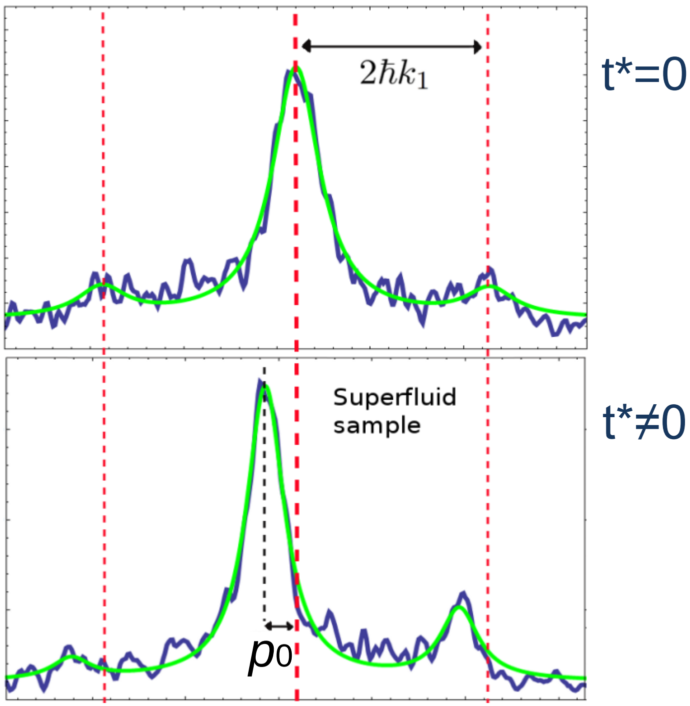




System at equilibrium

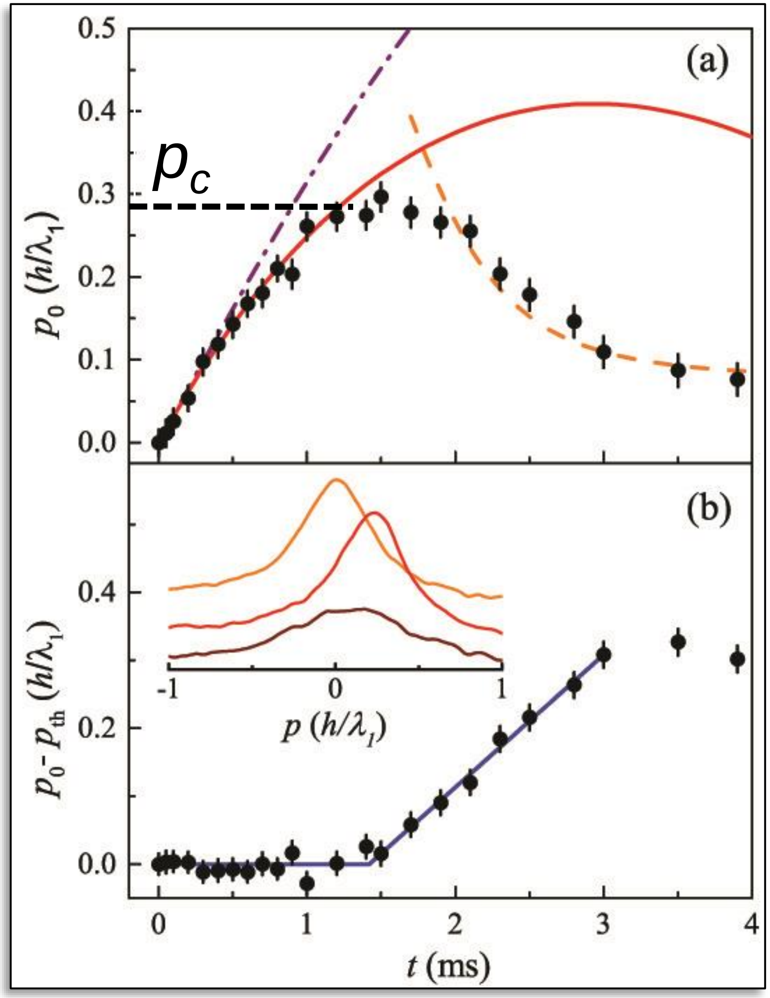
t=0
trap minimum is shifted

t=t*
all fields are switched off



TOF image (16.6 ms)

Critical momentum in the clean lattice



U/J=1.5
n=3.5

Existence of a critical moment:

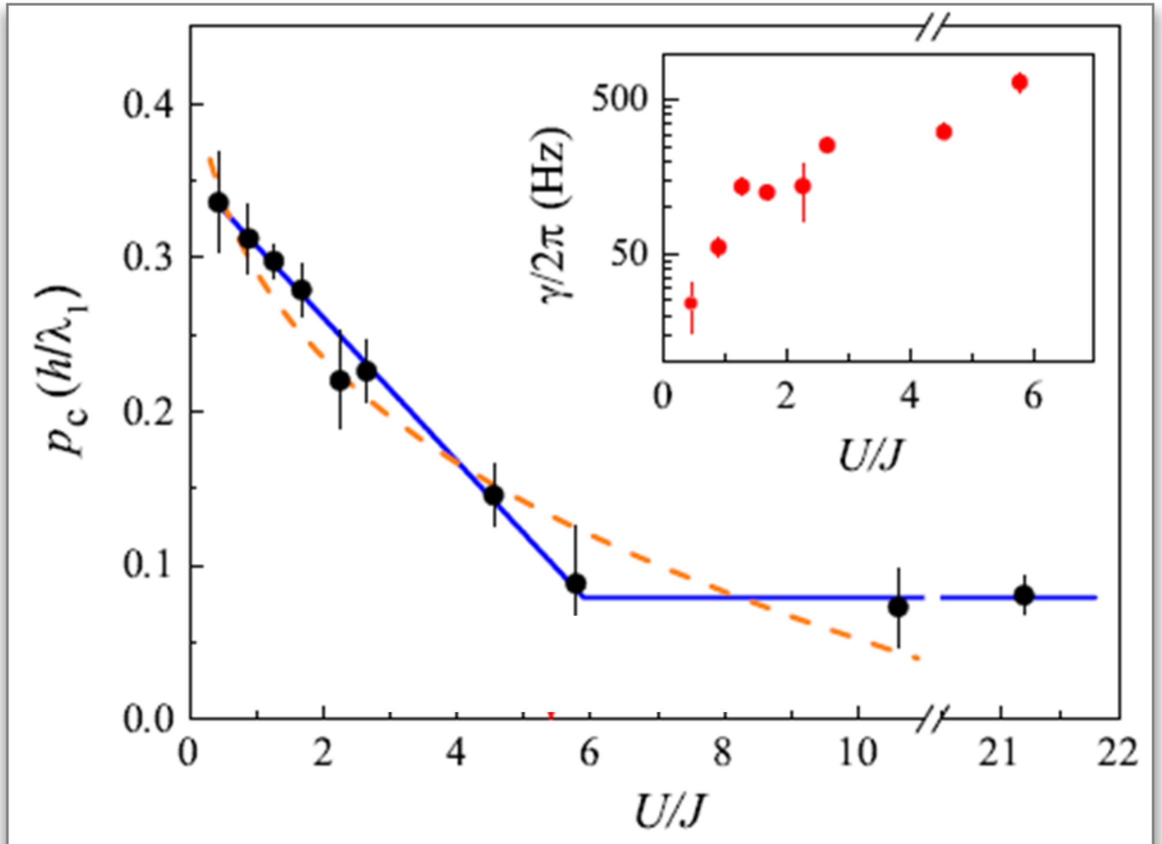
For vanishing interaction p_c is expected to be 0.5 → dynamical instability

Increasing the interactions we approach a phase transition (SF-MI) and there is a p-dependent damping due to Quantum phase slips

$$\Gamma_Q \propto \exp\left(-1.7\sqrt{\frac{nJ}{U}}\left(\frac{\pi}{2}-\frac{p\lambda_1}{2\hbar}\right)^{\frac{5}{2}}\right)$$

E. Altman et al, Phys. Rev. Lett. 95, 020402 (2005).
J. Schachenmayer, G. Pupillo, and A. J. Daley, New J. Phys. 12, 025014 (2010).
I. Danshita and A. Polkovnikov, Phys. Rev. A 85, 023638 (2012).
I. Danshita, Phys. Rev. Lett. 111, 025303 (2013).

Critical momentum in the clean lattice



Quantum phase slips

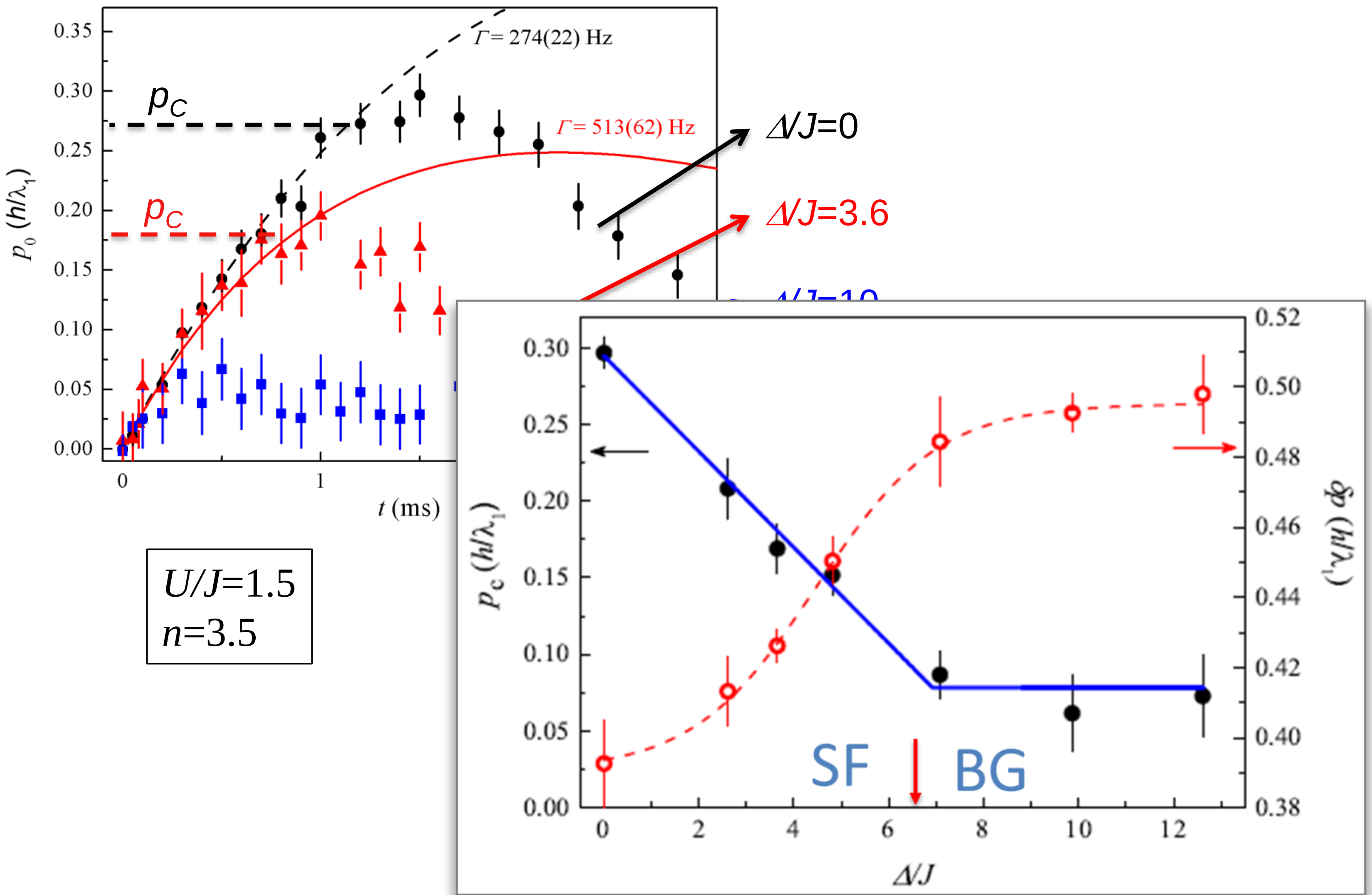
$$\Gamma_Q \propto \exp\left(-1.7\sqrt{\frac{nJ}{U}}\left(\frac{\pi}{2}-\frac{p\lambda_1}{2\hbar}\right)^{\frac{5}{2}}\right)$$

We identify the critical U/J for the MI «transition» the one for which we reach the minimum detectable *pc*

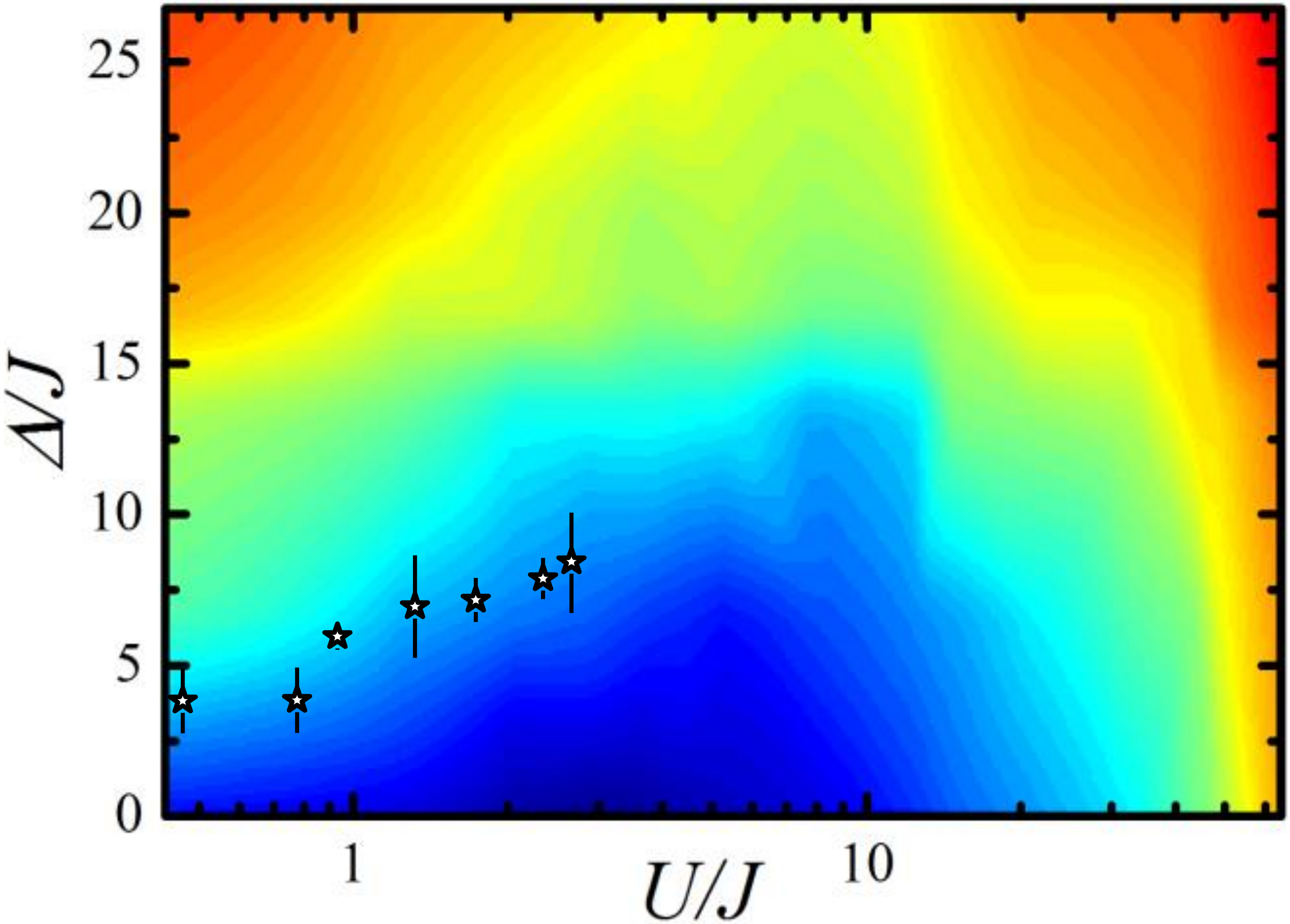
insulator→vanishing *pc*

Similar experiment in 3D: J. Mun et al., Phys. Rev. Lett. 99, 150604 (2007).

Critical momentum in the disordered lattice



"Experimental SF-BG transition"



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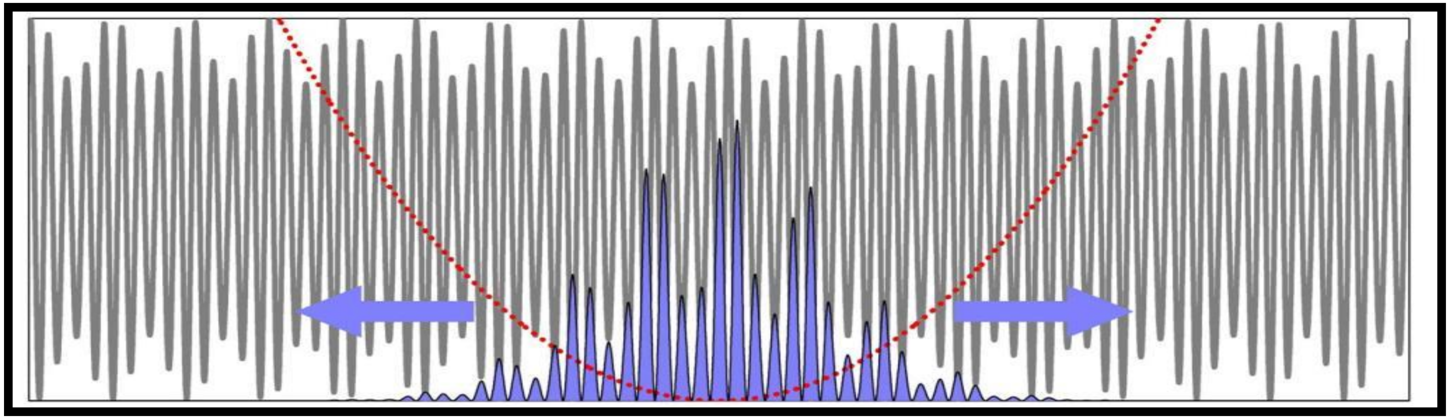
  Connection with zero-temperature phase diagram

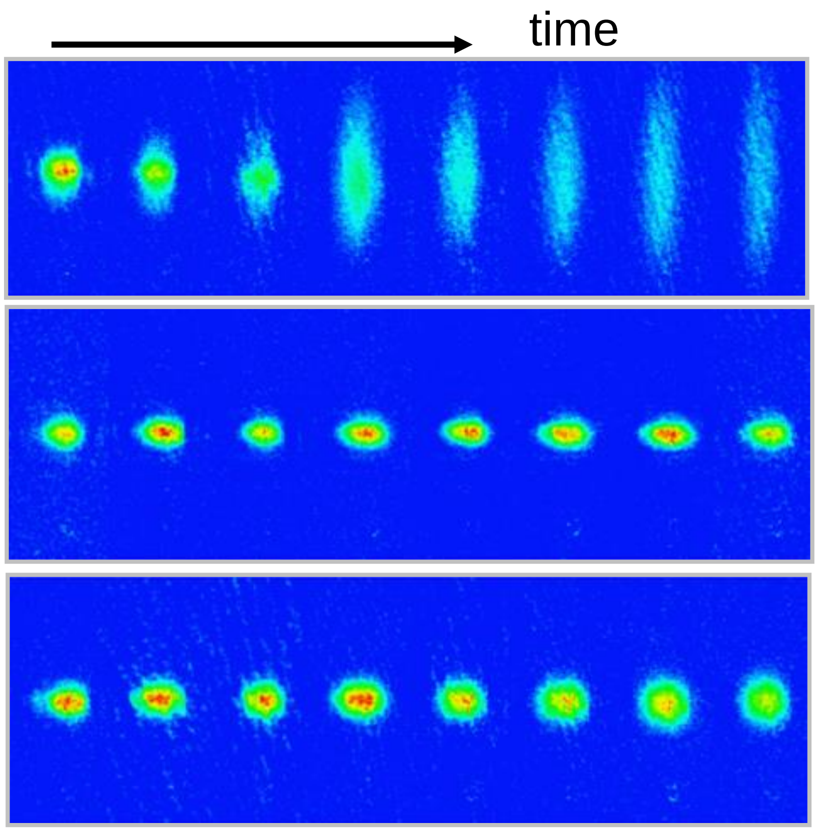
- Transport instability at the fluid-insulator transition:
  L. Tanzi et al., Phys. Rev. Lett. (2013)

  Dominant role of quantum phase slips
  «experimental» transition: vanishing of critical momentum

- Induced expansion dymanics in a disorder-localized system:
  E. Lucioni et al., Phys. Rev. Lett. 106, 23 (2011)
  E. Lucioni et al., Phys. Rev. E 87, 042922 (2013)
  C. D'Errico et al., New J. Phys.15, 045007 (2013)

Interaction-assisted expansion





Clean lattice: ballistic expansion

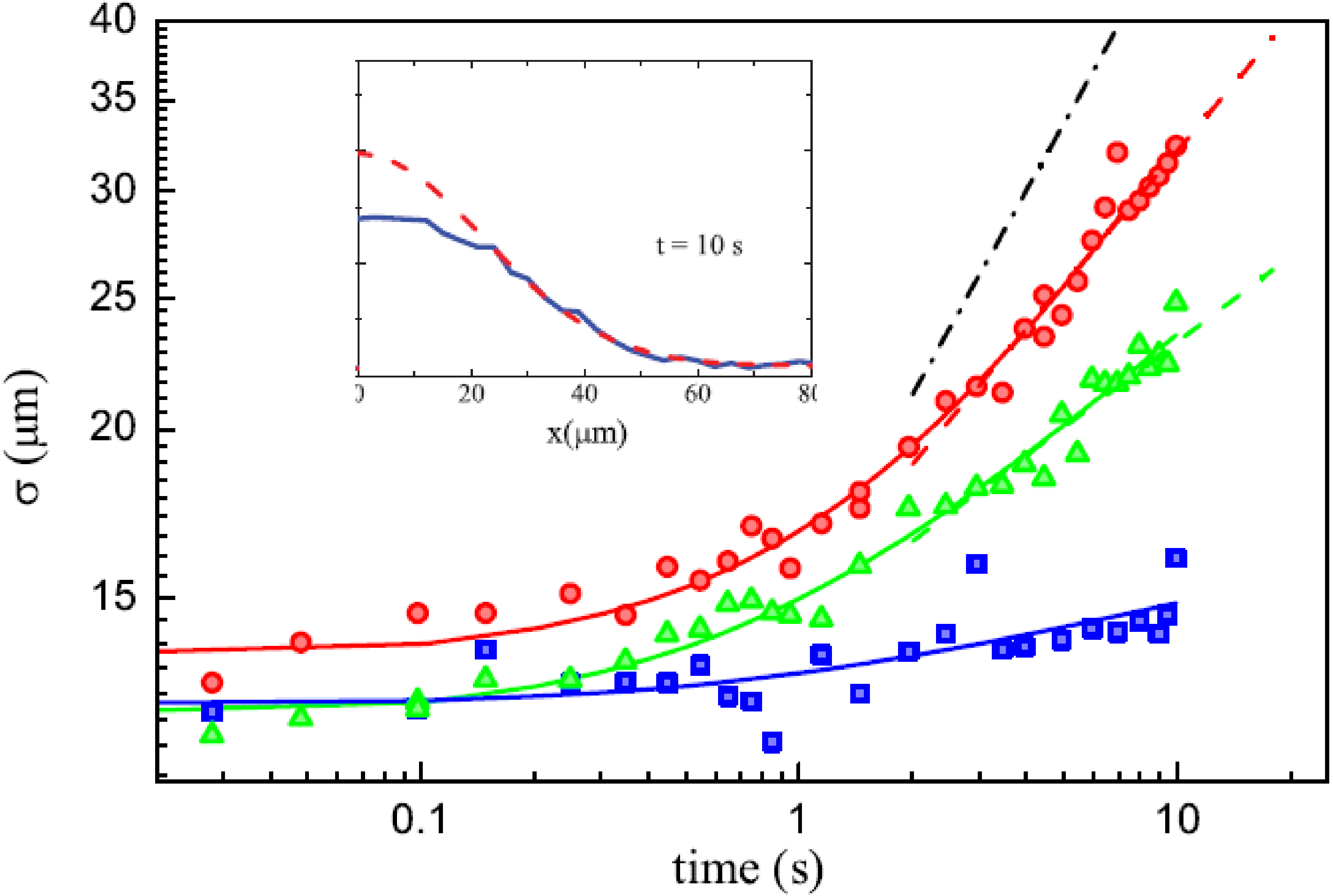
Non-interacting sample
in a disordered lattice: no expansion

Interacting sample
in a disordered lattice: slow expansion

Expansion dynamics: anomalous diffusion

$\sigma(t) \approx t^{\alpha} \qquad \alpha < 0.5$

D. L. Shepelyansky, Phys. Rev. Lett. 70, 1787 (1993)
S. Flach *et al*, Phys. Rev. Lett. 102, 024101 (2009)
M. Larcher *et al.* PRA **80**, 053606 (2009)



$nU = 1.2J$
$\alpha = 0.33 \pm 0.05$

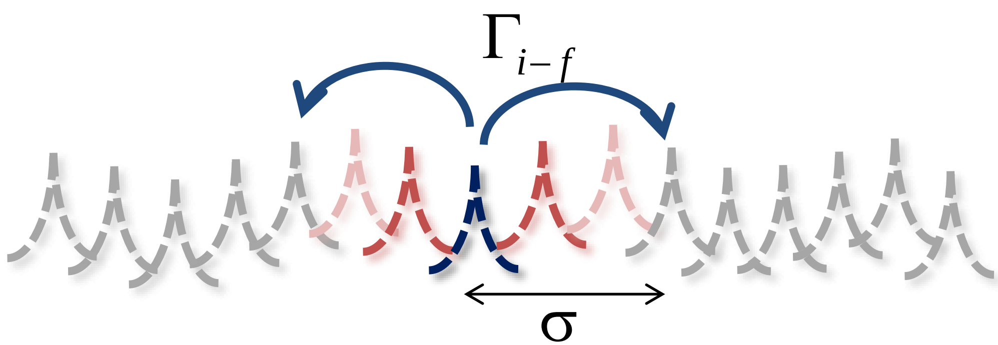
$nU = 0.8J$
$\alpha = 0.22 \pm 0.04$

$nU = 0$

$$\sigma(t) = \sigma_0 (1 + t/t_0)^{\alpha}$$

E. Lucioni *et al*., Phys. Rev. Lett. **106**, 23 (2011)

Interaction-assisted transport



Perturbative approach:

$$H' = H_{\text{int}} = U\sum n_j(n_j - 1)$$

$$D \propto \Gamma_{i-f} \approx \frac{\langle i|H'|f\rangle^2}{\delta E} \propto n^{\beta}(x,t) \propto \frac{1}{\sigma^{\beta}}$$

Non-linear diffusion equation:

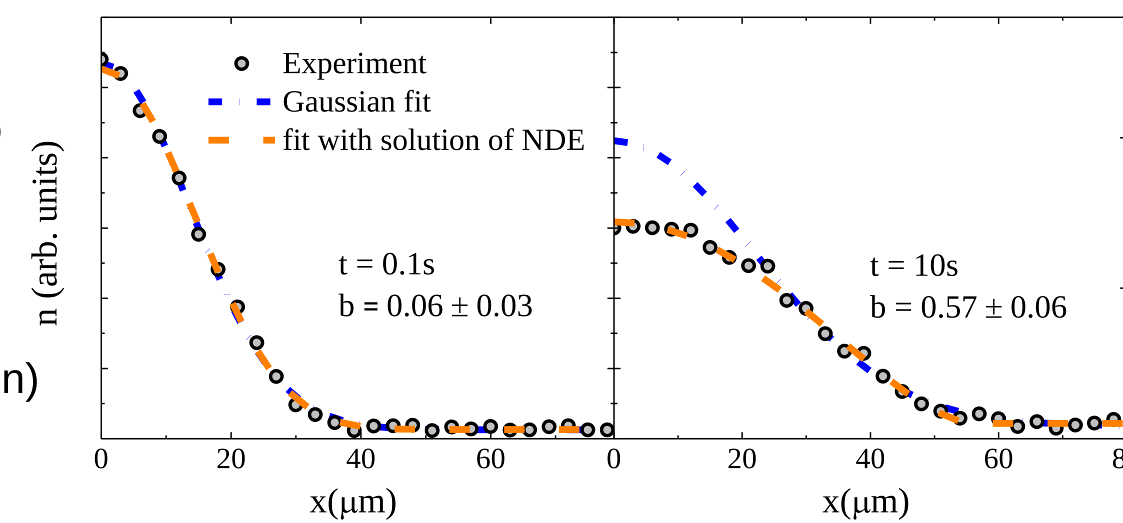
$$\frac{\partial n(x,t)}{\partial t} = \frac{\partial}{\partial x} D(x,t) \frac{\partial n(x,t)}{\partial x}$$

$$n(x,t) = B(b,w)\left(1 - \frac{b(t)x^2}{w^2(t)}\right)^{1/b(t)}$$

t=0 b(0)→0 (Gaussian)

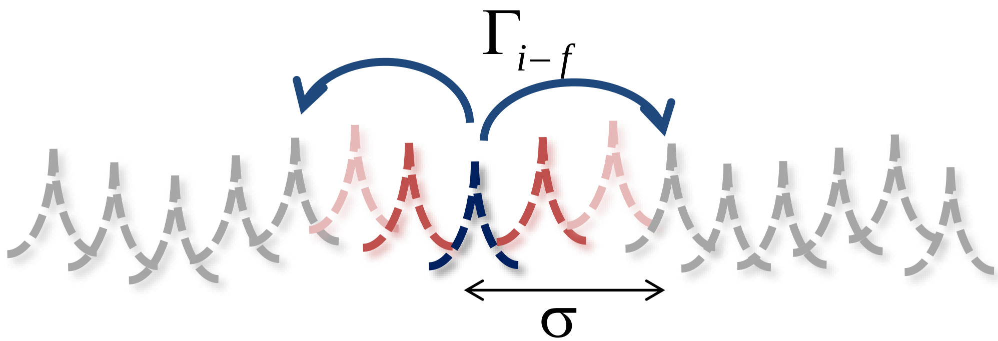
t>>0 b(t) →β (self-similar solution)

$$\sigma(t) \approx t^{\alpha} = t^{1/(2+\beta)}$$



E. Lucioni *et al.*, Phys. Rev. E 87, 042922 (2013)

Noise-assisted transport



Perturbative approach:

$$H' = \Delta A \cos(\omega_i t)\cos(2\pi \frac{\lambda_1}{\lambda_2} x)$$

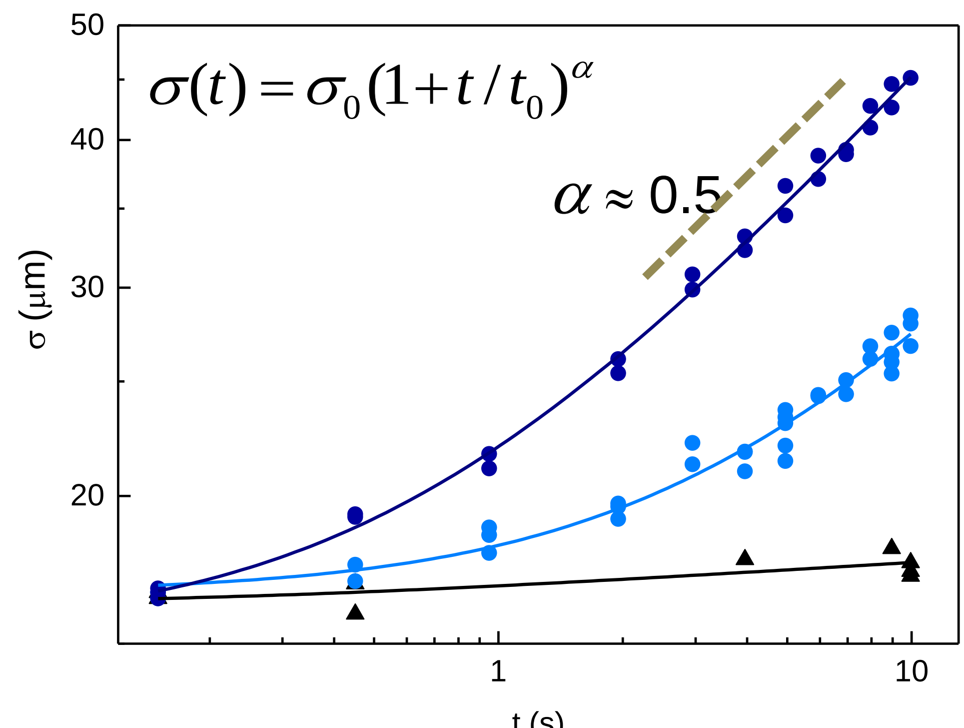
$$D \propto \Gamma_{i-f} \approx \frac{\langle i | H' | f \rangle^2}{\delta E} = const$$

Noise: sine modulation of the secondary lattice with a random frequency

Standard diffusion equation:

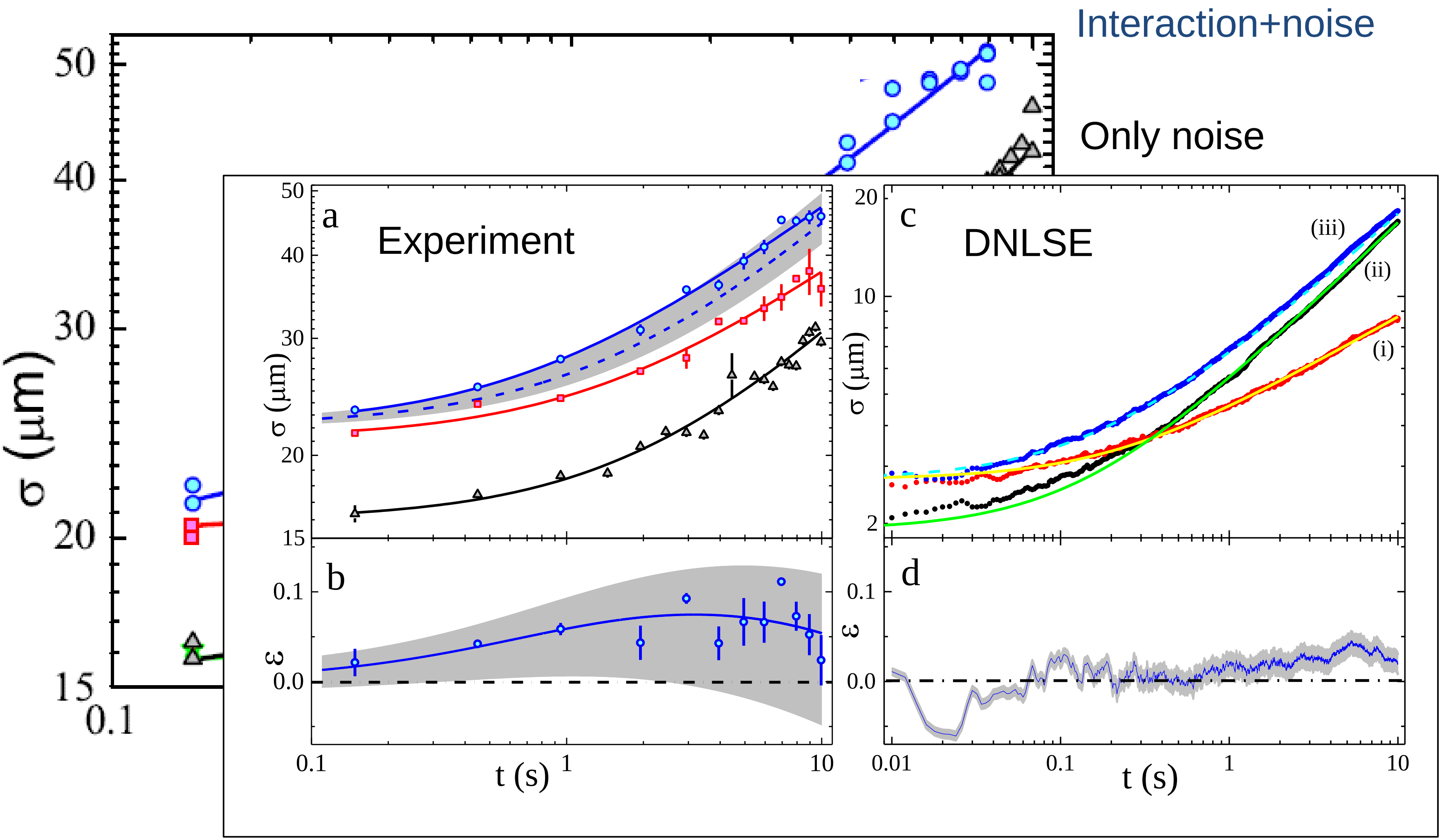
$$\frac{\partial n(x,t)}{\partial t} = D \frac{\partial^2 n(x,t)}{\partial x^2}$$

$$\sigma(t) \approx t^{1/2}$$



C. D'Errico et al., New J. Phys.15, 045007 (2013)

Interaction&Noise-assisted transport



$$D_{\mathrm{int}+noise}(t) = D_{noise} + D_{int}\ (t)$$

C. D’Errico et al., New J. Phys.15, 045007 (2013)

Experimental results and perspectives

- Investigation of the Δ-U diagram
  and comparison with zero-temperature theory
  C. D'Errico, E.Lucioni et al., submitted

  Reentrance of the Bose glass from coherence measurements
  Evidence of a strongly correlated BG from the excitation spectra
  Connection with zero-temperature phase diagram

- Transport instability at the fluid-insulator transition:
  L. Tanzi et al., Phys. Rev. Lett. (2013)

  Dominant role of quantum phase slips
  «experimental» transition: vanishing of critical momentum

- Induced expansion dymanics in a disorder-localized system:
  E. Lucioni et al., Phys. Rev. Lett. 106, 23 (2011),
  E. Lucioni et al., Phys. Rev. E 87, 042922 (2013)
  C. D'Errico et al., New J. Phys.15, 045007 (2013)

  interaction-induced transport
  noise-induced transport

- Perspectives: true disorder, higher dimensionality, role of the temperature, quantum quenches and thermalization in disordered system…

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Michele Modugno (now @ Bilbao)
Marco Larcher & Franco Dalfovo(Trento)
Marco Moratti
Filippo Caruso

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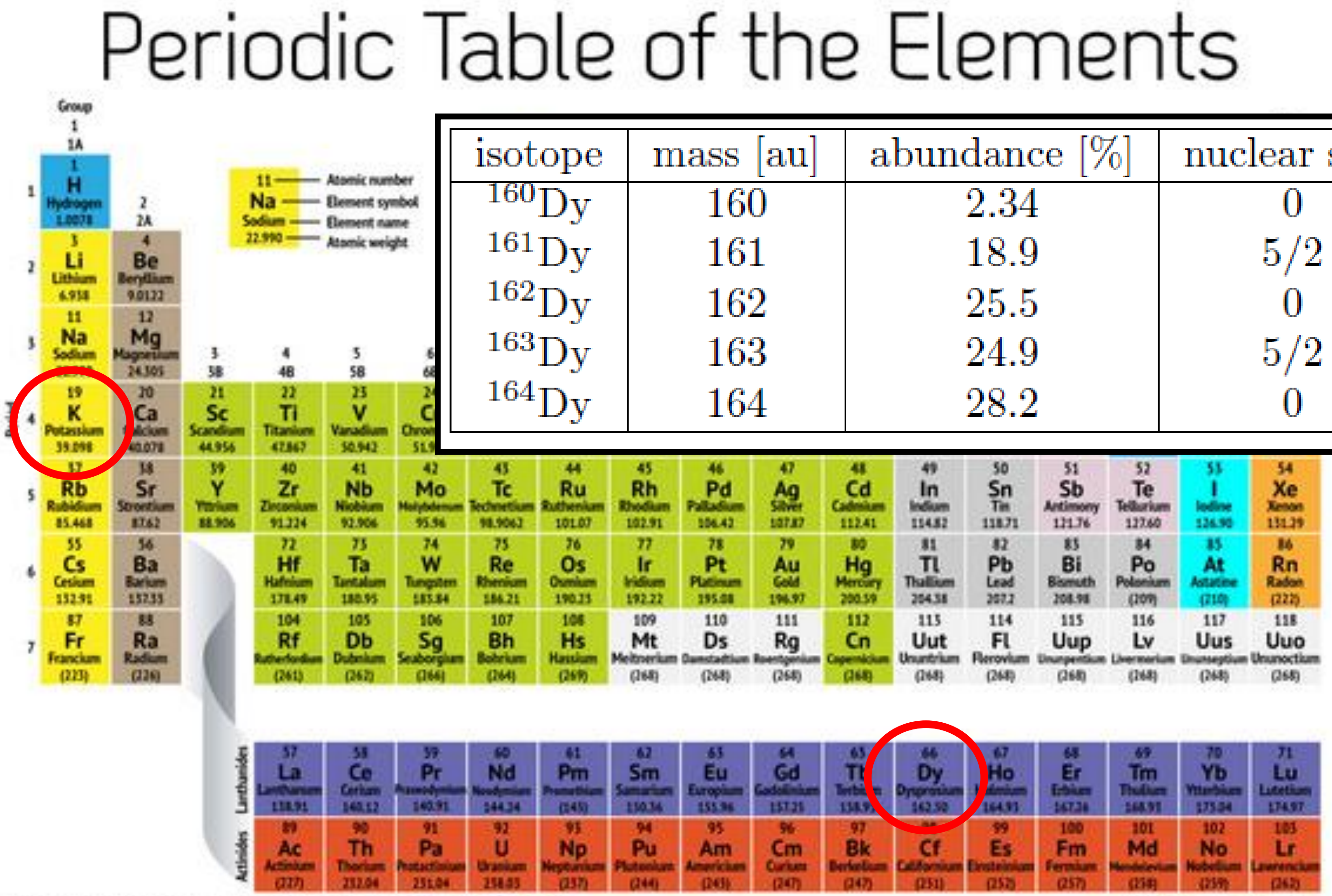
Quantum gases of «new» atoms



isotope	mass [au]	abundance [%]	nuclear spin	statistics
^{160}Dy	160	2.34	0	boson
^{161}Dy	161	18.9	5/2	fermion
^{162}Dy	162	25.5	0	boson
^{163}Dy	163	24.9	5/2	fermion
^{164}Dy	164	28.2	0	boson

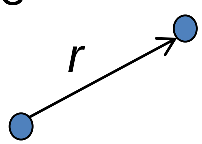
Dipolar physics with Dysprosium

Contrary to alkaline atoms, Dysprosium has a magnetic dipole moment

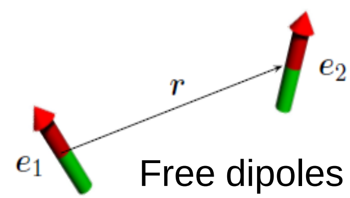
$$v_c(r-r') = \frac{4\pi\hbar^2}{m} a\,\delta(r-r')$$

$$v_{dd}(r) = \frac{C_{dd}}{4\pi}\frac{(e_1\cdot e_2)r^2 - 3(e_1\cdot r)(e_2\cdot r)}{r^5}$$

Contact interaction:
- Short range
- Isotropic

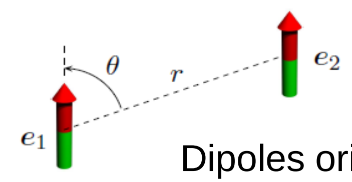


Tunable
via Feshbach resonances



Free dipoles

$$v_{dd}(r) = \frac{C_{dd}}{4\pi}\frac{1-3\cos^2\vartheta}{r^3}$$



Dipoles oriented
by an external field

Dipole-dipole interaction:
- Long range
- Anisotropic

$$C_{dd} = \begin{cases} \mu_0\mu^2 \\ d^2/\varepsilon_0 \end{cases}$$

For Dy:
$\mu = 10\mu_B$

The highest
In the periodic table

Dy is expected to have
many resonances

Dy PHYSICS IS DOMINATED
BY DIPOLAR INTERACTION

Thank you
for your attention!!!