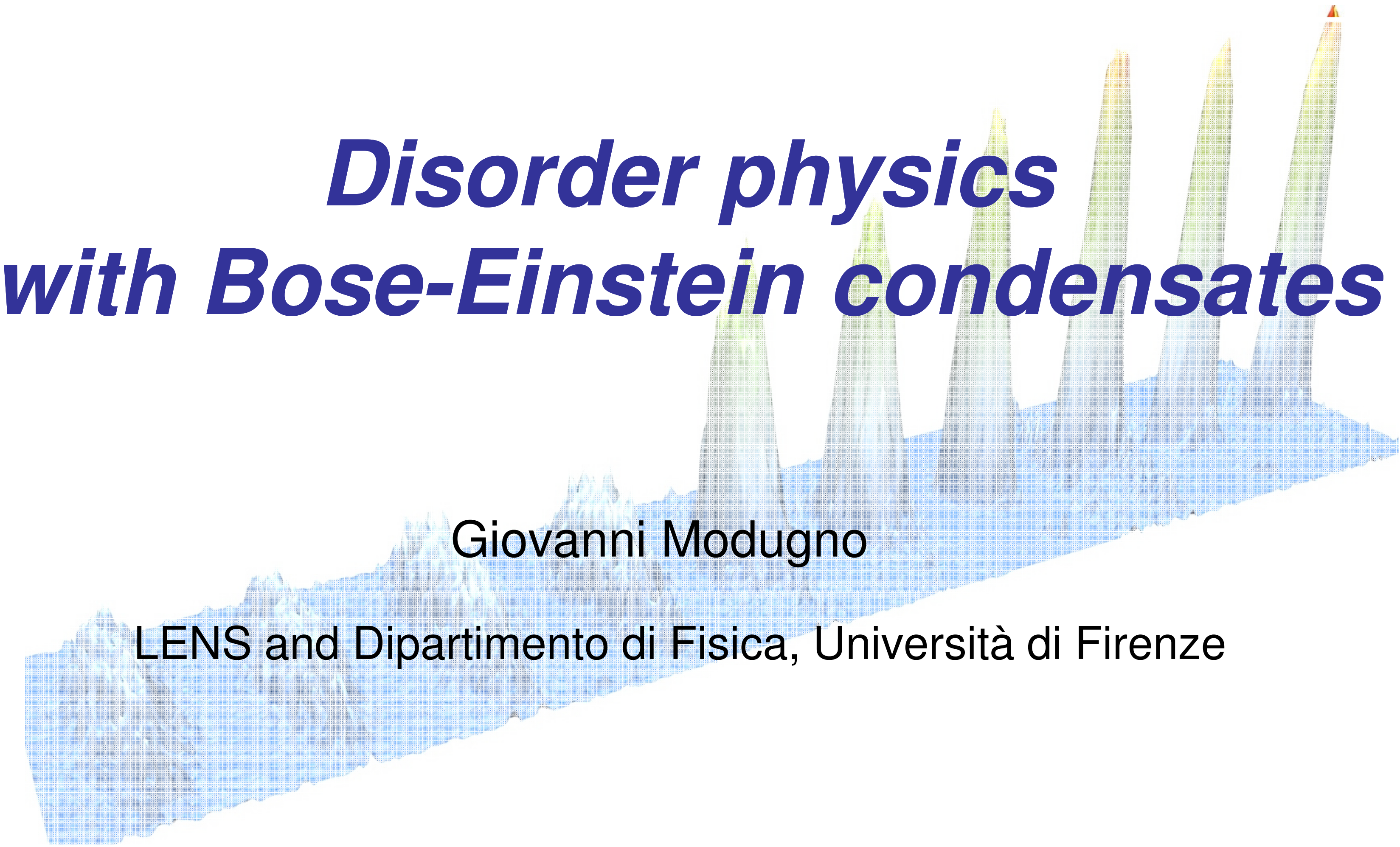
Disorder physics with Bose-Einstein condensates



Giovanni Modugno

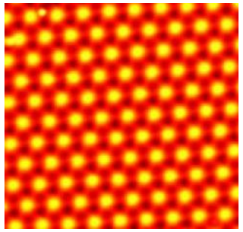
LENS and Dipartimento di Fisica, Università di Firenze

New quantum states of matter in and out of equilibrium

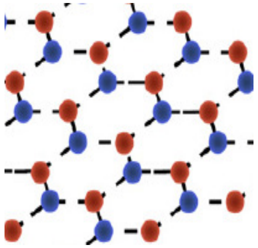
GGI , May 2012

Disorder and quantum gases

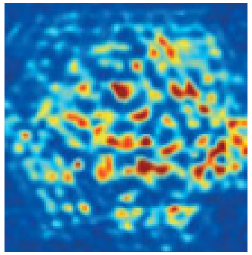
Disorder is everywhere, but it is hardly controllable.



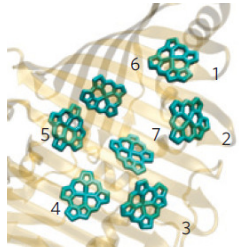
Superconductors



Graphene



Photonic media



Biological systems

Ultracold quantum gases can help answering to open questions.

VOLUME 91, NUMBER 8 PHYSICAL REVIEW LETTERS week ending 22 AUGUST 2003

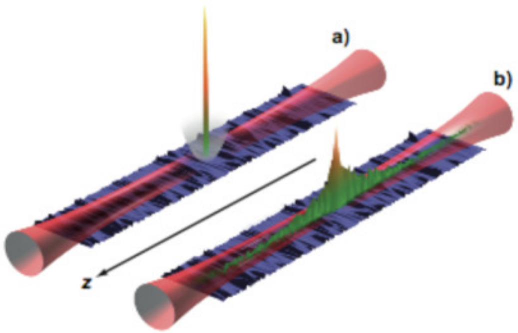
Atomic Bose and Anderson Glasses in Optical Lattices

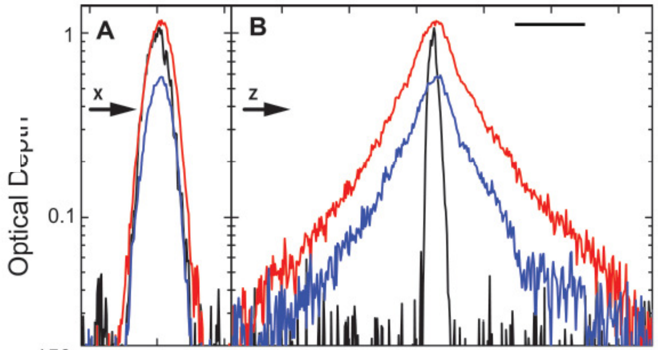
B. Damski,[1,2] J. Zakrzewski,[1] L. Santos,[2] P. Zoller,[2,3] and M. Lewenstein[2]

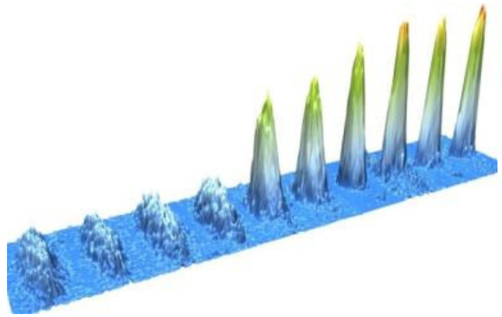
An ultracold atomic Bose gas in an optical lattice is shown to provide an ideal system for the controlled analysis of *disordered* Bose lattice gases. This goal may be easily achieved under the current experimental conditions by introducing a pseudorandom potential created by a second additional lattice or, alternatively, by placing a speckle pattern on the main lattice. We show that, for a noncommensurable

Current experimental studies

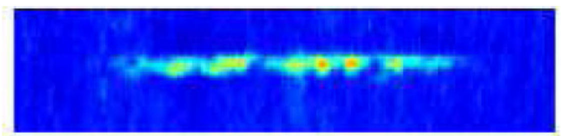
- Anderson localization in 1D-3D (Palaiseau, Florence, Urbana)

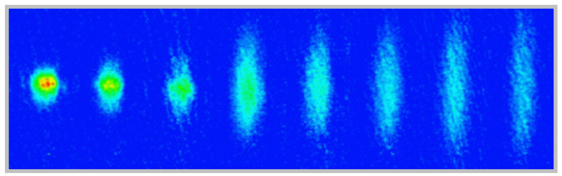






- Transport in disordered potentials (Rice, Florence)

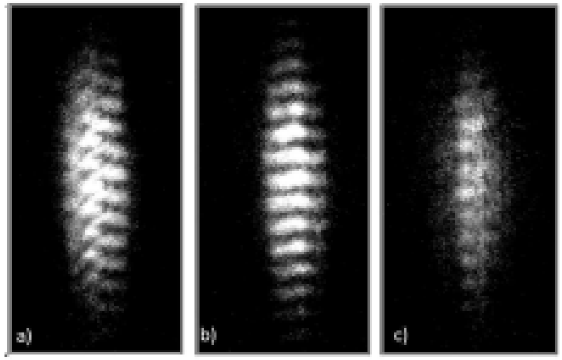




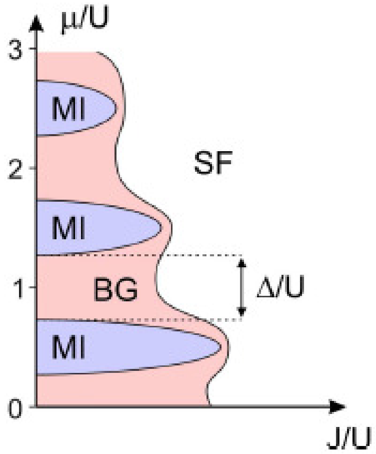
Aspect, Inguscio, Phys. Today 62, 30 (2009); Sanchez-Palencia, Lewenstein, Nat. Phys. 6, 87 (2010)
Modugno, Rep. Progr. Phys. 73, 102401 (2010)

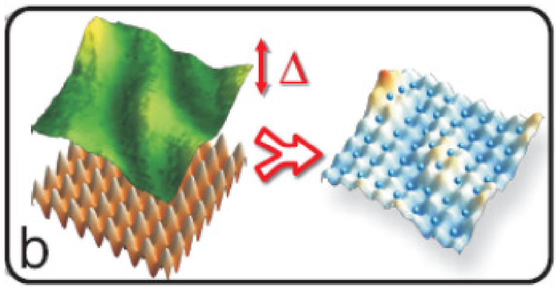
Current experimental studies

- BKT physics and disorder in 2D (Palaiseau, NIST-Maryland)



- Strongly correlated lattice phases (Firenze, Urbana, Stony Brook)

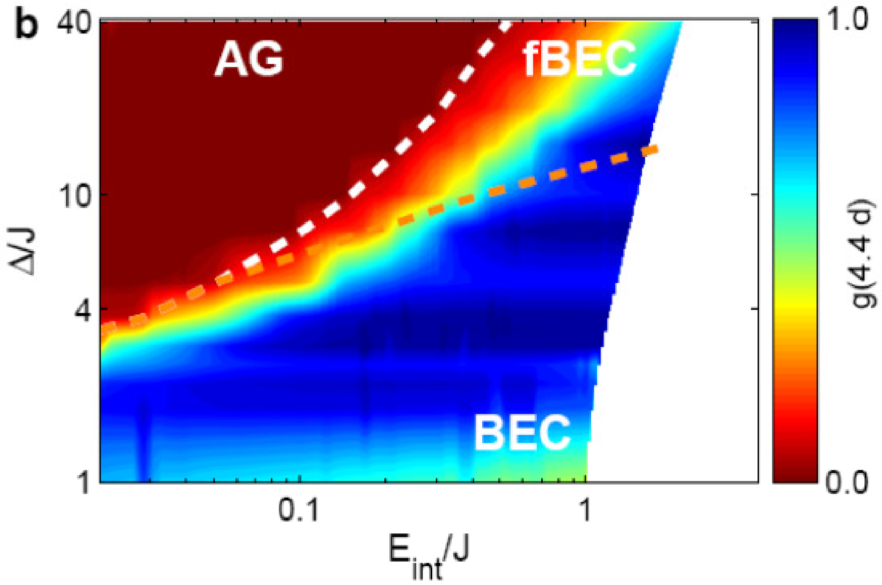




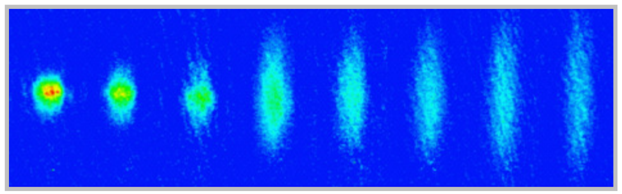
Current studies in Florence

Bosons in 1D lattices with tunable **disorder** and **interactions** (and **noise**).

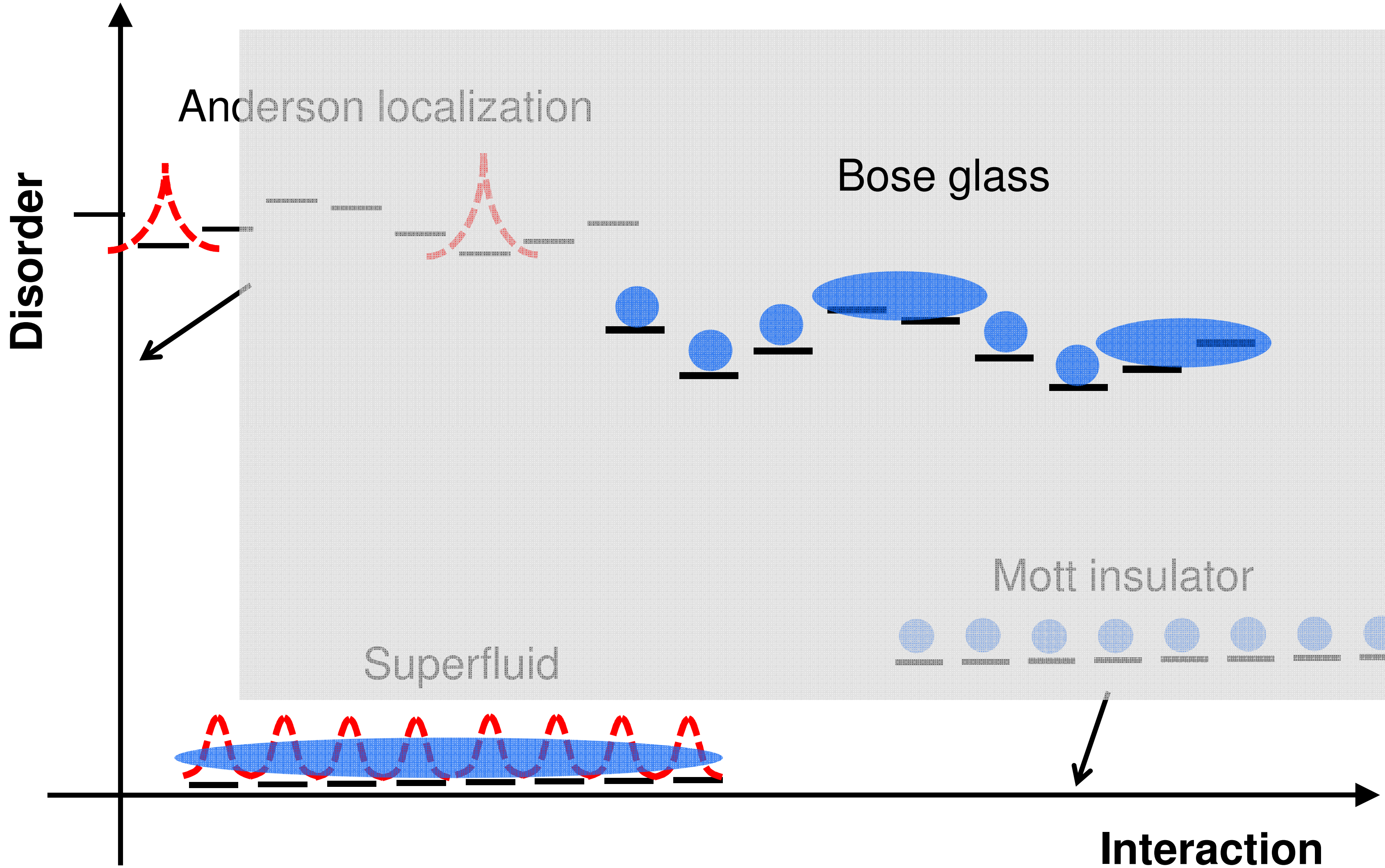
Quantum phases



Transport

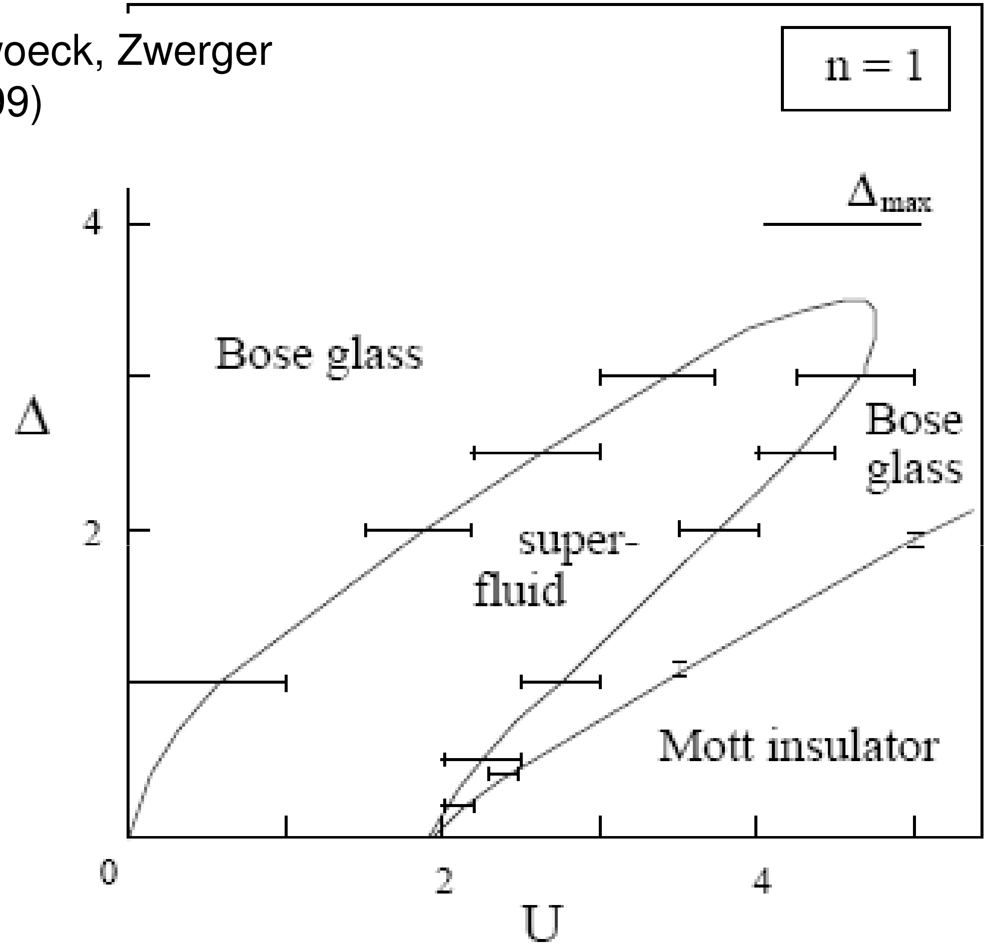


The phase diagram of disordered lattice bosons



The phase diagram of disordered lattice bosons

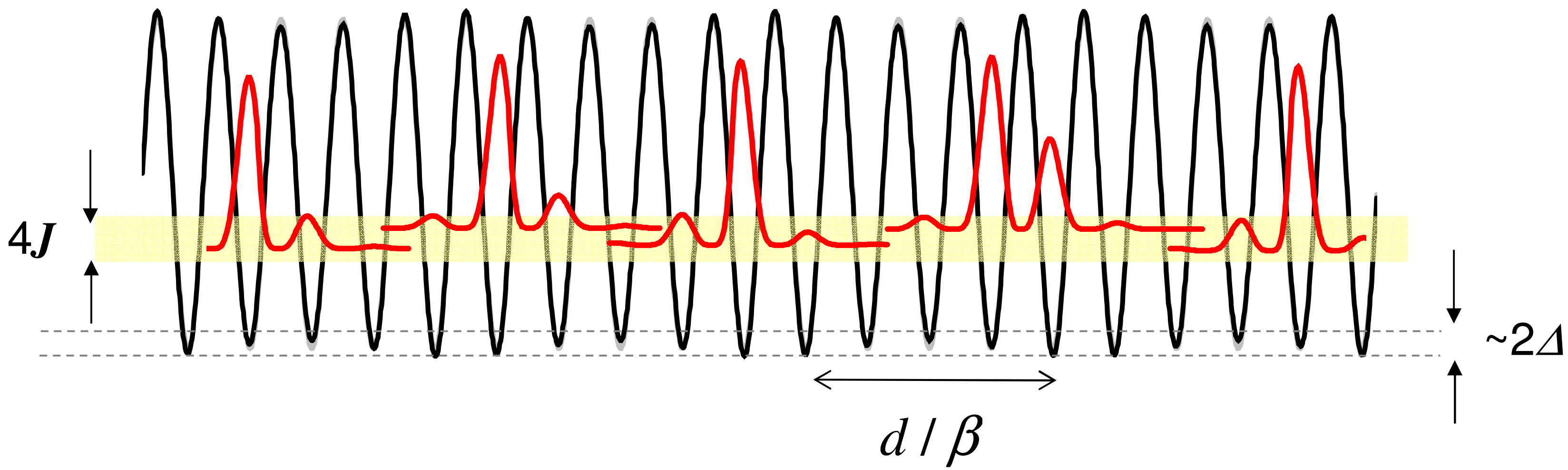
Rapsch, Schollwoeck, Zwerger
EPL 46 559 (1999)



Theory: Giamarchi and Schultz , PRB 37 325 (1988)
Fisher et al PRB 40, 546 (1989).

Experiment: Fallani et al., PRL 98, 130404 (2007);
Pasienski et al., Nat. Phys. 6, 677 (2010).

A quasi-periodic lattice



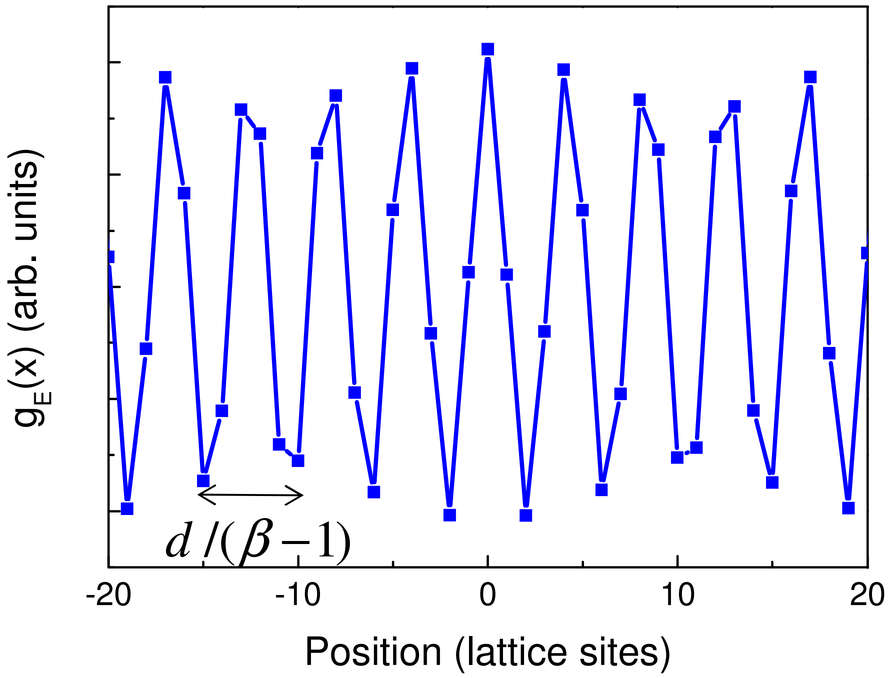
Harper or Aubry-Andrè model:

$$\hat{H} = -J \sum_{\langle i,j \rangle} \hat{b}_i^{+} \hat{b}_j + \Delta \sum_i \cos(2\pi\beta i)\ \hat{n}_i \qquad \beta = \frac{k_2}{k_1}$$

Metal-insulator transition at $\Delta = 2J$

S. Aubry and G. André, Ann. Israel Phys. Soc. 3, 133 (1980); Fallani et al., PRL 98, 130404 (2007); M. Modugno, New J. Phys. 11, 033023 (2009)

A quasi-periodic lattice

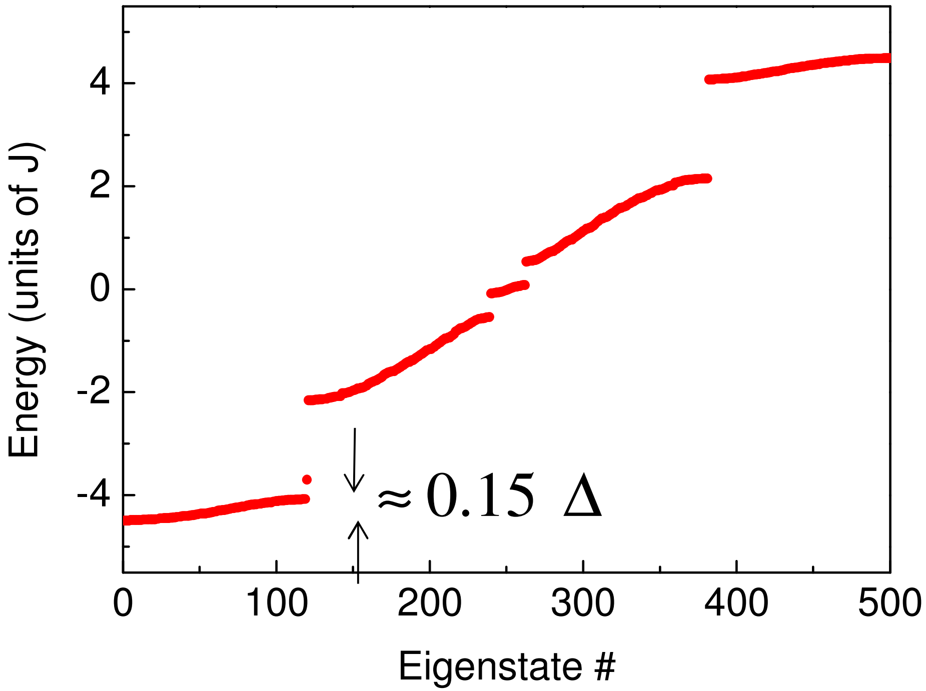


Rapidly oscillating correlation of the eigen-energies:

short localization length

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

… and energy gaps

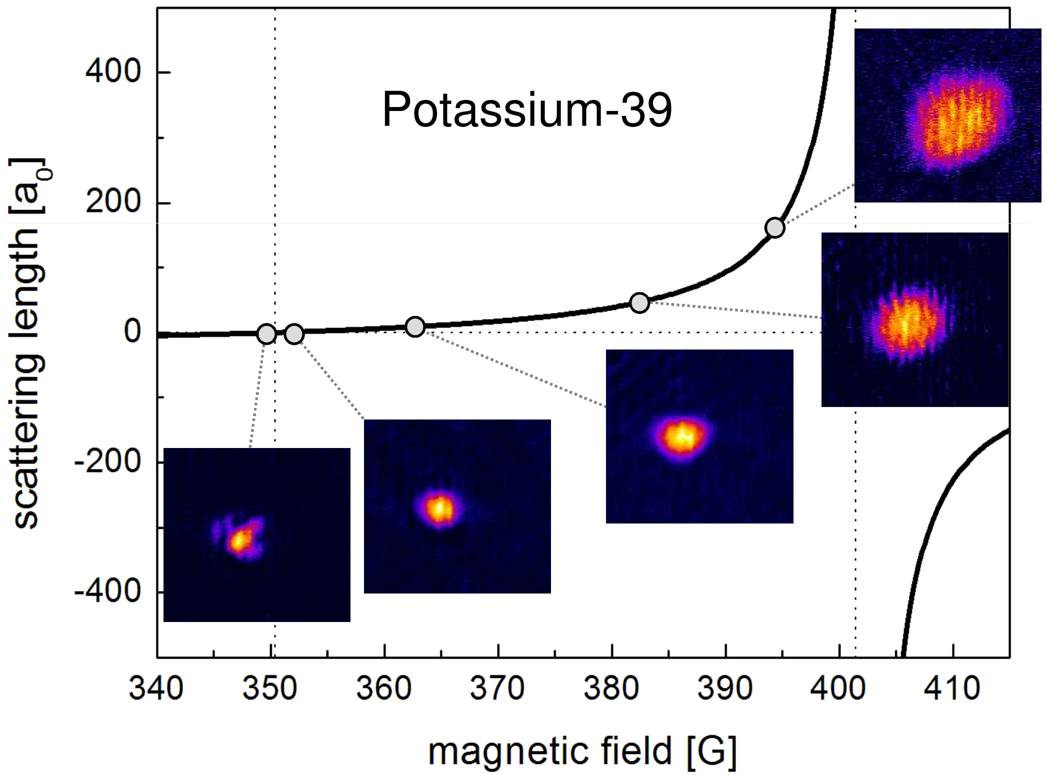


Tunable interactions

Quasi-periodic Bose-Hubbard model:

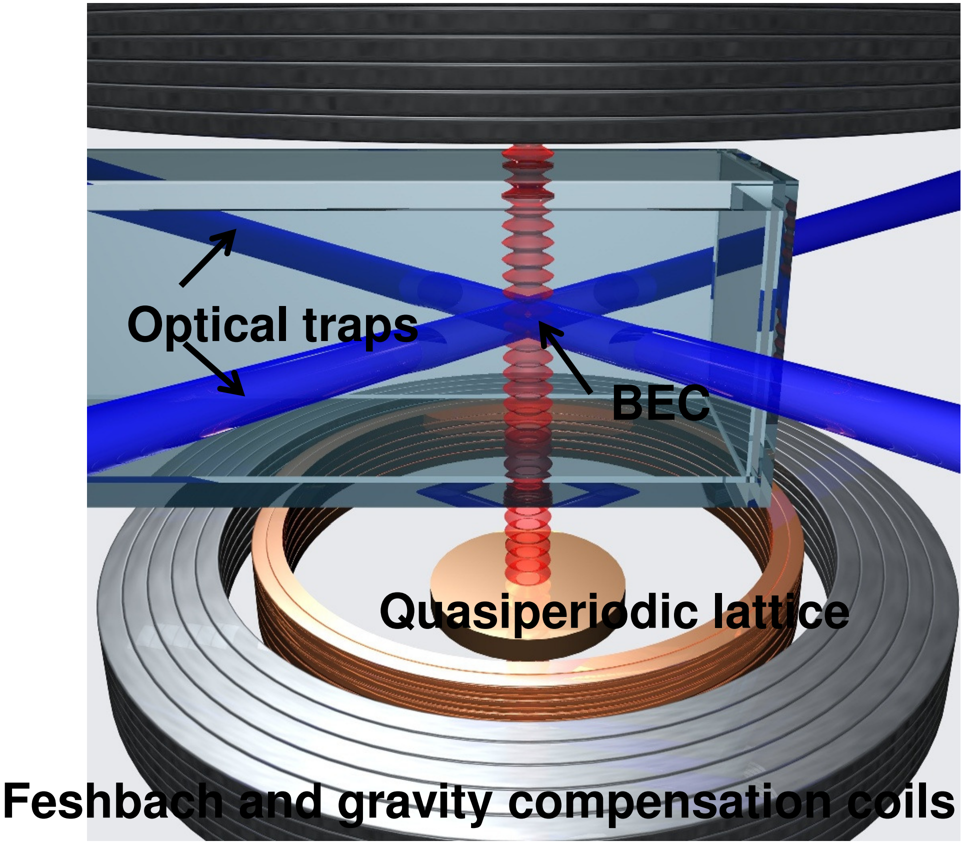
$$\hat{H} = -J\sum_{\langle i,j\rangle} \hat{b}_i^+ \hat{b}_j + \Delta\sum_i \cos(2\pi\beta i)\ \hat{n}_i + U(a)\sum_i \hat{n}_i(\hat{n}_i - 1)$$

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



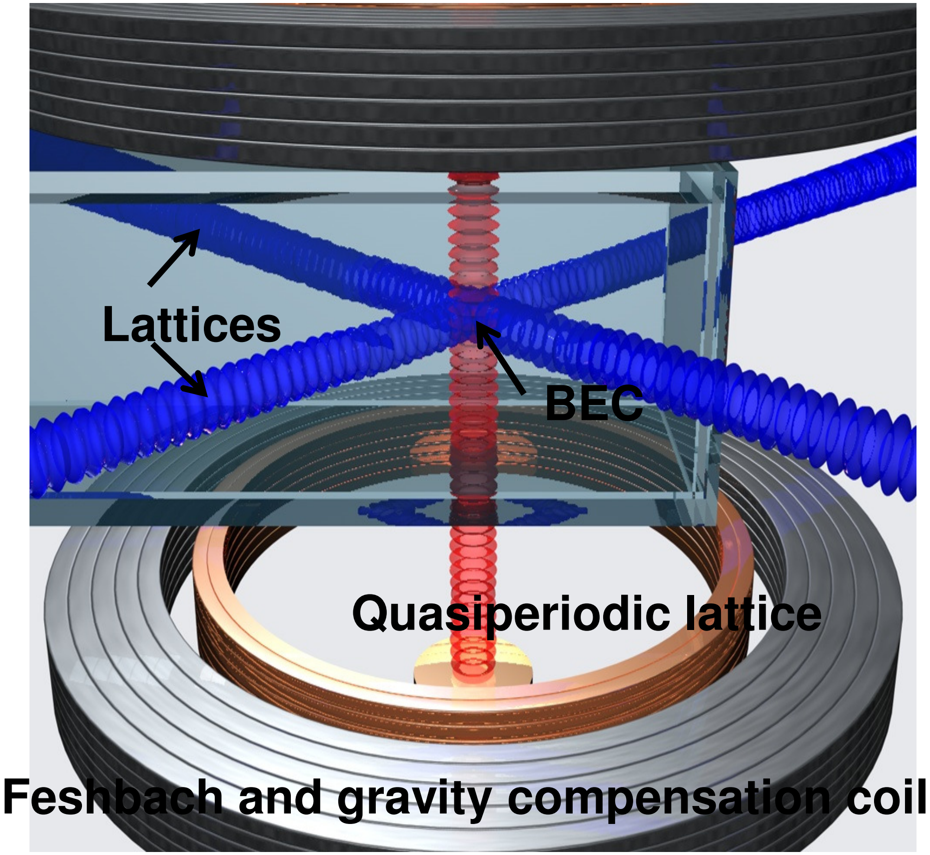
G. Roati, et al. Phys. Rev. Lett. 99, 010403 (2007).

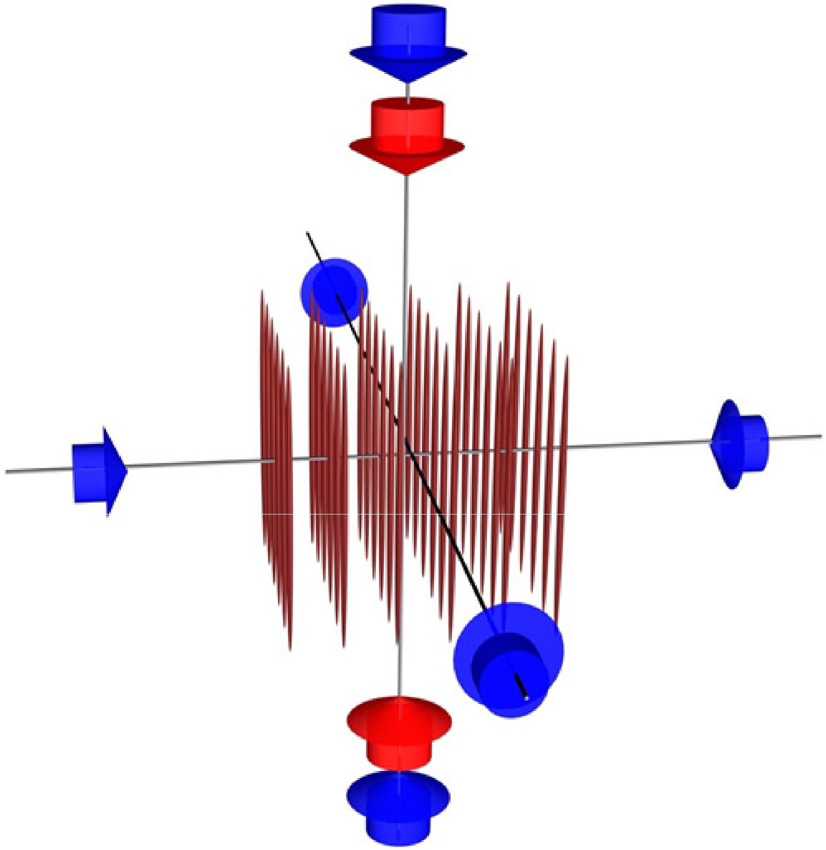
Weak interaction regime



Weak radial trapping (ν_r=50Hz): a 3D system with 1D disorder

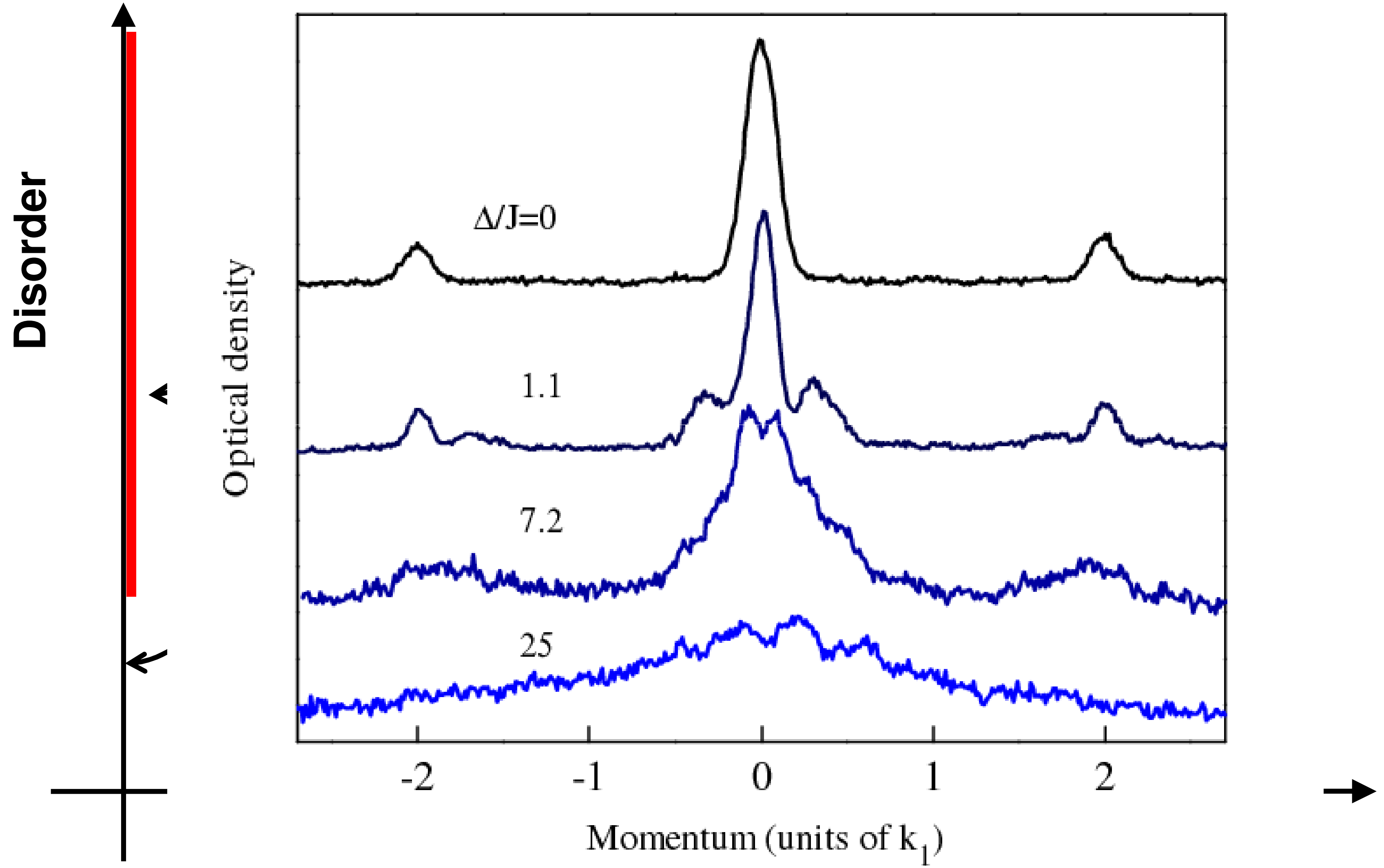
Strong interaction regime





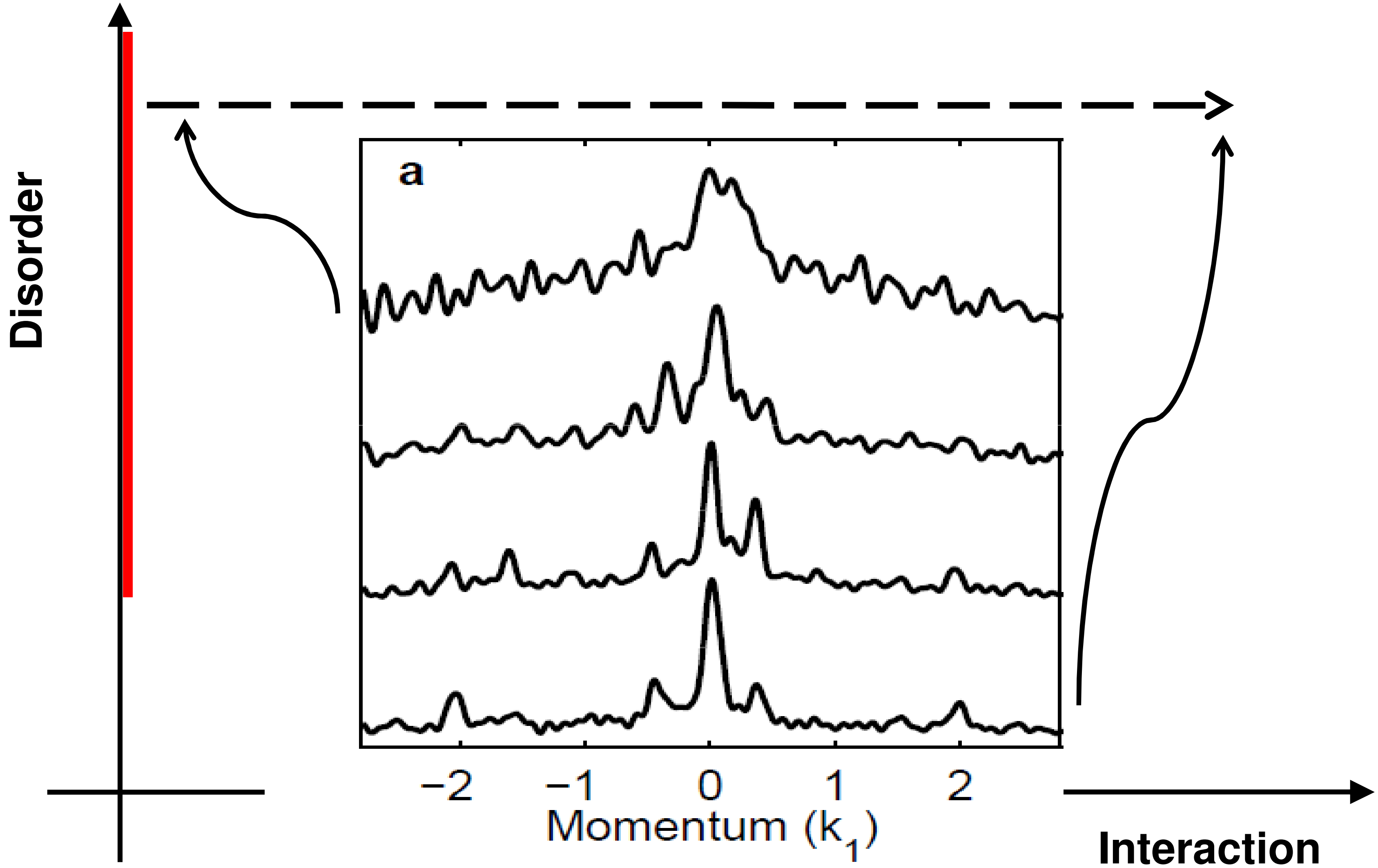
Strong 2D lattices (ν_r=50 kHz): many quasi-1D systems with 1D disorder

Momentum distribution



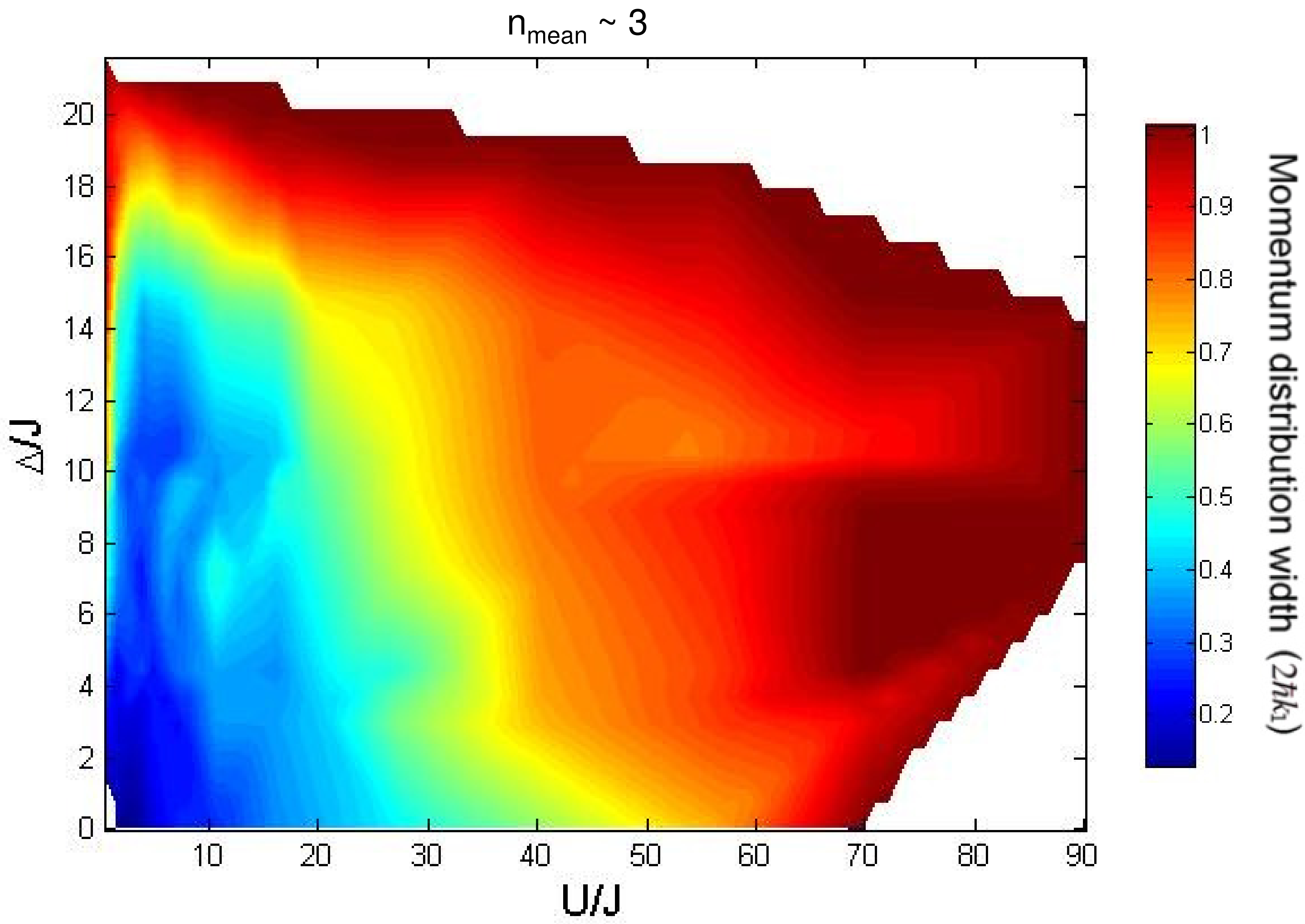
G. Roati et al., Nature 453, 895 (2008); B. Deissler et al, Nat. Phys. 6, 354 (2010).

Weak interactions: momentum distribution

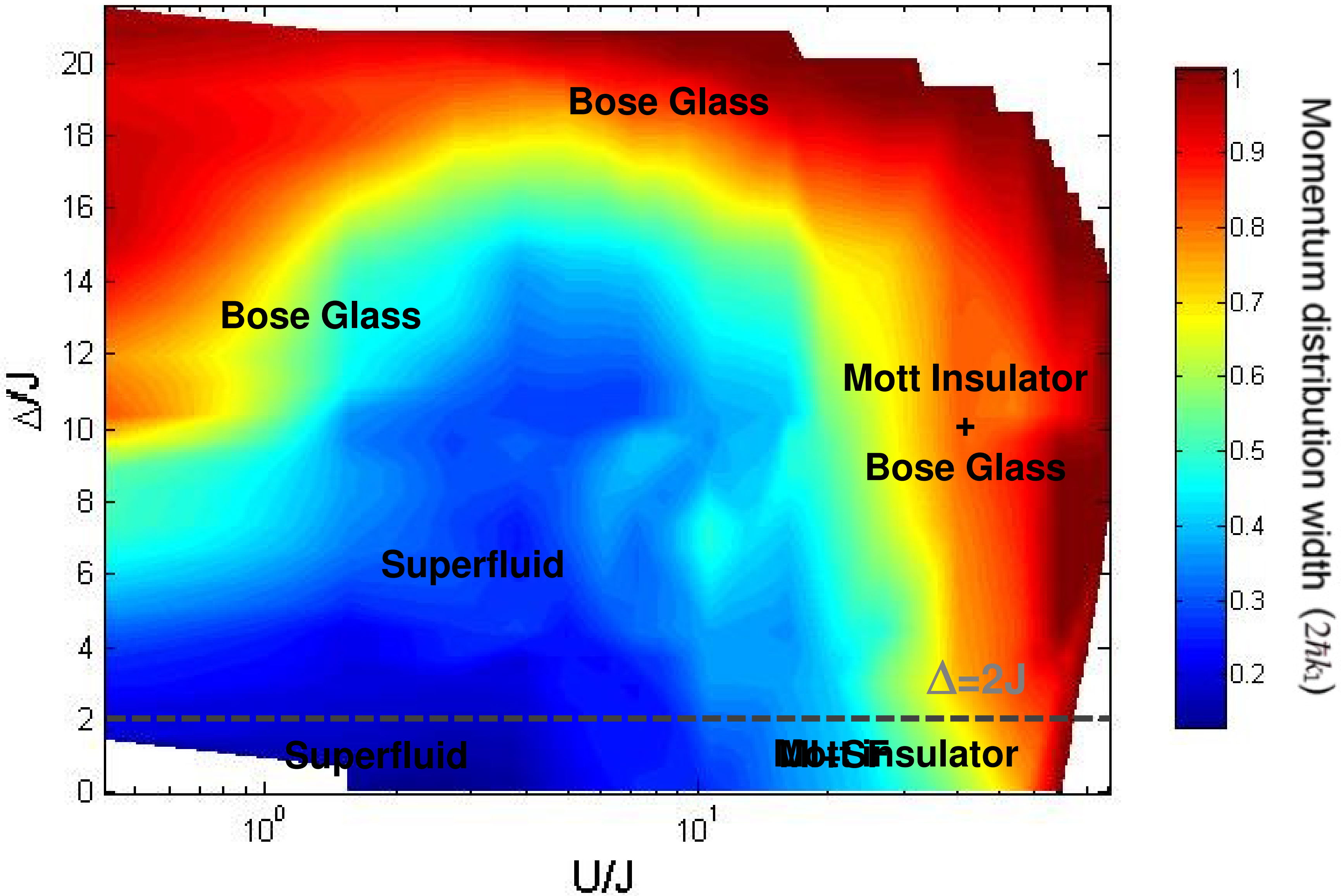


G. Roati et al., Nature 453, 895 (2008); B. Deissler et al, Nat. Phys. 6, 354 (2010).

Phase diagram from momentum distribution

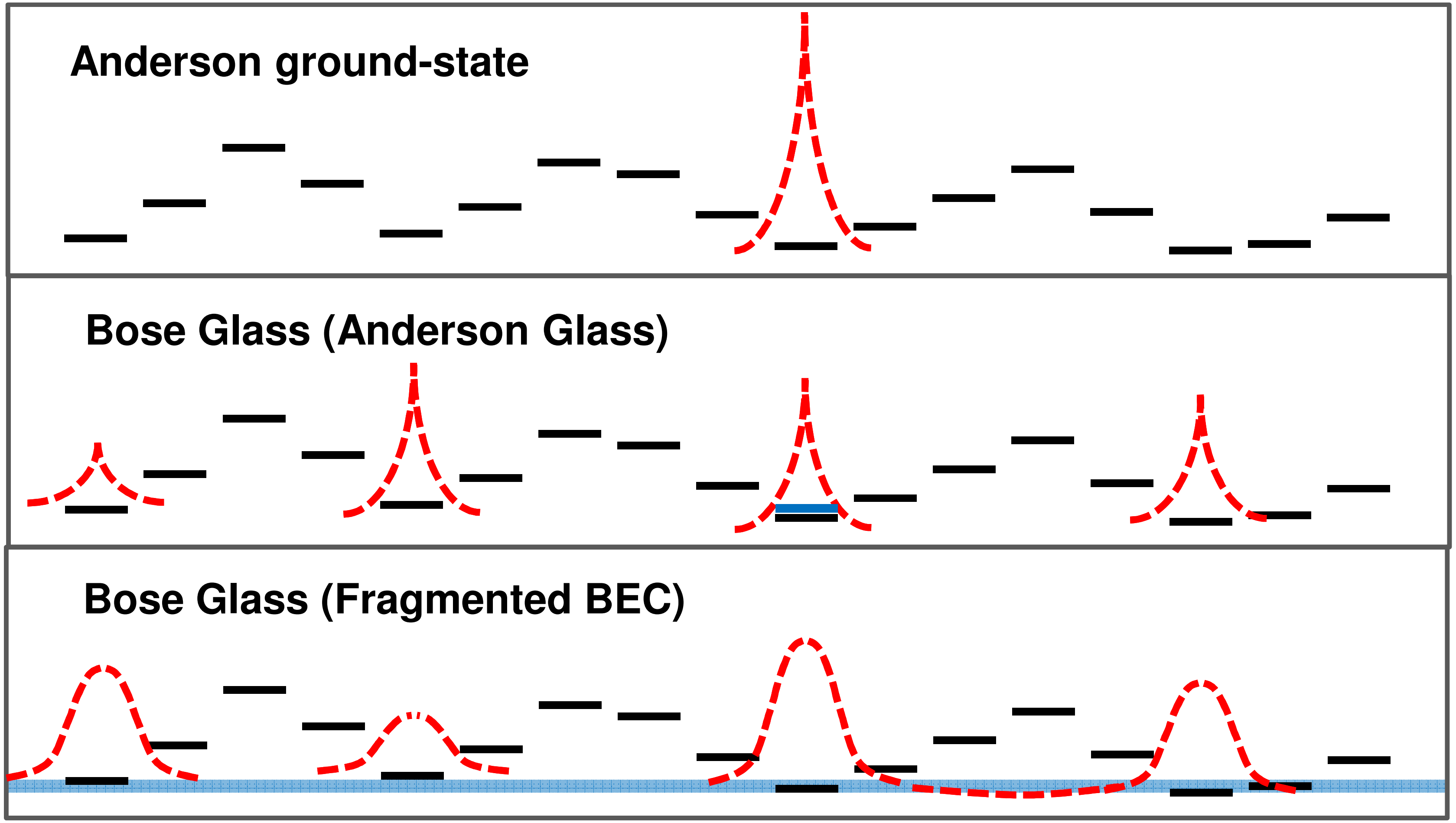


Phase diagram from momentum distribution



D'Errico et al, in preparation.

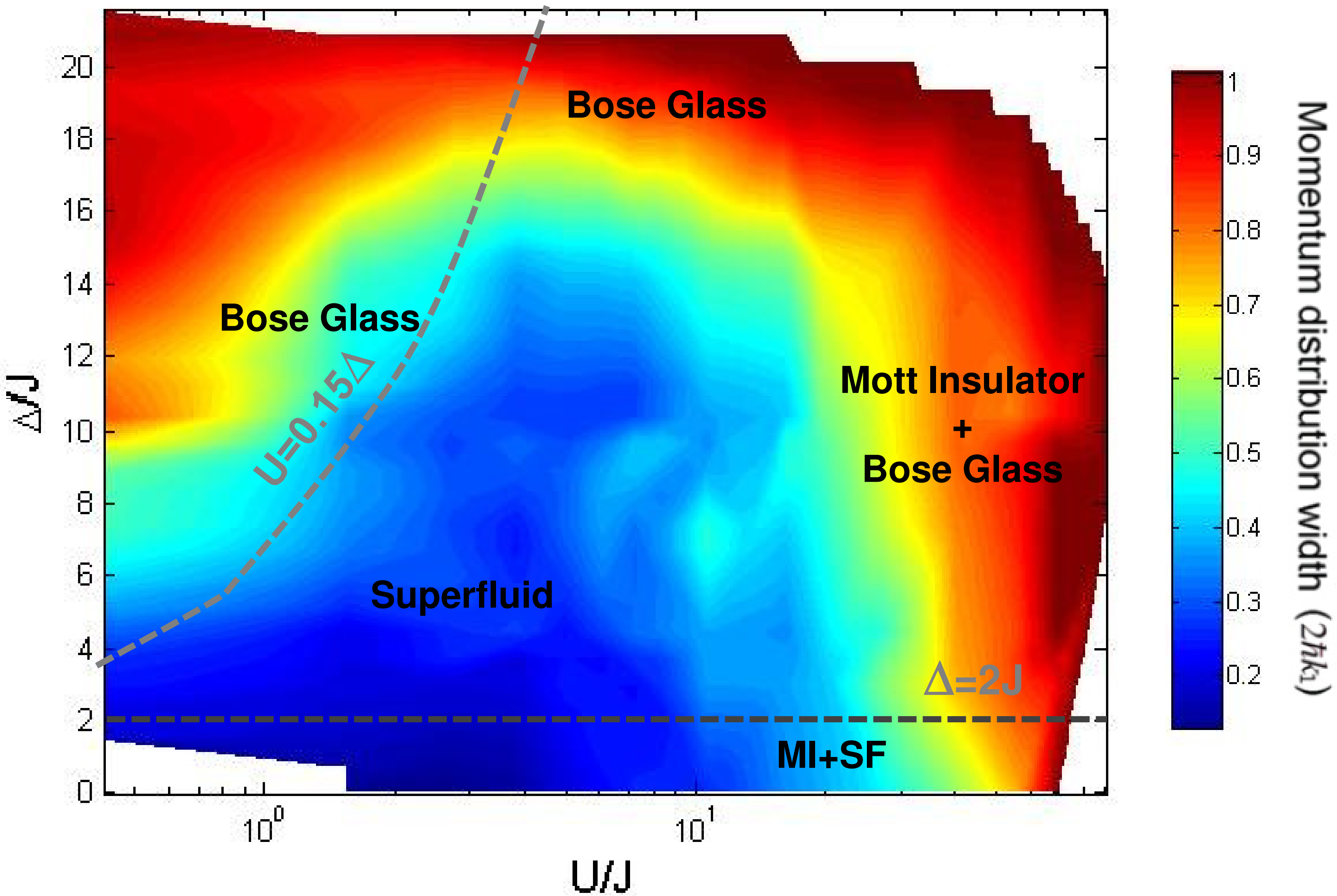
Weak interaction cartoon



Fermi golden rule $\langle i | H_{\text{int}} | f \rangle^2 g(E) \approx \frac{U}{\delta E} \int \varphi_1^2 \varphi_2^2 dx > 1$

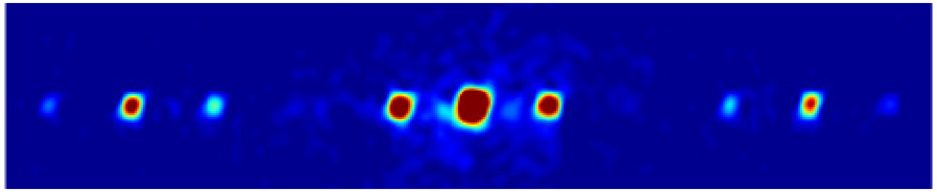
Aleiner, Altshuler, Shlyapnikov, Nat. Phys. 6, 900 (2010).

Phase diagram from momentum distribution

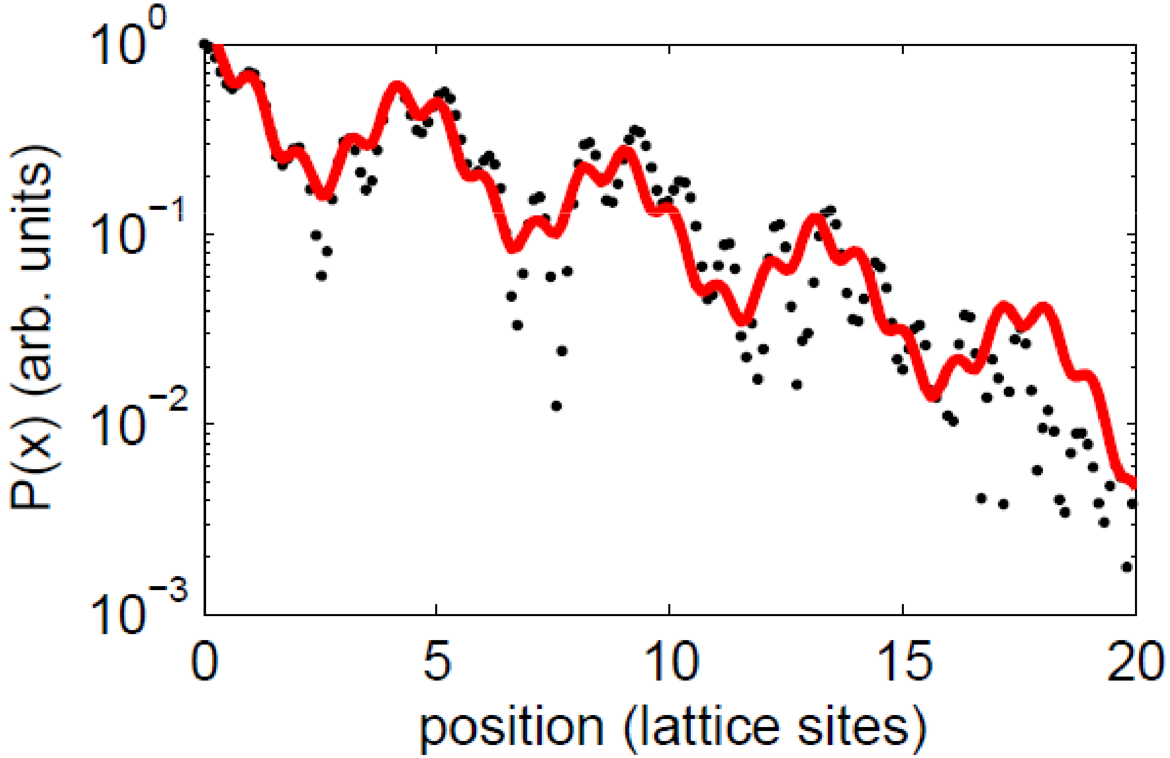


D'Errico et al, in preparation. Theory by T. Giamarchi, M. Modugno.

Correlation function

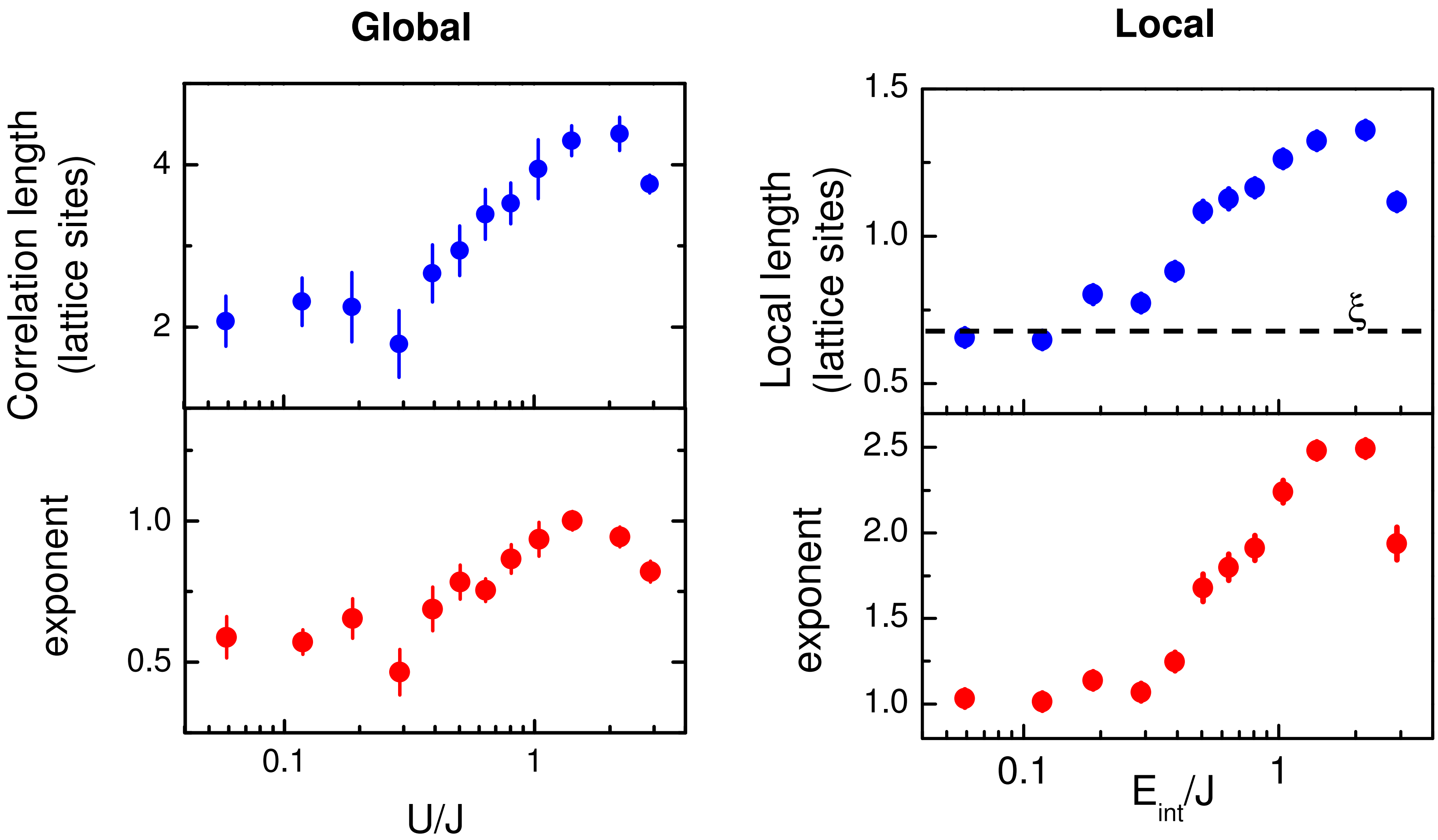


$$g(x) = \int dx' \left\langle \Psi^{+}(x)\Psi(x+x') \right\rangle = F \mid \Psi(k) \mid^{2}$$



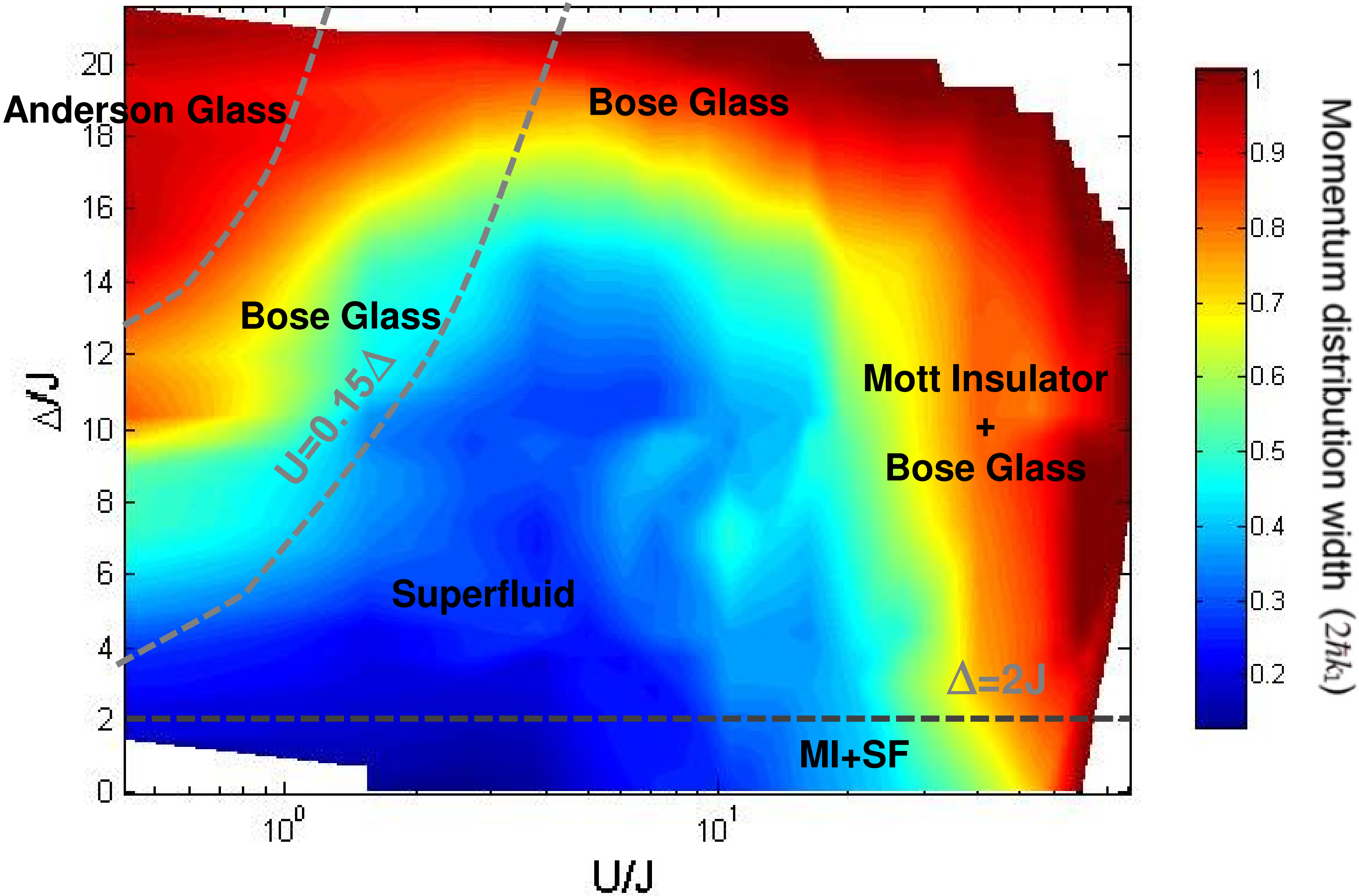
B. Deissler et al. New J. Phys. 13, 023020 (2011)

Global and local lengths



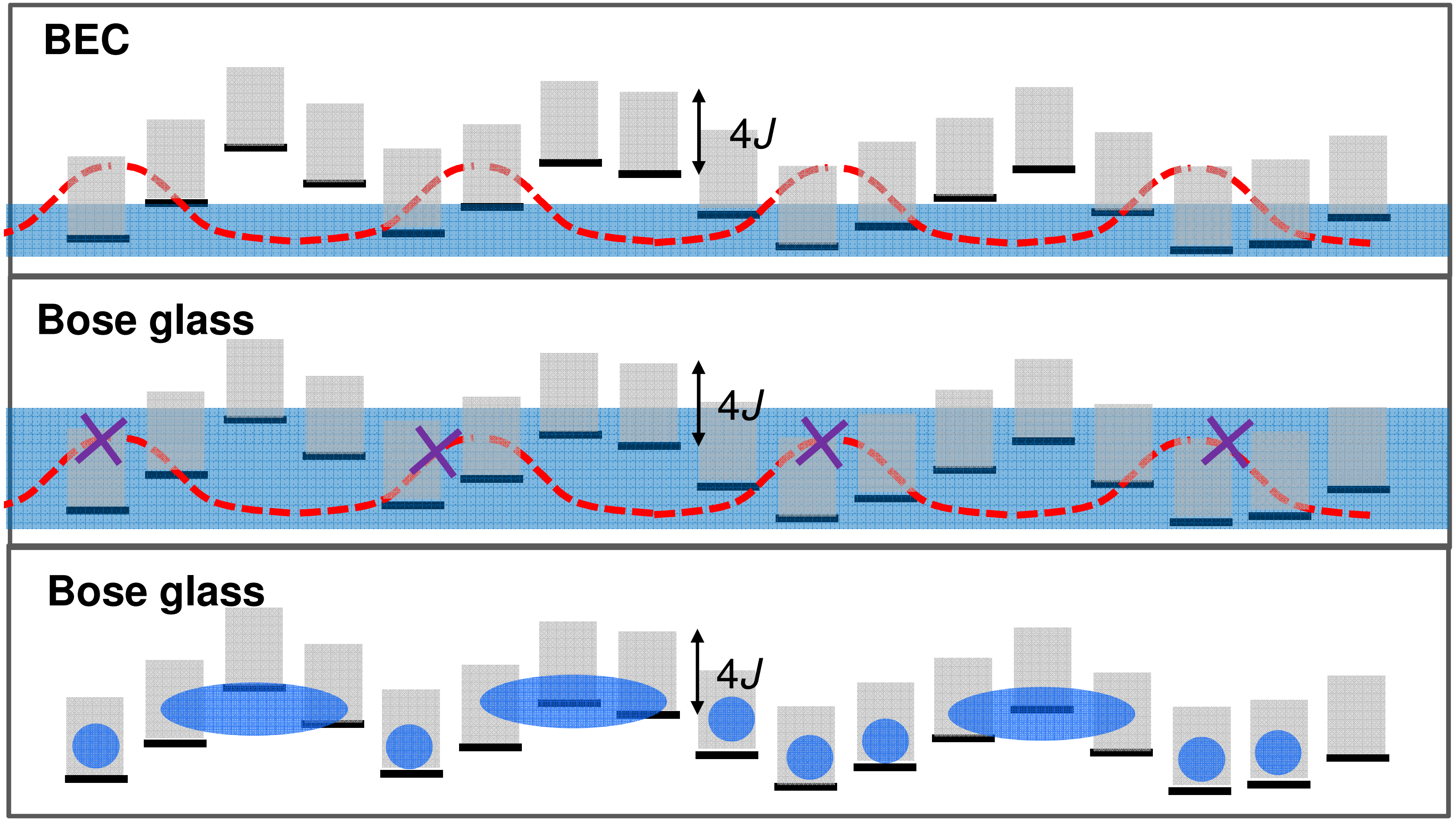
B. Deissler et al. New J. Phys. 13, 023020 (2011)

Phase diagram from momentum distribution

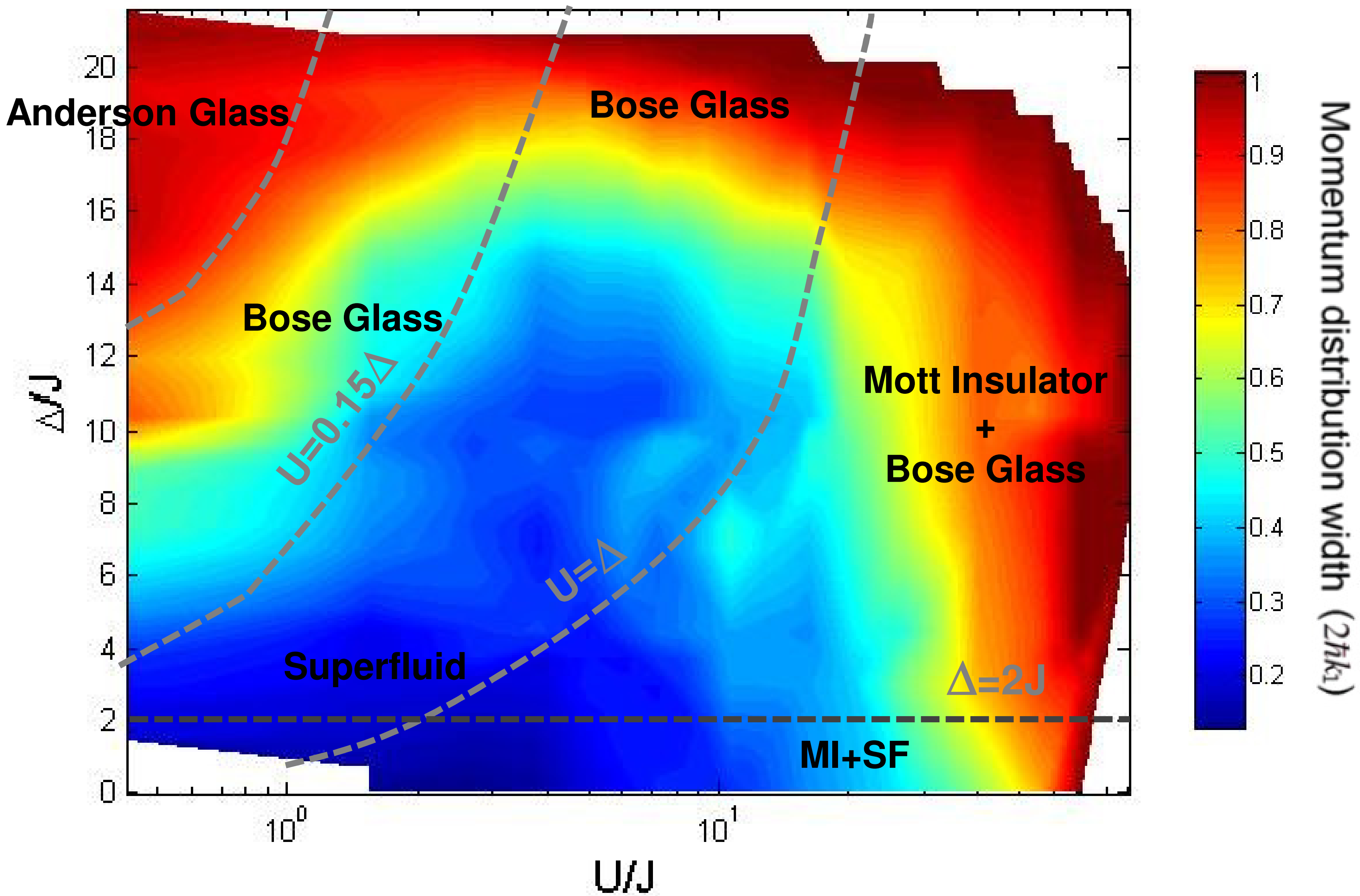


D'Errico et al, in preparation. Theory by T. Giamarchi, M. Modugno.

Strong interaction cartoon

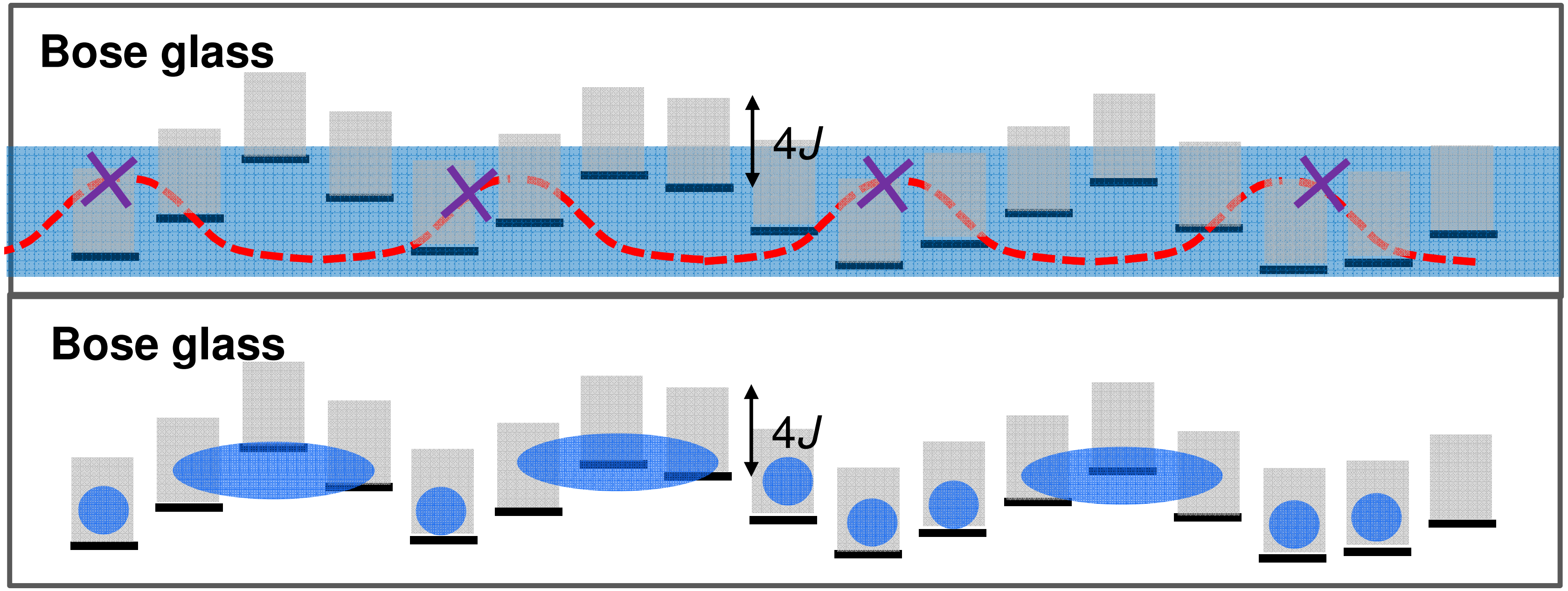


Phase diagram from momentum distribution



D'Errico et al, in preparation. Theory by T. Giamarchi, M. Modugno.

Strong interaction cartoon

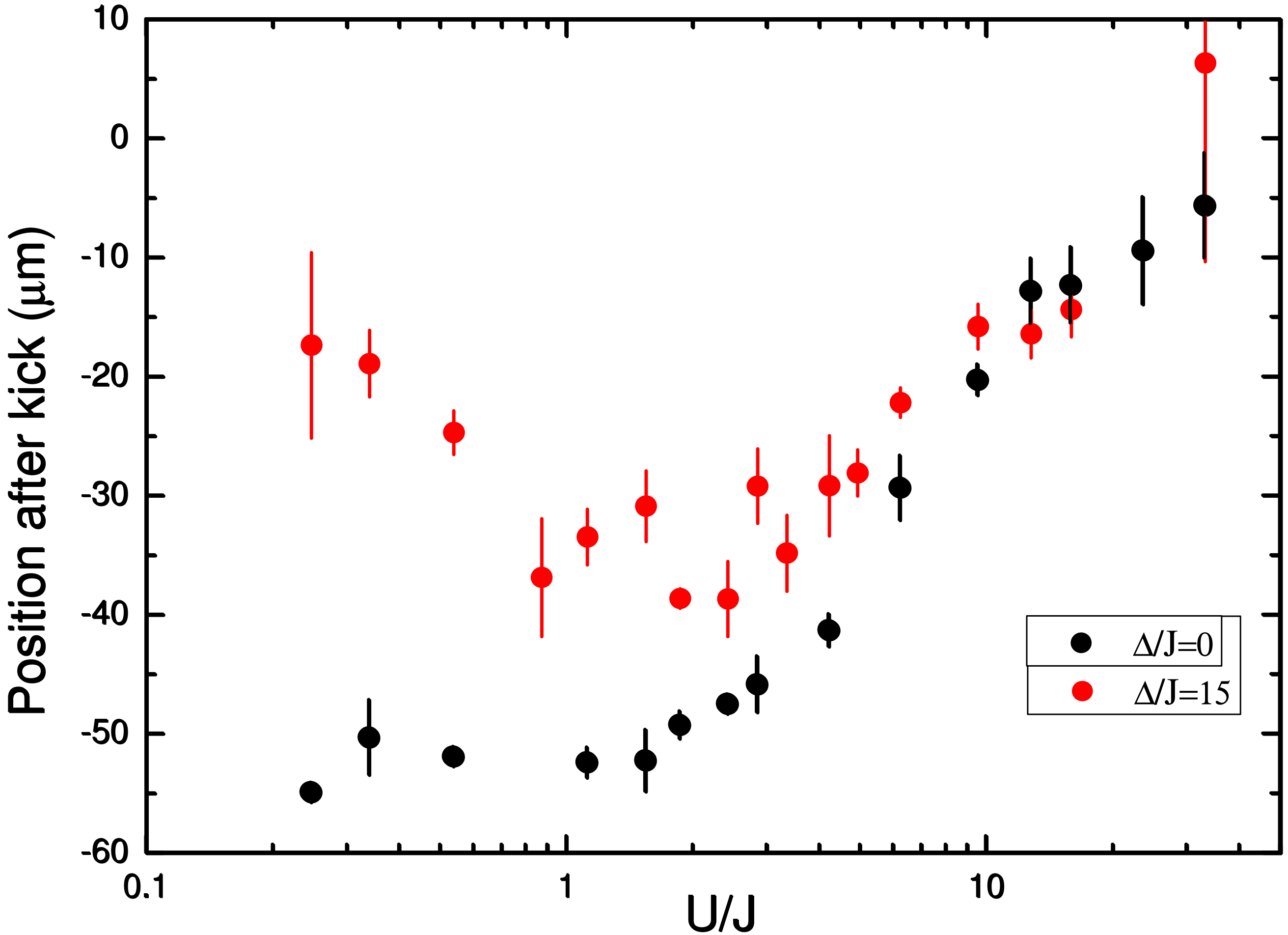


Strongly interacting Bose glass: **insulating** but **gapless**

Diagnostics:

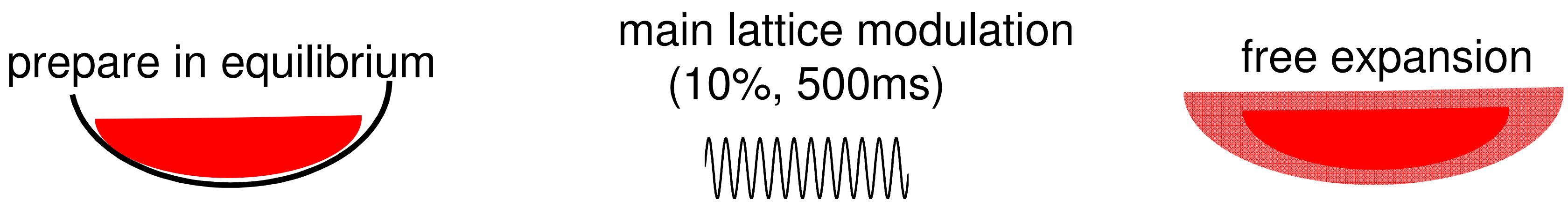
- momentum distribution/correlation function
- impulsive transport
- excitation spectrum

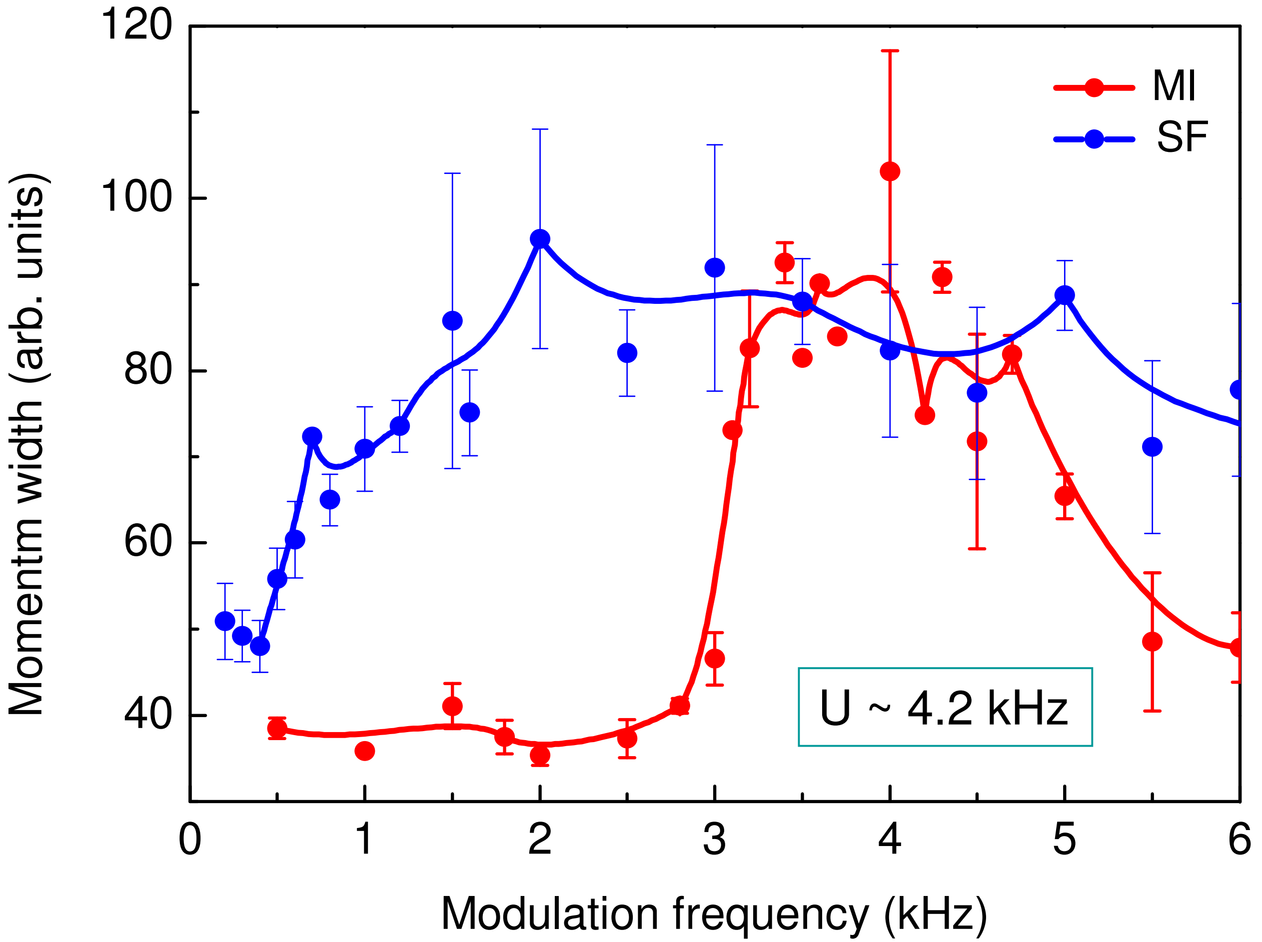
Impulsive transport



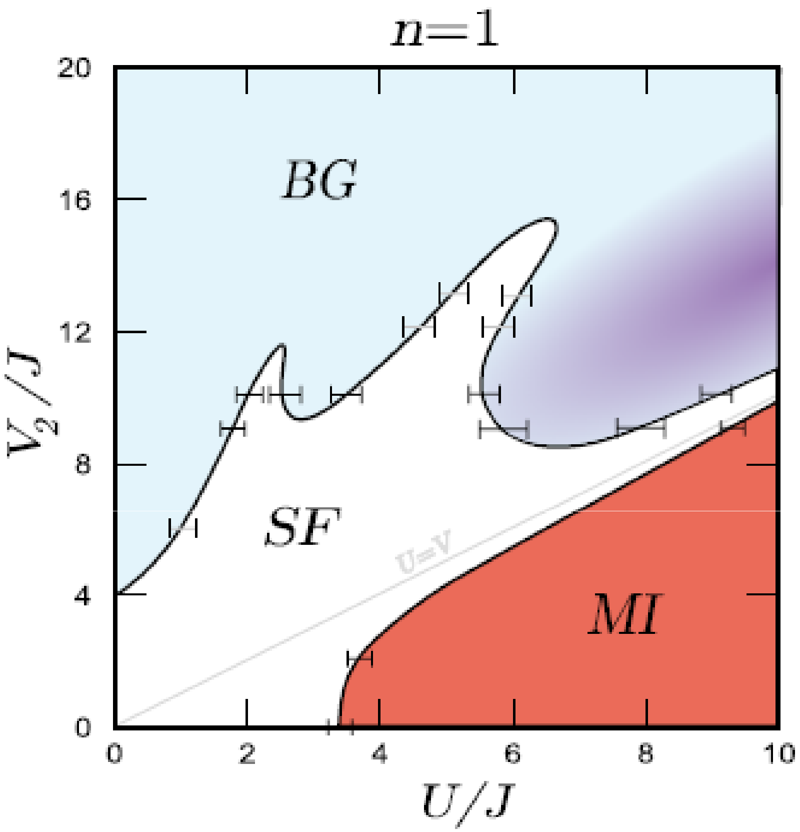
A. Polkovnikov et al. Phys. Rev. A 71, 063613 (2005); applied on Bose gases by DeMarco, Naegerl, Schneble

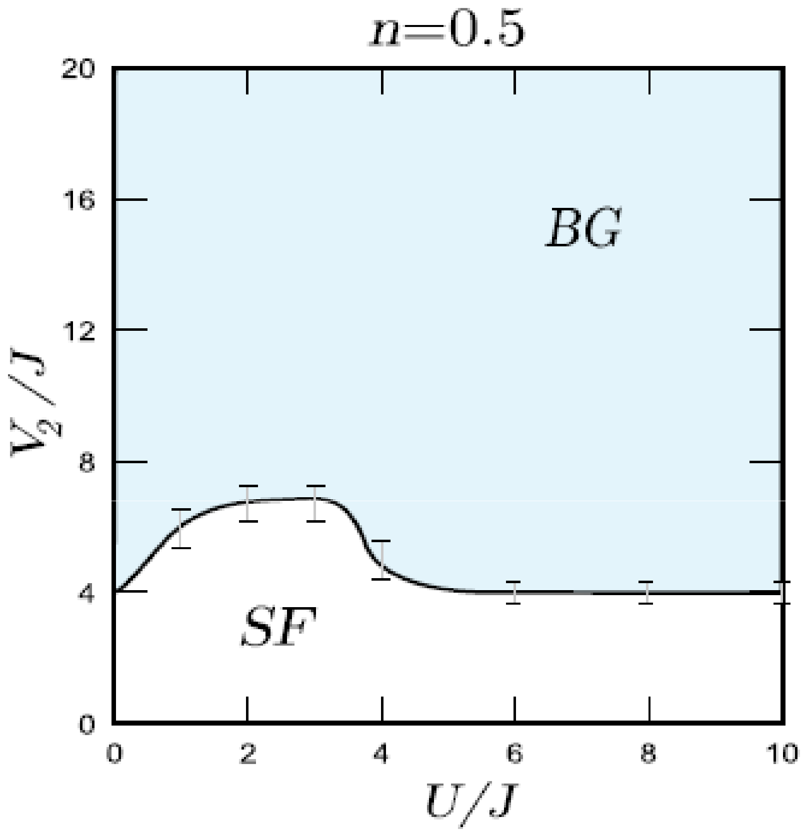
Excitation spectrum





Outlook

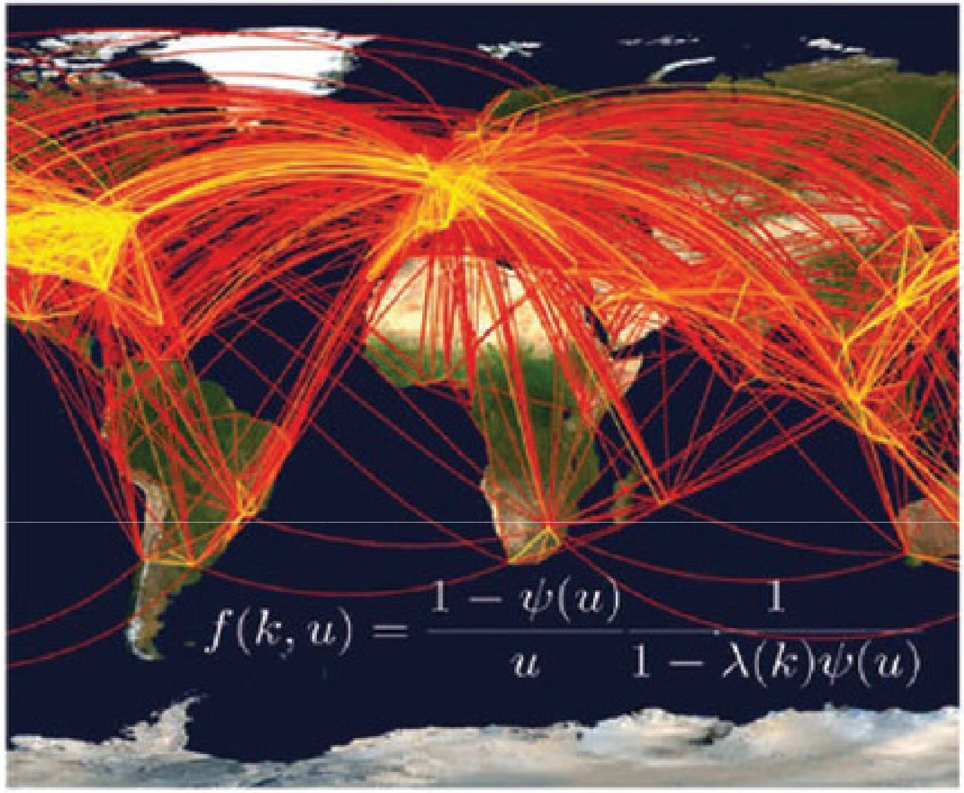




DMRG data, Roux et al., PRA **78**, 023628 (2008)

Comparison with theory, several issues: finite temperature, trap, averaging

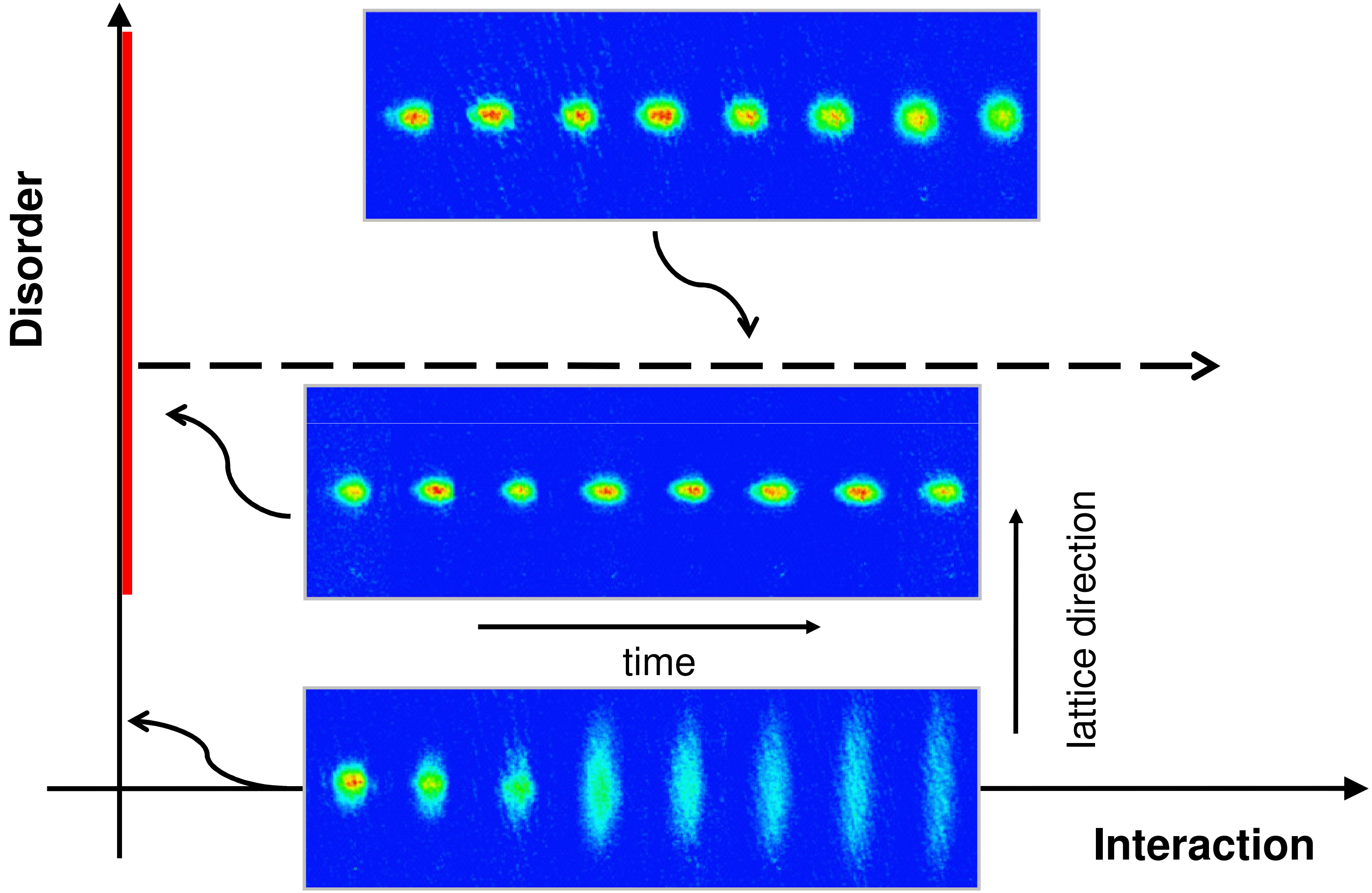
Anomalous transport in disorder



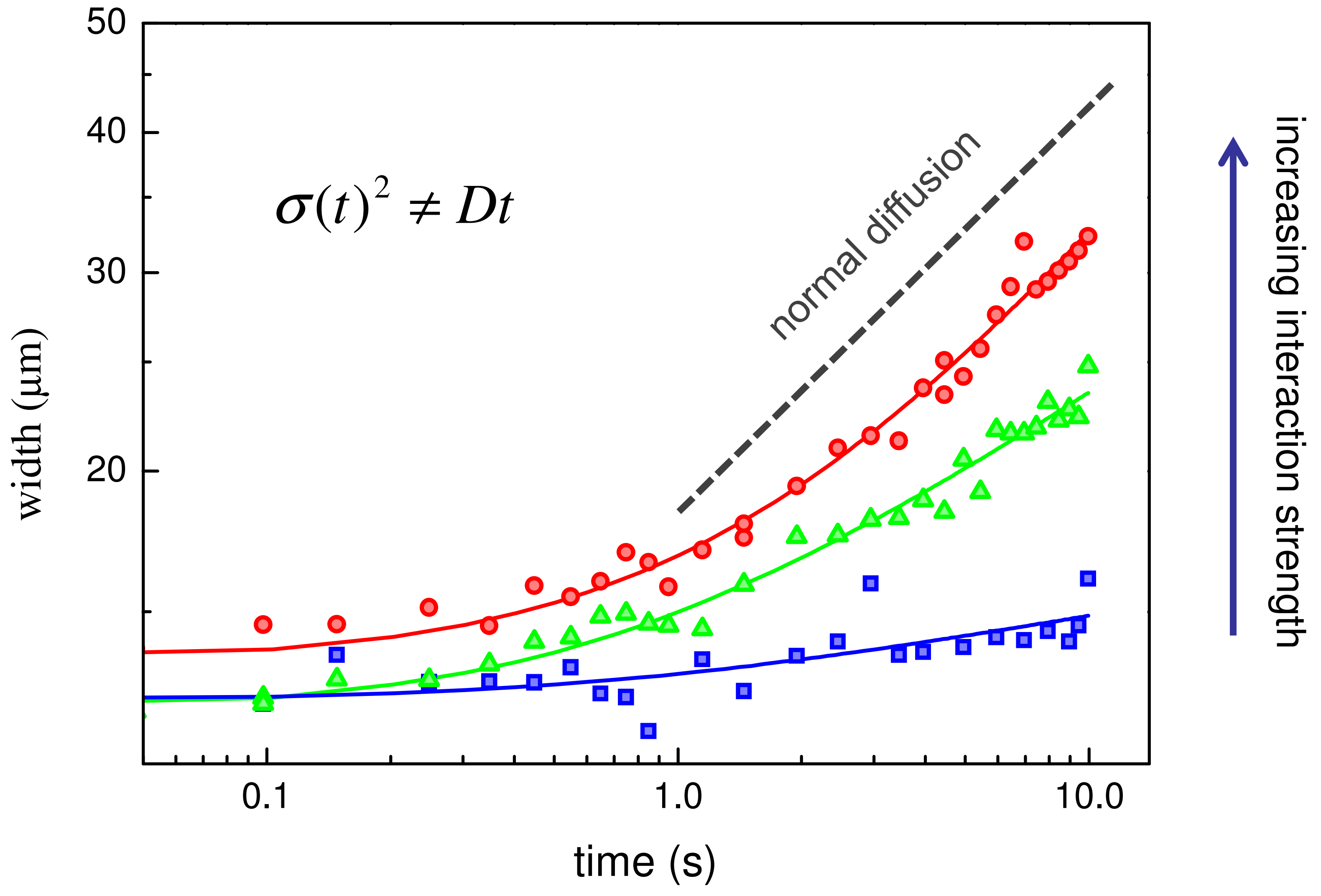
An open problem since decades, little data with nonlinearities:

J-P. Bouchaud and A .Georges, Phys. Rep. 195, 127 (1990)
D. L. Shepelyansky, Phys. Rev. Lett. 70, 1787 (1993)
S. Flach, et al, Phys. Rev. Lett. 102, 024101 (2009)
Klages, Radons, Sokolv, Anomalous transport (Wiley, 2010)

Expansion measurements

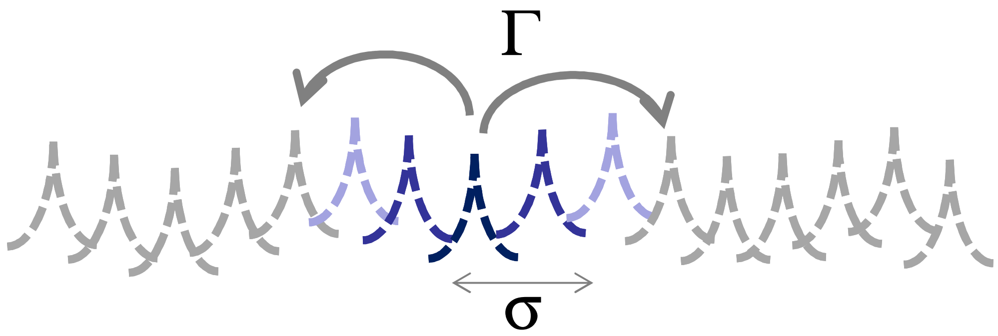


Interaction-assisted transport



Lucioni et al. Phys. Rev. Lett. 106, 230403 (2011)

Diffusion as hopping between localized states



Instantaneous diffusion

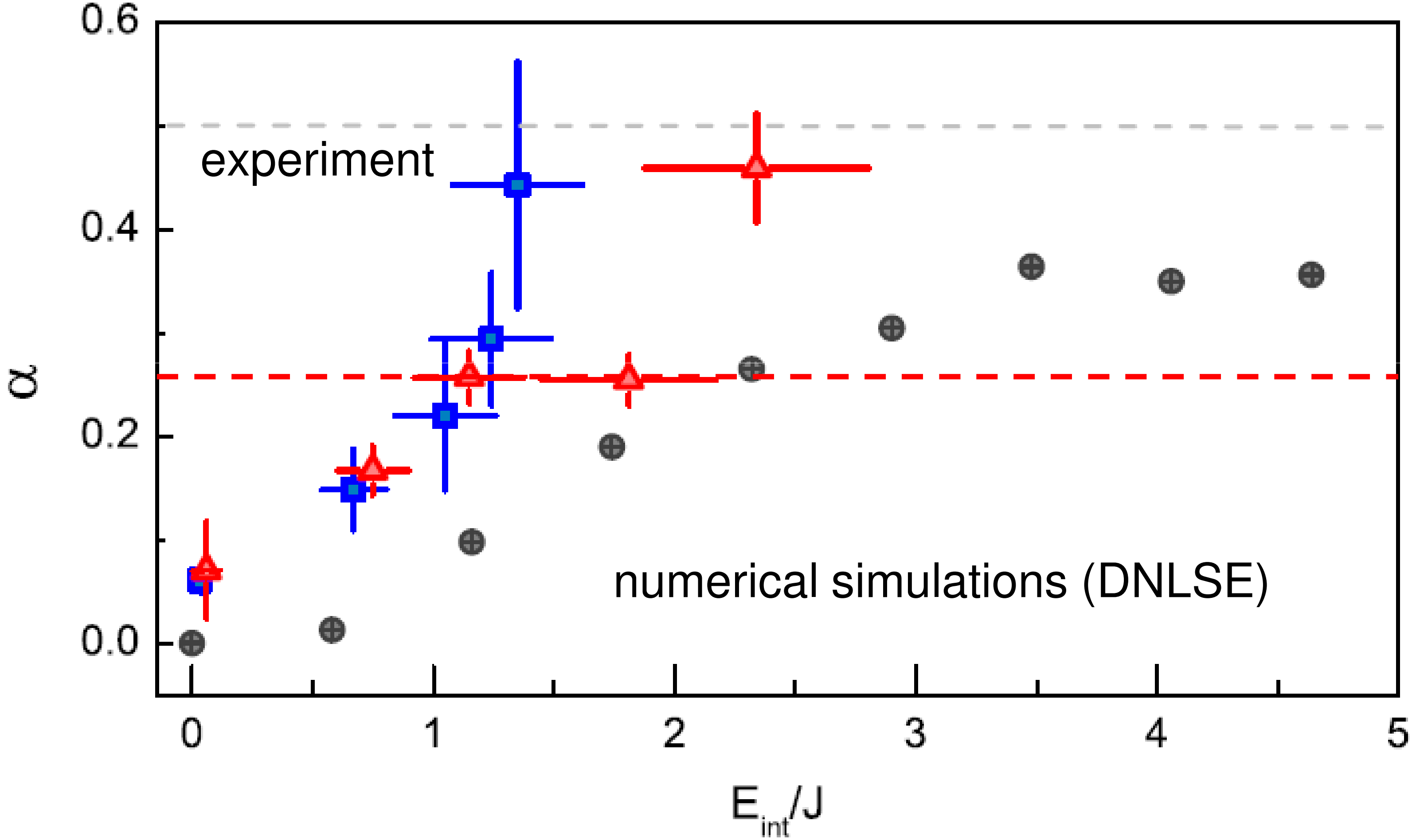
$$\frac{\partial \sigma^2}{\partial t} = D \approx \xi^2 \Gamma$$

with density-dependent rate

$$\Gamma \approx \frac{\langle i | H_{\text{int}} | f \rangle^2}{\delta E} \propto \frac{1}{\sigma^2} \qquad \sigma^2 \propto \sqrt{t}$$

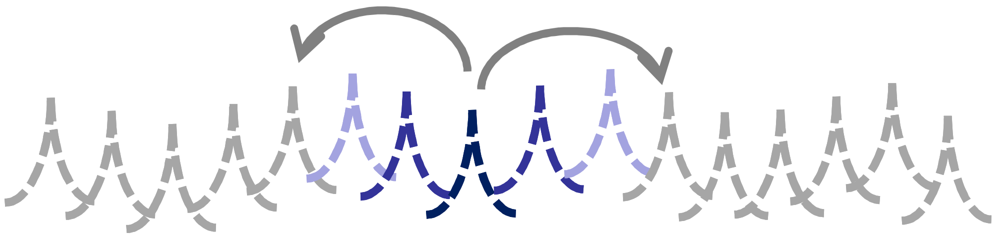
Several experts in theory: Shepeliansky, Fishman, Flach, Pikovsky, M.Modugno …
Intuitive description of the coupling: Aleiner, Altshuler, Shlyapnikov, Nat. Phys. 6, 900 (2010).

Subdiffusion exponent

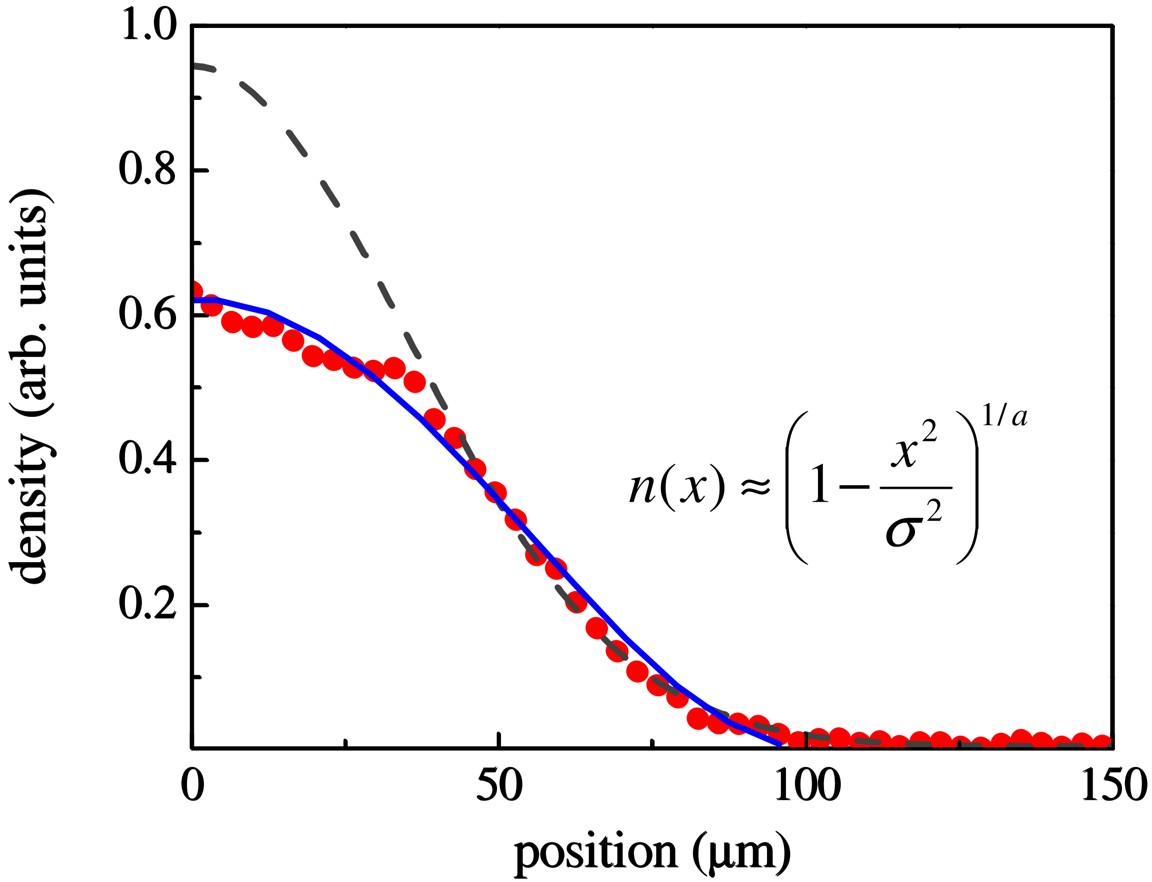


Various regimes of sub-diffusion, depending on the interaction energy: very weak interaction, self-trapping.

Spatial profiles



space-dependent diffusion constant

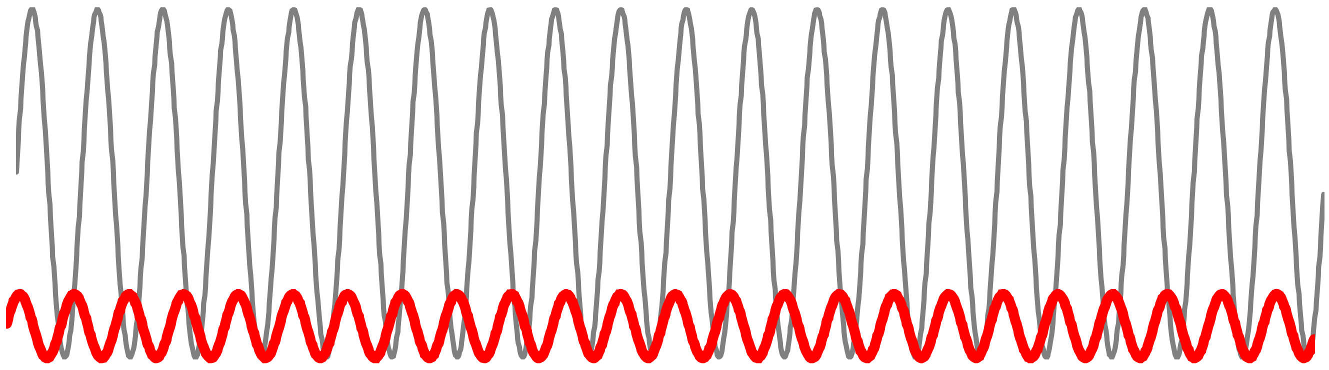


Nonlinear diffusion equation

$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial x}\left(D_0 n^a \frac{\partial n}{\partial x} \right)$$

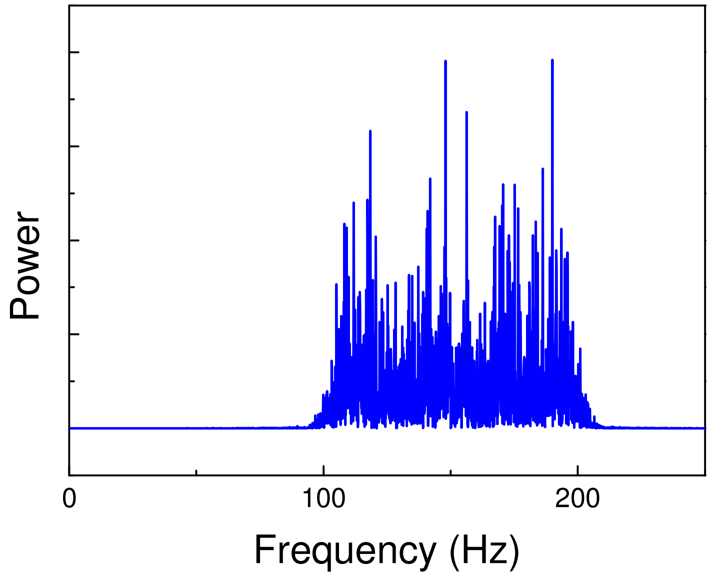
B. Tuck, Jour. Phys. D 9, 1559 (1976)

Noise-assisted transport



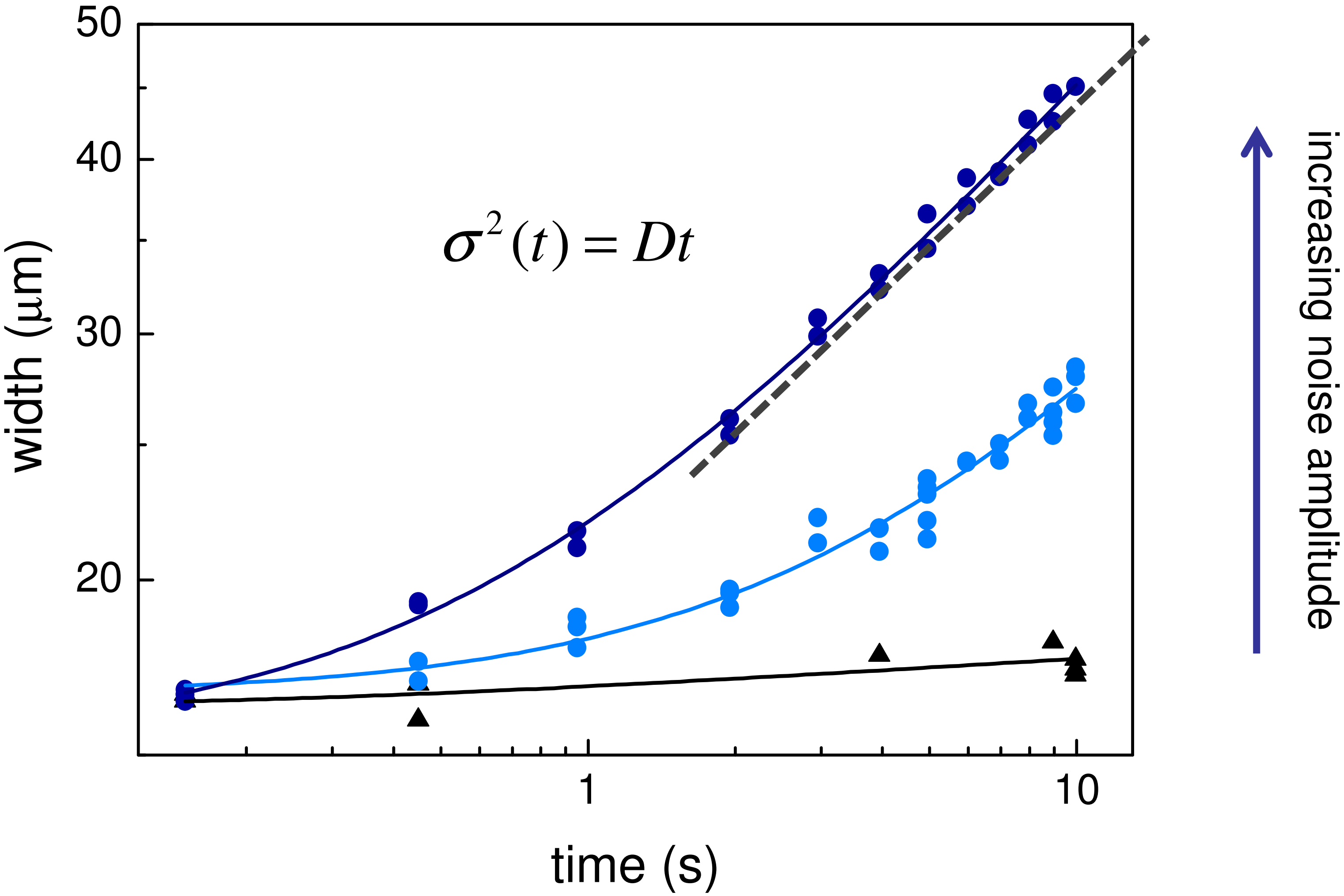
$$V_{dis} = \Delta\cos(2\pi\beta\, x)\;\;(1 + A\cos(\omega_i t))$$

Frequencies are picked randomly from a given interval, with time step T_d



Non stationary situation: no fluctuation-dissipation relation holds

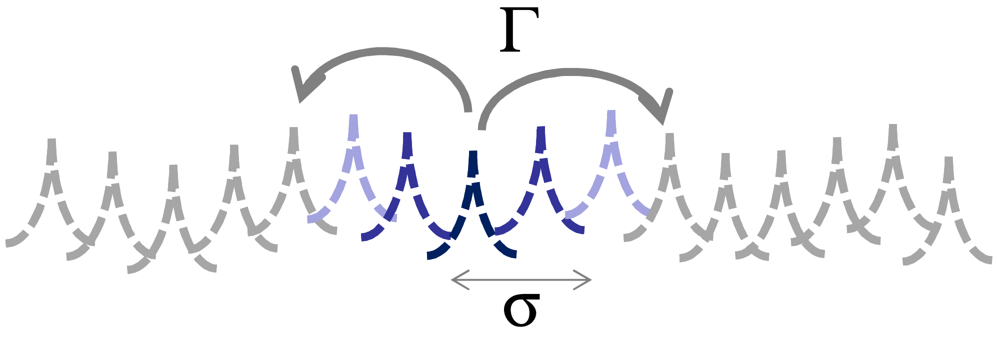
Noise-assisted transport



Also observed in atomic ionization (Walther), kicked rotor (Raizen) and photonic lattices (Segev&Fishman)

M. Arndt et al, Phys. Rev. Lett. 67, 2435 (1991); D. A. Steck, et al, Phys. Rev. E 62, 3461 (2000).

Diffusion as hopping between localized states



$$\frac{\partial \sigma^2}{\partial t} = D \approx \xi^2 \Gamma$$

Interaction:

$$\Gamma \approx \frac{\langle i | H_{\text{int}} | f \rangle^2}{\delta E} \propto \frac{1}{\sigma^2}$$

$$\sigma^2 \propto \sqrt{t}$$

Sub-diffusion

Noise:

$$\Gamma \approx \frac{\langle i | V'(t) | f \rangle^2}{\delta E} = const$$

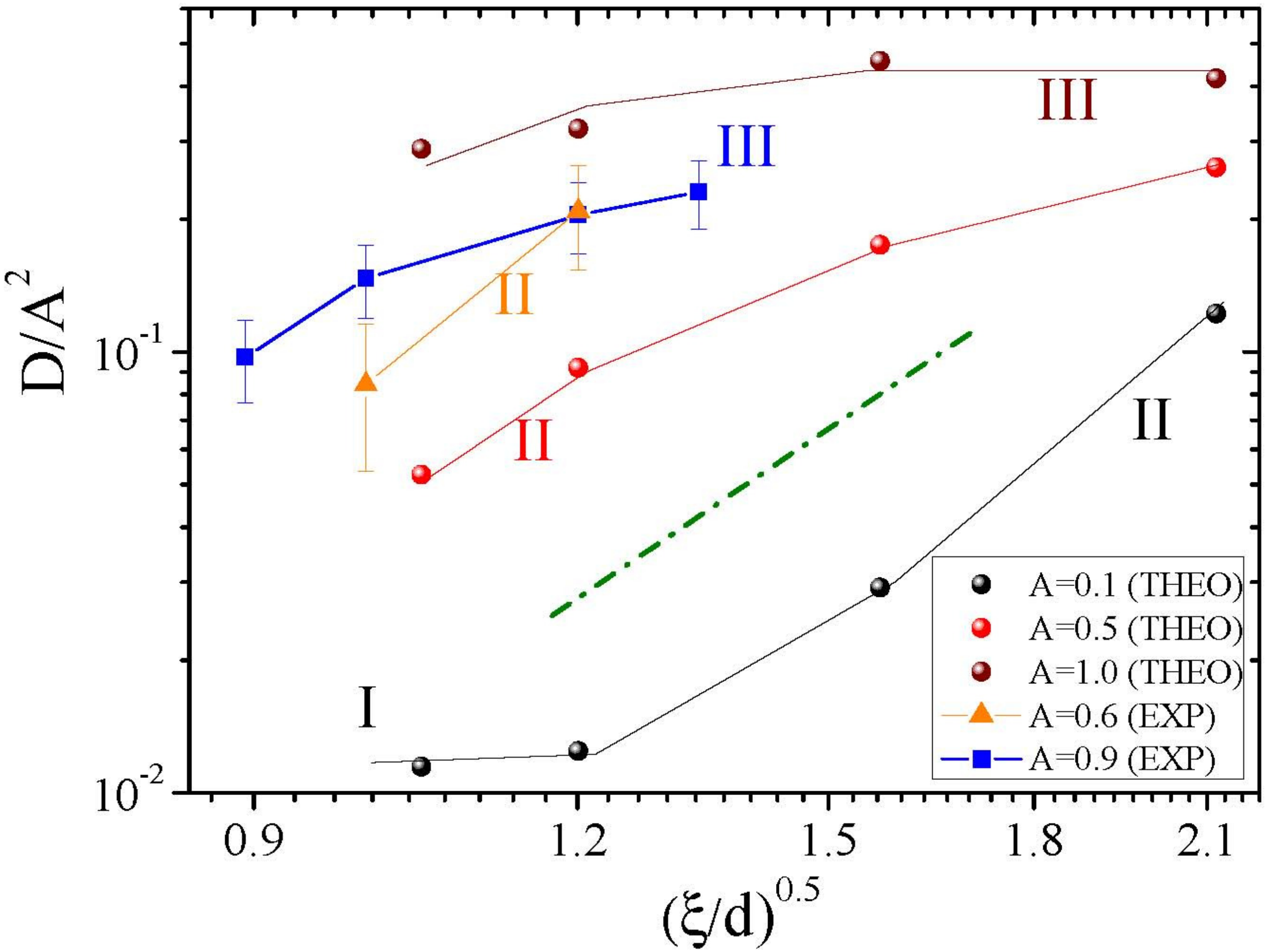
$$\sigma^2 = Dt$$

Normal diffusion

Theory: Ovchinnikov, Ott, Shepeliansky, Bouchaud&Georges, … and many others.

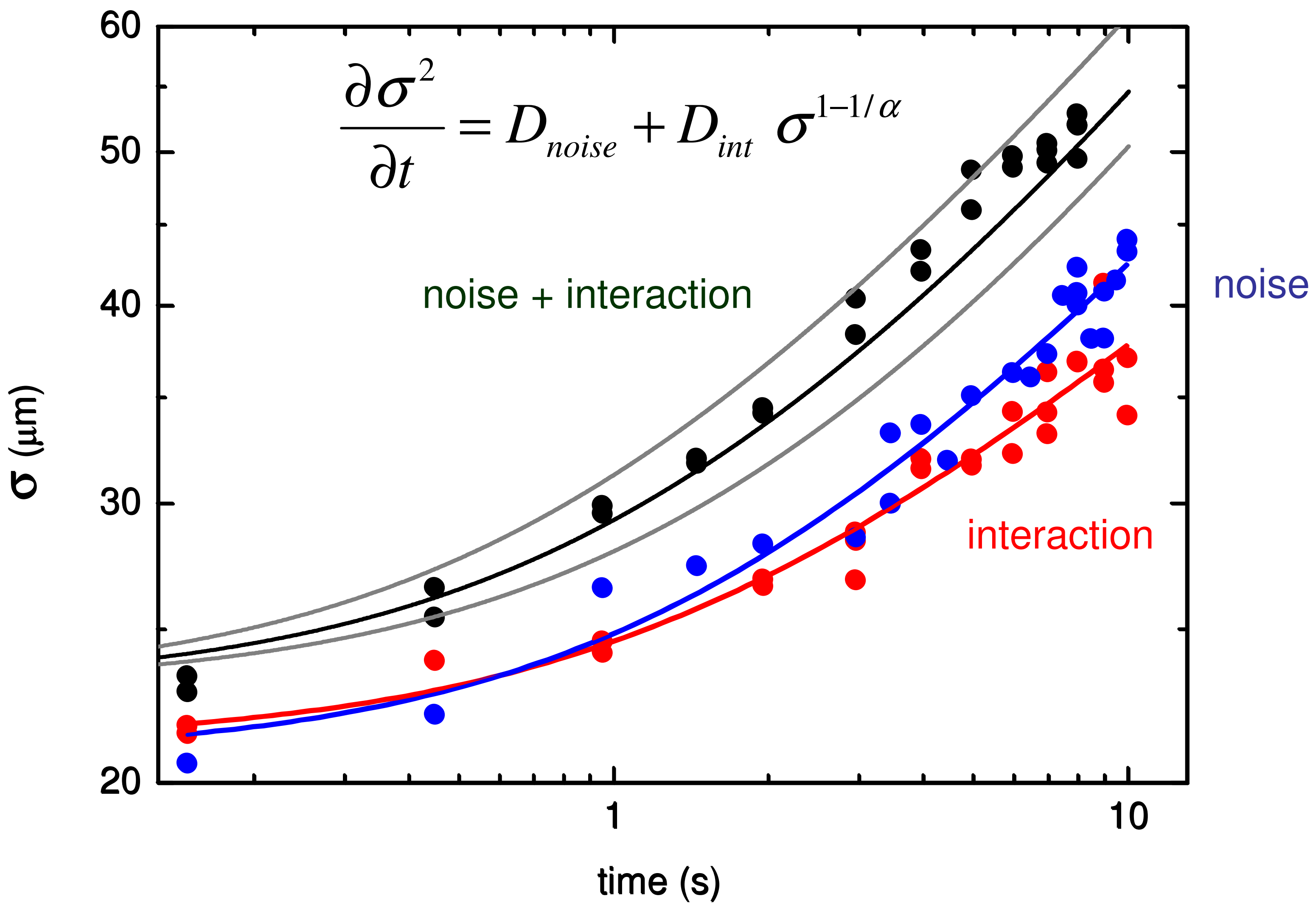
An extended perturbative model

C. D'Errico et al., arXiv:1204.1313

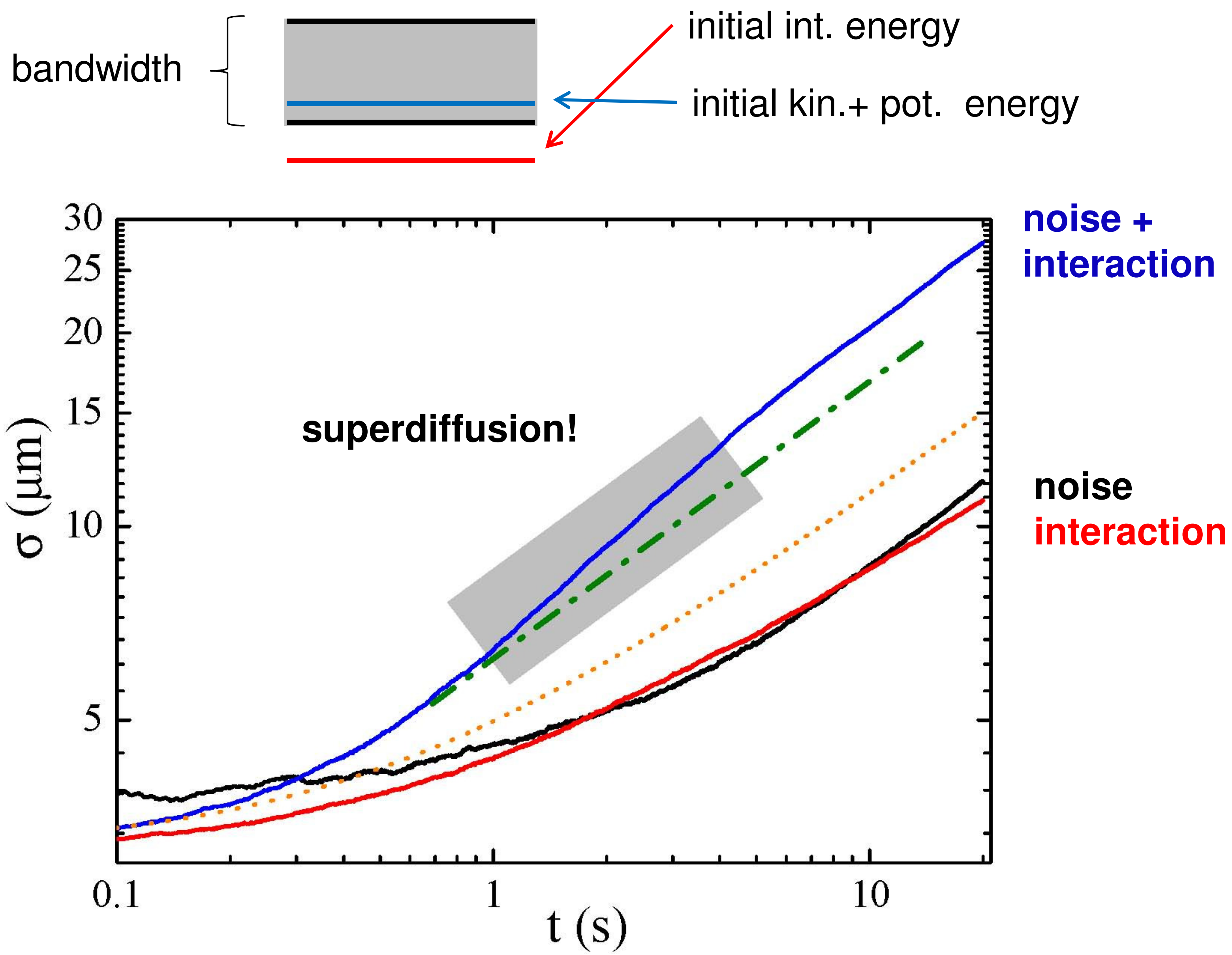


E. Ott, T. M. Antonsen and J. D. Hanson, Phys. Rev. Lett. 53, 2187 (1984);
J.P. Bouchaud, D. Toutati and D. Sornette, Phys. Rev. Lett. 68, 1787 (1992).

Noise and interaction

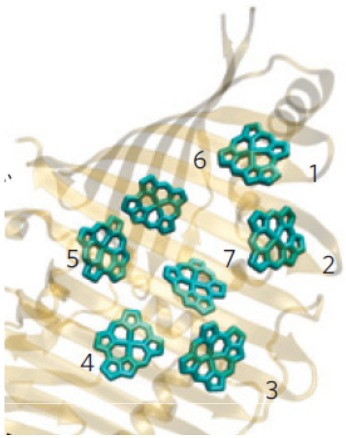


Anomalies: self-trapping and super-diffusion

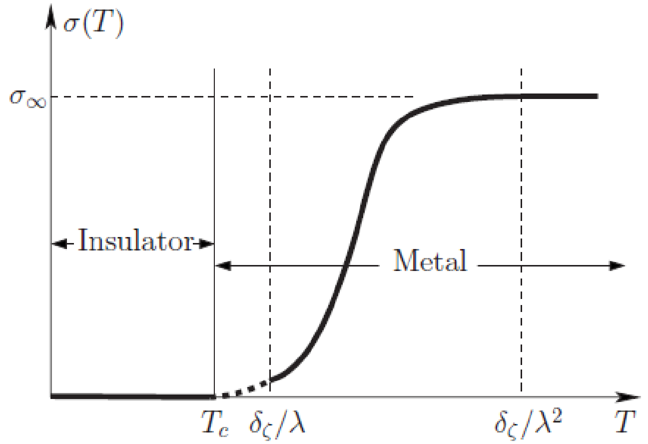


Outlook

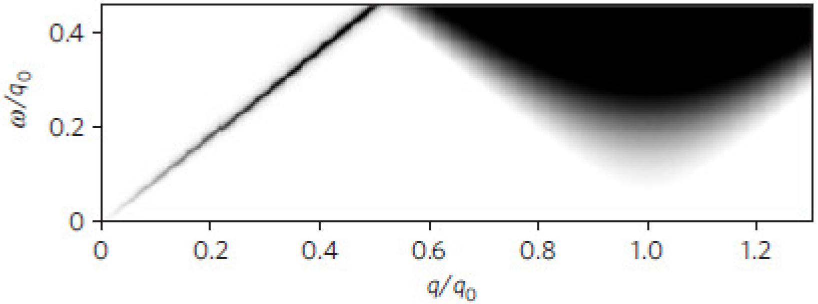
Towards improved spatial resolution, noise-induced heating, stationary noise (another atomic species):



Noise-assisted trasport in natural disordered media



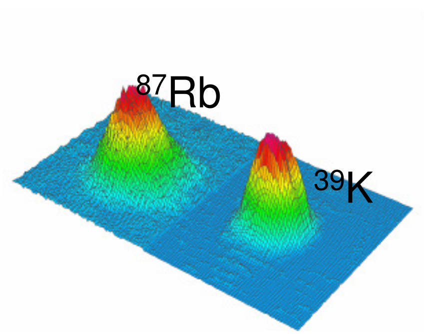
Many-body localization transition in disorderd Bose and Fermi systems



Out-of-equilibrium quantum phase transitions

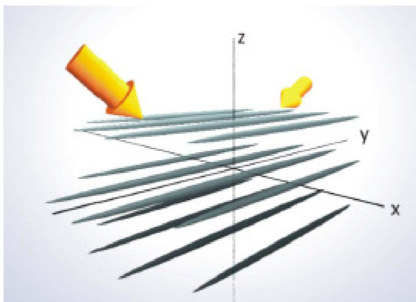
Future directions in Florence

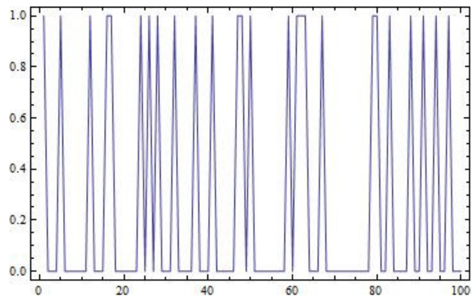
- Impurity and other disorder types: effect of disorder correlations and distributions
- Strongly interacting1D bosons with weak disorder
- Interactions and Anderson localization in higher dimensions
- Strongly correlated phases and frustration in higher dimensions
- Fermi gases; dipolar systems; …



Impurities and thermal baths

Bragg spectr.





Engineered disorder

The team

Experiment:

Chiara D'Errico
Luca Tanzi
Benjamin Deissler
G.M.

Eleonora Lucioni
Lorenzo Gori

Massimo Inguscio

Theory:

Filippo Caruso (Ulm-LENS)
Marco Moratti
Marco Larcher (Trento)

Martin Plenio (Ulm)
Michele Modugno (Bilbao)
Franco Dalfovo (Trento)

acknowledgments:

B. Altshuler, S. Flach, T. Giamarchi, G. Shlyapnikov, M. Mueller, …
C. Fort, L. Fallani, M. Fattori, F. Minardi, G. Roati, A. Smerzi, …