Experiments with disordered, interacting Bose gases

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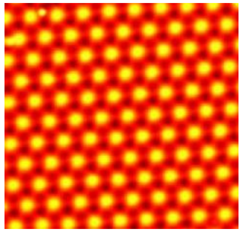
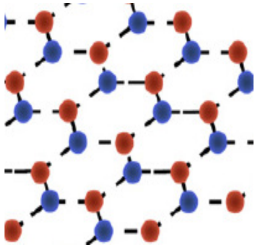
Quantum Simulations with Ultracold Atoms
ICTP, Trieste, July 2012

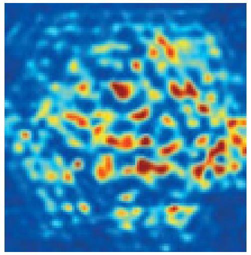
Disorder and quantum gases



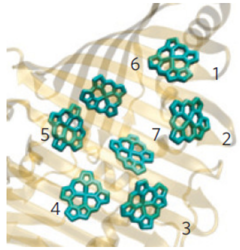
Superconductors



Graphene



Photonic media



Biological systems

Disorder tends to localize single particle eigenfunctions or classical waves (well known even before Anderson’s work from 1958).

Anderson localization in 3D is hard to observe, model and numerically simulate.

The interplay of disorder and interactions is still far from being understood.

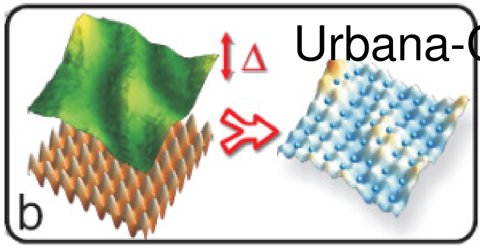
Ultracold atoms: new experimental regimes and better control.

Disorder and quantum gases

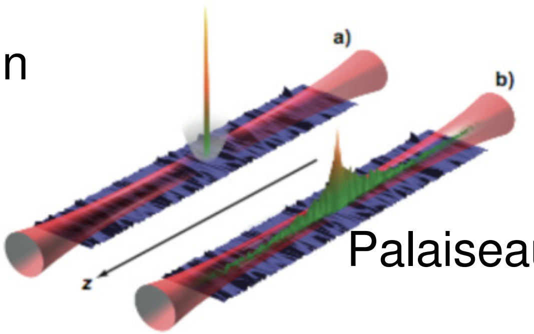
Theory:

E. Altman, B. Altshuler, Y. Castin, E. Demler, T. Giamarchi, S. Giorgini, C. Kollath, M. Lewenstein, A. Minguzzi, M. Mueller, G. Mussardo, G. Orso, N. Prokofiev, A. Polkovnikov, C. Sa De Melo, L. Sanchez-Palencia, L. Santos, G. Shlyapnikov, A. Trombettoni,T. Roscilde, and many others

Experiments:

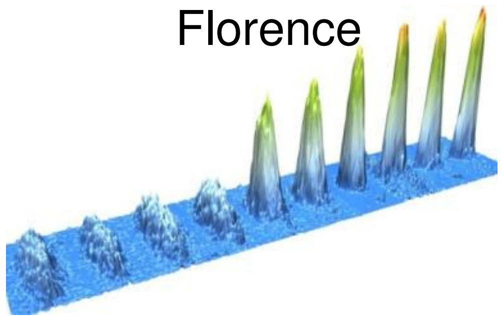


Urbana-Champaign

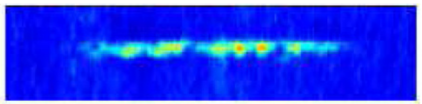


Palaiseau

Florence



Rice U.

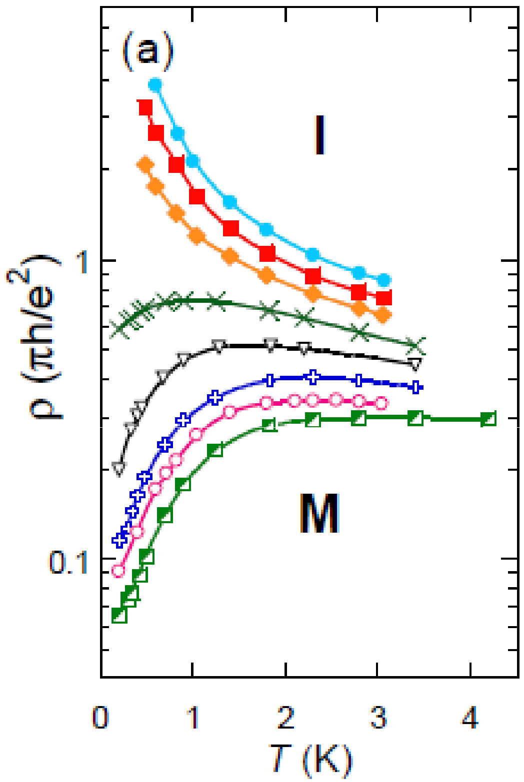


U. Hannover, NIST-Maryland, Stony-Brook

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); B. Shapiro, arXiv:1112.5736.

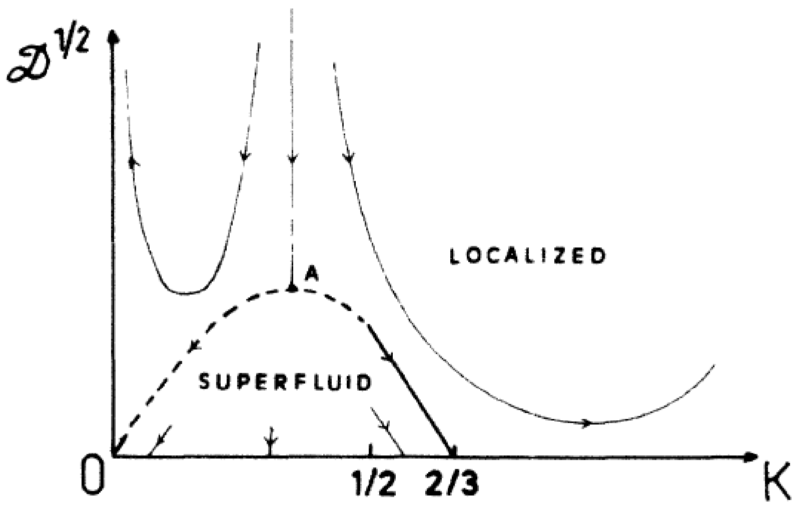
Interplay of disorder and interactions

Fermions in condensed-matter systems:
superconducting or insulating as $T \to 0$



Punnoose & Finkel'stein, Science 310, 289 (2005)

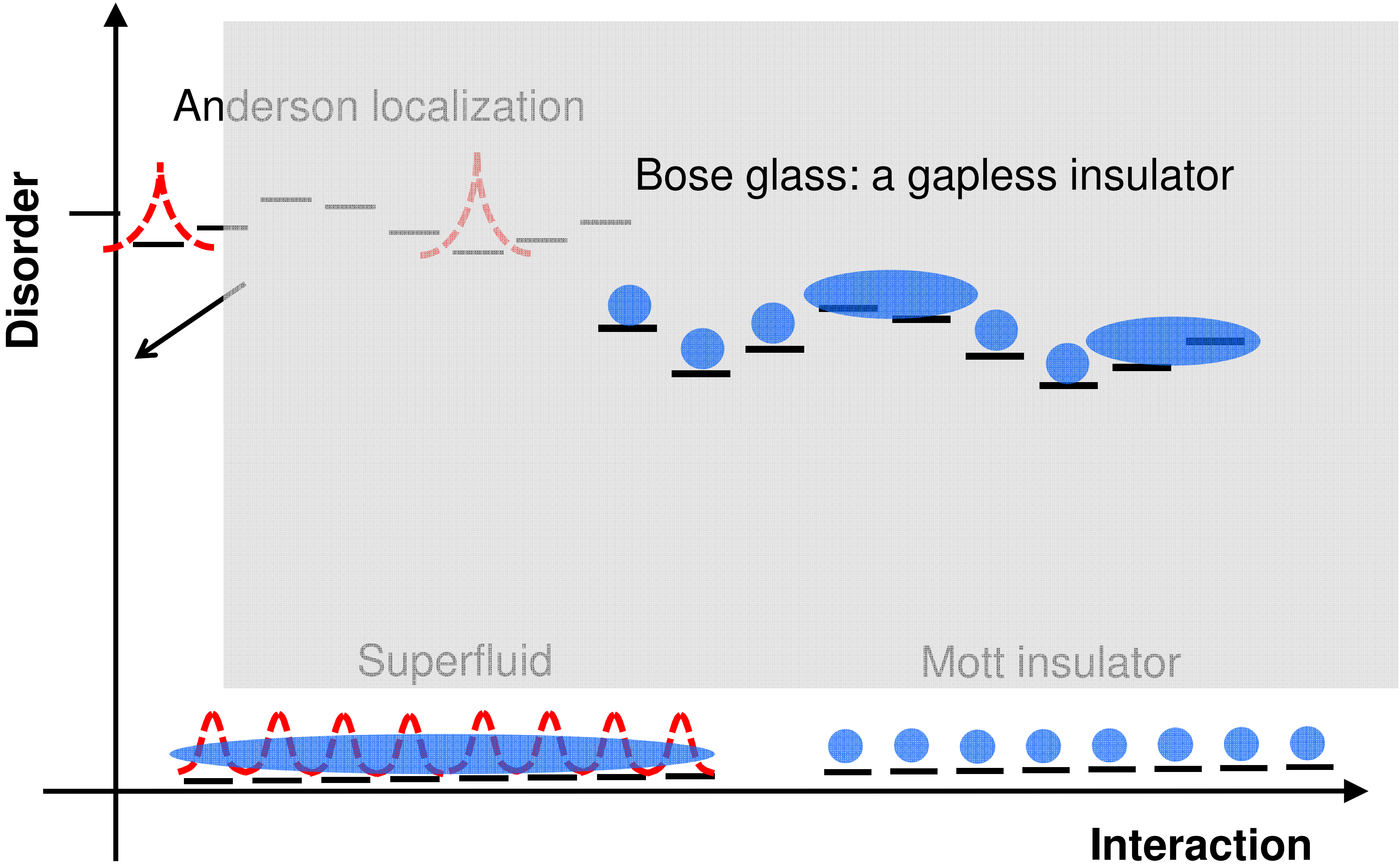
Bosons (in theory): quantum phases at T=0



Giamarchi & Schultz, PRB 37 325 (1988)

Our goal: characterize the phase diagram of disordered bosons, starting from 1D and T~0

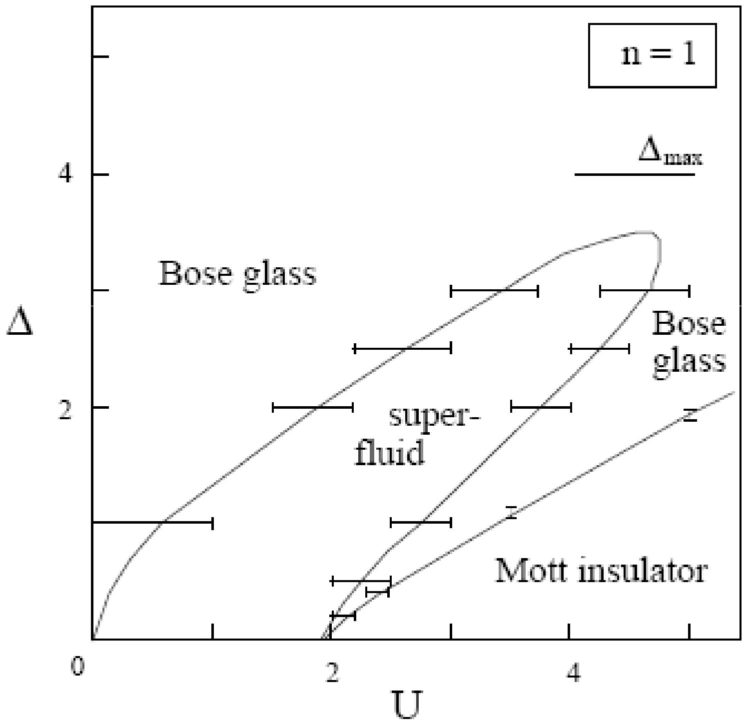
Disordered lattice bosons



Disordered lattice bosons in 1D: theory

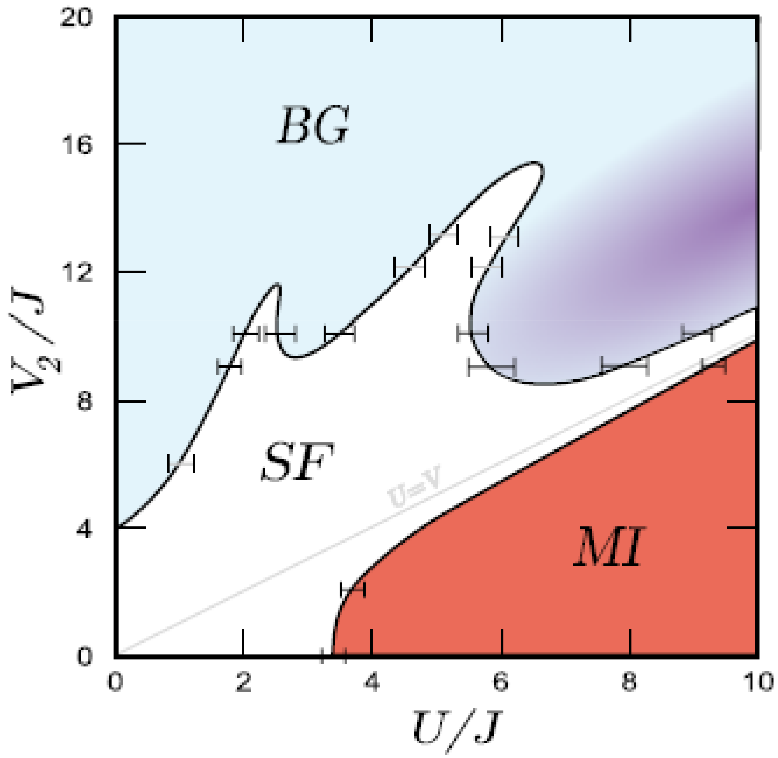
Seminal work: Giamarchi and Schulz , PRB 37 325 (1988)
Fisher et al PRB 40, 546 (1989), …

Random disorder



Rapsch, Schollwoeck, Zwerger
EPL 46 559 (1999)

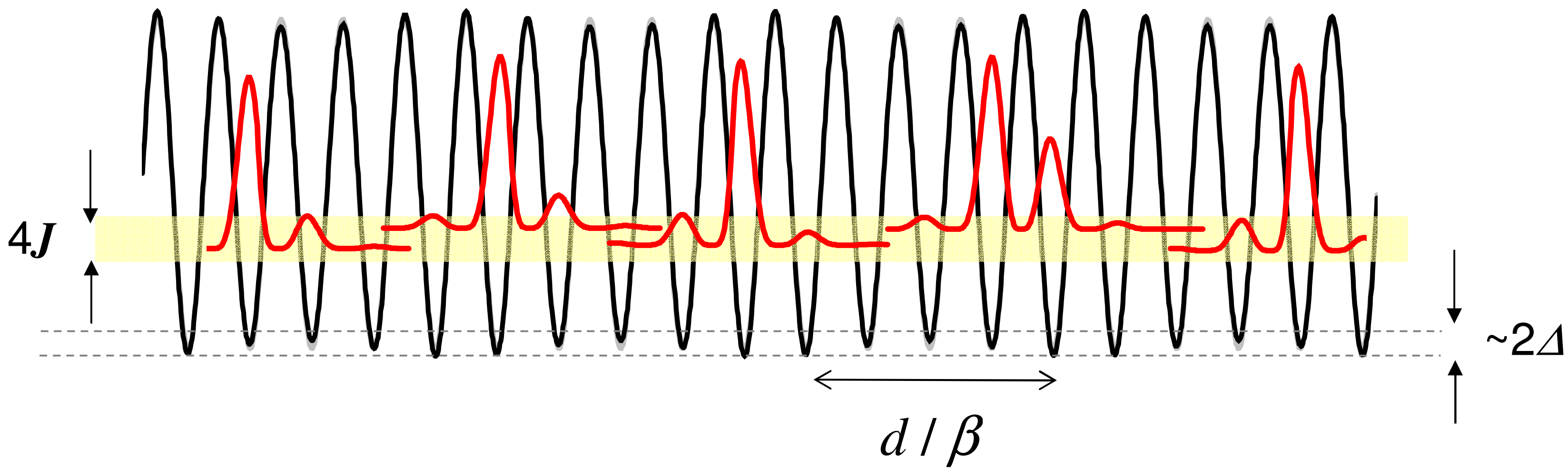
Quasiperiodic lattice



Roux et al., PRA 78, 023628 (2008)

Bose glass: no superfluid fraction, exponentially decaying correlations, compressible, ...

A quasi-periodic lattice



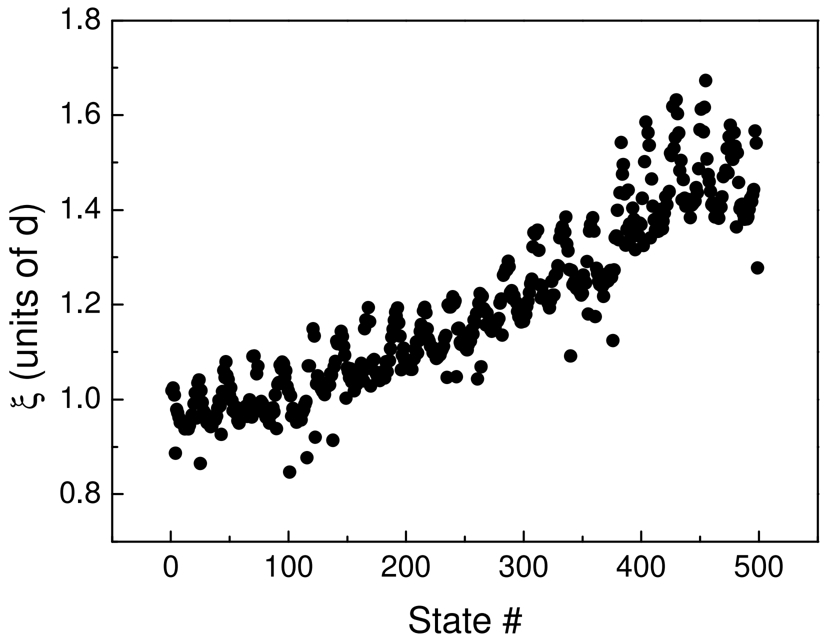
Aubry-Andrè, or Harper model:

$$\hat{H} = -J \sum_{\langle i,j \rangle} \hat{b}_i^+ \hat{b}_j + \Delta \sum_i \cos(2\pi\beta i)\ \hat{n}_i \qquad \beta = \frac{k_2}{k_1} \mathrm{mod} 1$$

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

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

A quasi-periodic lattice

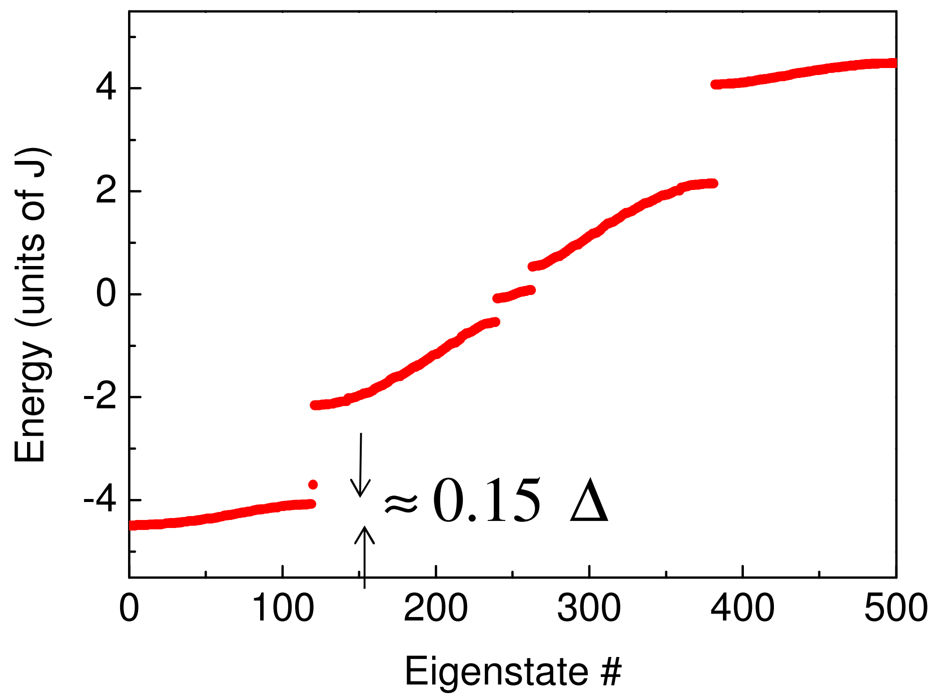


Rapidly oscillating correlation of the potential:

Short, uniform localization length

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

… and energy gaps

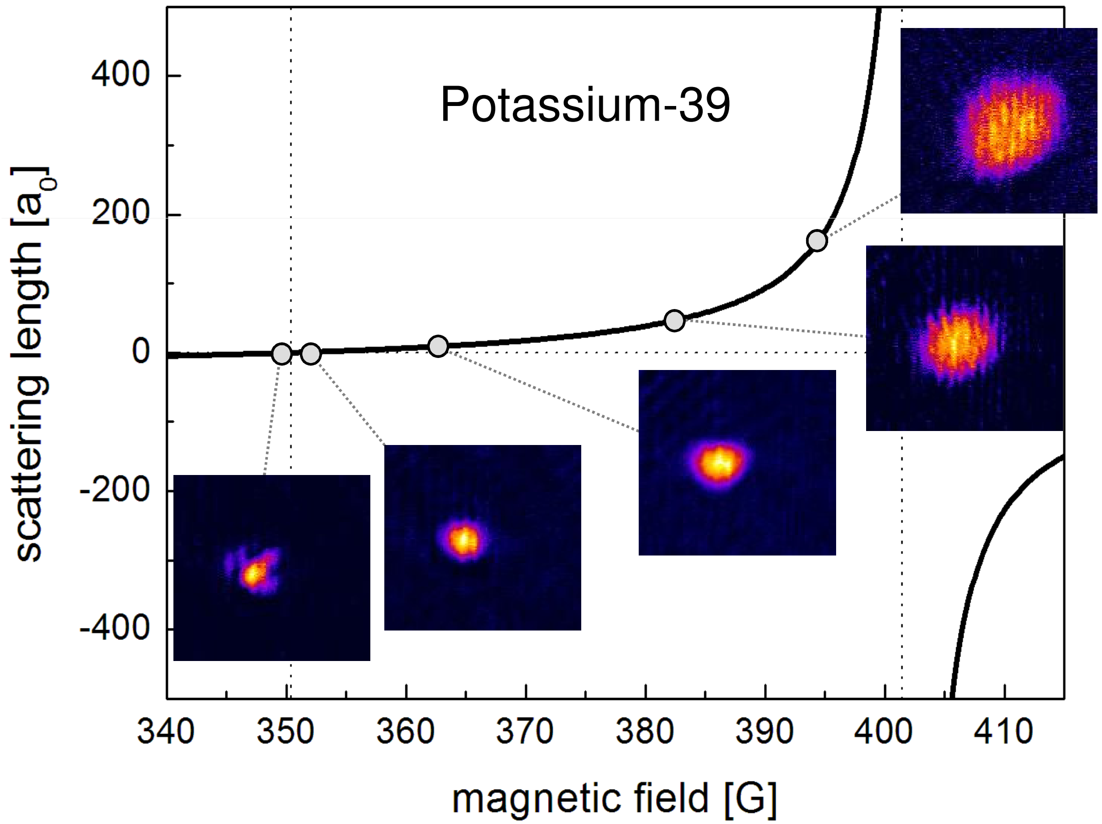


Tunable interactions via Feshbach resonances

Interacting Aubry-Andrè or quasi-periodic Bose-Hubbard model:

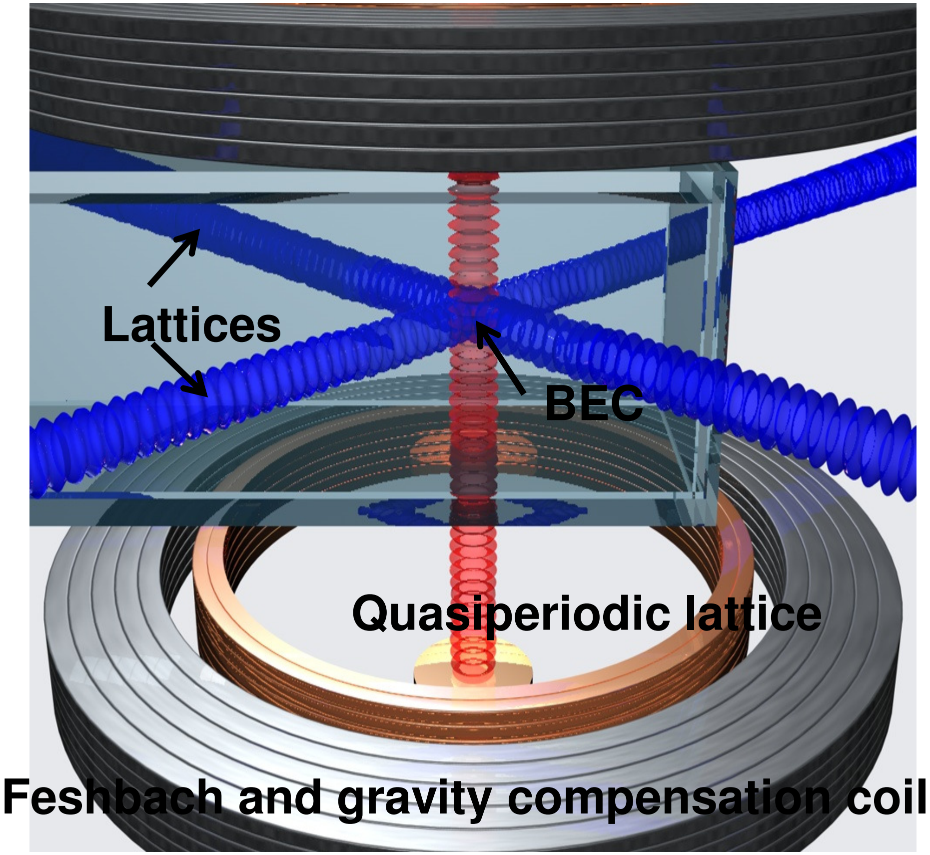
$$\hat{H} = -J\sum_{\langle i,j\rangle} \hat{b}_i^{+}\hat{b}_j + \Delta\sum_i \cos(2\pi\beta i)\ \hat{n}_i + U(a)\sum_i \hat{n}_i(\hat{n}_i - 1)$$

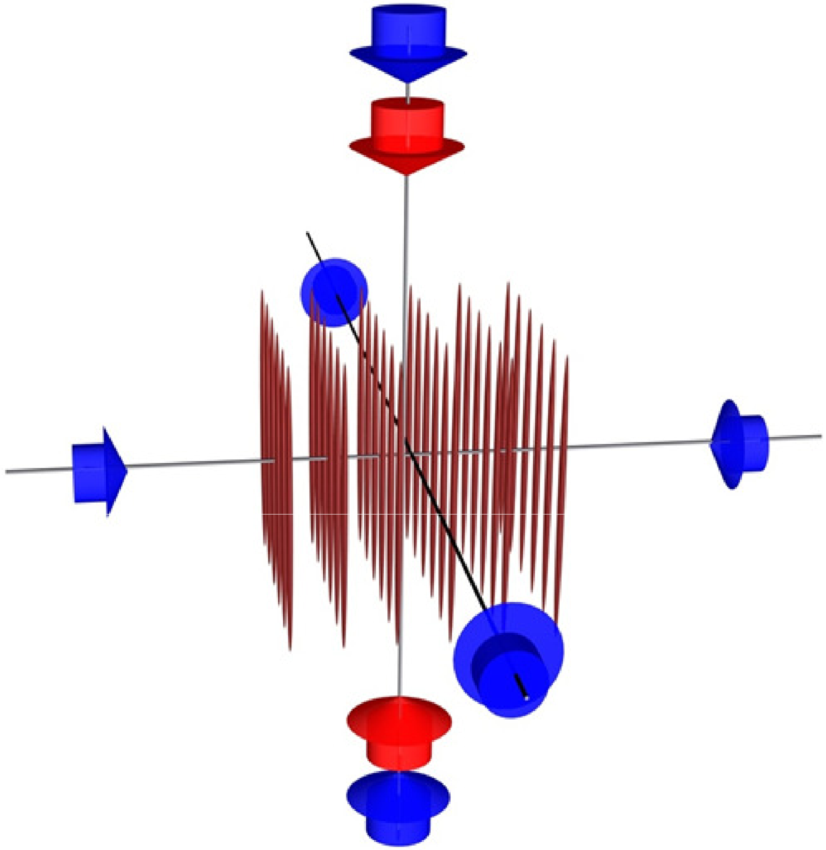
$$U = \frac{2\pi\hbar^2}{m} a \int |\varphi(x)|^4\, d^3x$$



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

Experimental scheme





Strong 2D lattices with weak 3D harmonic trapping.

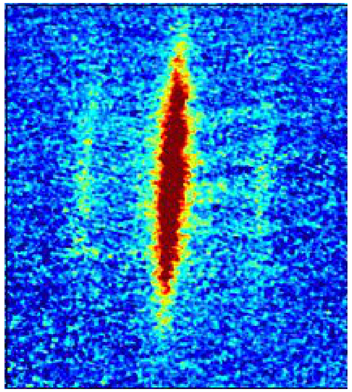
The radial energy separation is much larger than kinetic, potential and interaction energies: ν_r=50 kHz; J/h=100 Hz

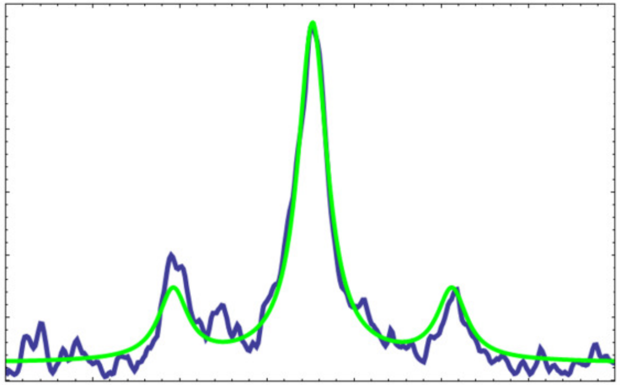
Momentum distribution

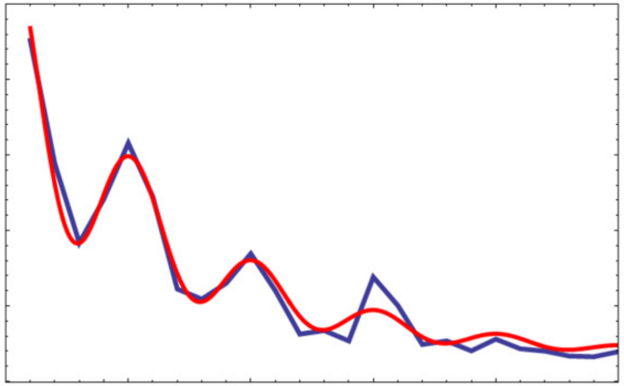
Δ=0, U=J

$|\Psi(k)|^2$

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







Finite temperature 1D Bose gas: exponential decay of correlations

$$|\Psi(k)|^2 \propto \frac{1/L_\phi}{k^2 + (0.67/L_\phi)^2} \qquad g(x) \propto \exp(-0.67\,|x|/L_\phi)$$

$$L_\phi = \frac{n\hbar^2}{m^* k_B T}$$

Estimated temperature: T≈5J

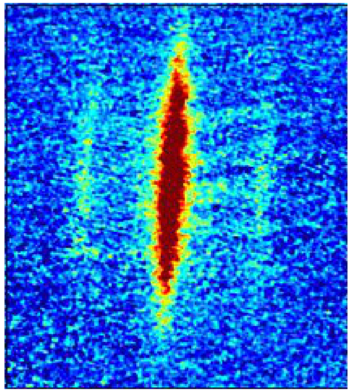
Olshanii, Shlyapnikov, Aspect, Bloch,...

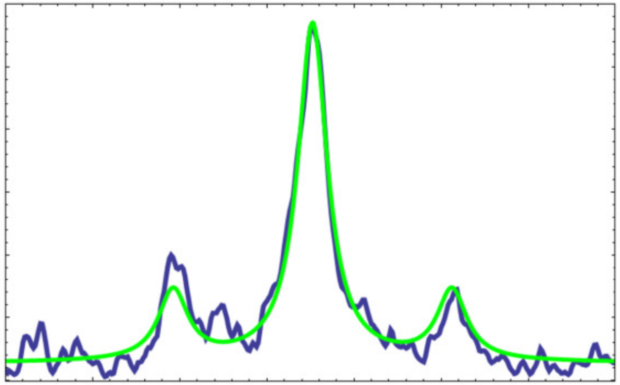
Momentum distribution: SF to MI

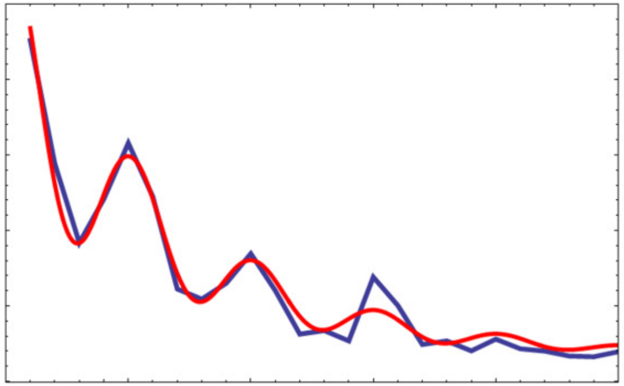
$|\Psi(k)|^2$

$$g(x) = \int dx' \langle \Psi^+(x)\Psi(x+x') \rangle$$

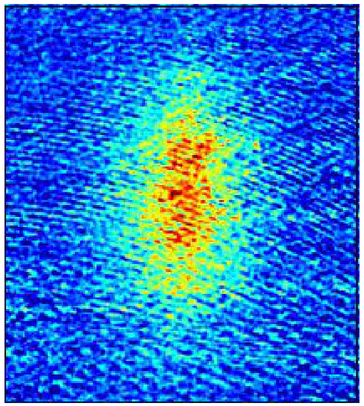
Δ=0, U=J

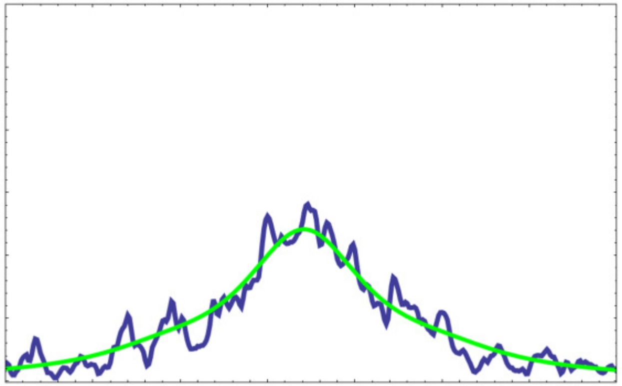


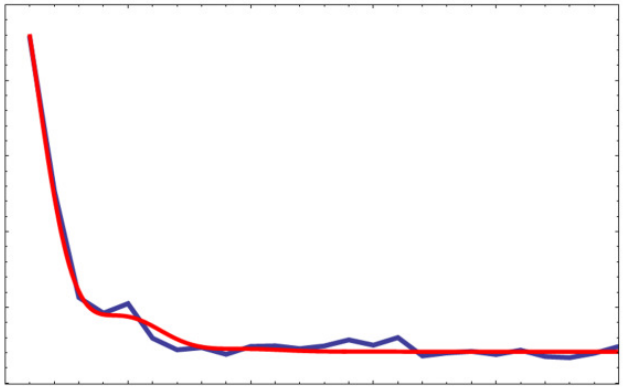




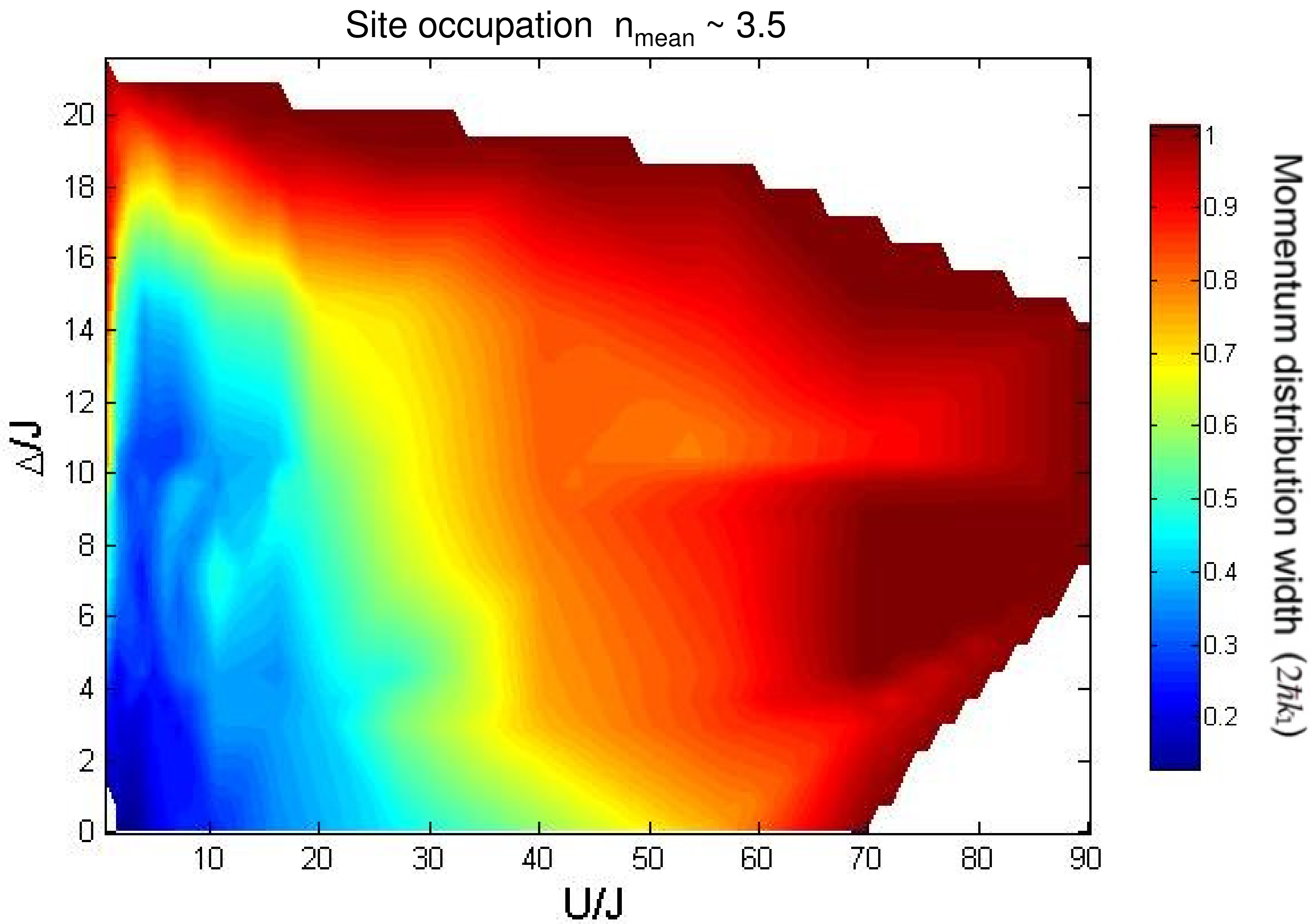
Δ=0, U>5J





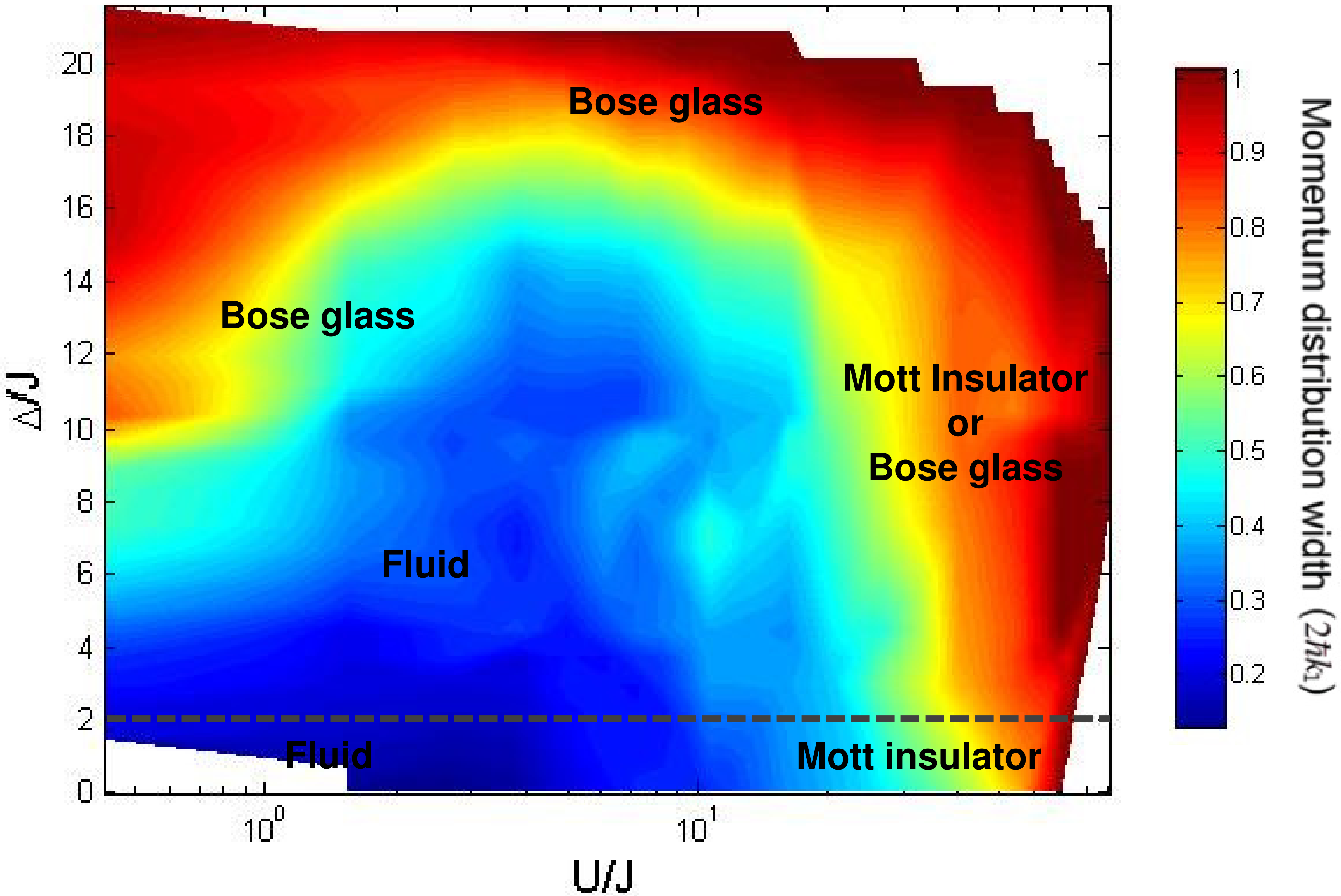


Phase diagram from momentum distribution



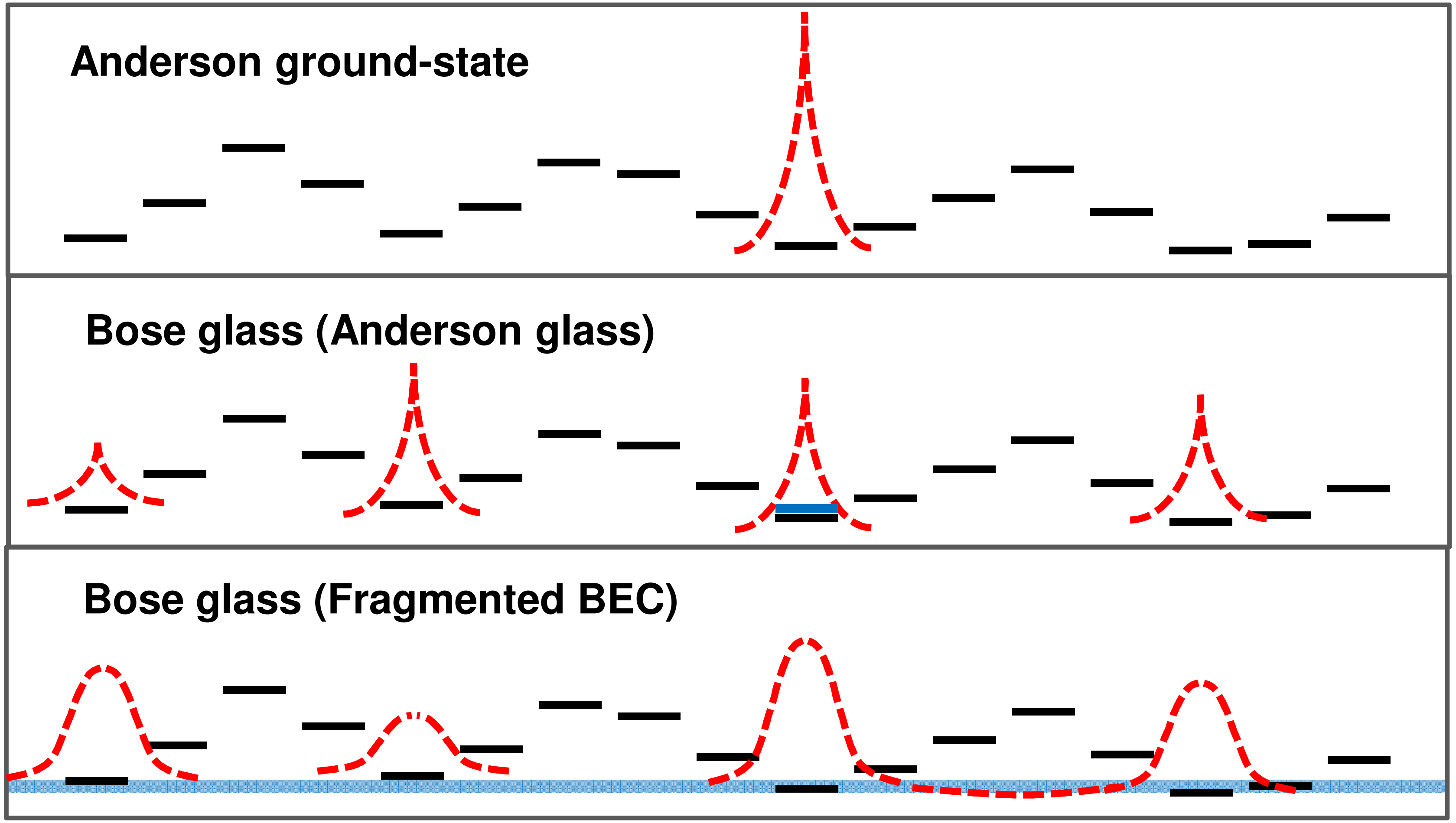
Phase diagram from momentum distribution

Site occupation n_{mean} ~ 3.5



D'Errico et al, in preparation.

Weak interaction: a cartoon



Fermi golden rule

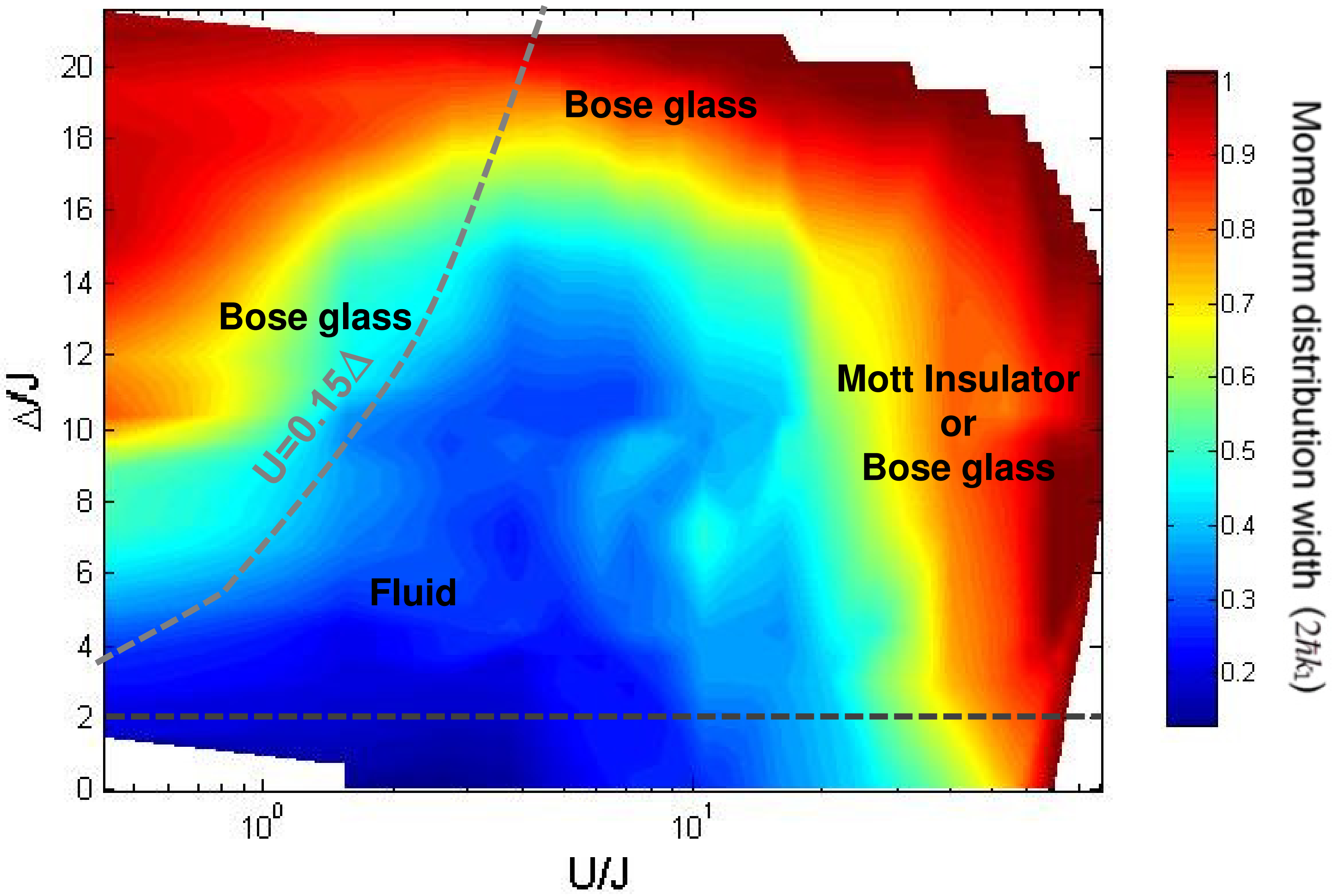
$$\langle i | H_{\text{int}} | f \rangle^2 g(E)$$

Coupling is possible if

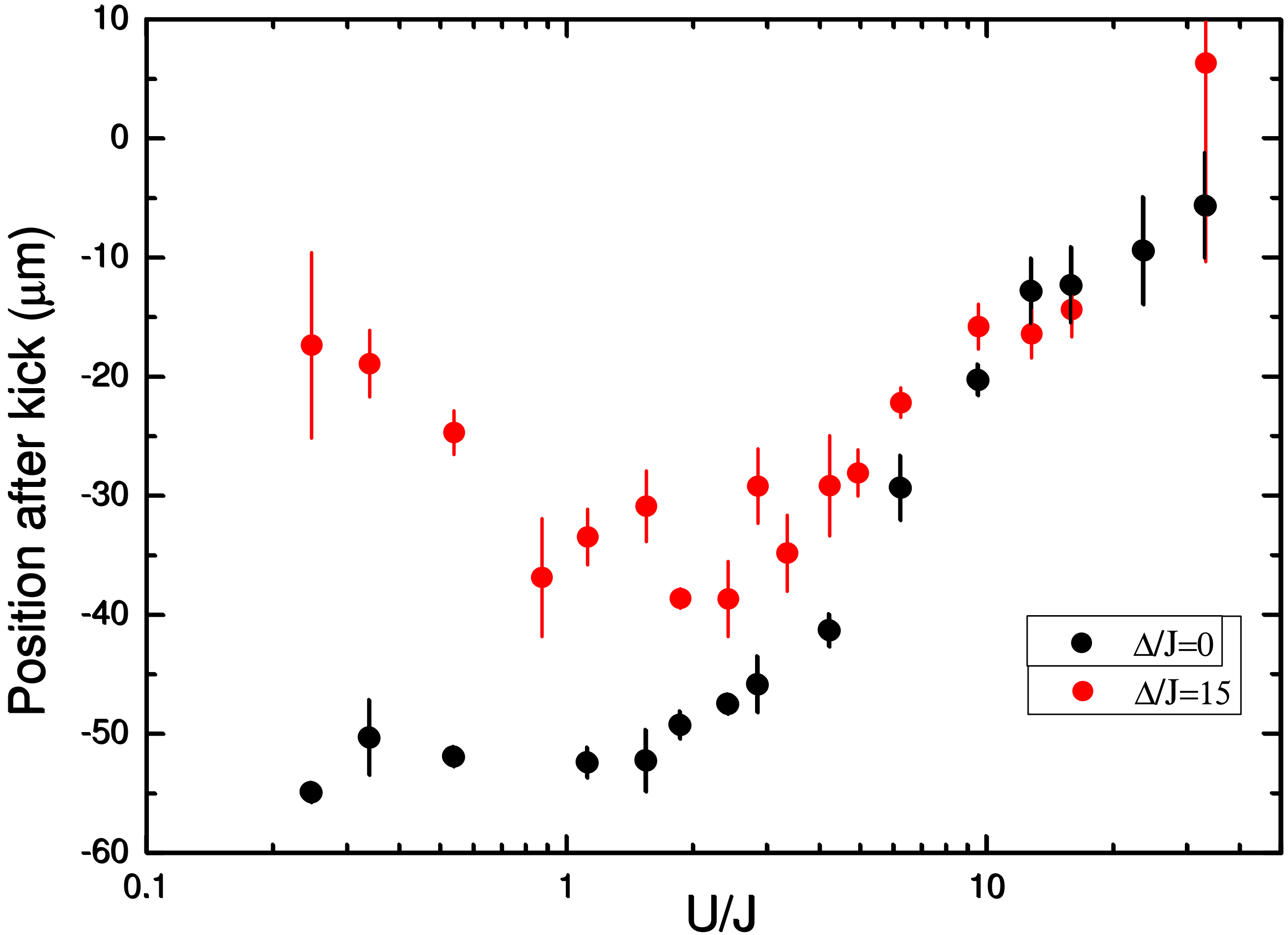
$$U \int \varphi_1^2 \varphi_2^2 dx \geq \delta V$$

Lugan, PRL 98, 170403 (2007); Aleiner et al., Nat. Phys. 6, 900 (2010); Lucioni et al. PRL 106, 230403 (2011).

Phase diagram from momentum distribution

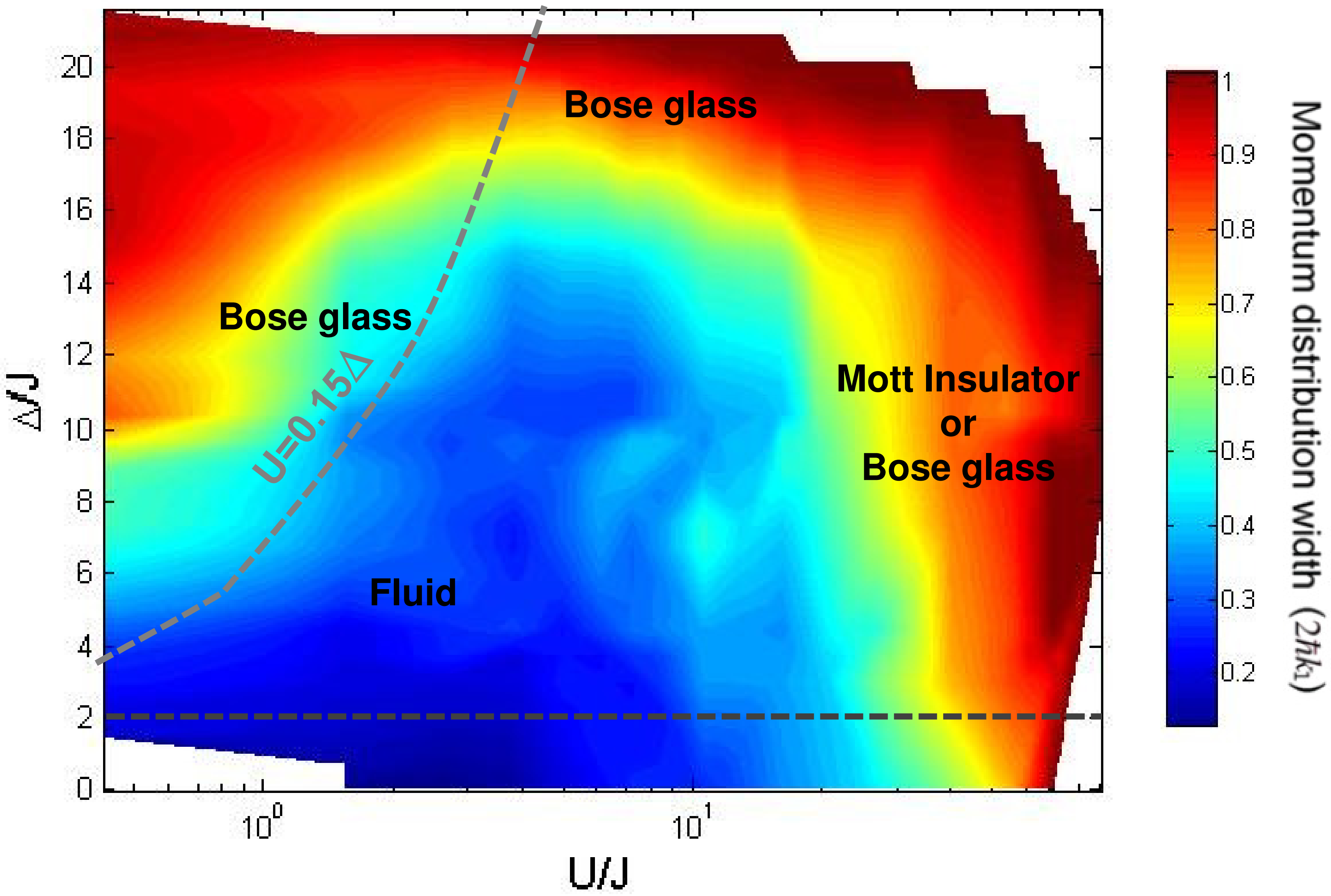


Transport

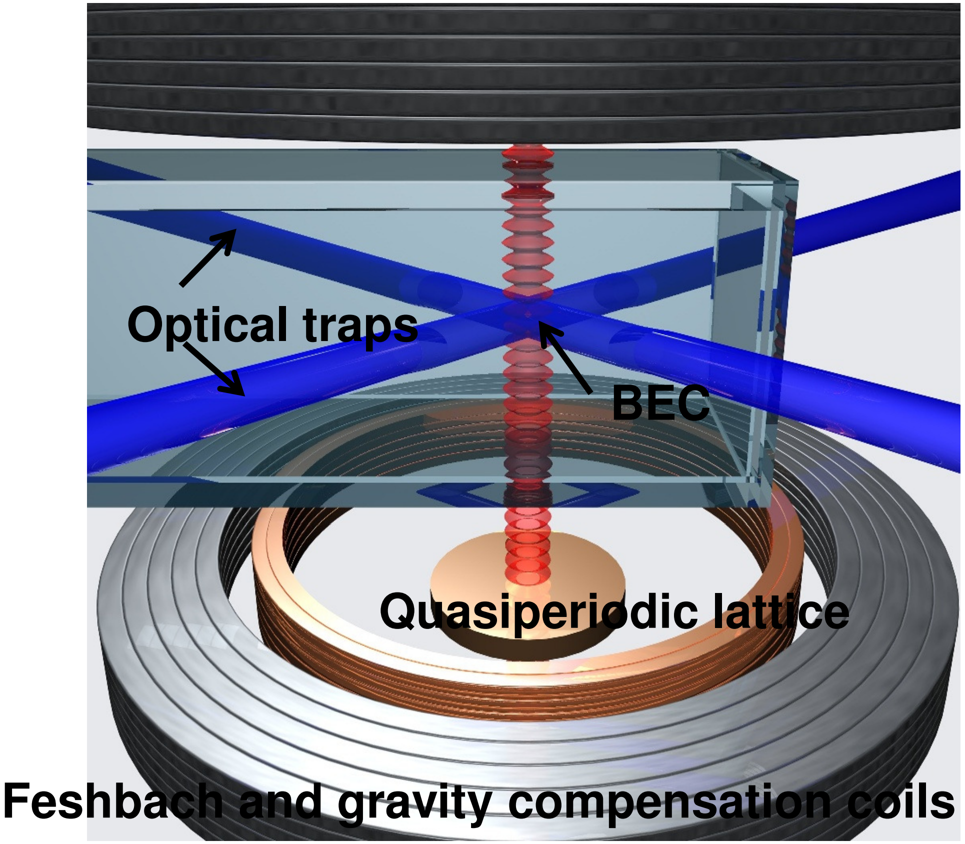


A. Polkovnikov et al. Phys. Rev. A 71, 063613 (2005); applied on Bose gases by DeMarco, Naegerl, Schneble

Phase diagram from momentum distribution

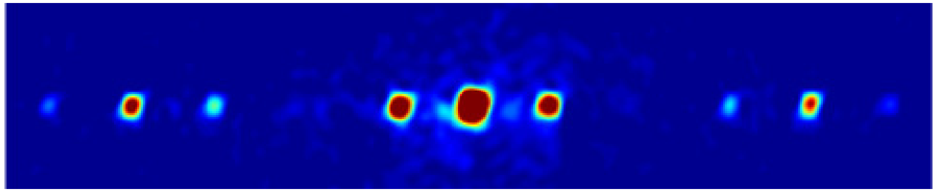


Weak interaction regime

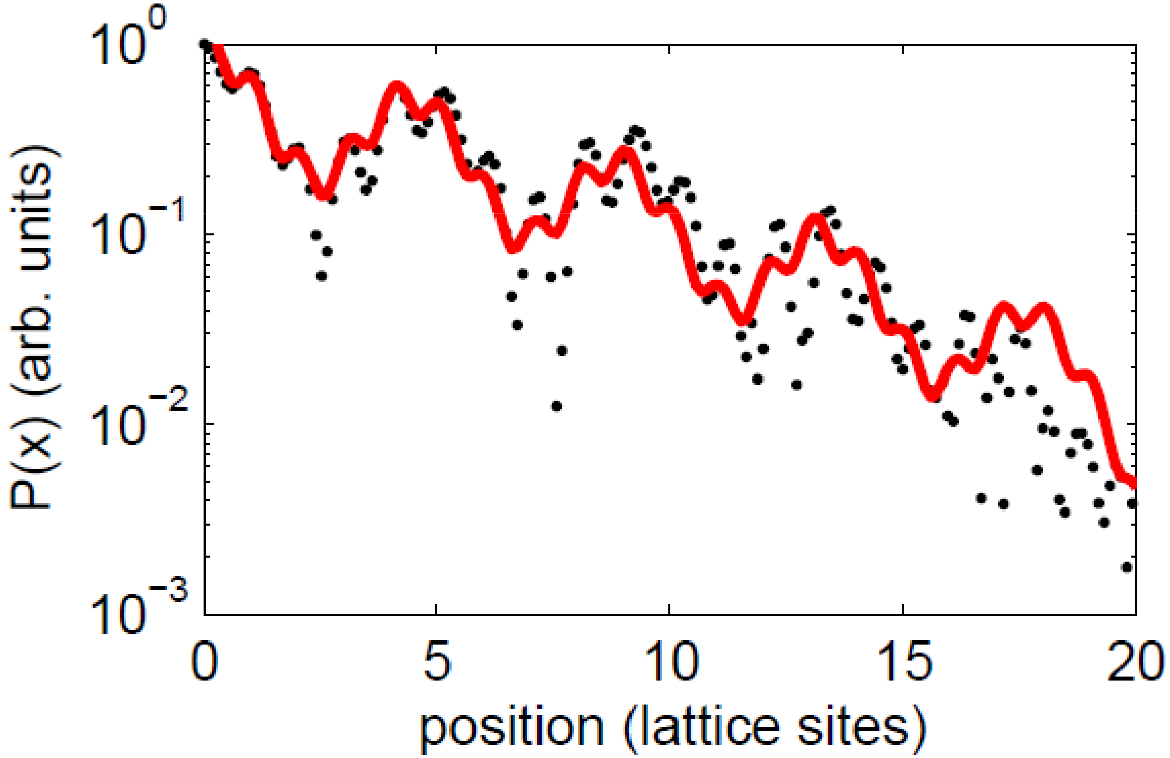


Weak radial trapping (ν_r=50Hz): a 3D system with 1D disorder

Correlation function

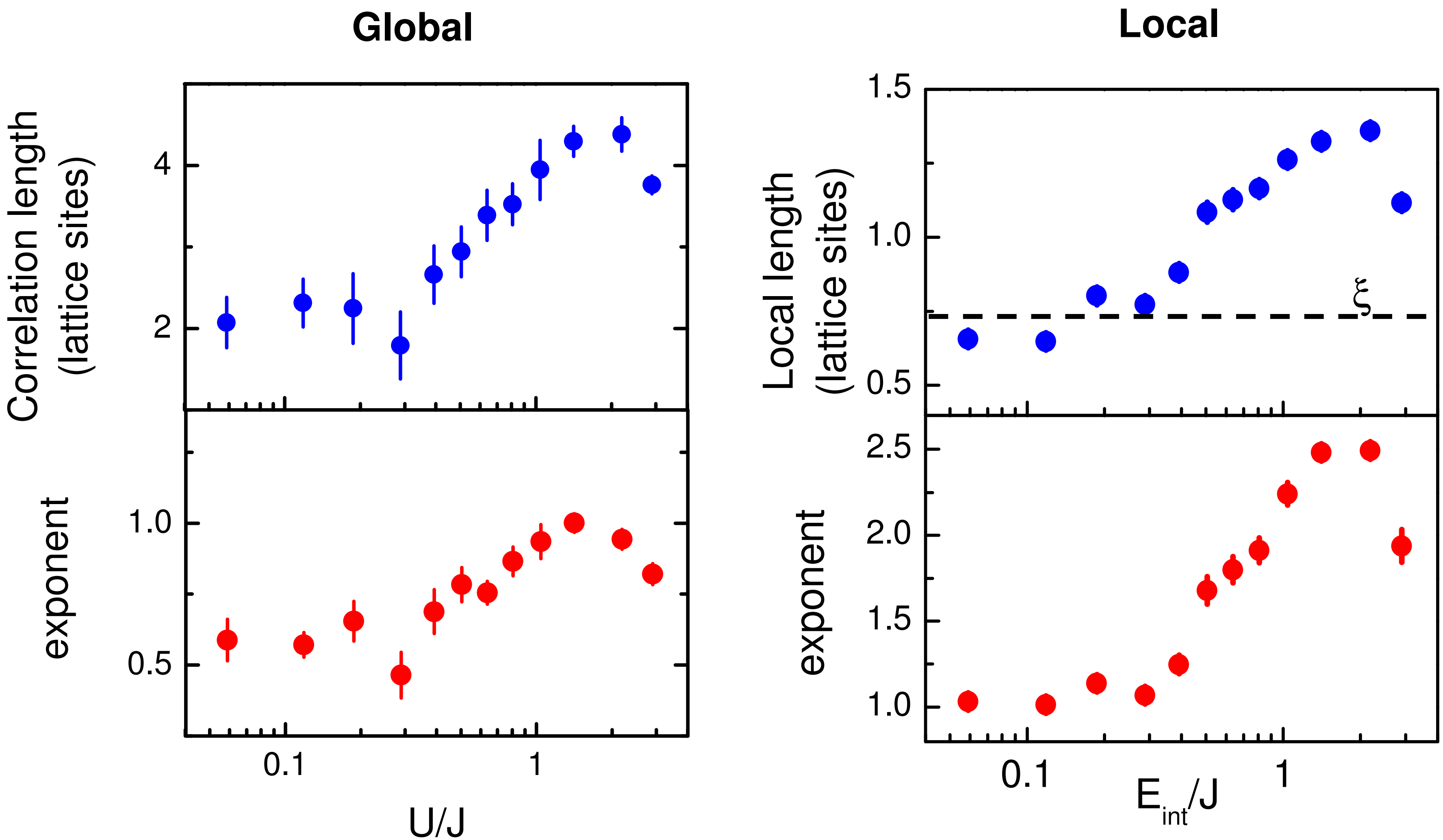


$$g(x) = \int dx' \left\langle \Psi^{+}(x)\Psi(x+x') \right\rangle = F \,|\, \Psi(k) \,|^{2}$$



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

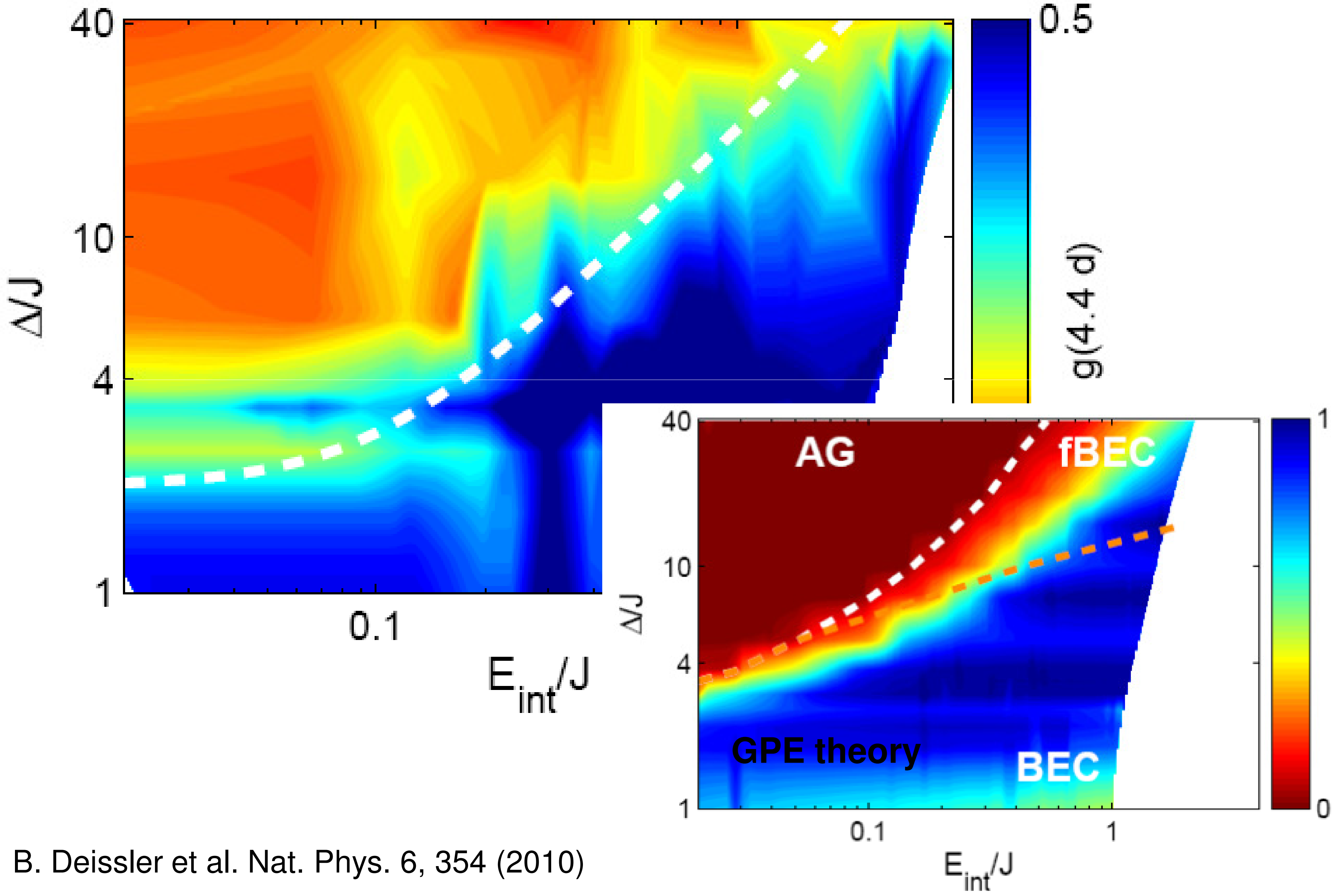
Global and local lengths



Finite-T, finite-size effects do not allow to see the predicted change of exponent

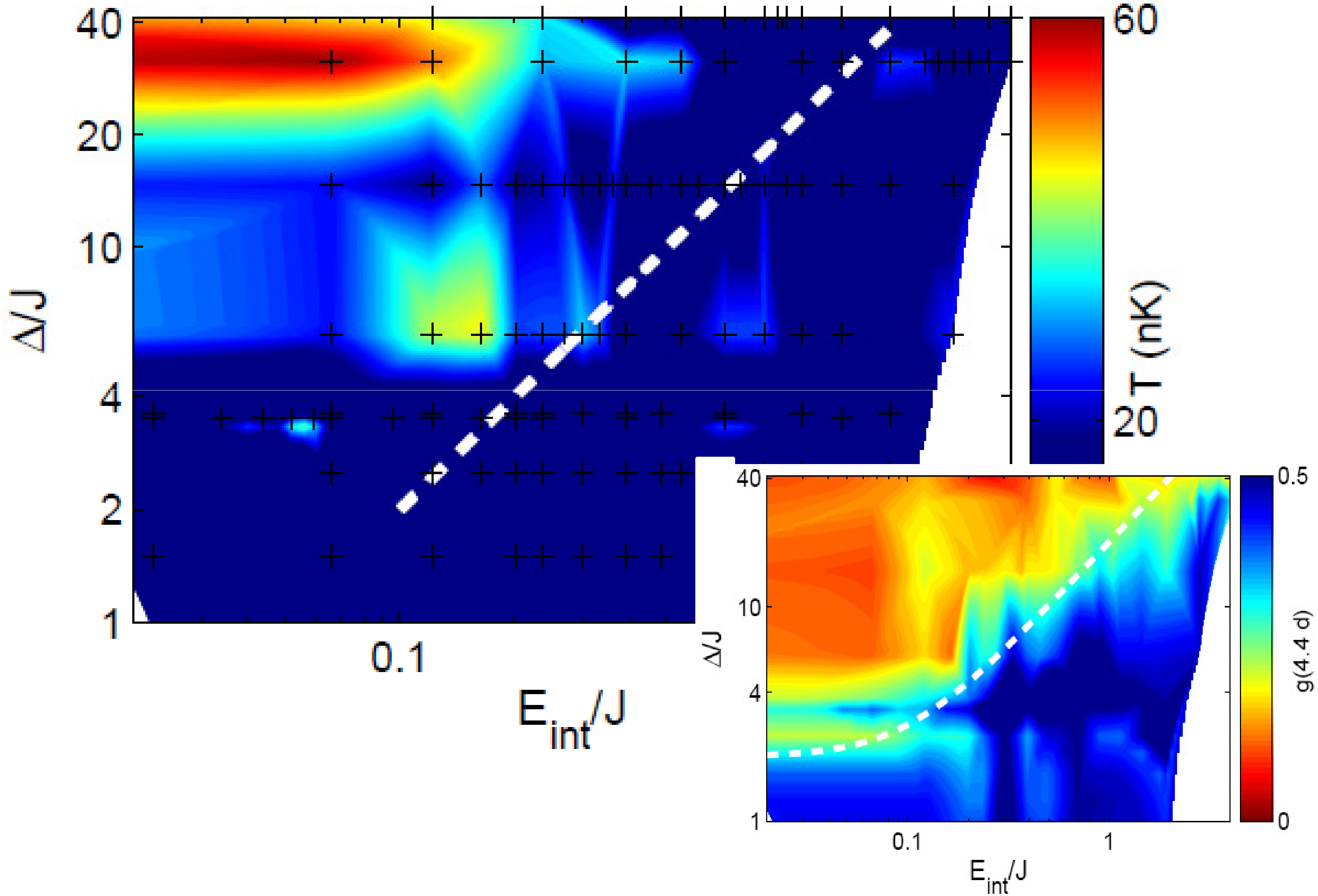
B. Deissler et al. New J. Phys. 13, 023020 (2011). Theory: Altman, Giamarchi, Savona, …

Correlation diagram



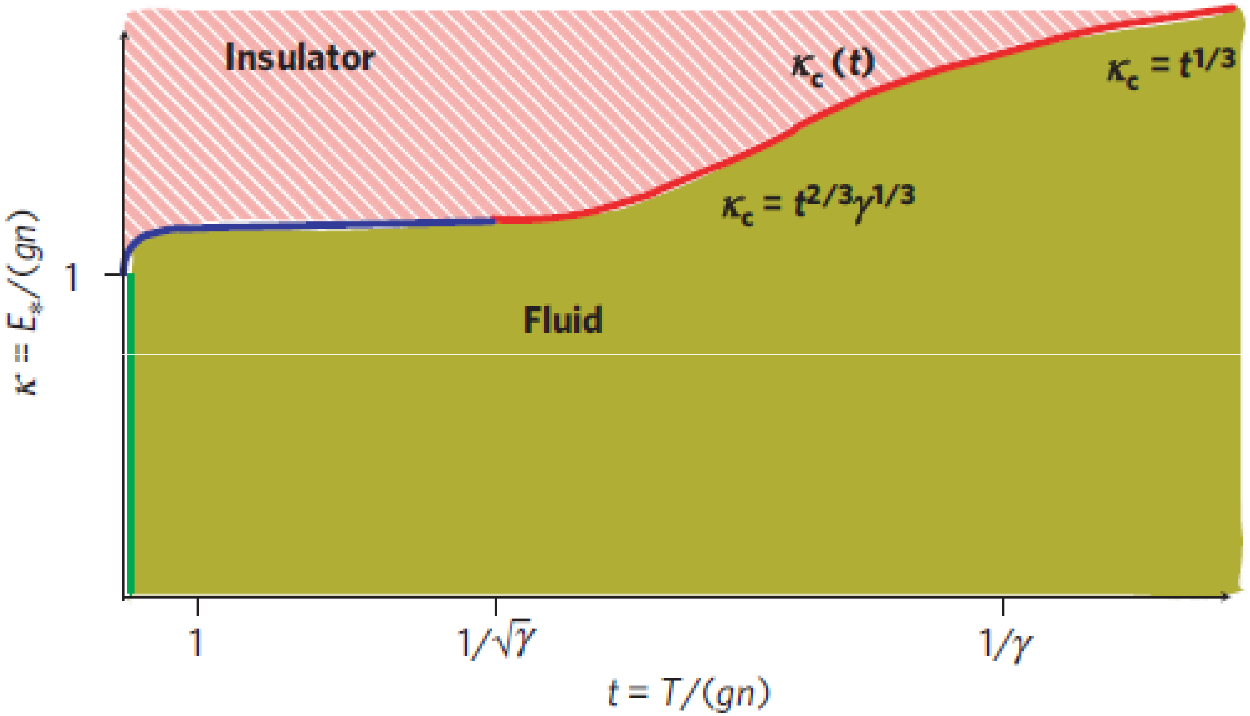
B. Deissler et al. Nat. Phys. 6, 354 (2010)

Finite "temperature" estimation: 3D



Finite temperature effects

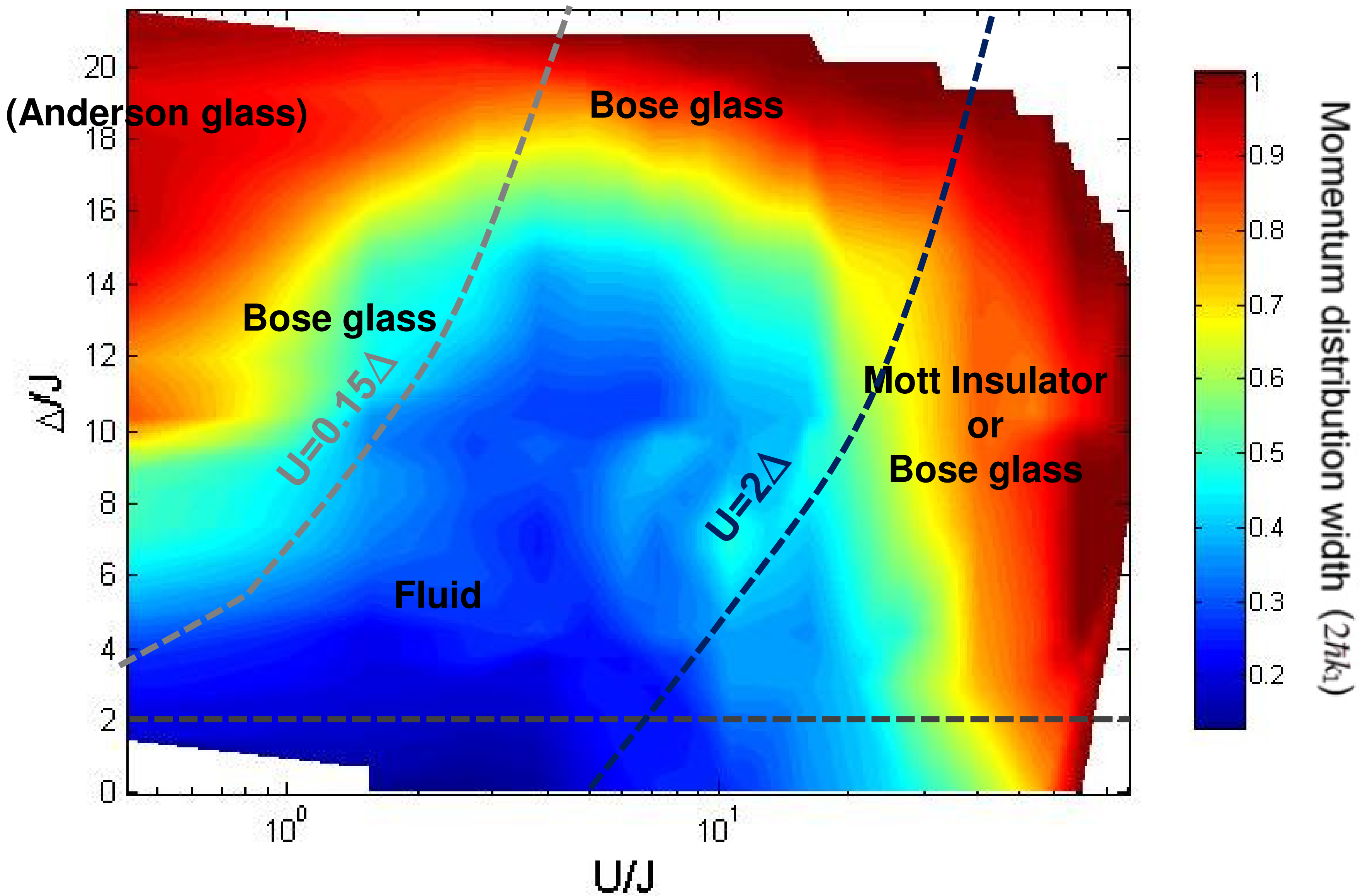
The Bose glass to fluid transition shows a systematic shift to U lower than in theory.



A finite temperature should favour the coupling between localized states.

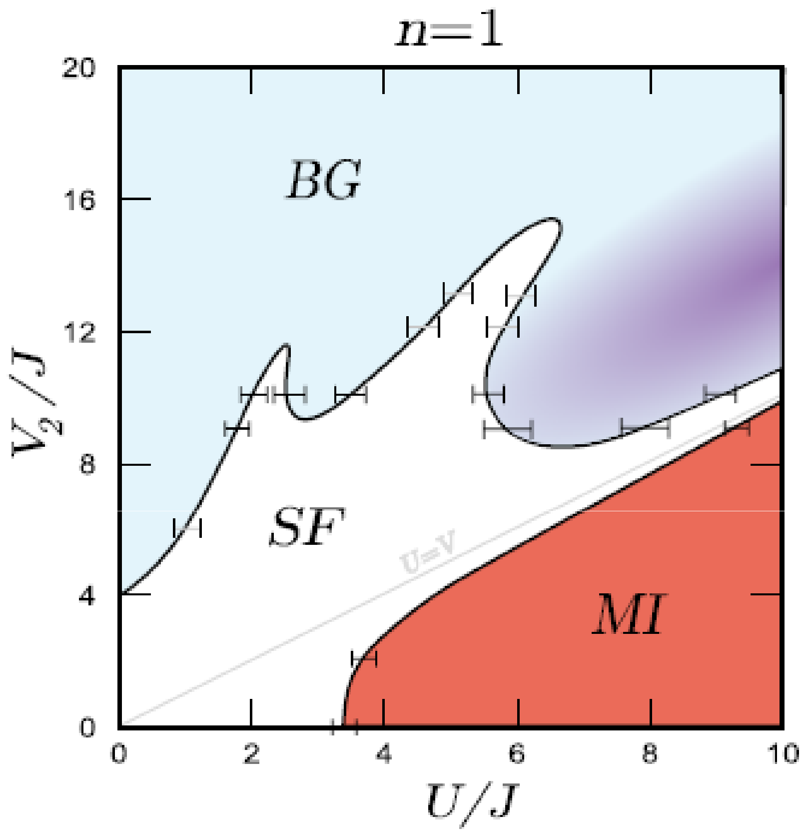
Aleiner, Altshuler, Shlyapnikov, Nat. Phys. 6, 900 (2010).

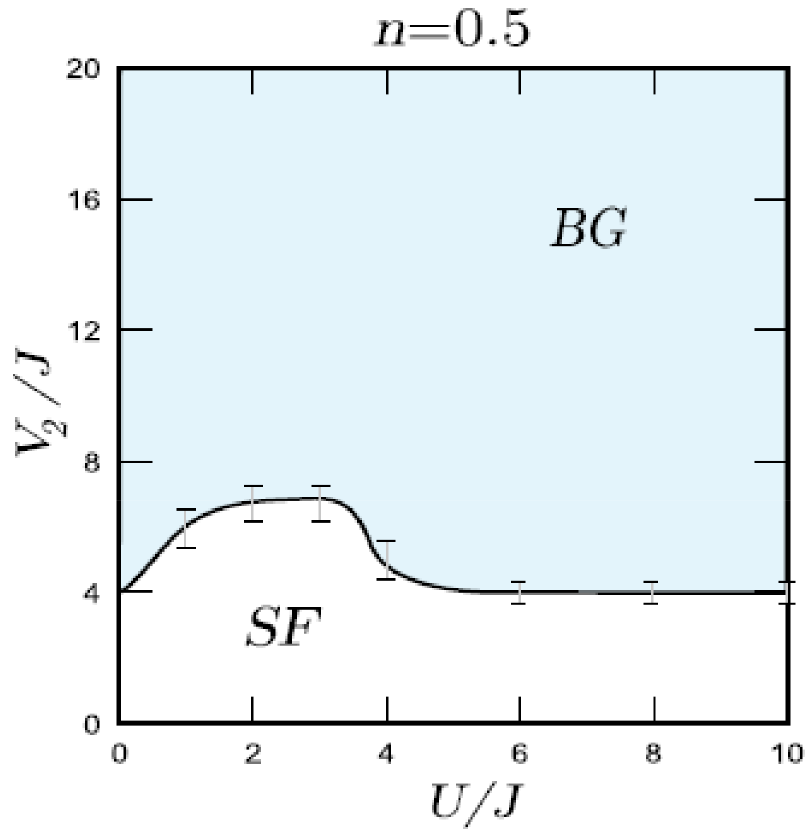
Phase diagram from momentum distribution



T. Giamarchi: work in progress to compare the exp. data to theory

Comparison with theory





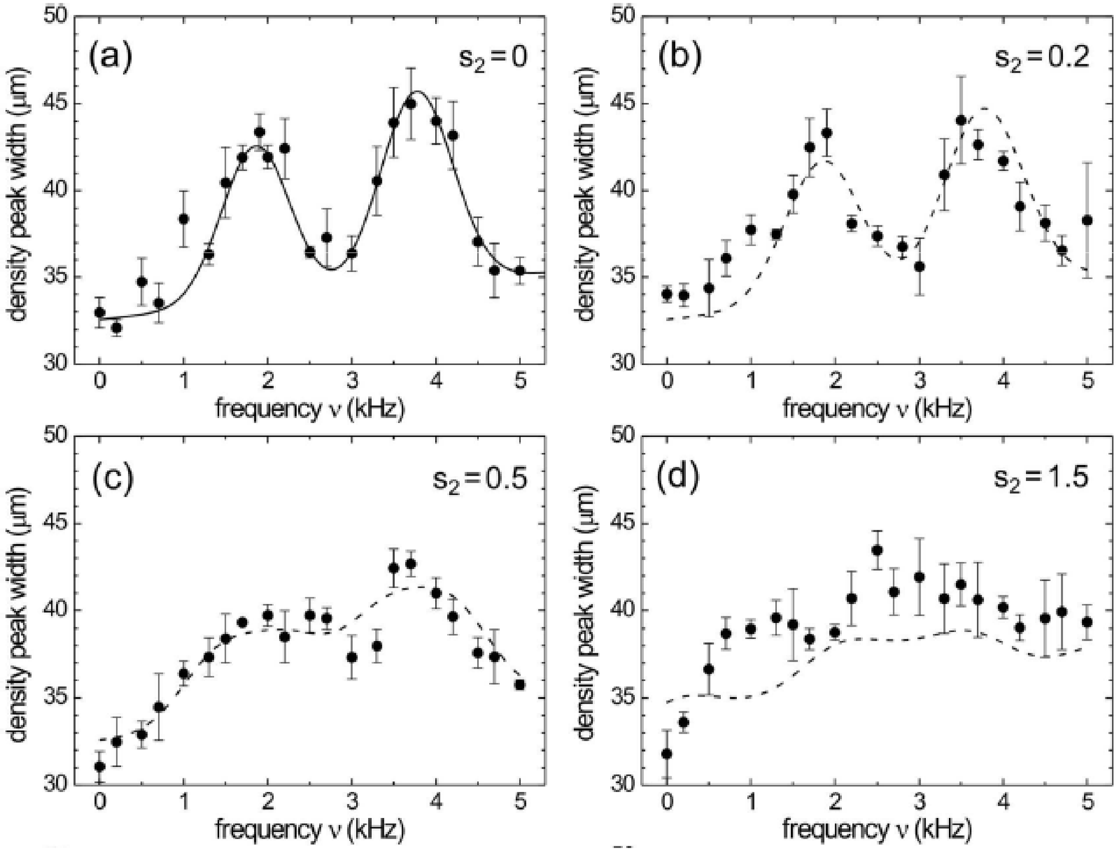
DMRG data, Roux et al., PRA 78, 023628 (2008)

Several issues in the comparison with theory: finite temperature, trap, averaging over density, …

Disordered lattice bosons: experiments

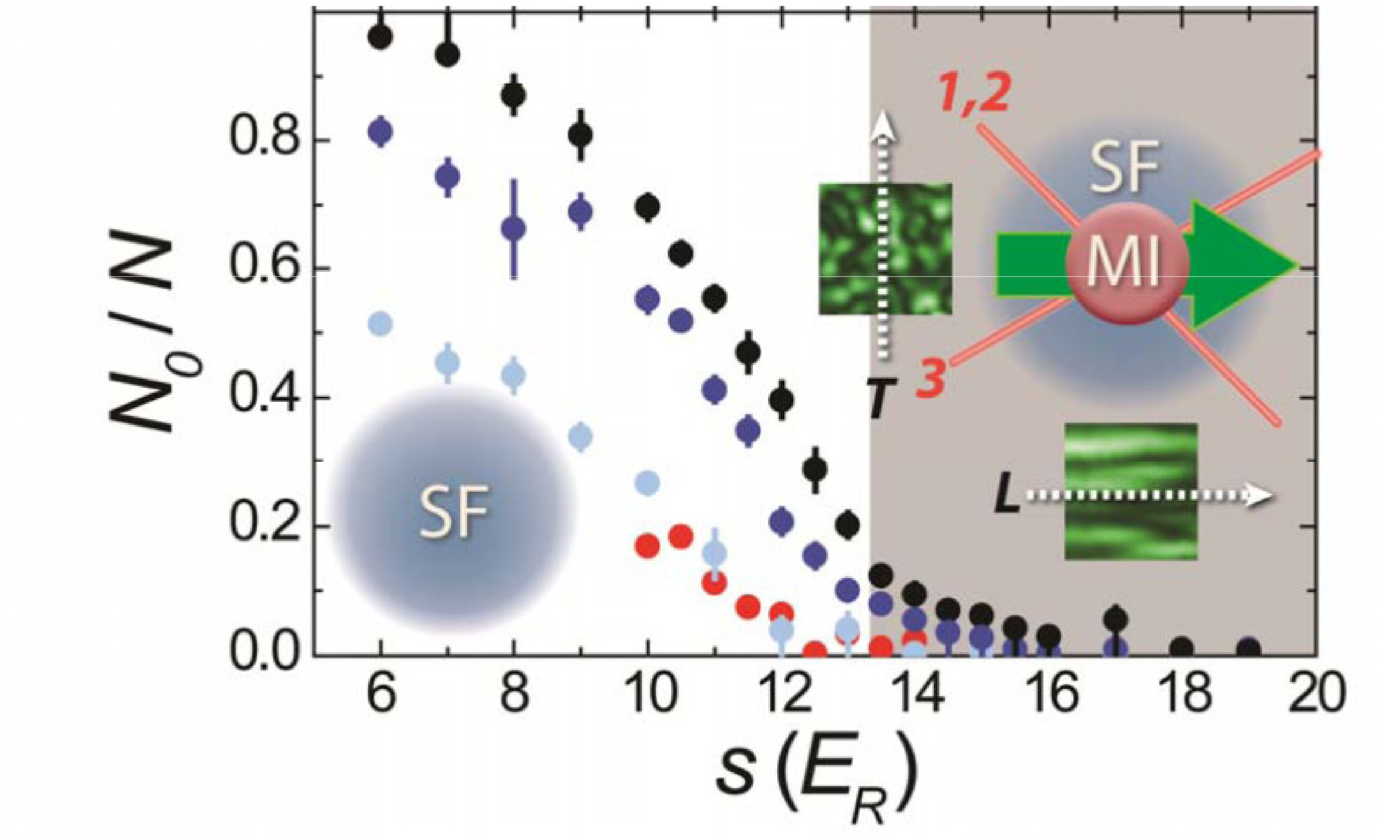
- The Mott insulating phase is destroyed by a strong disorder in 1D (Florence)

  L. Fallani et al., PRL 98, 130404 (2007), V. Guarrera et al., PRL 100, 250403 (2008))

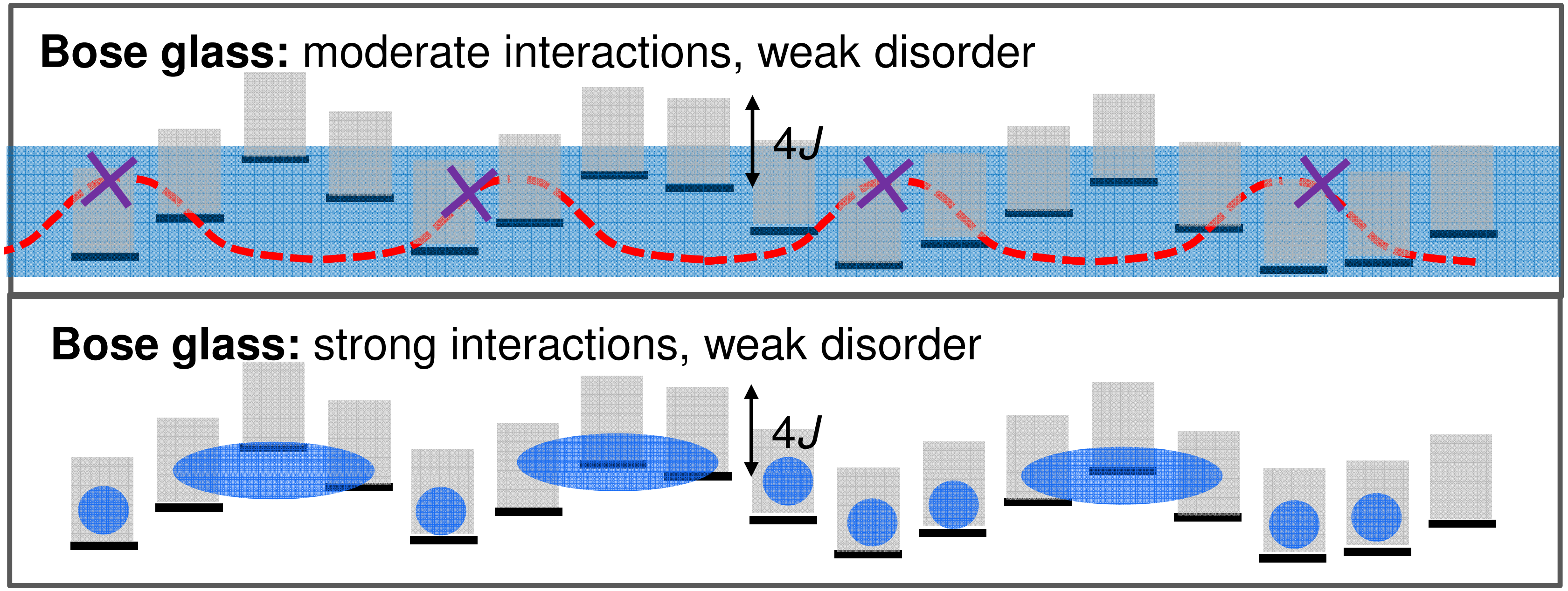


Disordered lattice bosons: experiments

- Disorder drives an anticipated insulating phase in 3D (Urbana)
  M. Pasienski et al., Nat. Phys. **6**, 677 (2010)



Strong interaction cartoon

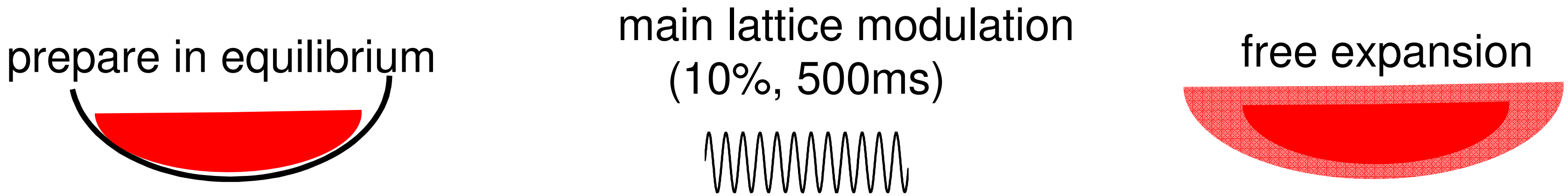


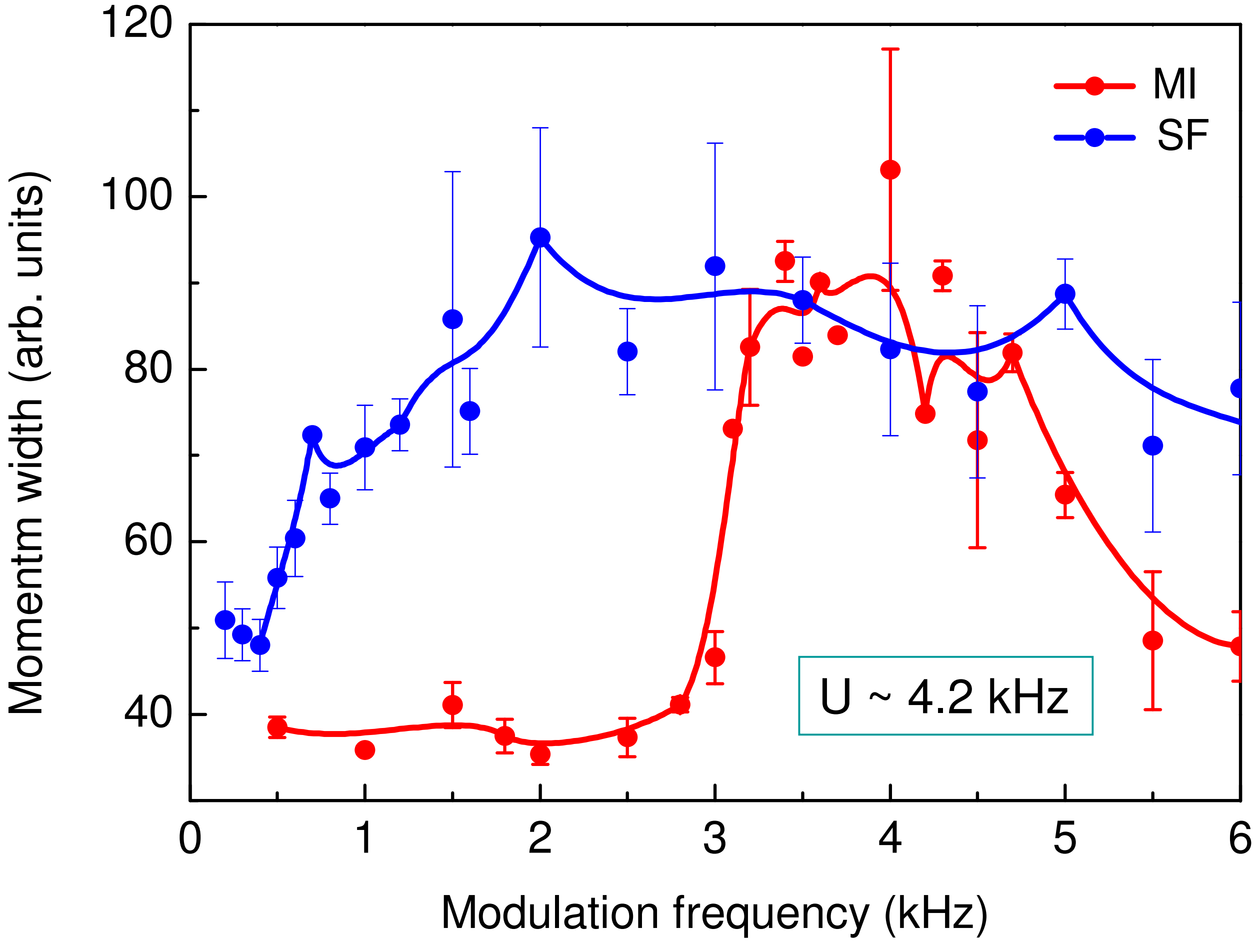
Bose glass: **insulating** but **gapless**

Diagnostics:

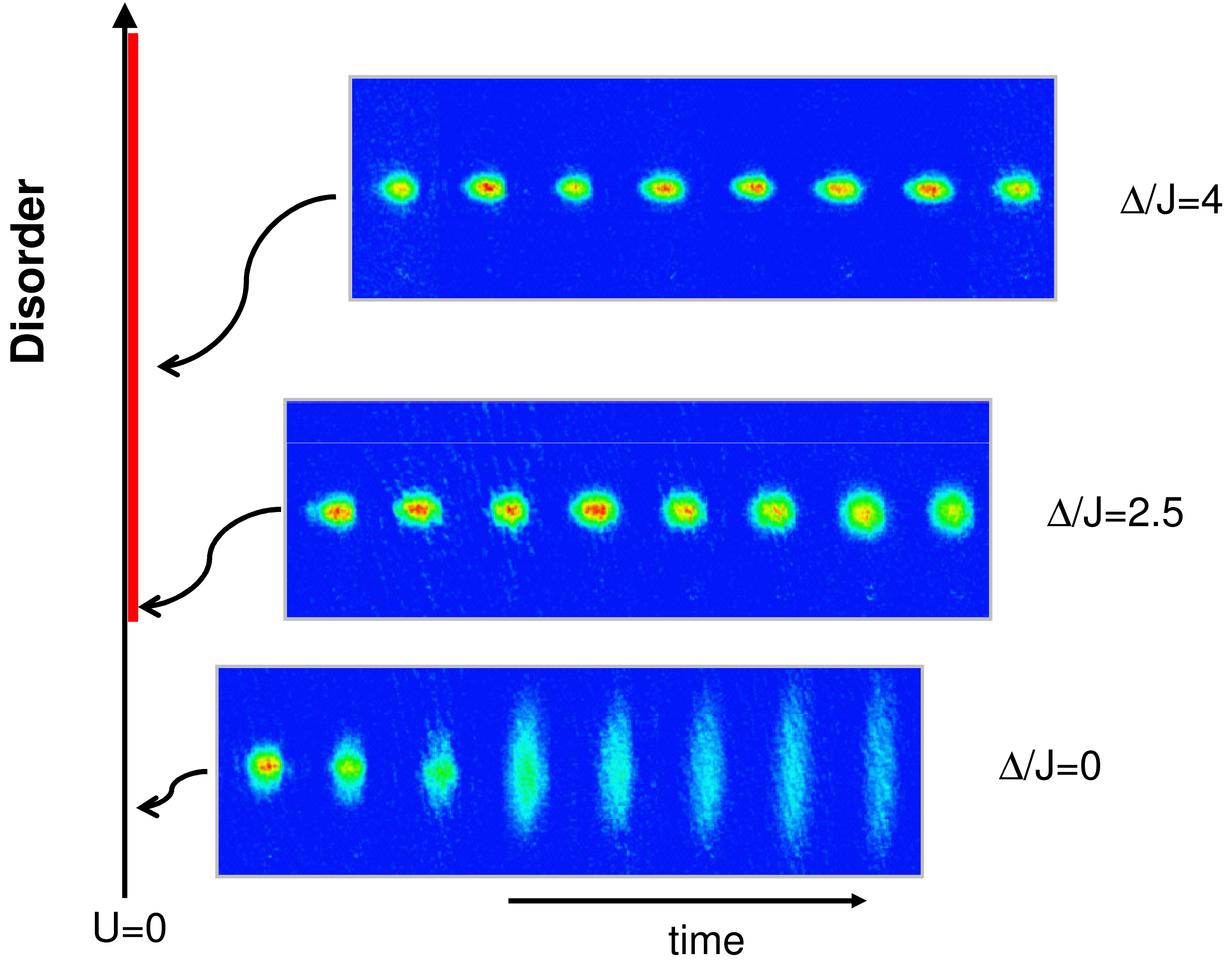
- momentum distribution
- transport
- excitation spectrum (theory by G. Orso et al. PRA **80**, 033625 (2009))

Excitation spectrum



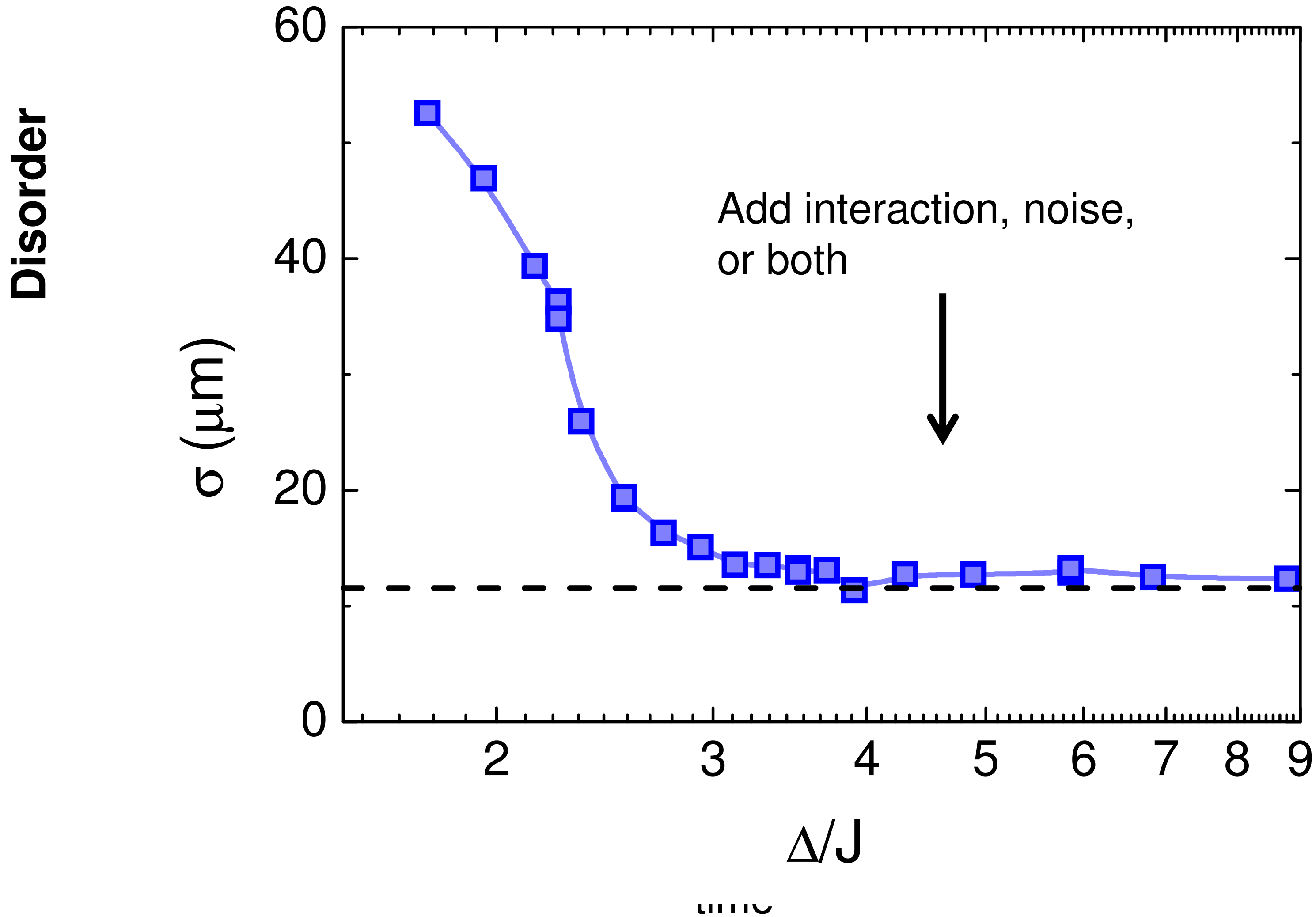


Wavepacket spreading



G. Roati et al., Nature 453, 895 (2008); analogous work in Palaiseau: J. Billy et al., Nature 453, 891 (2008).

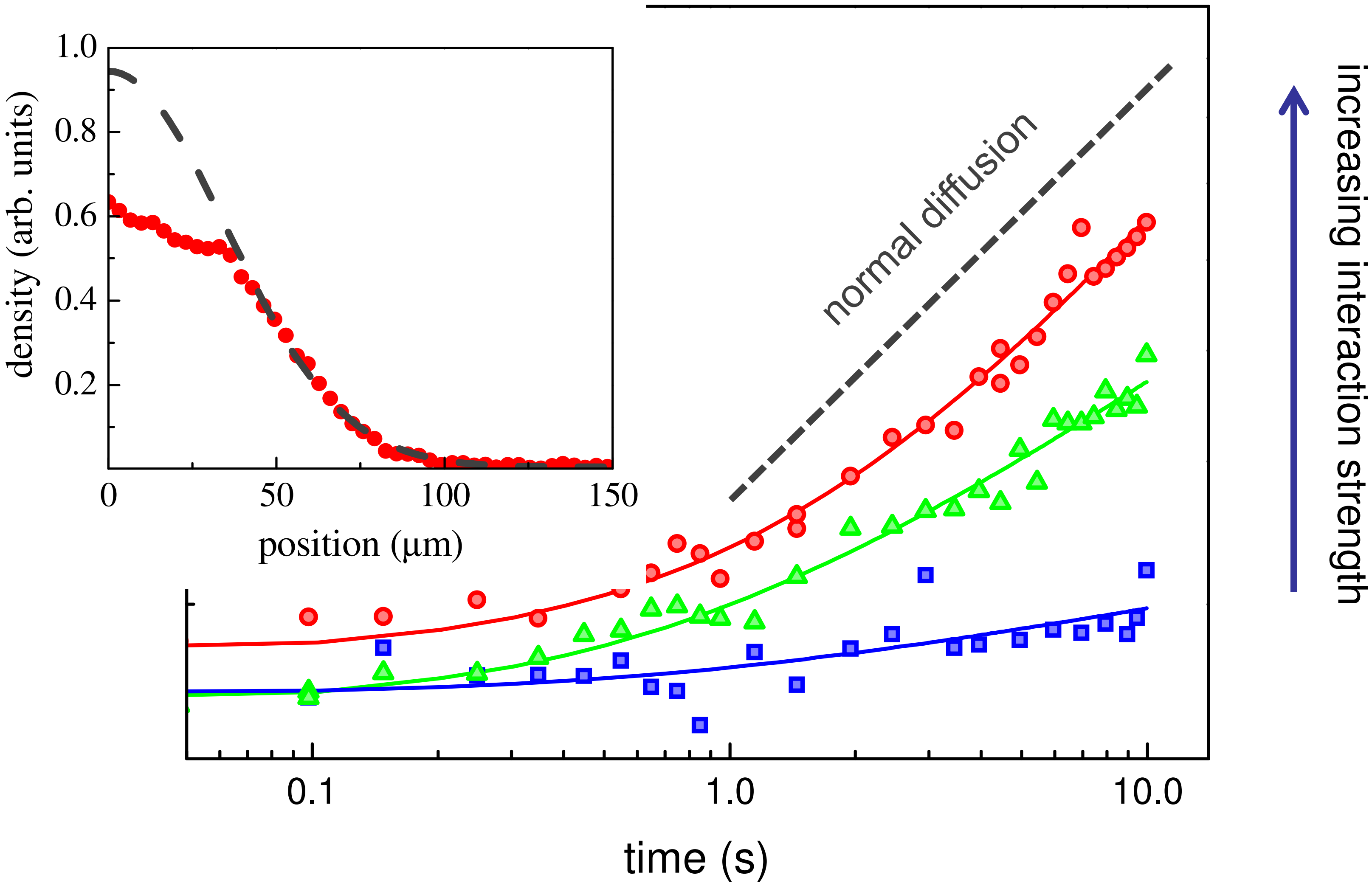
Wavepacket spreading



G. Roati et al., Nature 453, 895 (2008); analogous work in Palaiseau: J. Billy et al., Nature 453, 891 (2008).

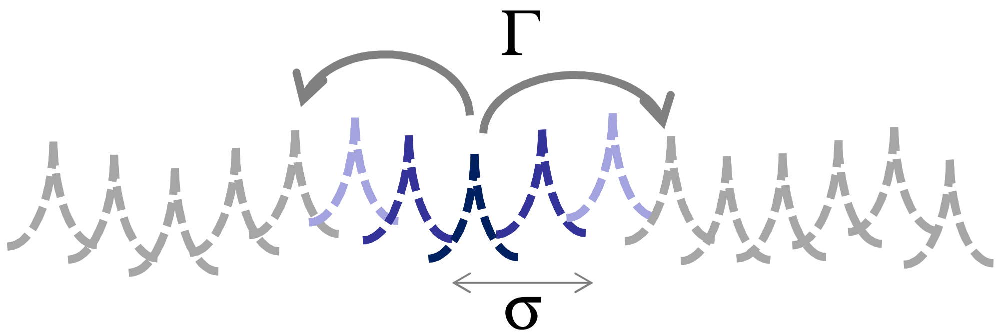
Interaction-assisted spreading

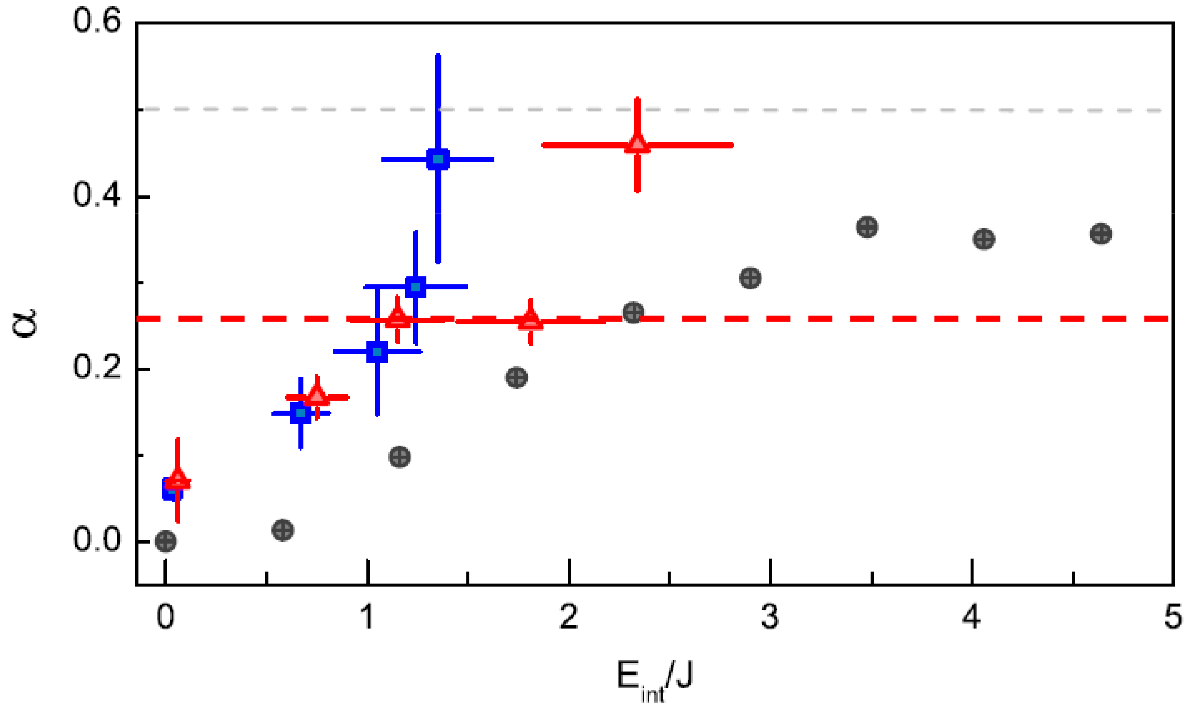
$$\sigma(t)^2 = \sigma_0^2(1+t/t_0)^{2\alpha} \quad \alpha < 0.5$$



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

Coherent hopping between localized states



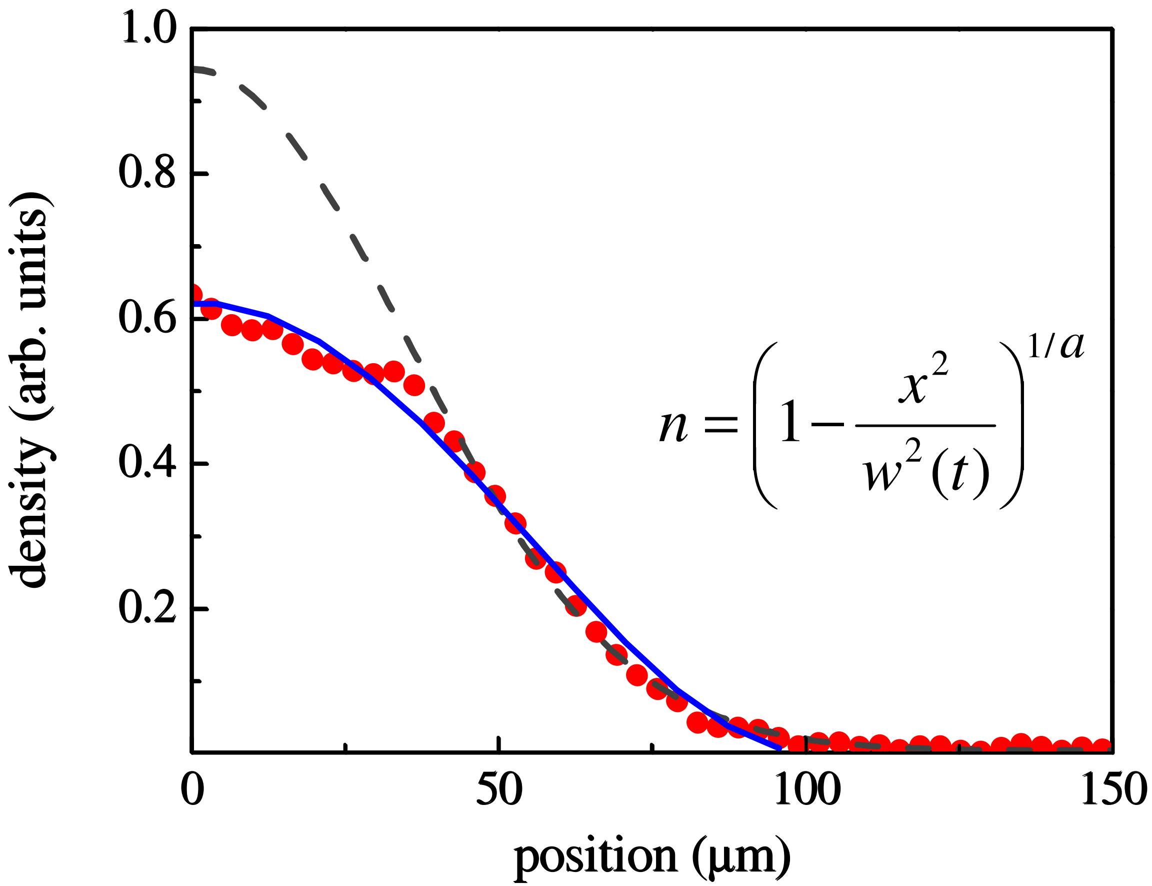


$$\sigma^2 \propto \sqrt{t}$$

Theory: Shepeliansky, Fishman, Aubry, Flach, Mulansky, Pikovsky, M. Modugno, Larcher, Dalfovo, …

Fitting with a nonlinear diffusion equation

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

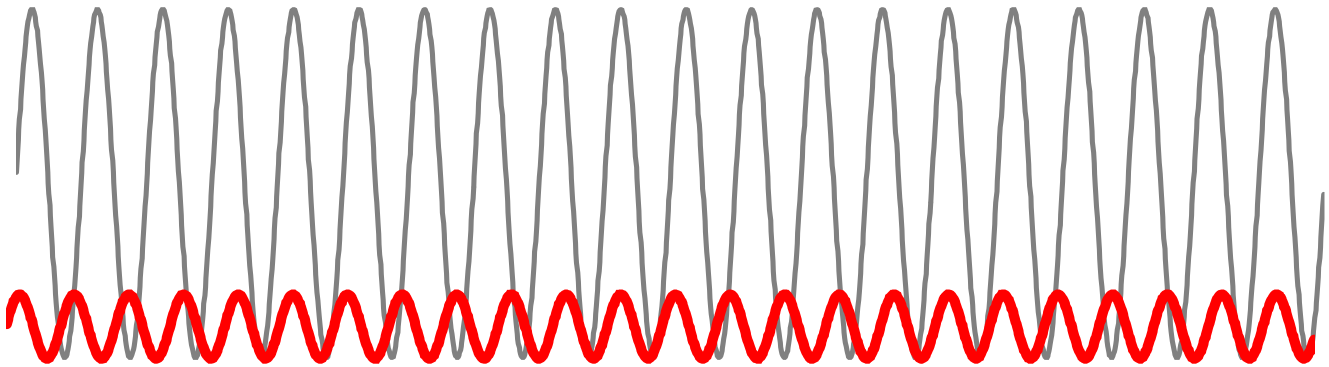


$$n = \left(1 - \frac{x^2}{w^2(t)}\right)^{1/a}$$

$$w(t) \propto t^{\frac{1}{2+a}}$$

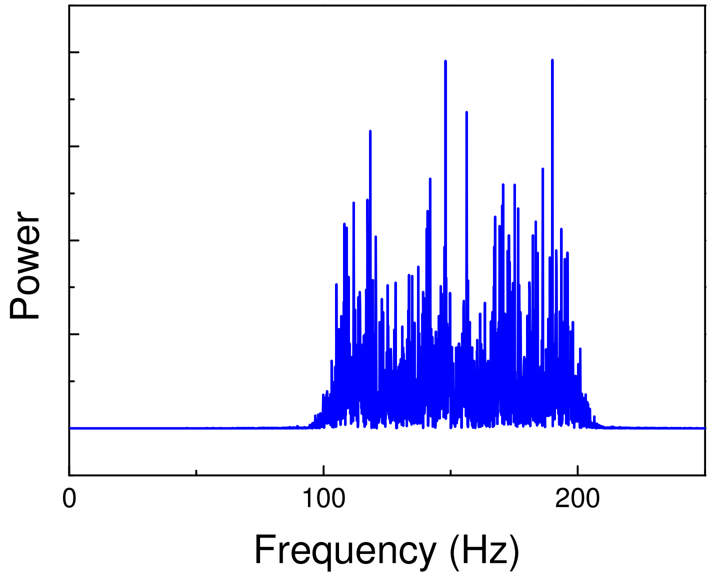
B. Tuck, Jour. Phys. D 9, 1559 (1976); M. Mulansky, et al. Phys. Rev. E **83**, 026205 (2011), Lucioni et al., in preparation.

Noise-assisted spreading



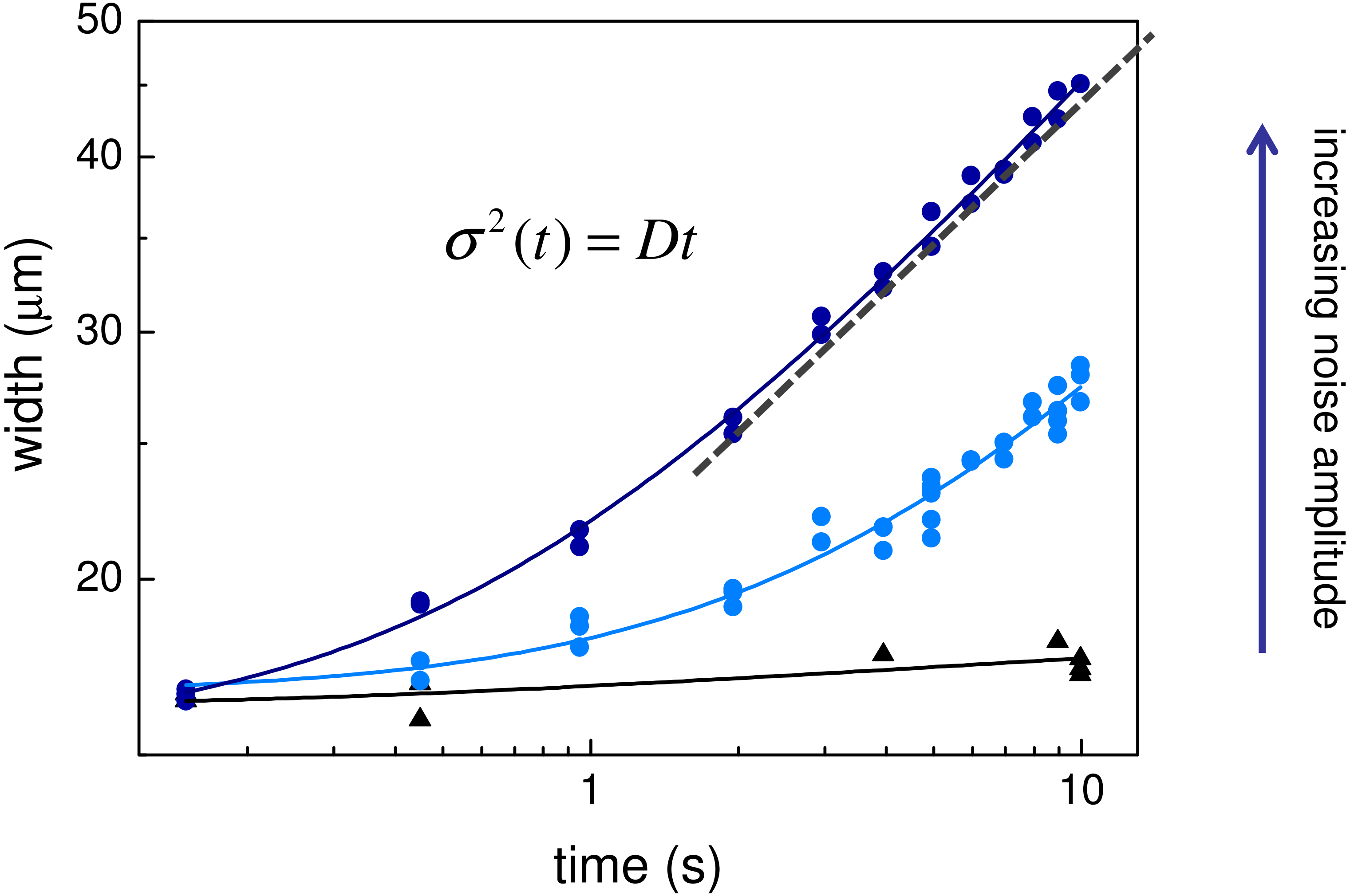
$$V_{dis} = \Delta \cos(2\pi\beta\, x)\ (1 + A\cos(\omega_i t))$$

Out of equilibrium noise: no fluctuation-dissipation relation



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

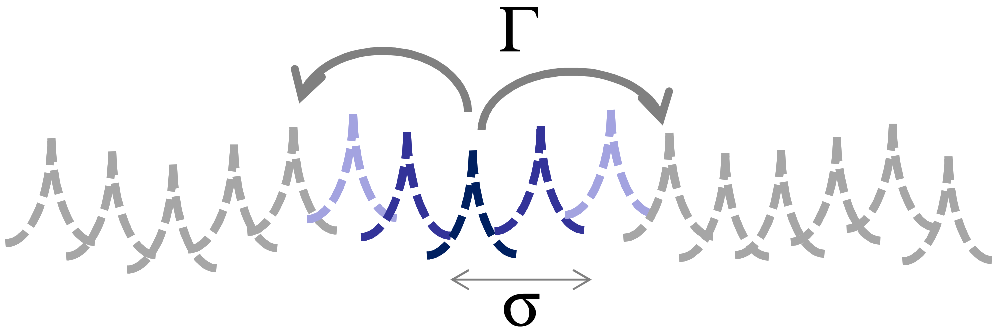
Noise-assisted spreading



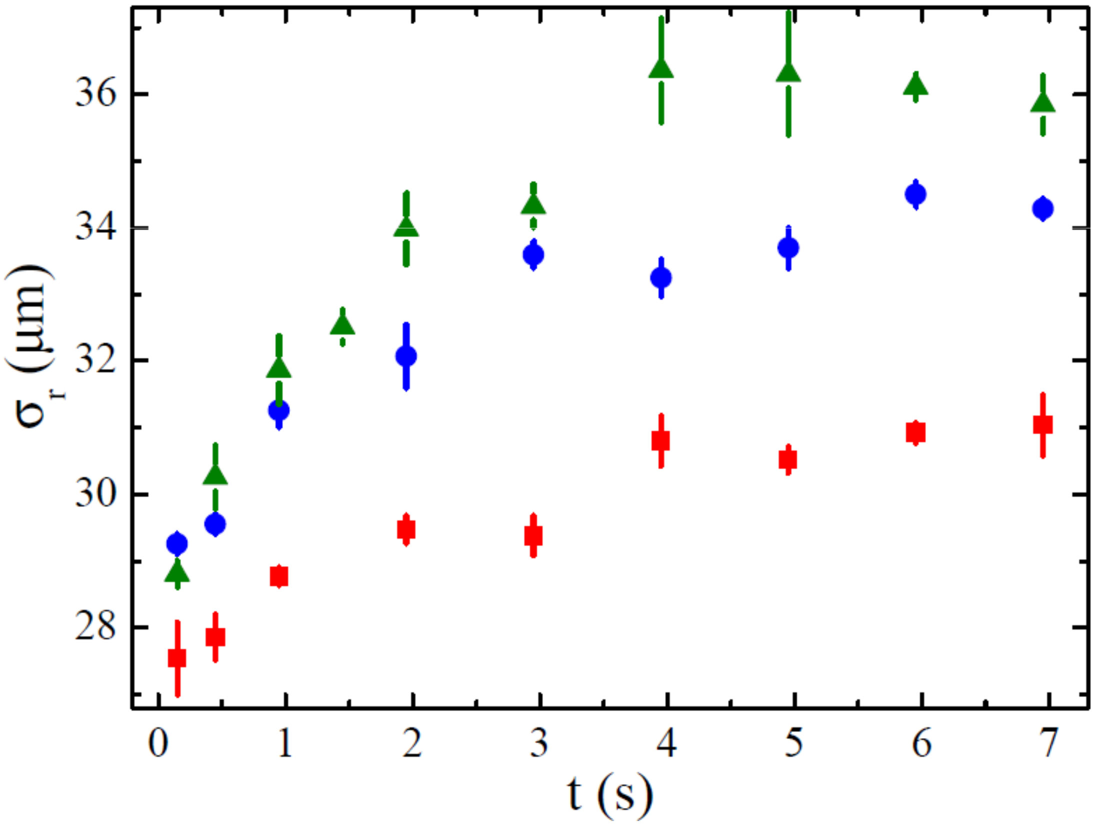
Also observed in atomic ionization (Walther), kicked rotor (Raizen) and photonic lattices (Segev&Fishman):

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

Incoherent hopping between localized states



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



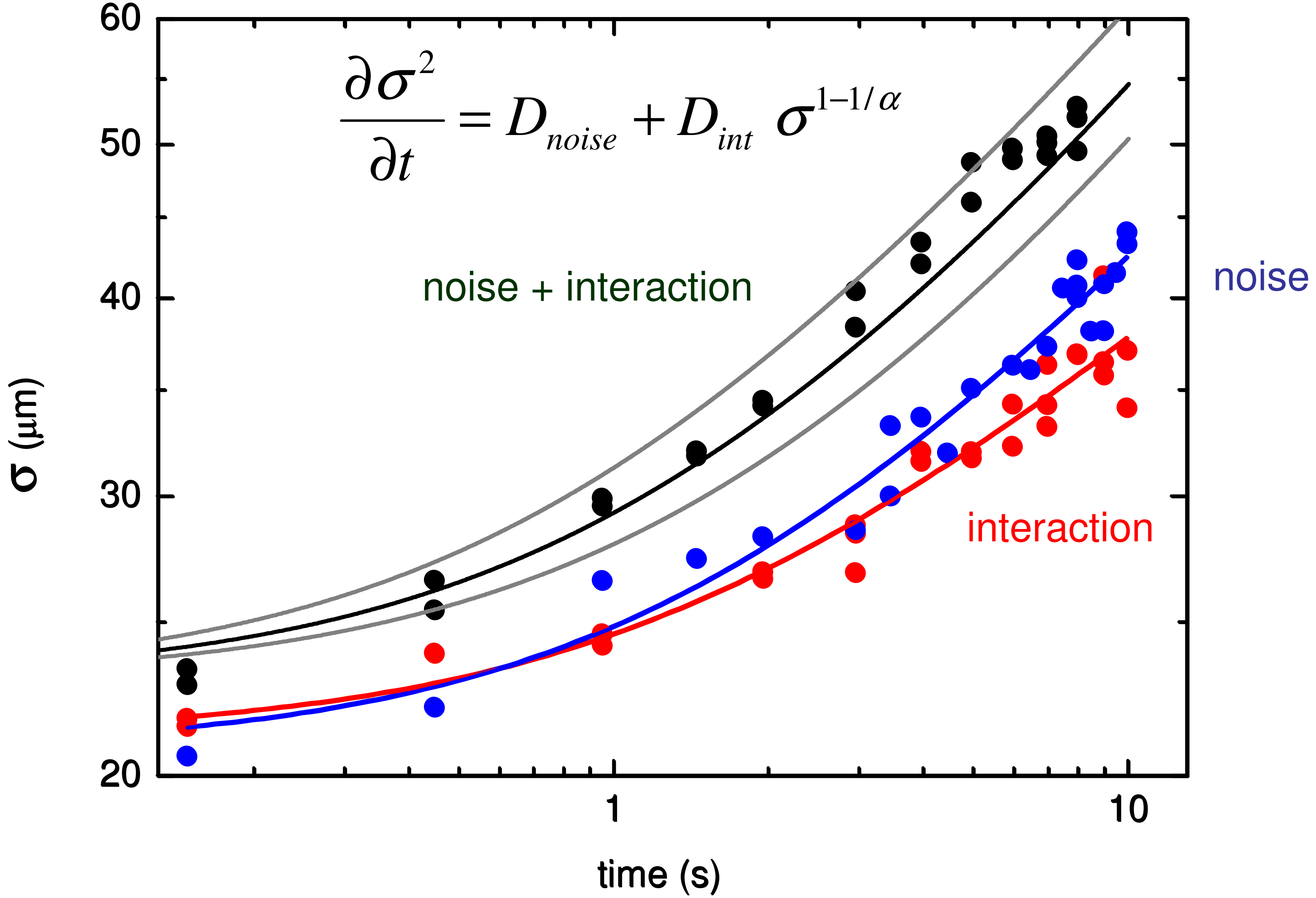
$$\sigma^2 = Dt$$

Out of equilibrium noise: energy is not conserved.

Future studies with thermal noise will be interesting.

Theory: Ovchinnikov, Ott, Shepeliansky, Bouchaud&Georges, ….

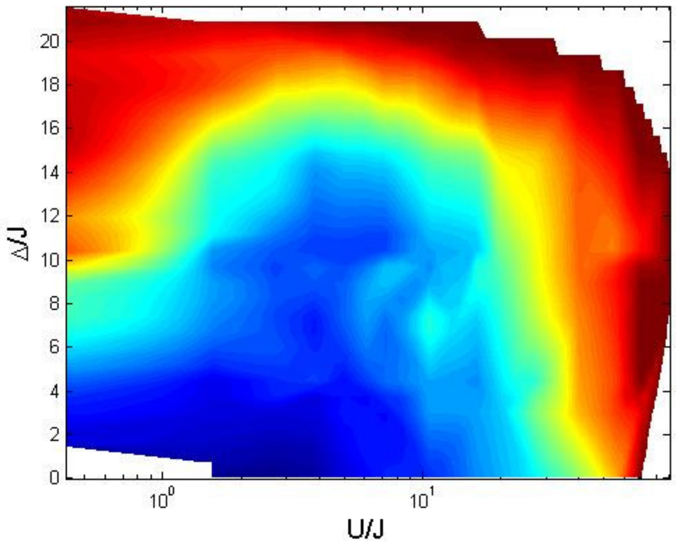
Noise and interaction



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

Conclusions and outlook

Phase diagram of 1D lattice bosons:

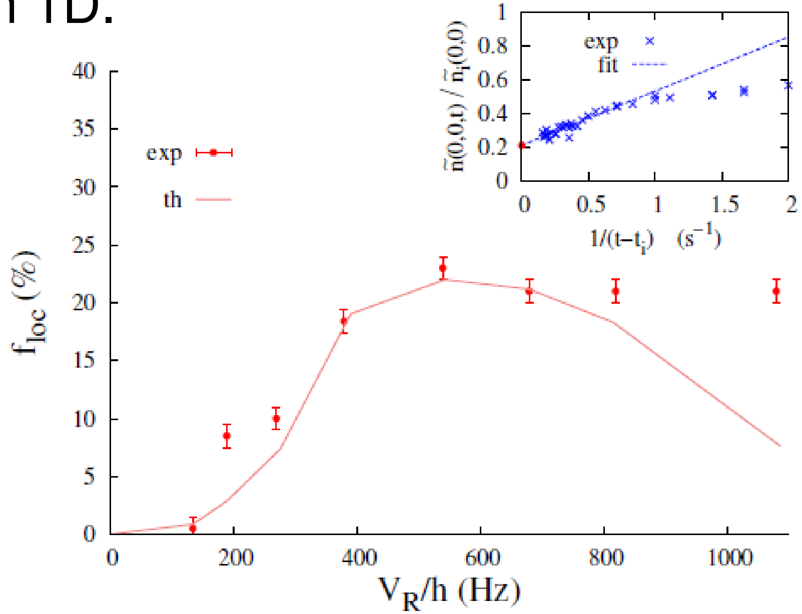


Excitation spectrum
Transport
High temperature behaviour

Transport with interactions and noise in 1D.

Many-body localization in 3D:

How do interactions change the localization behavior close to the mobility edge?



Jendrzejewski et al.,Nat. Phys. 8,398 (2012)

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