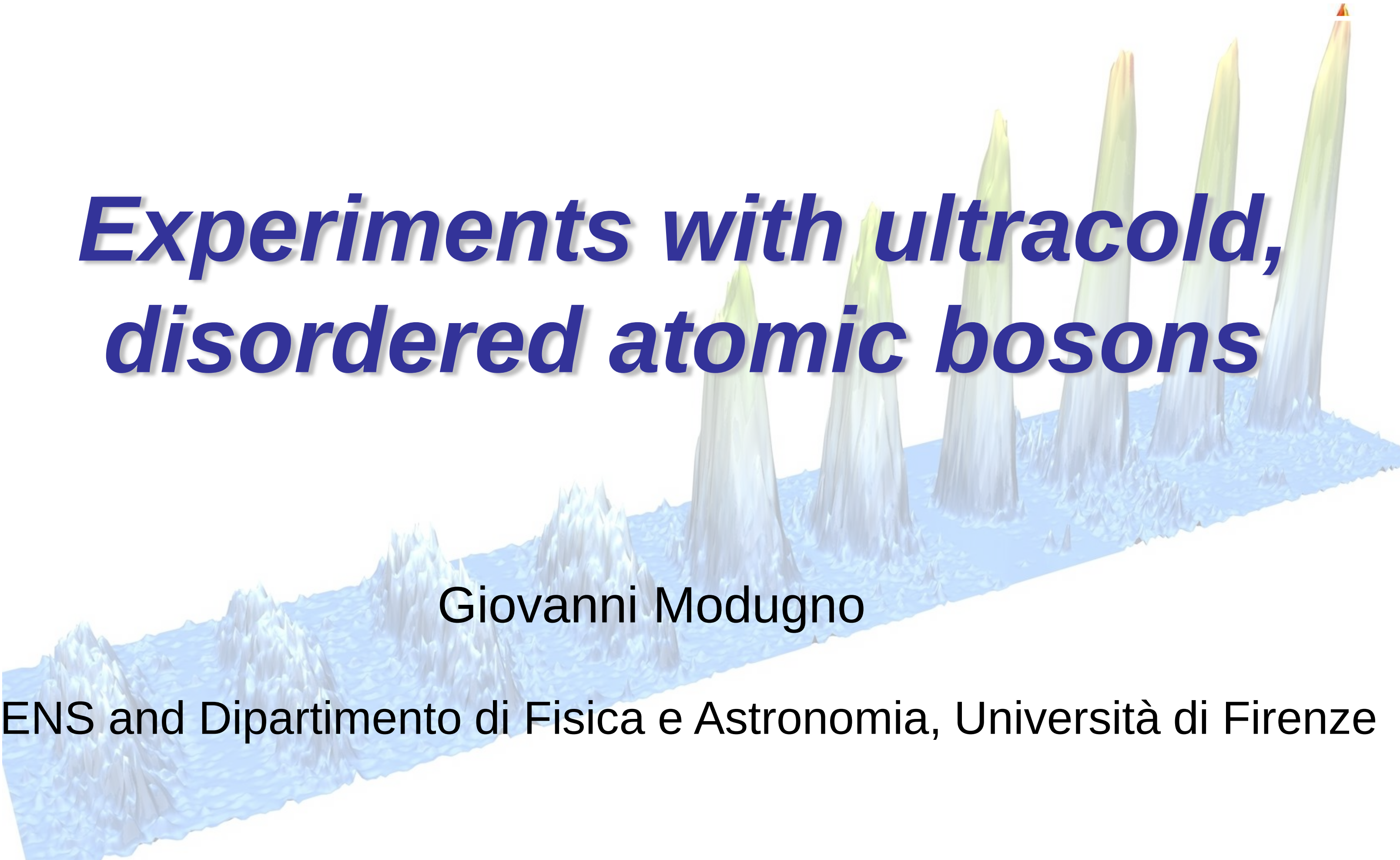
# *Experiments with ultracold, disordered atomic bosons*

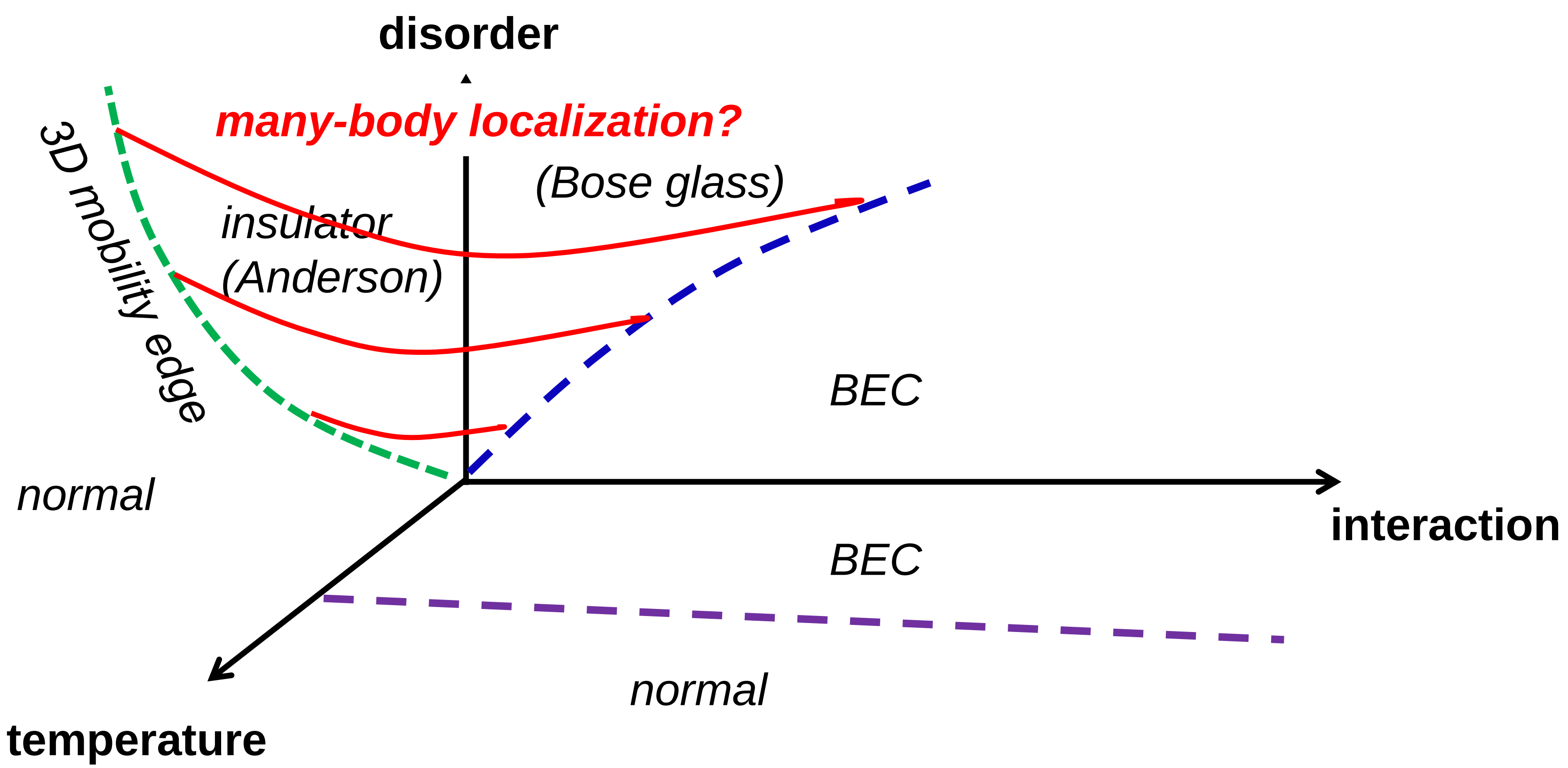


Giovanni Modugno

LENS and Dipartimento di Fisica e Astronomia, Università di Firenze

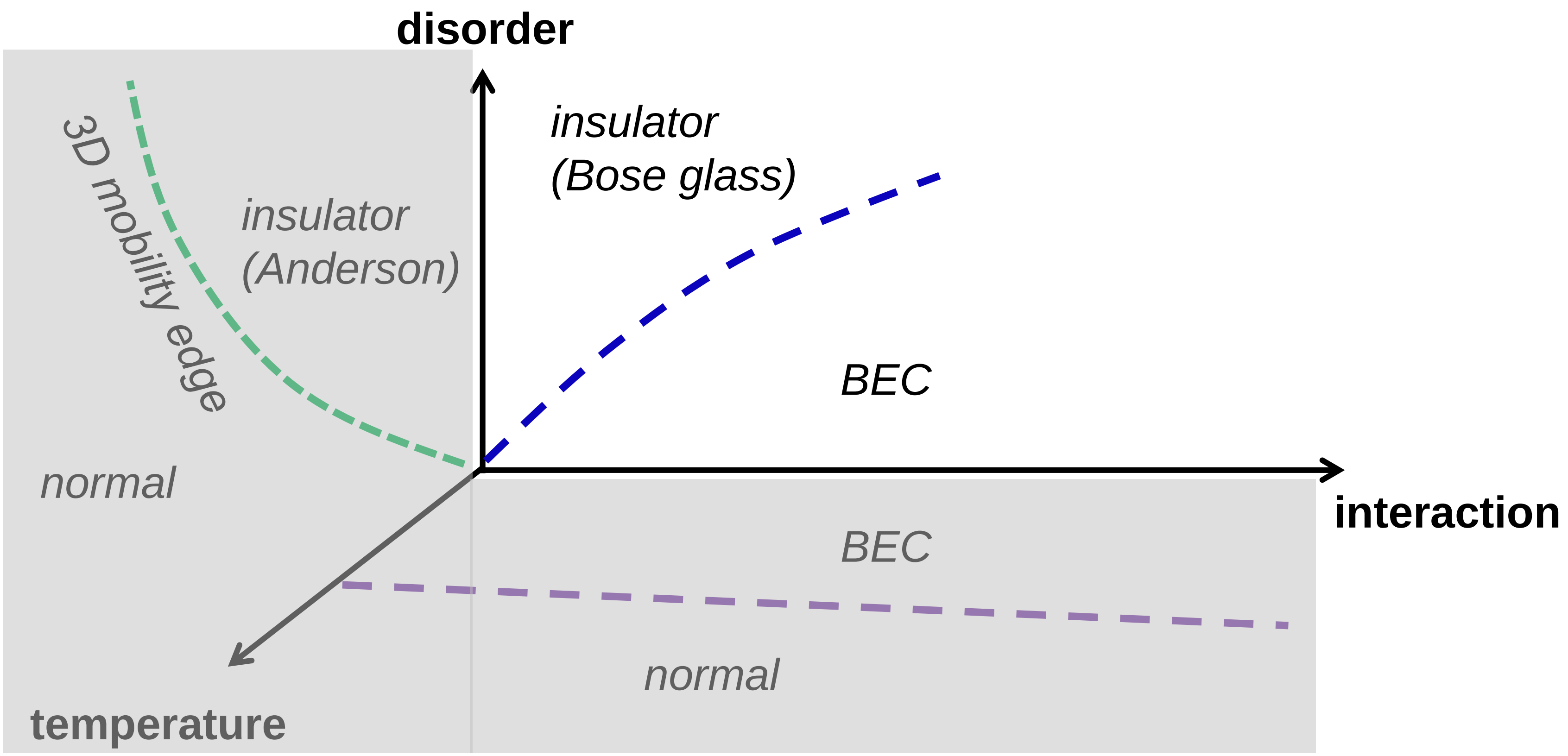
EXS2014, ICTP, Trieste

# Disordered bosons: an open problem

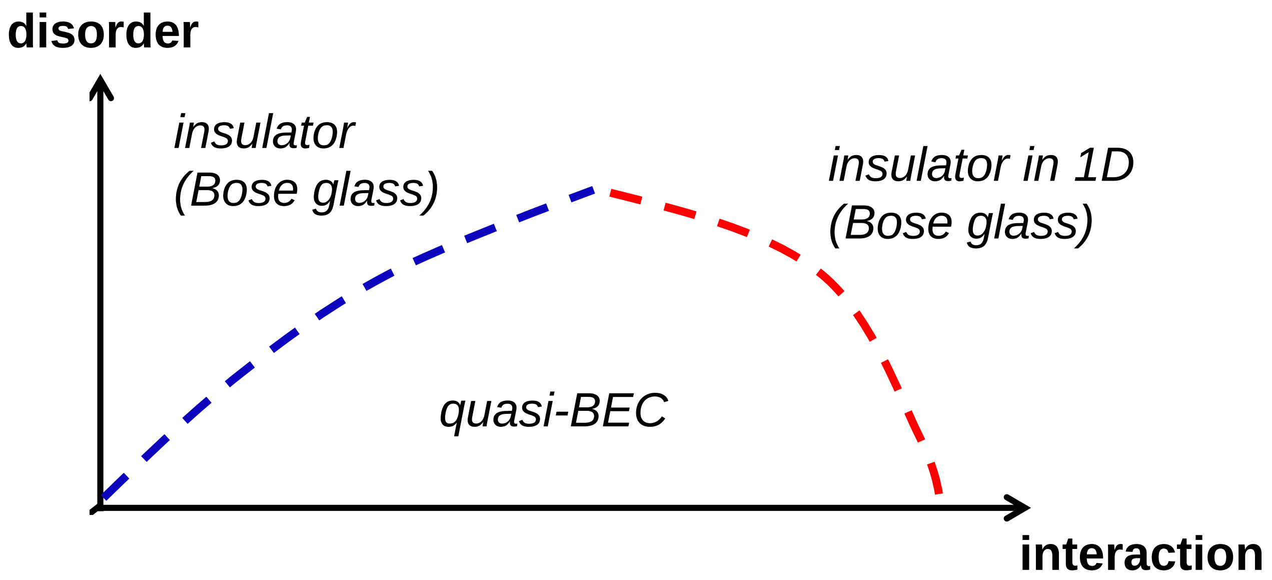



only partially understood in theory; very few experiments

# Interacting bosons in 1D, at T~ 0



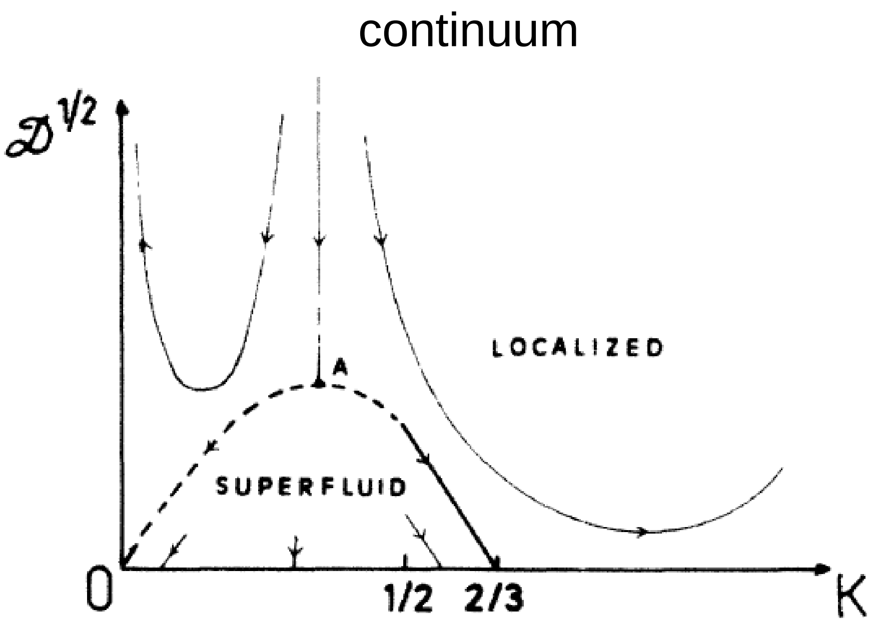
# Interacting bosons in 1D, at T~ 0



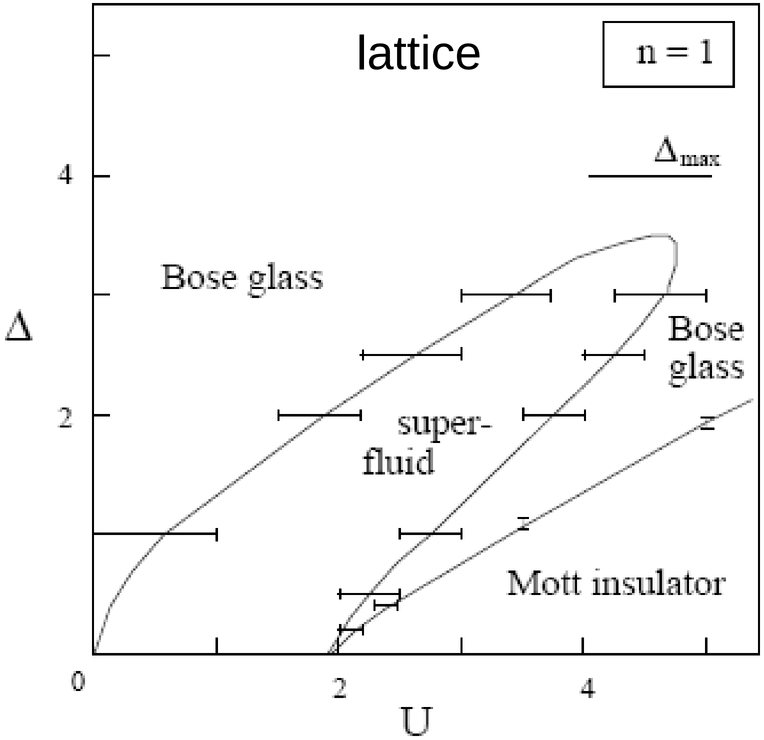

One dimension. Main results from theory:

- Anderson localization depends only weakly on energy
- Bose-Einstein condensation is marginal
- a small $E_{int}$ competes with disorder and tends to restore superfluidity
- for $E_{int}/E_{kin}>1$ the bosons progressively behave like non-interacting fermions and get again localized

# Disordered bosons at T=0



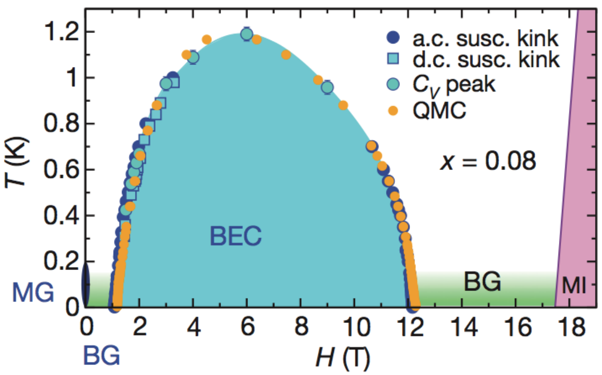

Giamarchi & Schulz, PRB 37 325 (1988), …




Fisher et al PRB 40, 546 (1989),
Rapsch, et al., EPL 46 559 (1999), …

In a lattice: non-trivial competition between Bose glass, Mott insulator and superfluid, depending on the site occupation *n*

# Disordered, interacting bosons: experiments



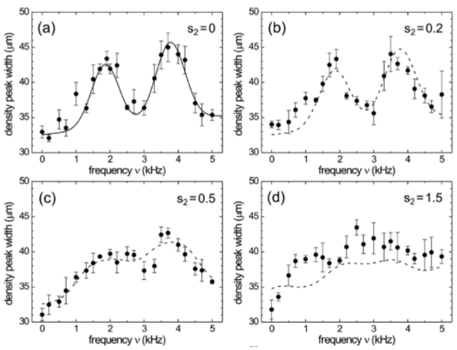

Yu et al., *Nature* **489** (2012)

**Quantum magnets**:

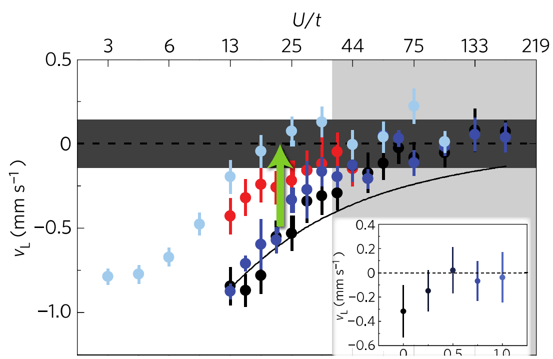
thermodynamical systems
tuning of disorder and interactions is hard

**Cold atoms**:

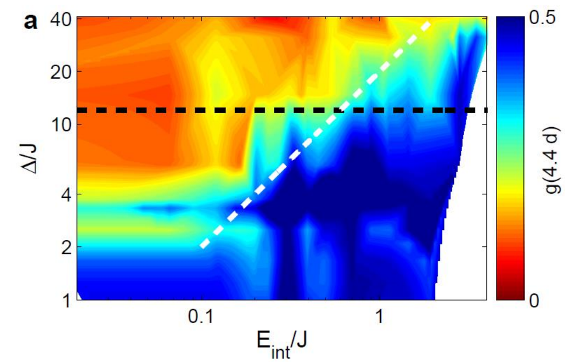
tuning of disorder and interactions is possible
inhomogeneous, temperature control is hard




Fallani et al., PRL **98** (2007)

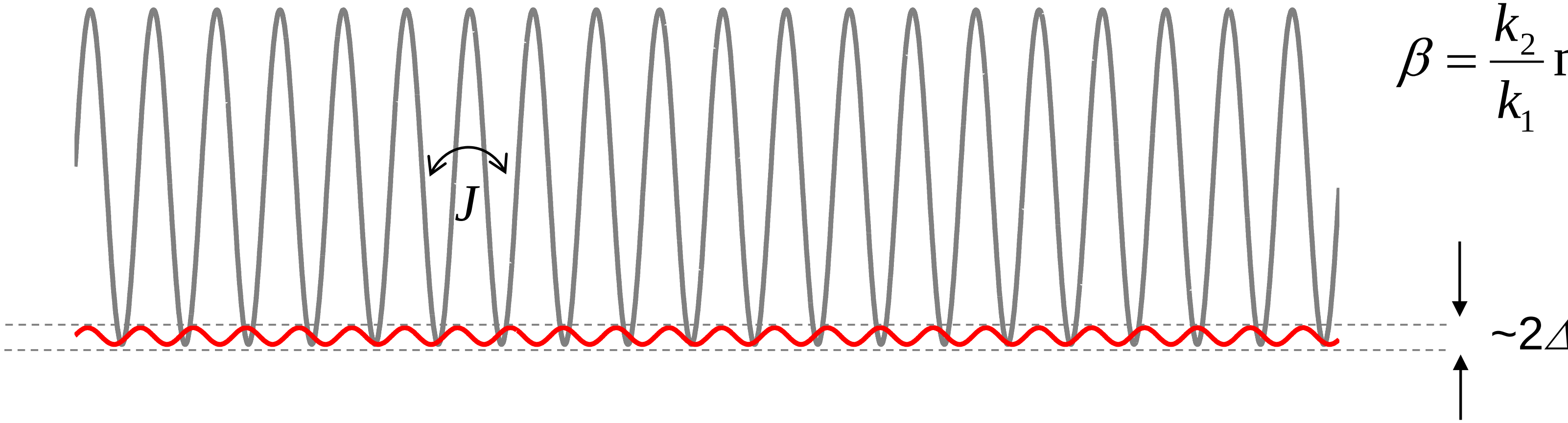



Pasienski et al., *Nat. Phys.* **6** (2010);
Gadway et al., PRL **107** (2011)




Deissler et al., *Nat. Phys.* **6** (2010)

# The quasi-periodic lattice




$$\beta = \frac{k_2}{k_1} \bmod 1$$

$$\hat{H} = -J\sum_i \left(\hat{b}_i^+ \hat{b}_{i+1} + h.c.\right) + \Delta \sum_i \cos(2\pi\beta i + \varphi)\hat{n}_i + \frac{U}{2}\sum_i \hat{n}_i(\hat{n}_i - 1)$$

Aubry-Andrè model with metal-insulator transition at $\Delta = 2J$

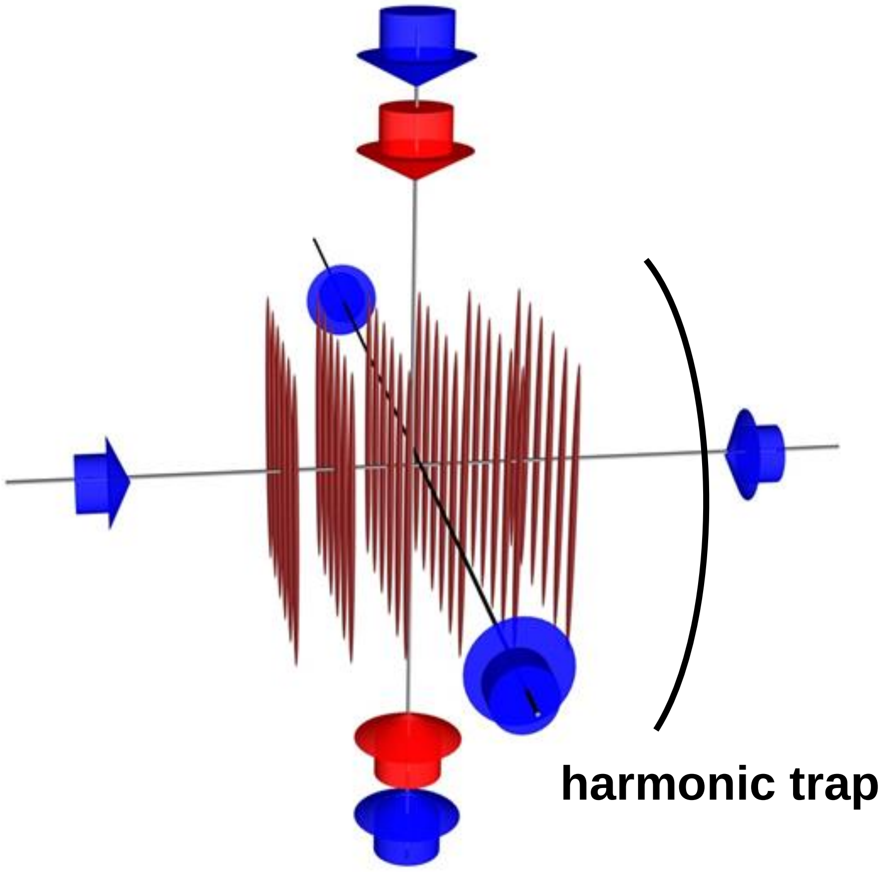
Exponentially localized states with uniform $\xi_{\mathrm{LOC}}$

Interaction tuned via a Feshbach resonance ($^{39}K$ atoms)

$$U = \frac{2\pi\hbar^2}{m} a \int \varphi^4 dx$$

S. Aubry and G. André, Ann. Israel Phys. Soc. 3, 133 (1980). Theory by M. Modugno, A. Minguzzi, ...

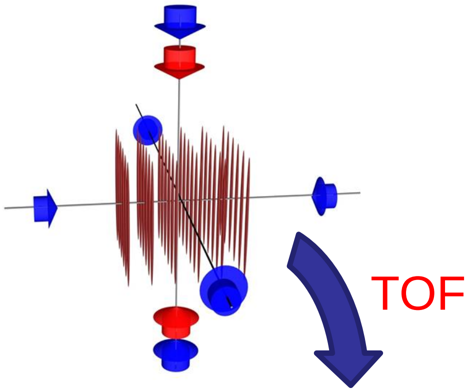
# One-dimensional lattices




Quasi-1D: the radial trapping energy much larger than the other energy scales

Longitudinal trapping: inhomogeneity

# Coherence from momentum distribution

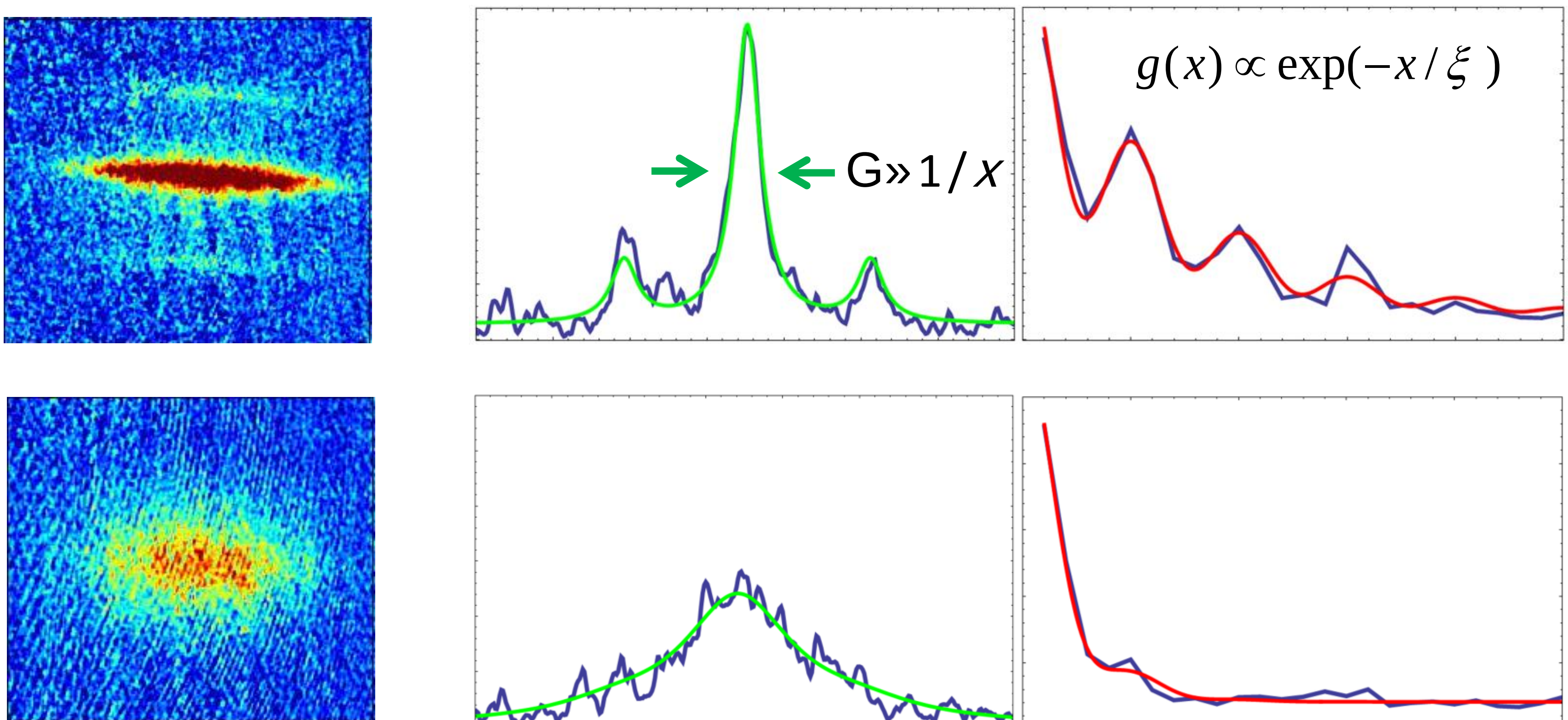



FT

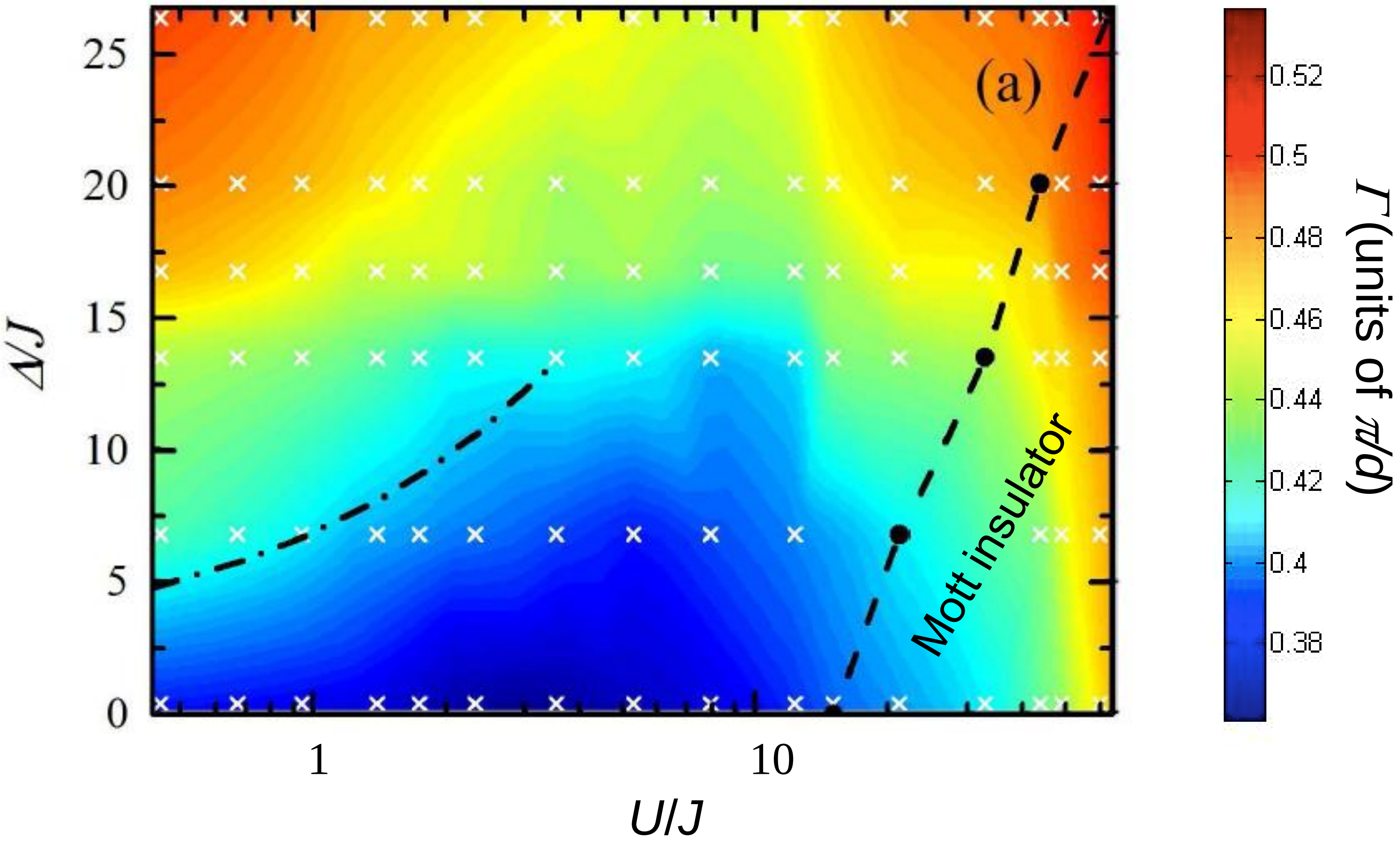
$$|\Psi(k)|^2 \quad \longrightarrow \quad g(x) = \int dx' \langle \Psi^+(x)\Psi(x+x') \rangle$$

Momentum distribution

Spatially averaged correlation function



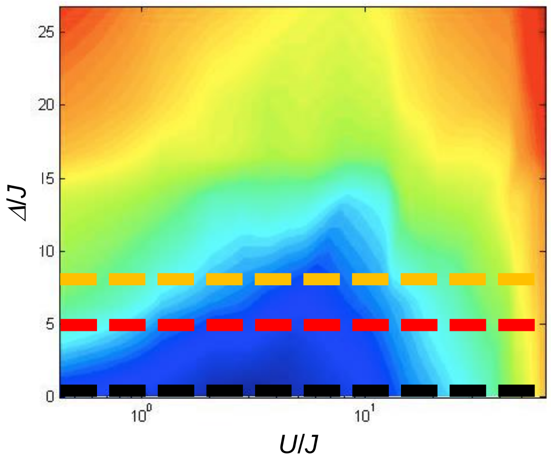
# Coherence from momentum distribution

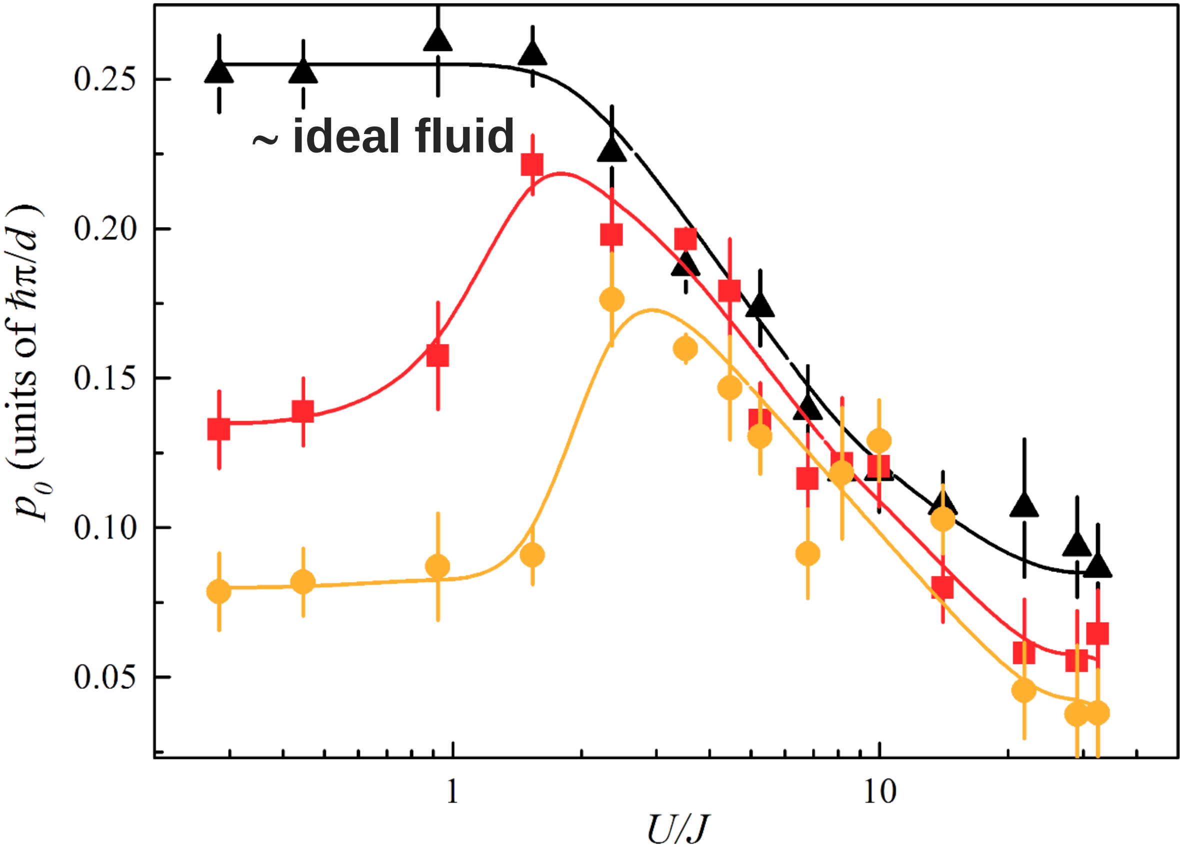



D'Errico, Lucioni et al., Phys. Rev. Lett. 113, 095301 (2014)

The small-U line is from P. Lugan, et al., Phys. Rev. Lett. 98, 170403 (2007), ...

# Transport: mobility measurements

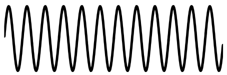




Incoherent regimes
are also insulating

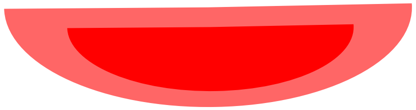
# Excitation spectra

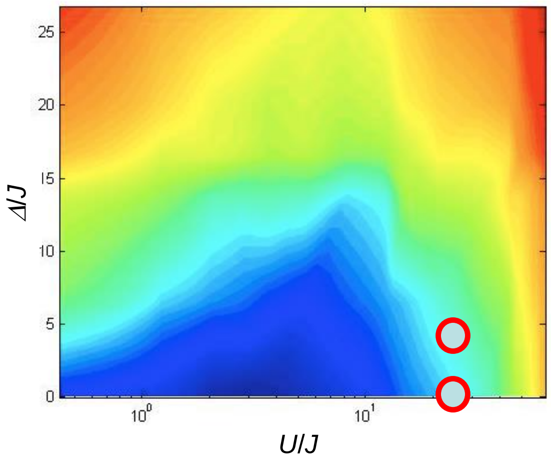
prepare in equilibrium

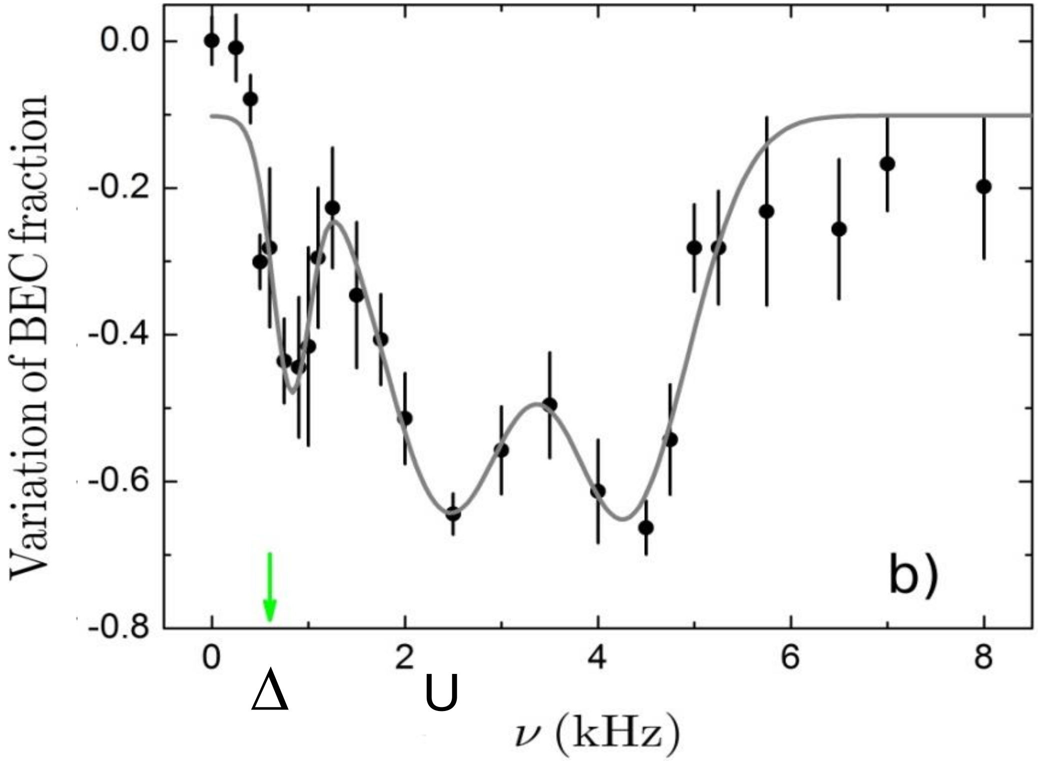
main lattice modulation (15%, 200ms)



“energy” measurement



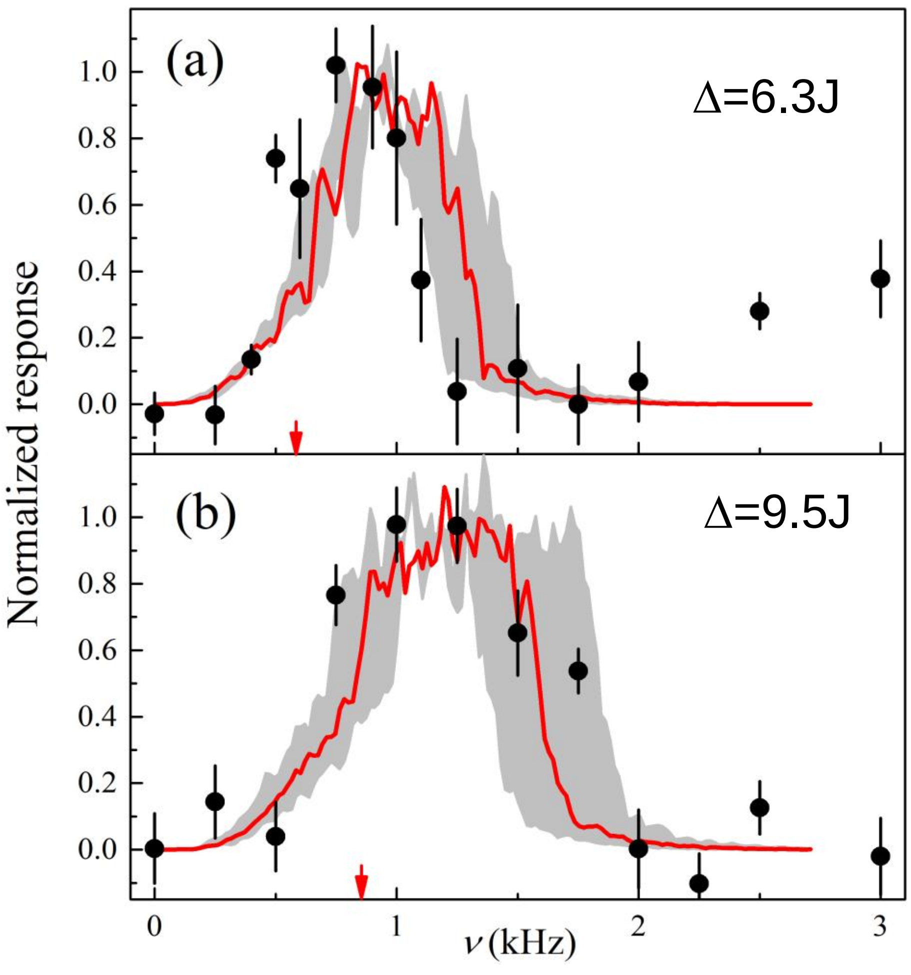



Ströferle et al., Phys. Rev. Lett. 92, 130403 (2004), Iucci et al. Phys.Rev. A 73, 041608 (2006); Fallani et al., PRL 98, 130404 (2007).

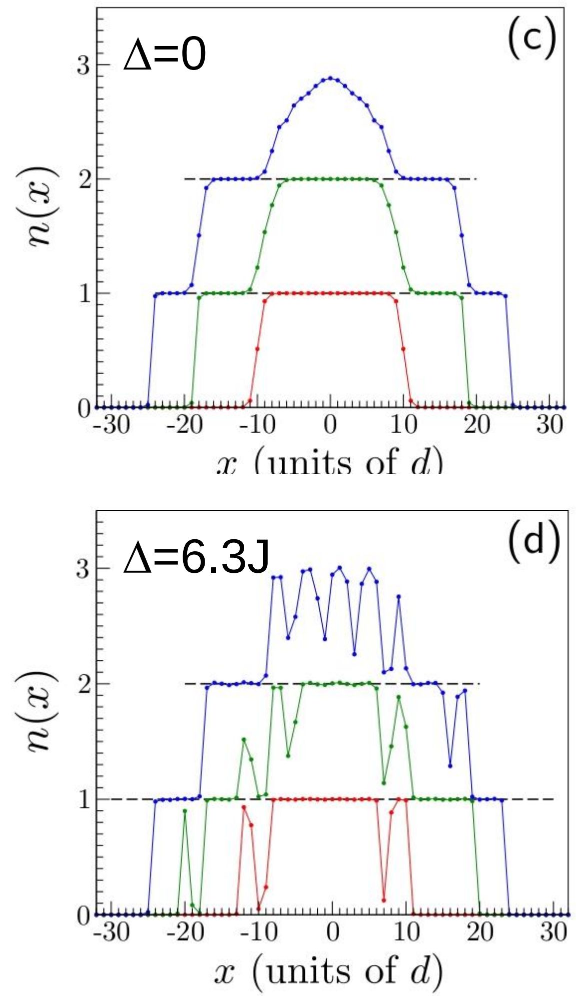
# Excitation spectra vs non-interacting fermions

—— excitation spectrum of non-interacting fermions (correlation function of the hopping operator)




G. Orso et al., Phys. Rev. A 80 033625 (2009)
G. Pupillo et al, New. J. Phys. 8, 161 (2006).

Density by DMRG




Theory by T. Giamarchi (Geneva), G. Roux (Orsay)

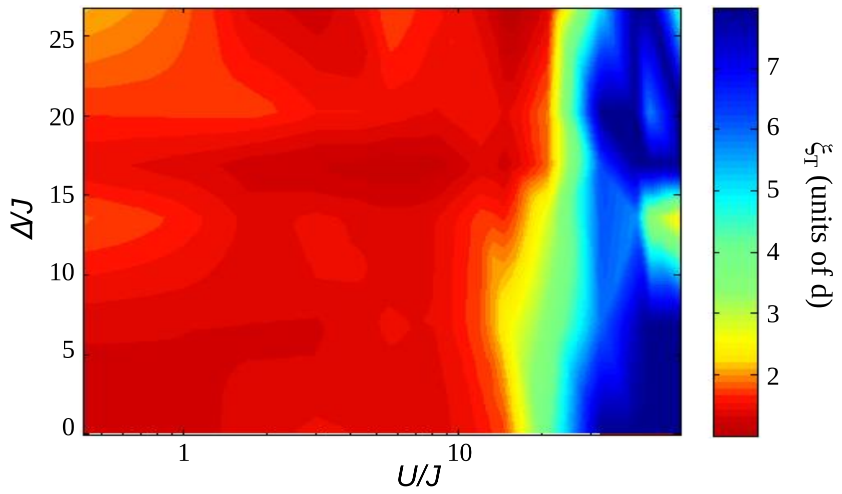
# Finite-T effects and comparison with theory

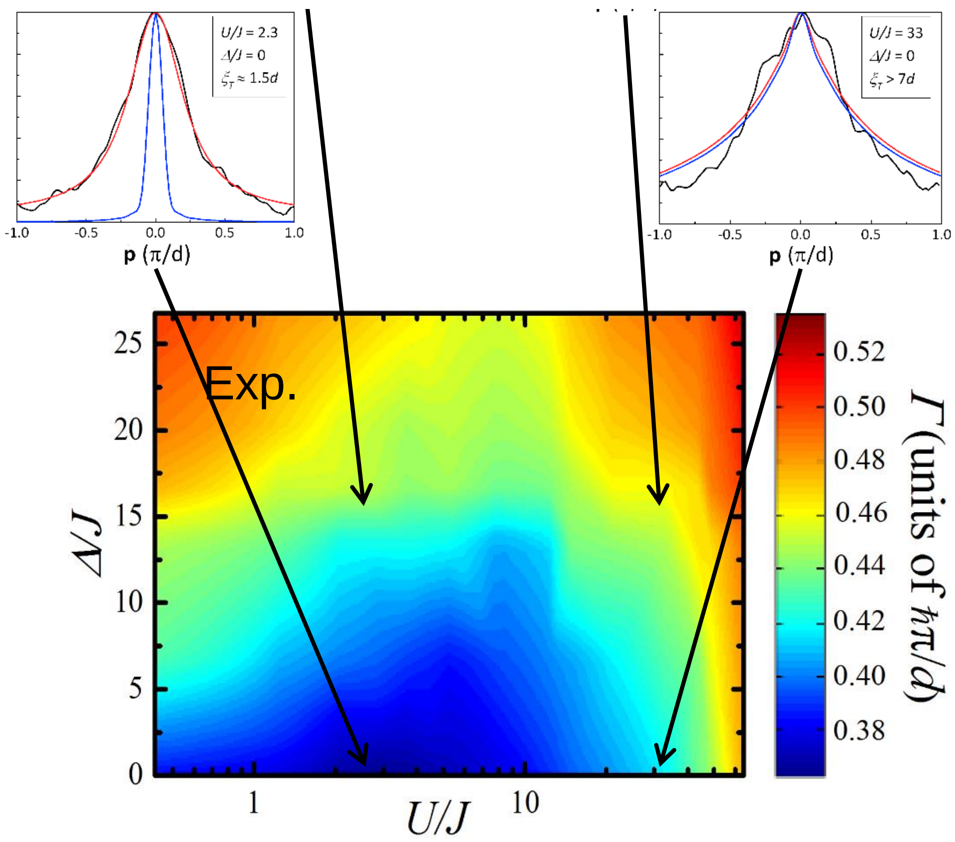
beyond Luttinger:

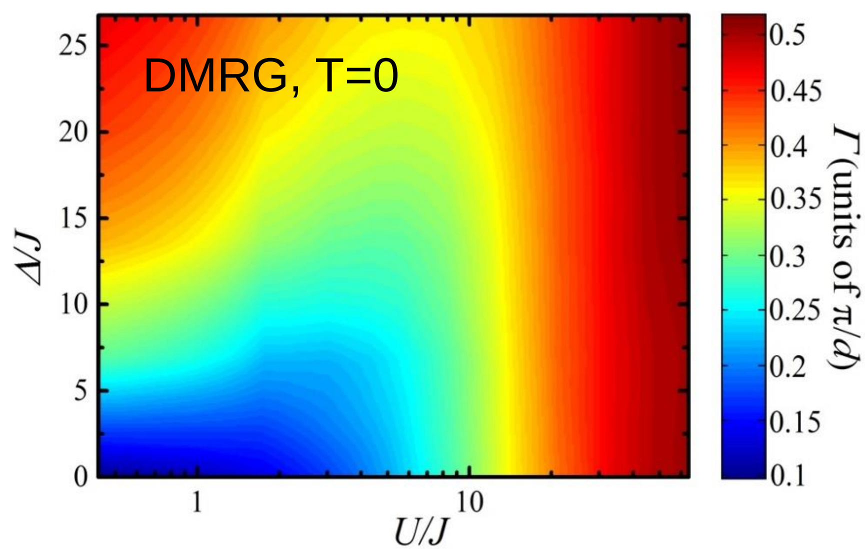
$$\xi_T = d/\mathrm{arcsinh}\left(k_B T / J n^{1/2}\right)$$

$$T_{exp} = 3\text{-}6\ J$$

fitted thermal length

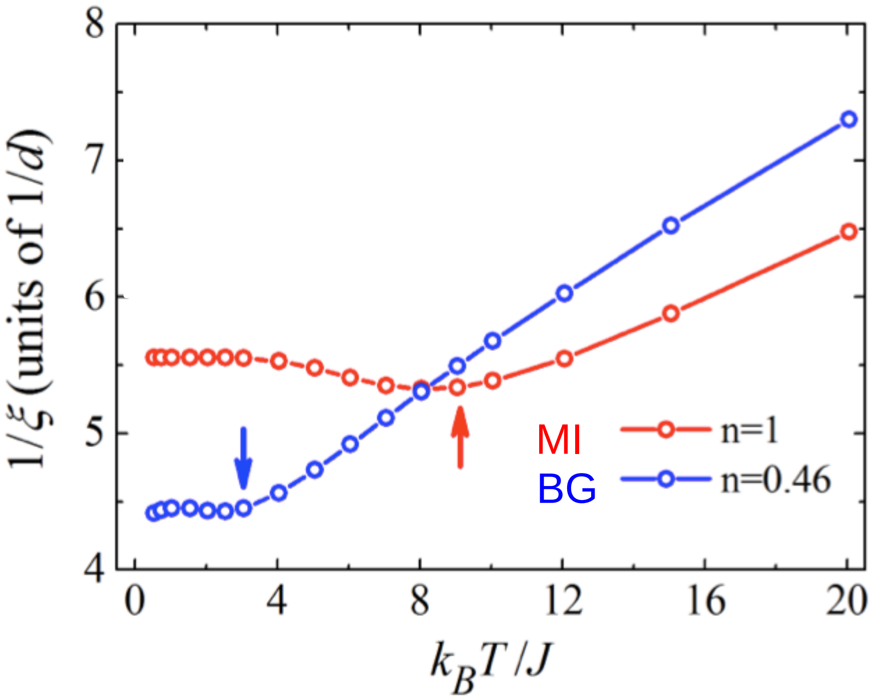


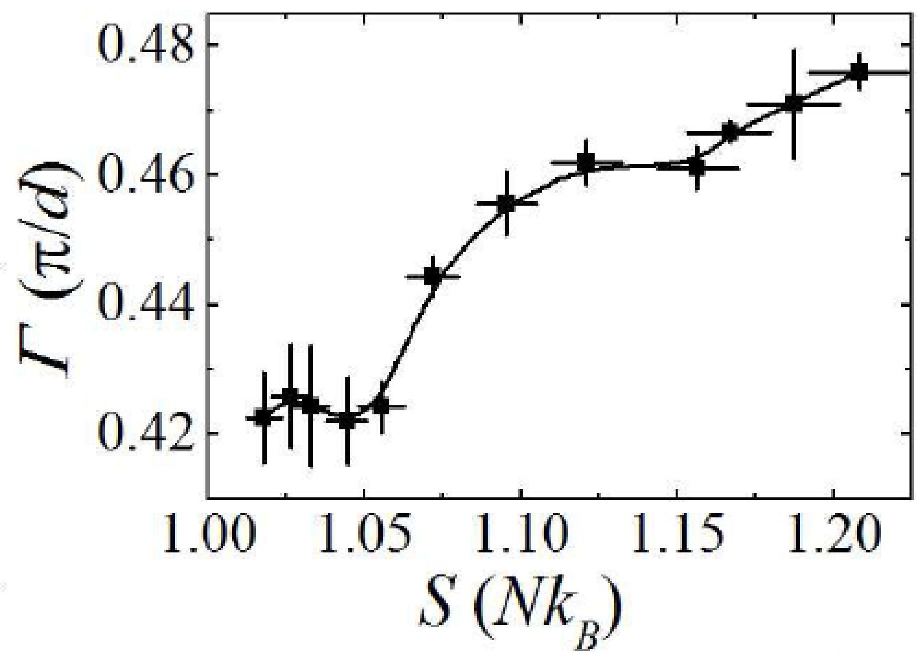



# Finite-T effects: large U

Exact diagonalization for large U



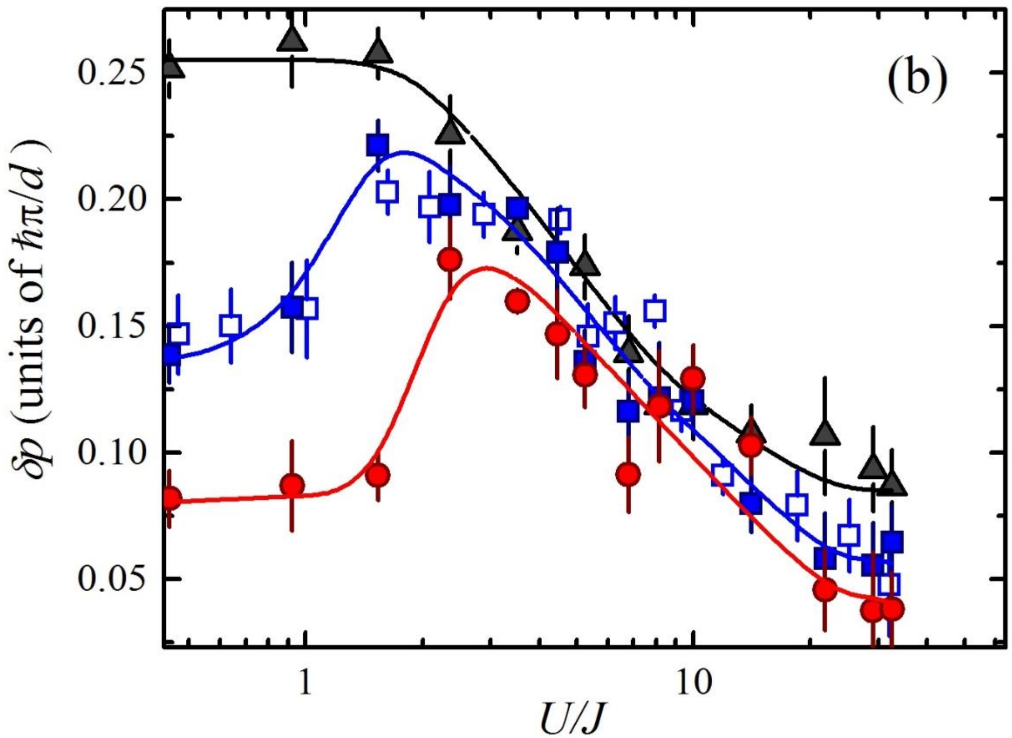




Thermal broadening appears only above a sizable crossover temperature.

The strongly-correlated Bose glass survives at the experimental temperatures (an effect of the “Fermi energy” of fermionized bosons).

# Finite-T effects: small U

We have evidence of a large thermal broadening, but…




■ $k_BT$=3.1(4)J

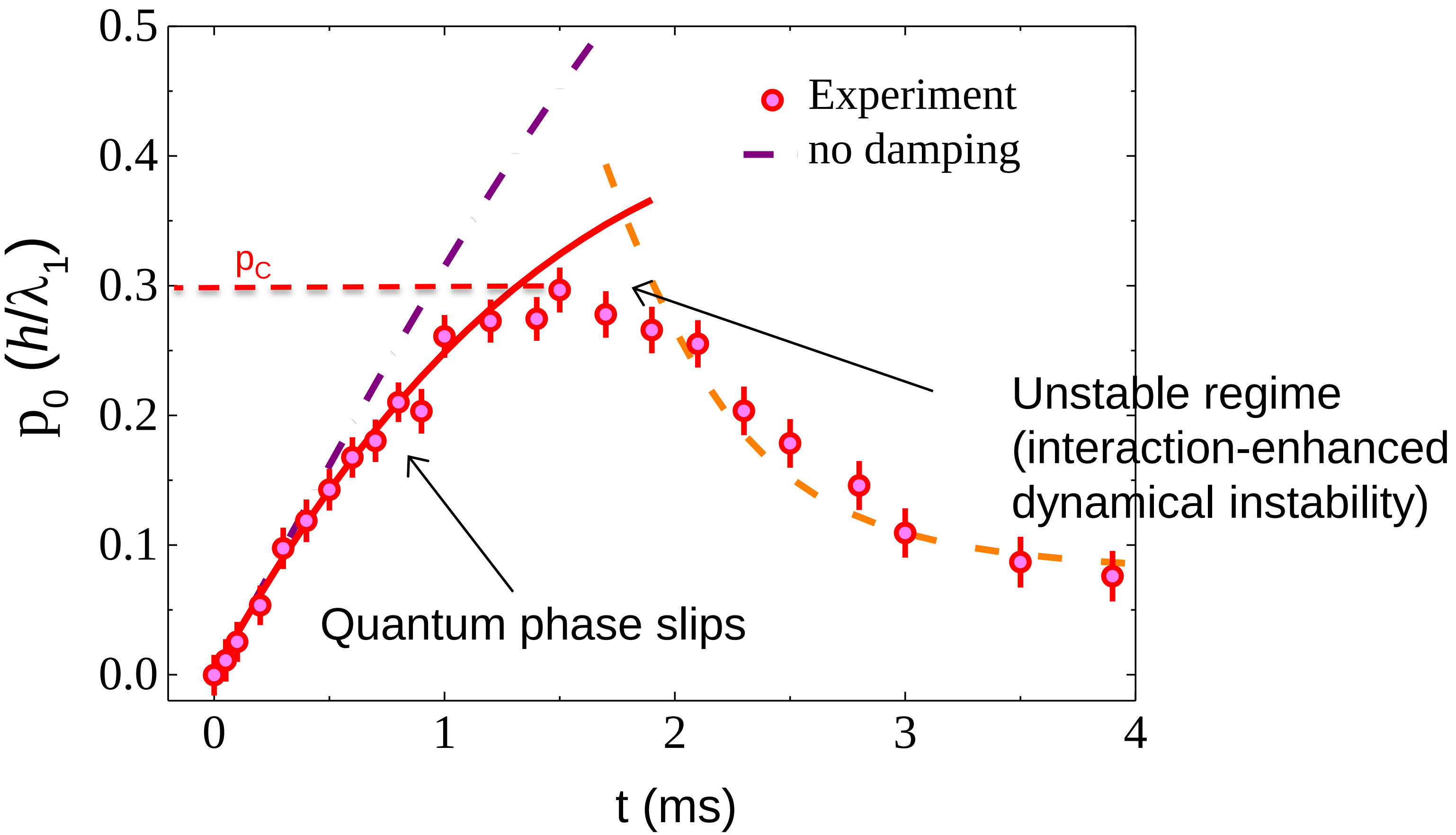
□ $k_BT$=4.5(7)J

... the mobility does not show a relevant change with temperature.

Relation with many-body localization?

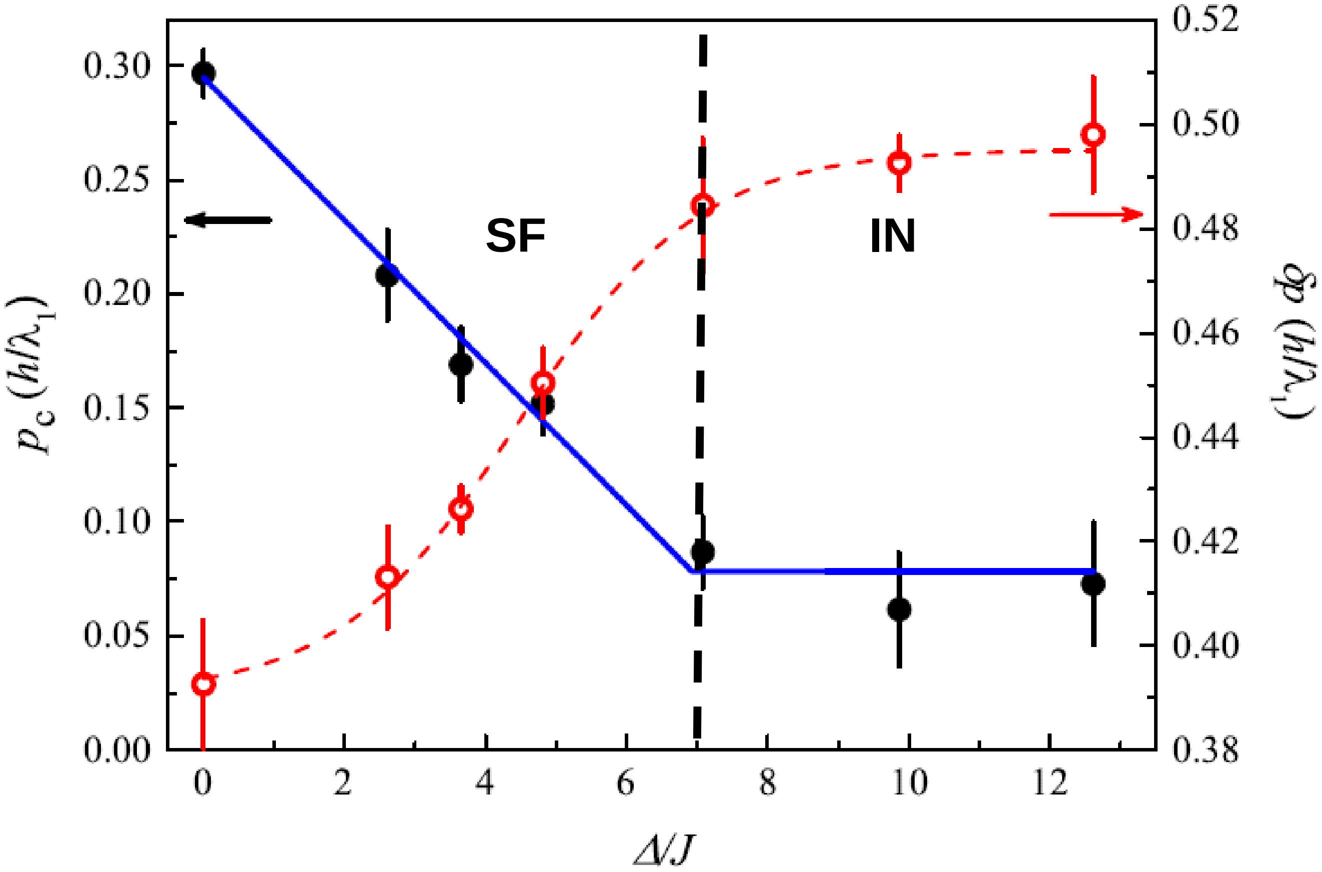
(Aleiner, Altshuler, Shlyapnikov, Nature Physics 6, 900 (2010); Michal, Altshuler, Shlyapnikov, arXiv.1402.4796.)

# Transport revisited: clean system


L.Tanzi, et al. Phys. Rev. Lett. 111, 115301 (2013)

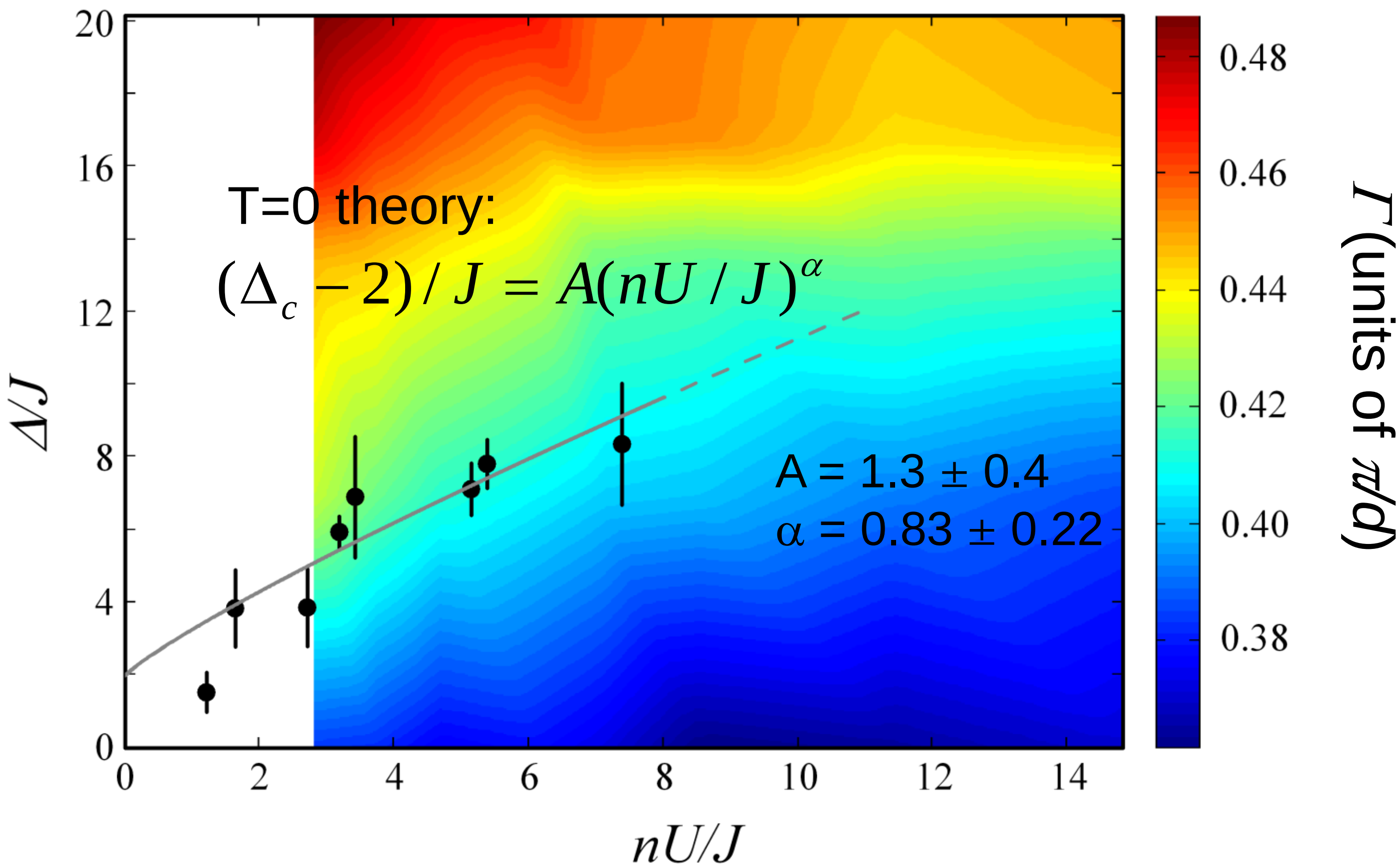
# Transport revisited: disordered system




The critical momentum is reduced by disorder

As $p_c \rightarrow 0$ : the SF to IN crossover from a generalized Laundau criterion

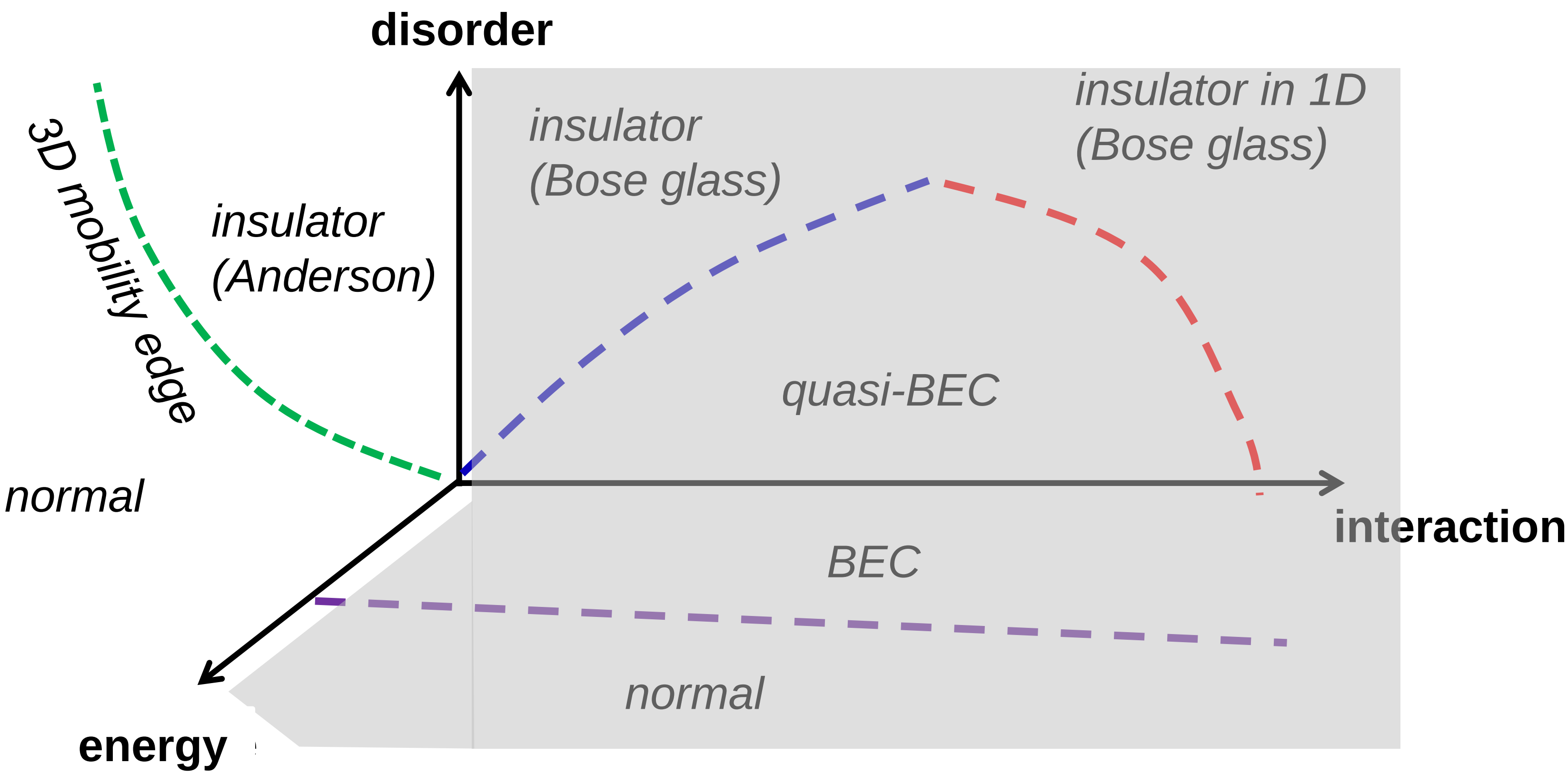
# Fluid-insulator crossover from transport




First steps towards a quantitative analysis of Bose glass and many-body localization physics in 1D

Theory: P. Lugan, et al., Phys. Rev. Lett. 98, 170403 (2007), L. Fontanesi, et al., Phys. Rev. A 81, 053603 (2010), Altman et al. , ....

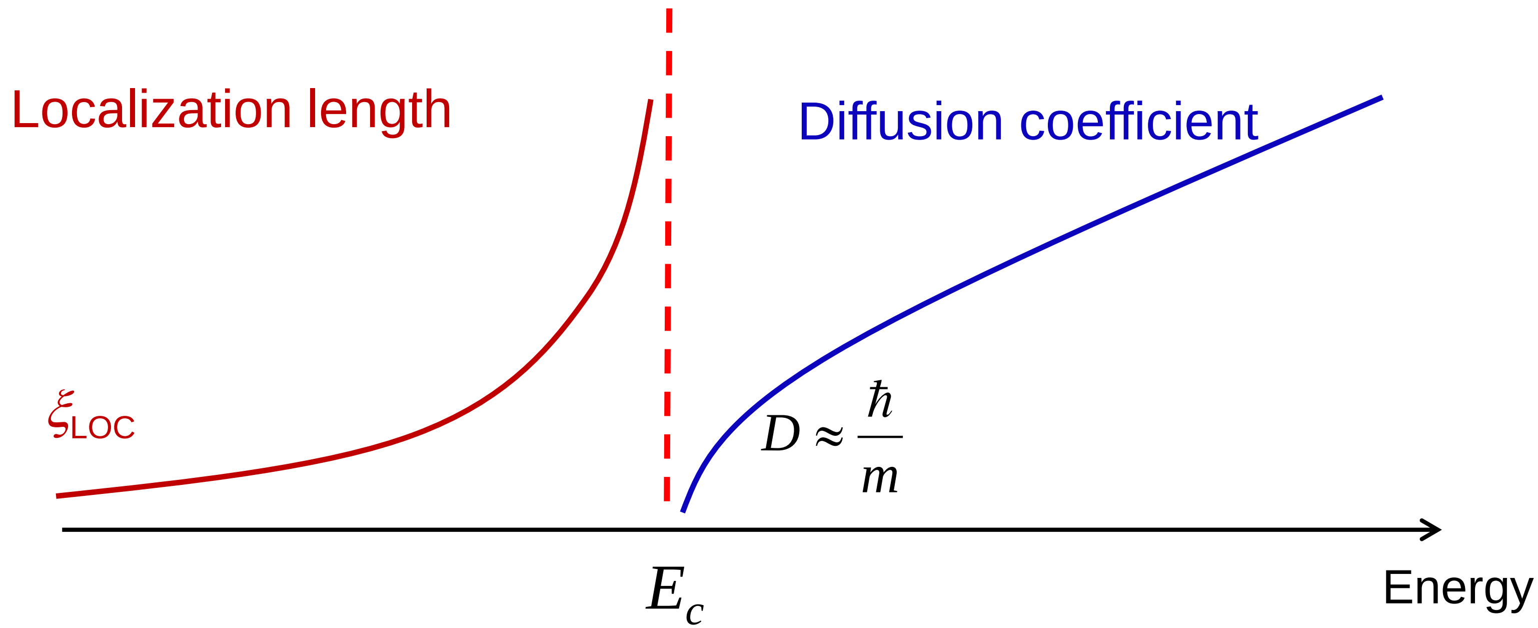
# Non interacting particles in 3D disorder




There is a critical energy for localization (Anderson transition): P. W. Anderson, Phys. Rev. 109, 1492 (1958) , ...

Not yet measured in experiments!

# Simple picture of the mobility edge

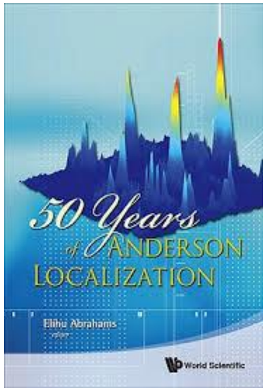



Critical behavior: $\xi_{LOC} \propto |E - E_c|^{-\nu}$ $D \propto |E - E_c|^{\nu}$ $\nu \approx 1.6$

Critical energy: $E_c \approx \Delta$

50 years of theory of Anderson localization!

e.g. E. Abrahams ed. World Scientific 2013



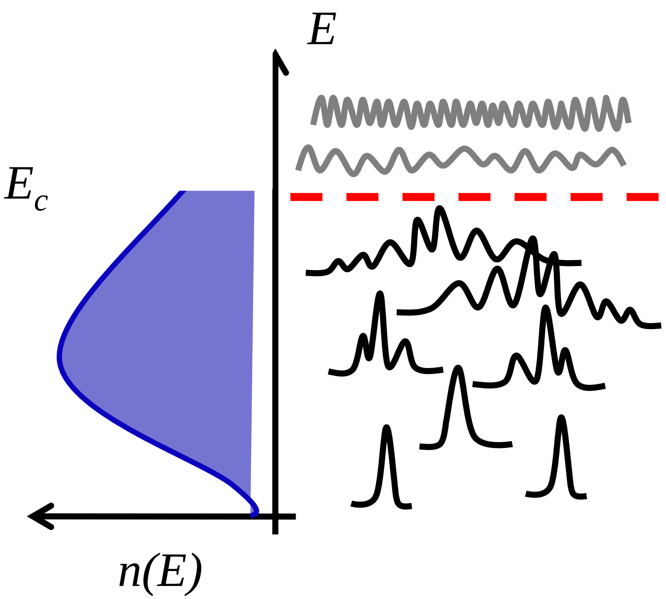
# Experiments on Anderson localization in 3D

**Light waves**: Sperling, et al. Nat. Photonics (2012), Wiersma et al, ....

**Sound waves**: Hu et al, Nat. Physics 4, 945 (2008).

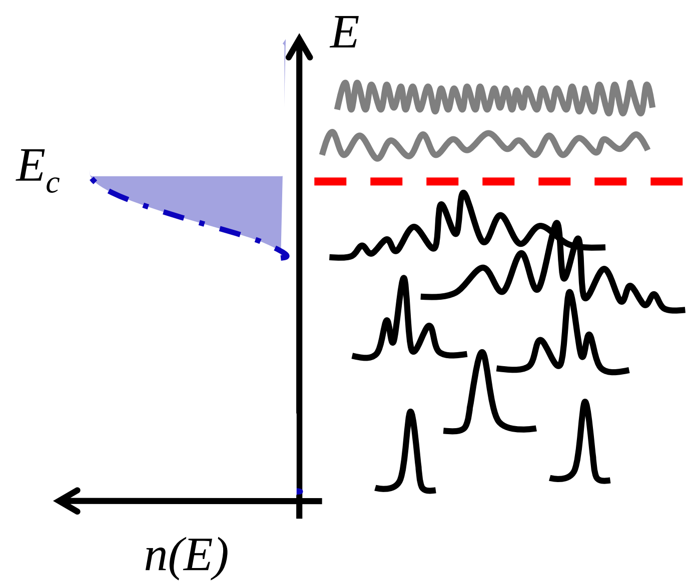
**Atomic kicked rotor**: a momentum space version of the Anderson model
Chabé et al. Phys. Rev. Lett. 101, 255702 (2008), ...

**Ultracold atoms**:
Non-interacting fermions




Kondov et al, Science 334,63 (2011)

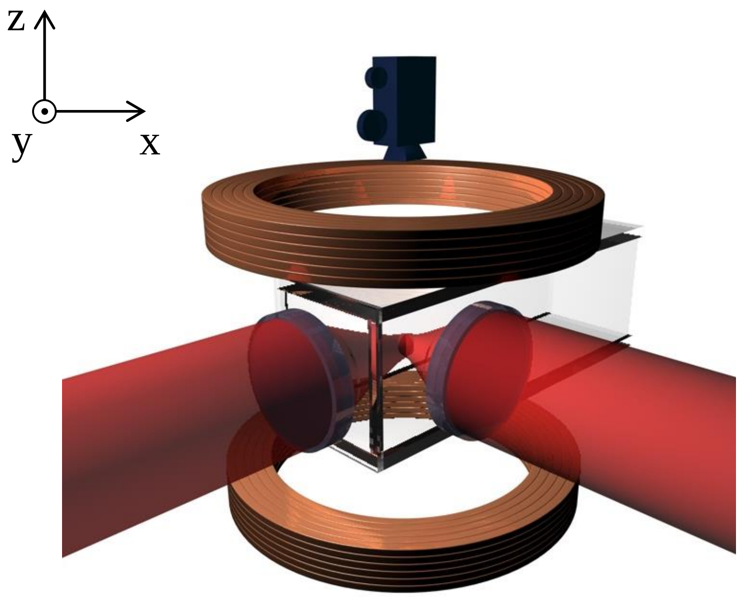
Interacting BEC

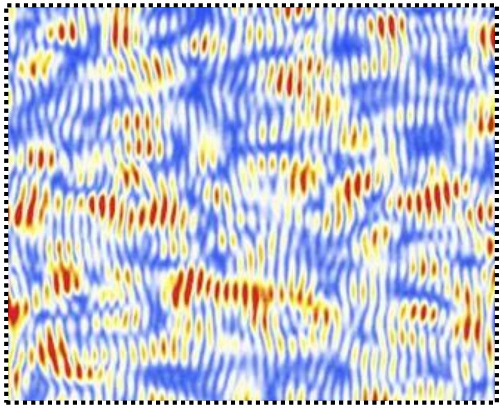


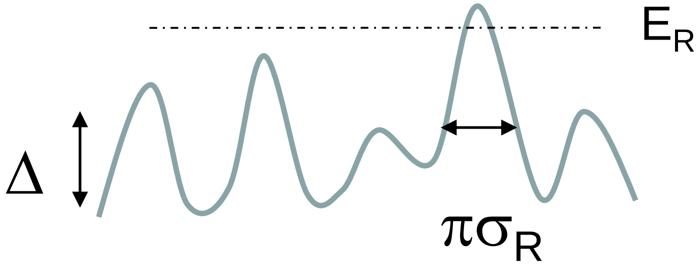

F. Jendrzejewski et al, Nat. Physics 8, 398 (2012)

# 3D speckles disorder

Same coherent speckles as in Palaiseau



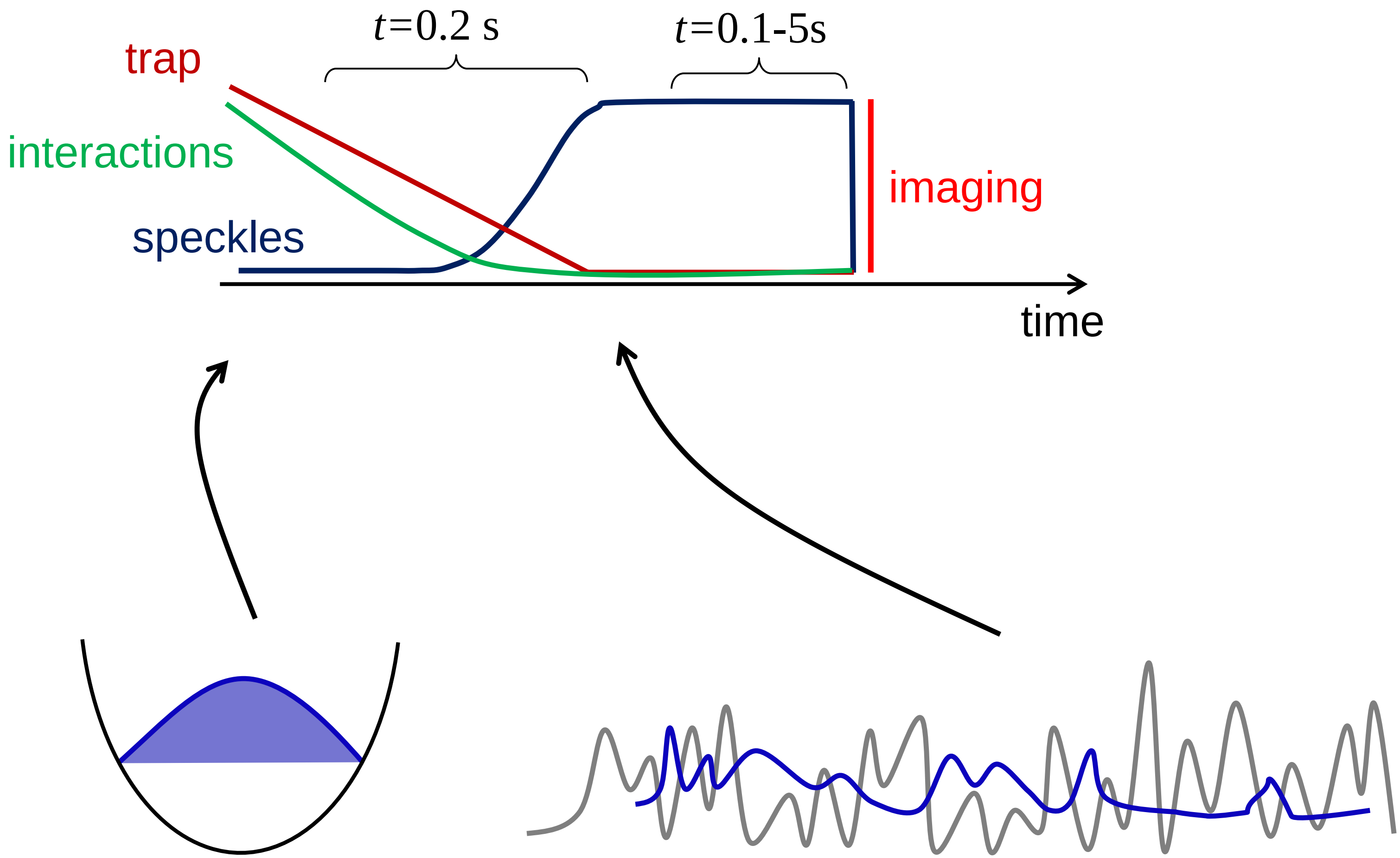



but $^{39}$K atoms with tunable interaction

$E_R \leq \hbar^2/m\sigma_R^2 \approx 70\text{nK}$

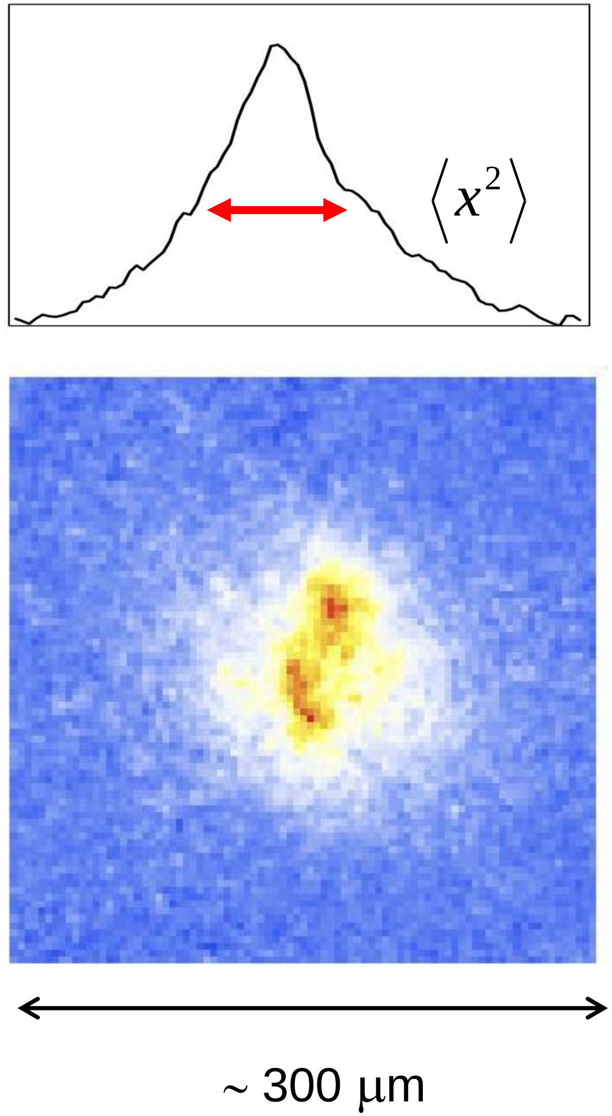
Semeghini, Landini et al., arXiv:1404.3528

# Quasi-adiabatic preparation

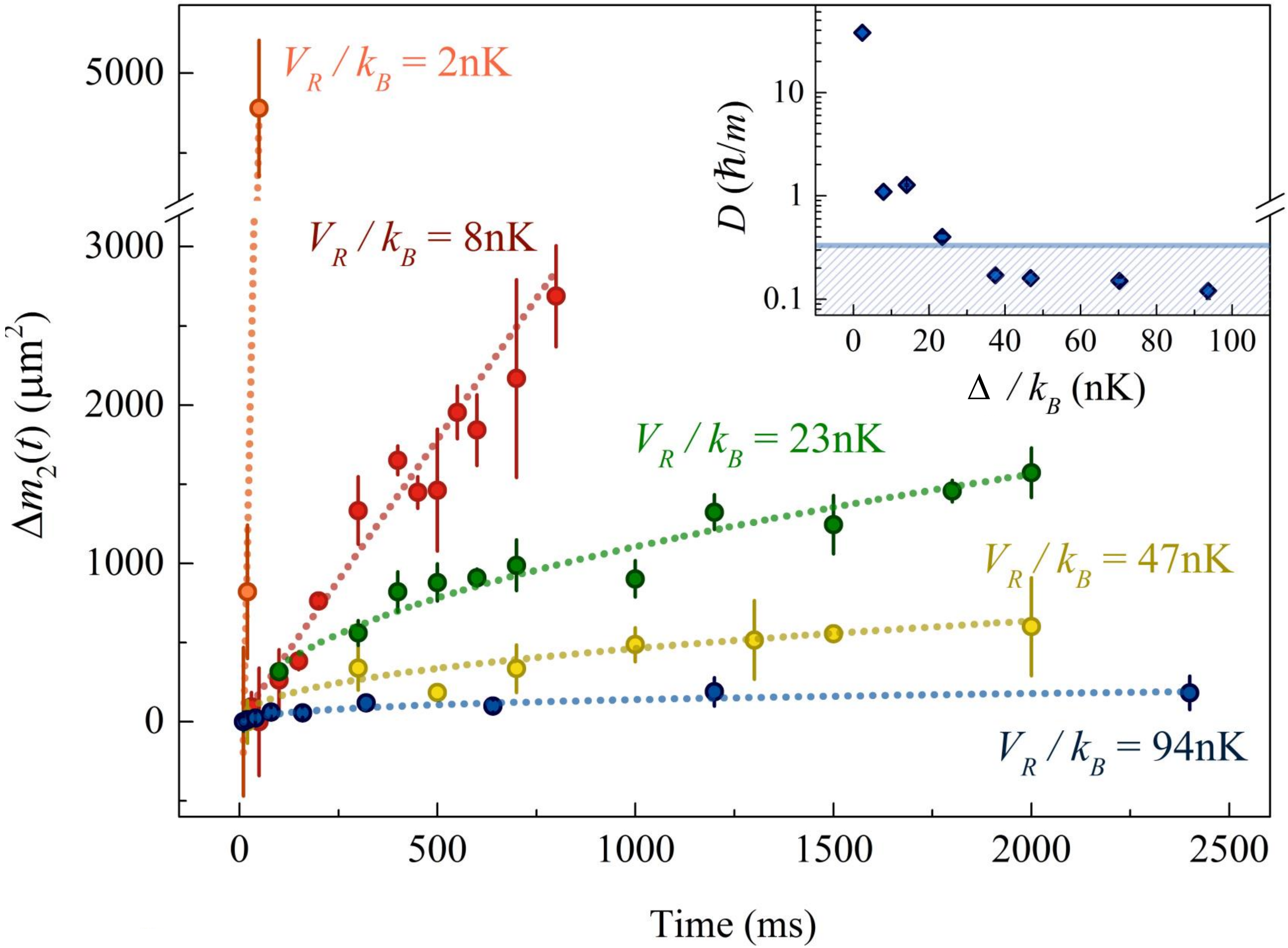



Optimized by minimizing the kinetic energy

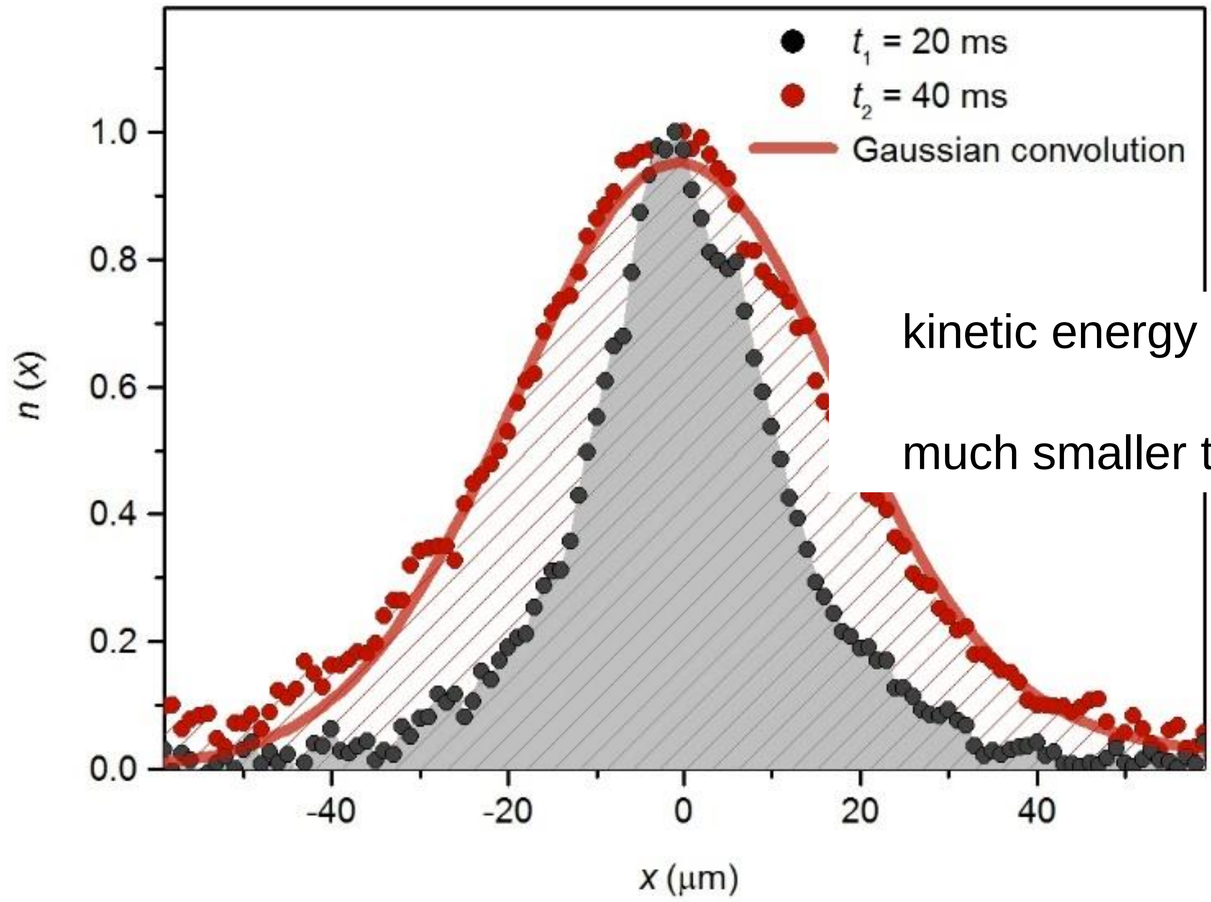
# Time evolution of the spatial distribution



# From diffusion to localization



# Momentum distribution

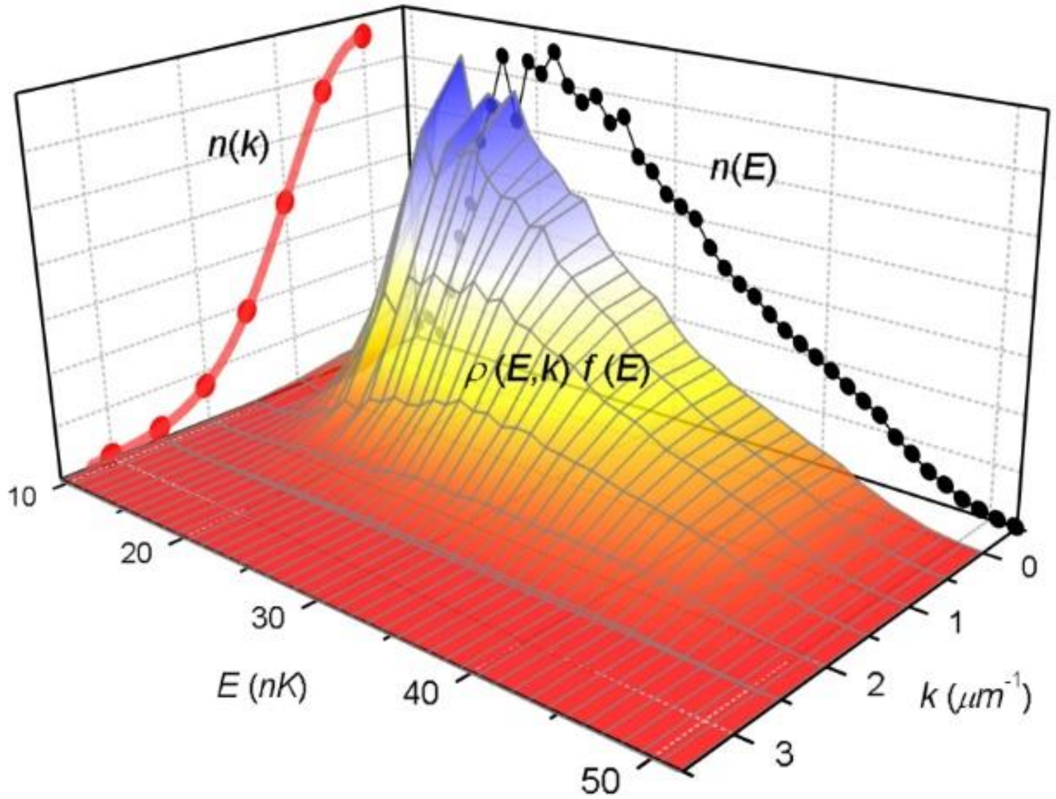



kinetic energy ~10 nK

much smaller than $\Delta$ =47 nK

The momentum and energy distributions are related by the spectral function $\rho(E,k)$: probability of having a momentum $k$ at an energy $E$

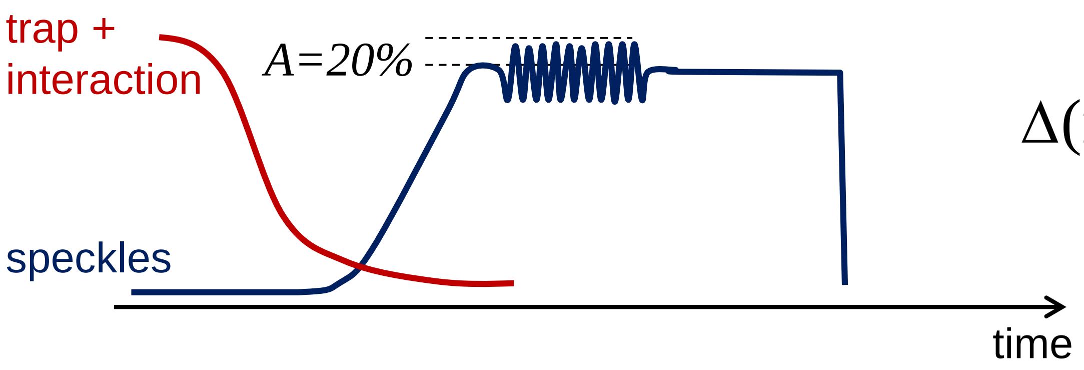
# Energy distribution from momentum distribution




$$n(k) = \int \rho(E,k)\, f(E)\, dE \qquad f(E) \approx \exp(-E/E_m)$$

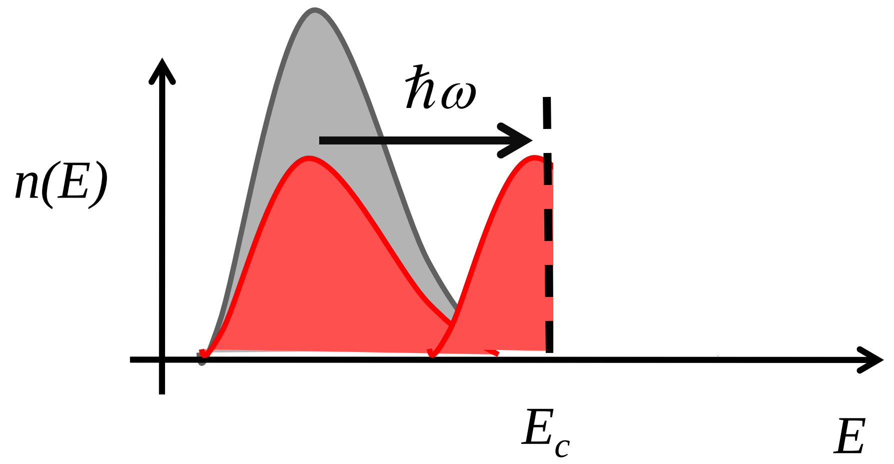
$$n(E) = \int \rho(E,k)\, f(E)\, dk = g(E)\, f(E)$$

# Excitation spectroscopy

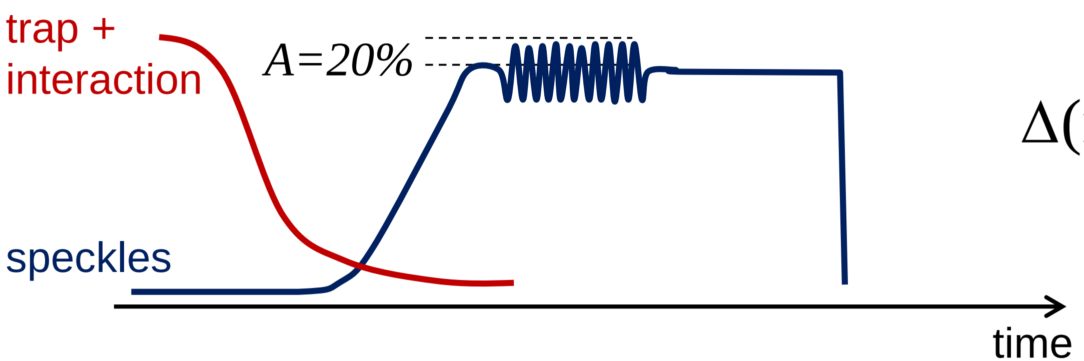



$$\Delta(\mathbf{r},t) = \Delta(\mathbf{r})(1 + A\cos(\omega t))$$

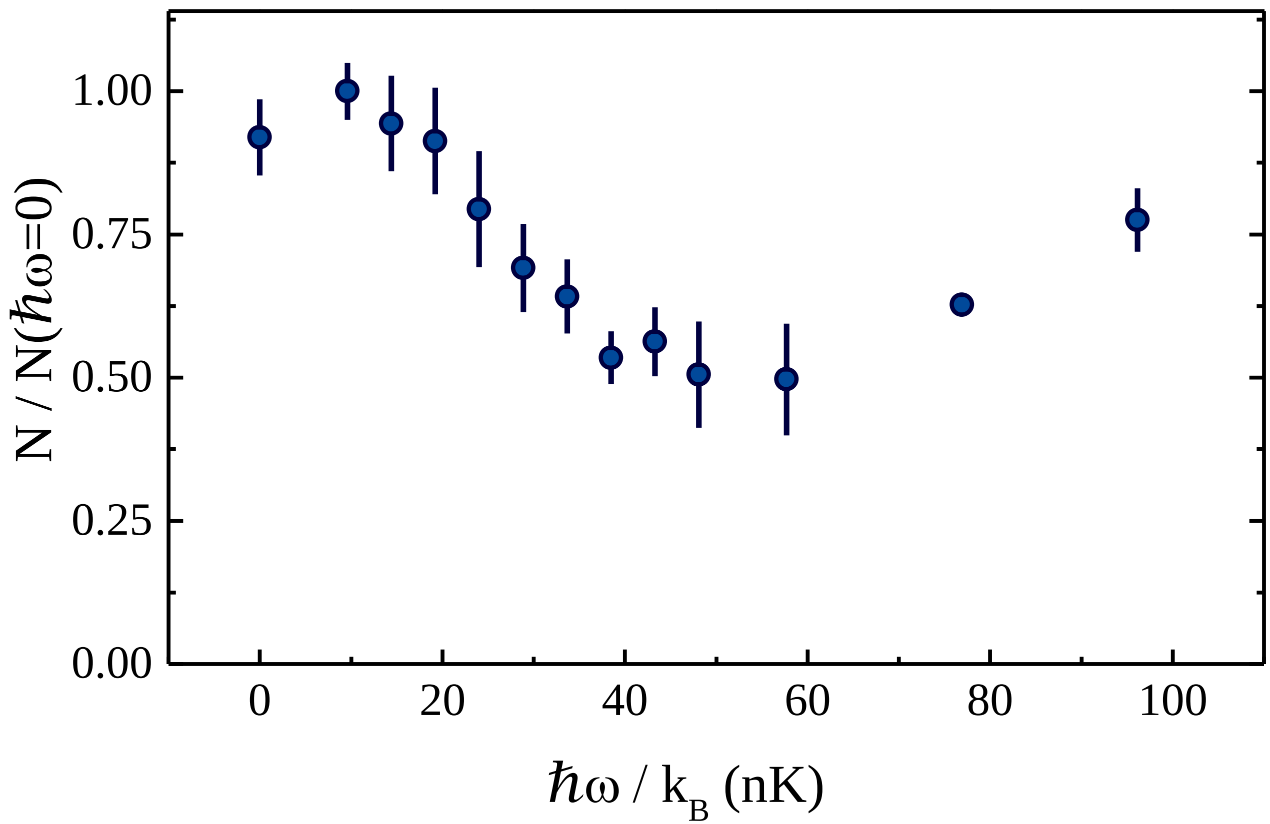
In the linear regime: $$P(\omega) \approx \sum_{i,f} f(E_i) \left|\langle f|\Delta(\mathbf{r})|i\rangle\right|^2 \delta(E_f - E_i - \hbar\omega)$$



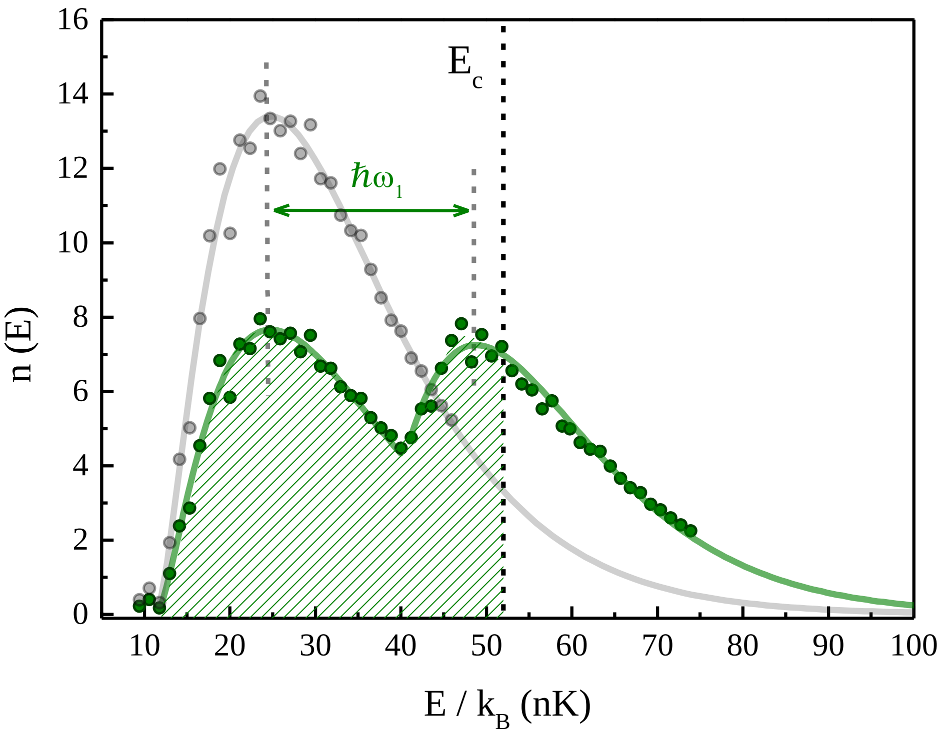
# Excitation spectroscopy




$$\Delta(\mathbf{r},t) = \Delta(\mathbf{r})(1 + A\cos(\omega t))$$



# Excitation spectroscopy



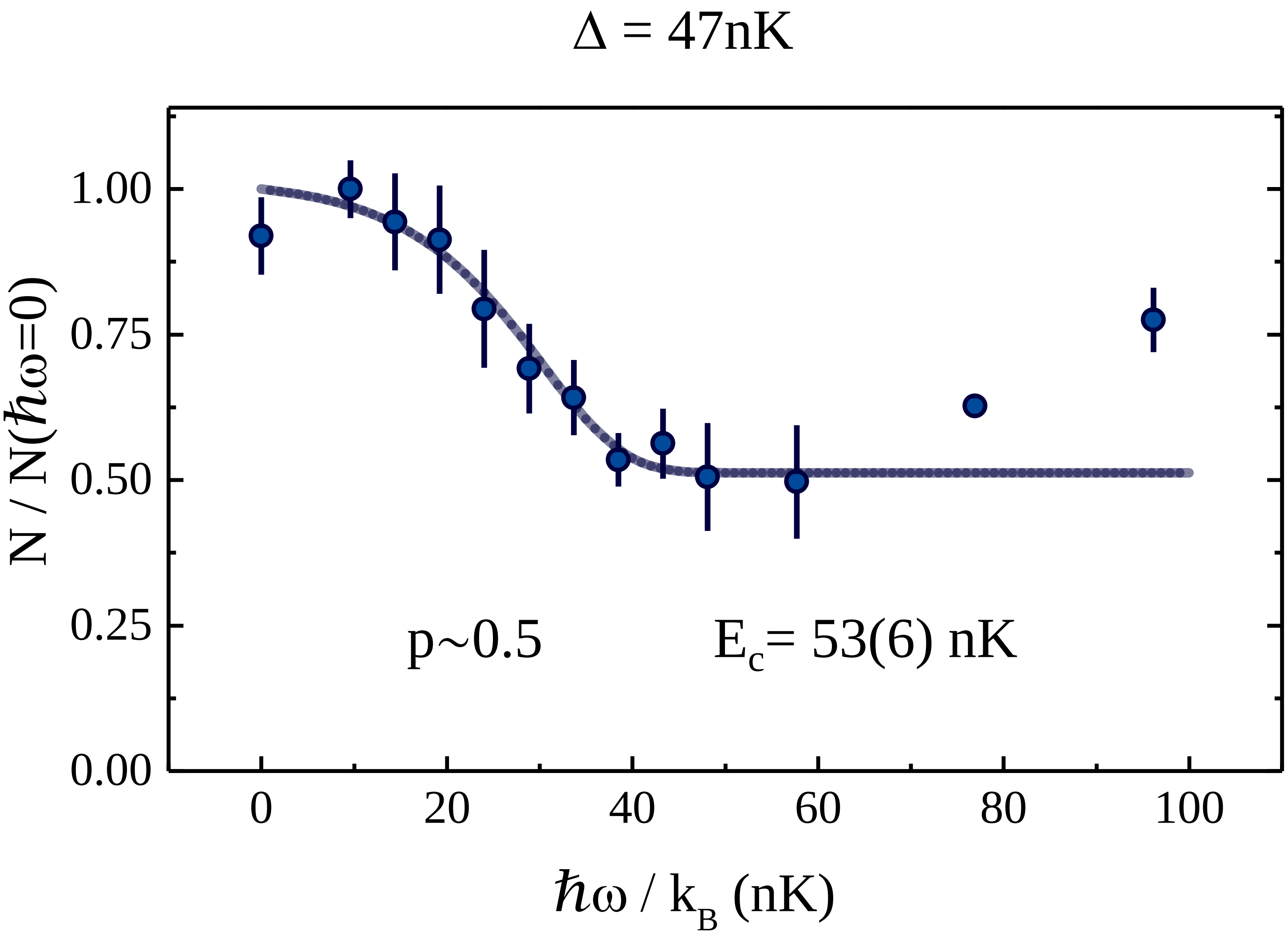

Fitting model for the mobility edge:

$$N(\omega) = \int_0^{E_c} n'(E,\omega)dE$$

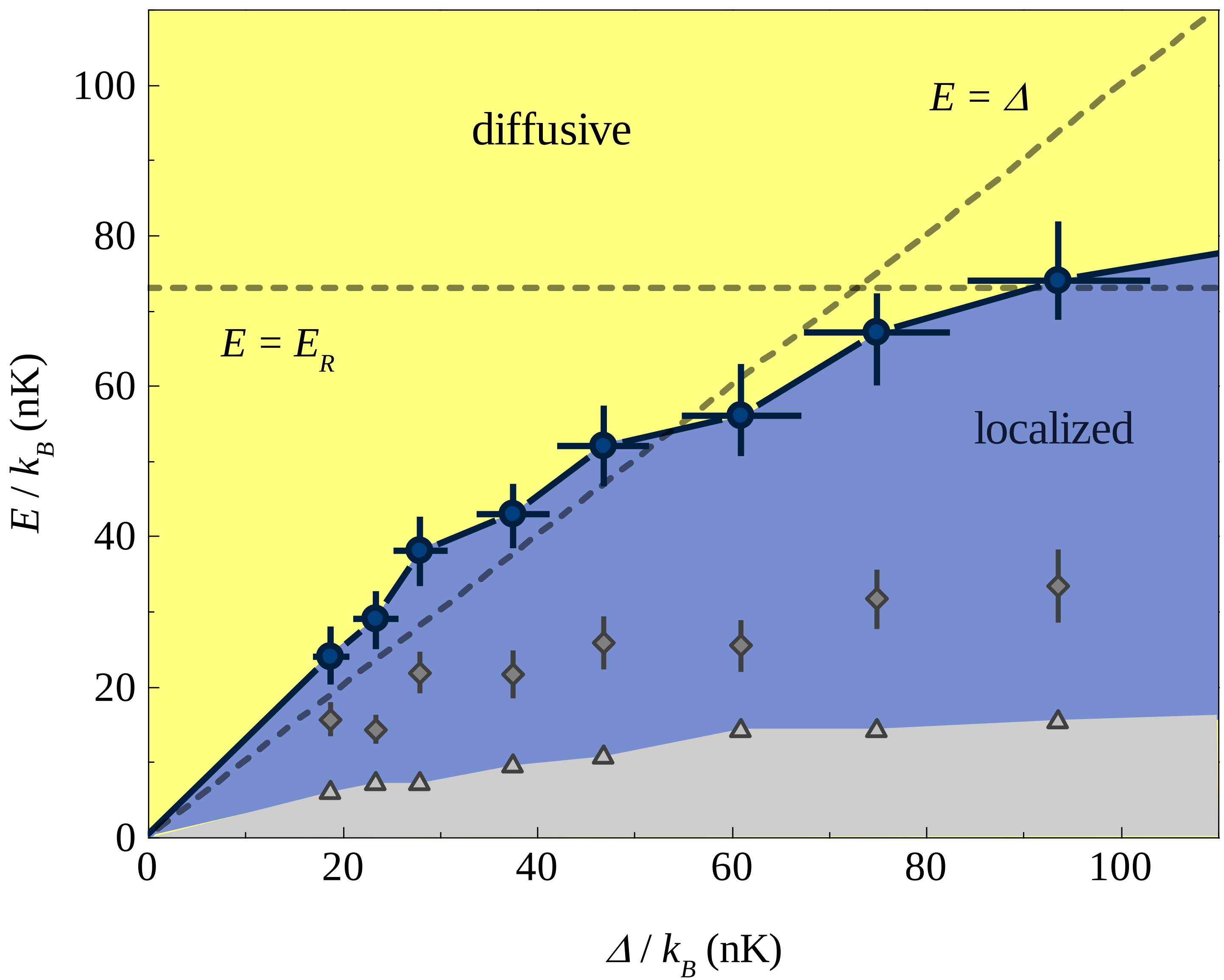
$$n'(E,\omega) = (1-p)n(E) + pn(E-\hbar\omega)$$

$p$ and $E_c$ are fitting parameters

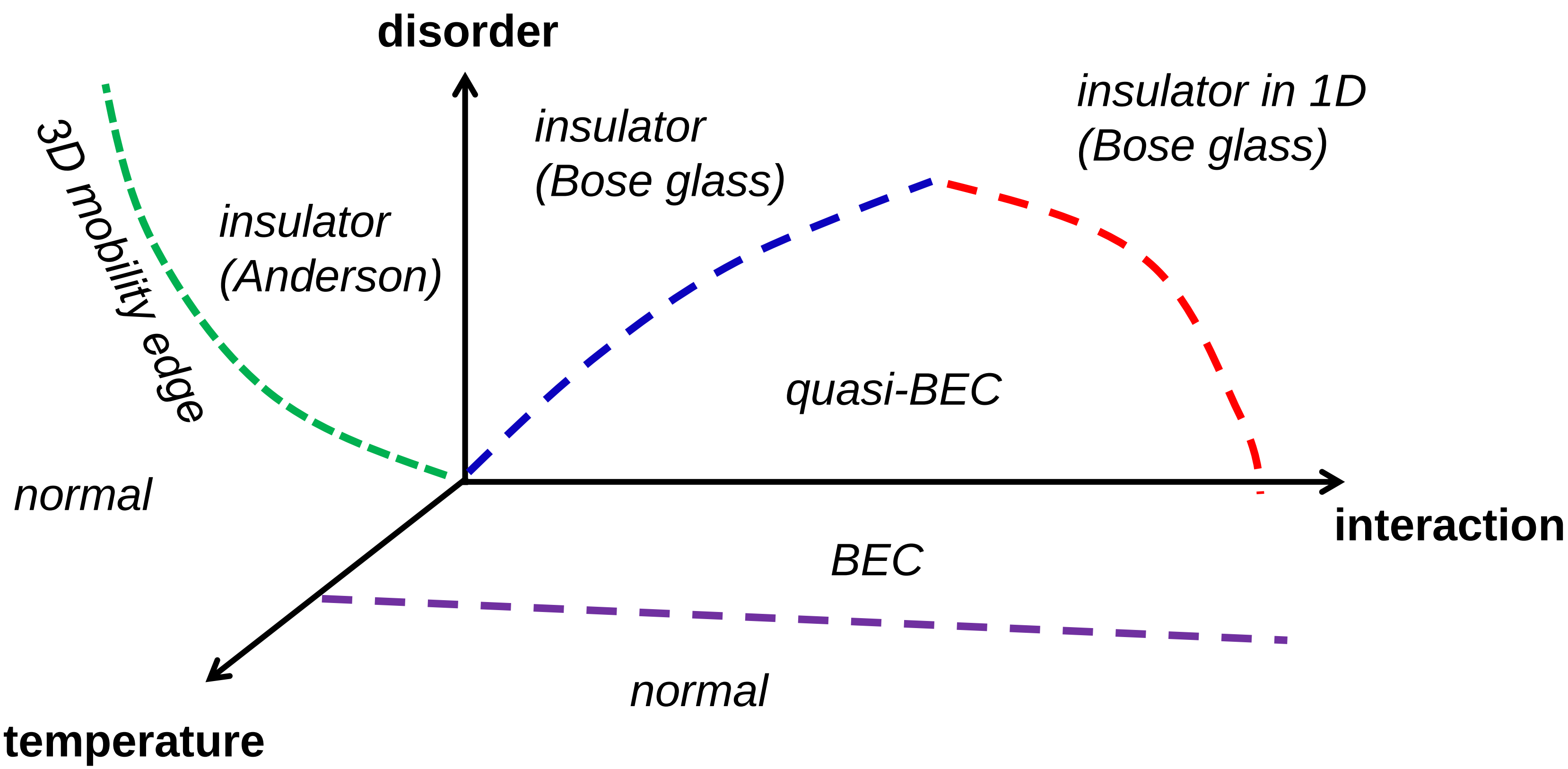
# Excitation spectroscopy



# The mobility edge



# Outlook




**Open questions**:

- Anderson localization with interactions: many-body localization?
- the Bose glass at finite temperature (without Mott physics)
- BEC in disorder

# The team

**One dimension:**

Chiara D'Errico

Eleonora Lucioni

Luca Tanzi

Lorenzo Gori

Avinash Kumar, Saptarishi Chaudhuri

**Theory:** Guillaume Roux, Ian Mc Culloch, Thierry Giamarchi

**Three dimensions:**

Manuele Landini

Giulia Semeghini

Patricia Castilho, Sanjukta Roy, Andreas Trenkwalder, Giacomo Spagnolli, Marco Fattori, Massimo Inguscio