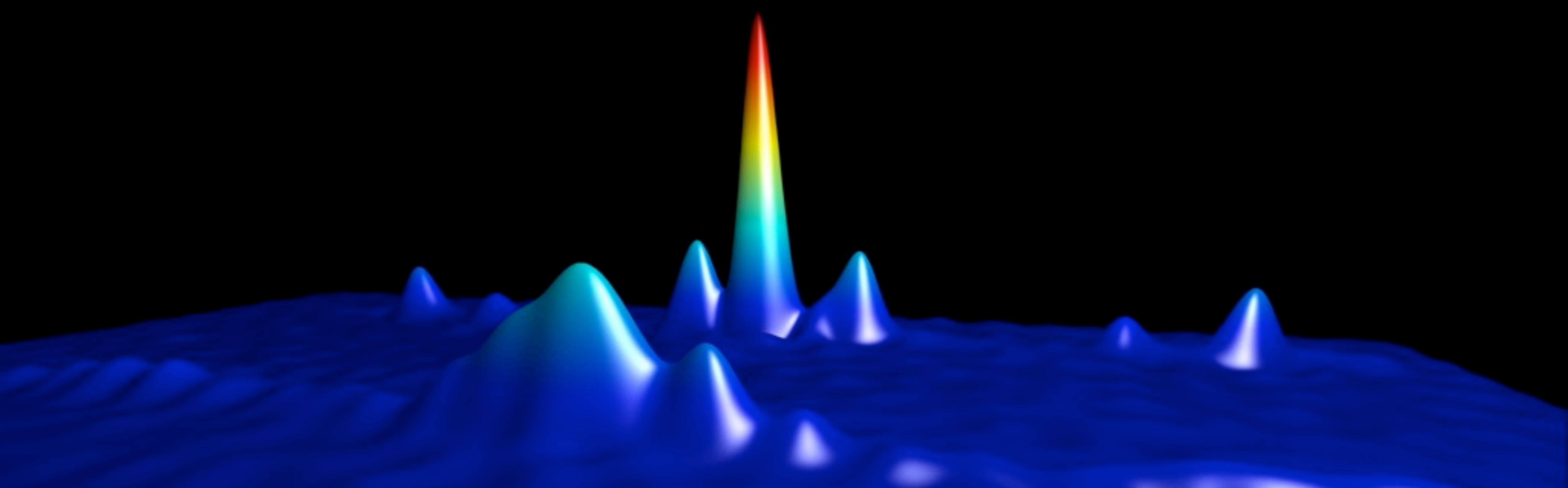
# A tunable Bose-Einstein condensate in disordered potentials



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University of Virginia

April 12th 2010

# People


Prof. Massimo Inguscio

Prof. Giovanni Modugno

Experiment:

Ben Deissler

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Matteo Zaccanti (Innsbruck, Grimm group)

Chiara D' Errico (MIT, Vuletic group)

Marco Fattori

Theory:

Prof. Michele Modugno (to Bilbao)

Franco Dalfovo (Trento)
Marco Larcher (Trento)

# Motivations

Ultracold atoms as quantum simulator ???

- Superfluidity: atomic BEC <-> Helium (critical velocity, vortices, QT regime, ...)
- Single order parameter: macroscopic coherence (interference, Josephson junctions..)
- Quantum Statistics at demand: Fermi & Bose systems
- Interactions at demand: weakly and strongly correlated regimes
- BCS-BEC crossover: connecting superfluidity and superconductivity
- Designing crystals with light: perfect lattices (Bloch oscillations, band insulators...)
- Implementing quantum hamiltonians: quantum phase transitions (Mott, Tonks, BKT, quantum magnetism)

YeS, atomic gases are a definitively nice tool for simulating nature...

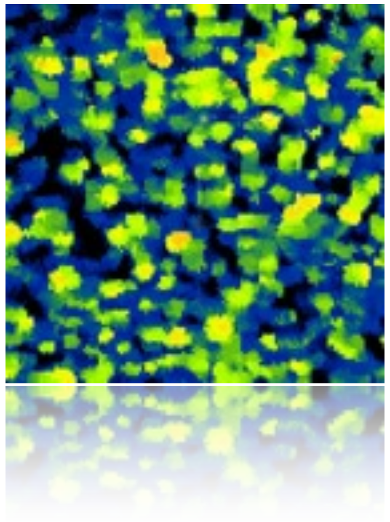
But, so far, only a pretty perfect nature....

An example:

Real crystals are not standing waves, so full of vacancies and impurities and of course electrons like to interact a lot

In fact, nature is not so perfect as we like to pretend...

Disorder is ubiquitous in nature, since nature is disordered !!!
And many phenomena depends critically by the presence of disorder.



High Tc granular superconductors (image from J. C. Davis, Berkeley USA)

*Journal of Low Temperature Physics, Vol. 87, Nos. 3/4, 1992*

**Superfluid Helium in Porous Media**

**John D. Reppy**

*Laboratory of Atomic and Solid State Physics and the Materials Science Center, Cornell University, Ithaca, New York*

The study of superfluid helium in porous media has a history dating from the time of the discovery of the phenomenon of superfluidity itself.

PHYSICAL REVIEW VOLUME 109, NUMBER 5 MARCH 1, 1958

**Absence of Diffusion in Certain Random Lattices**

P. W. ANDERSON
*Bell Telephone Laboratories, Murray Hill, New Jersey*

(Received October 10, 1957)

This paper presents a simple model for such processes as spin diffusion or conduction in the "impurity band." These processes involve transport in a lattice which is in some sense random, and in them diffusion is expected to take place via quantum jumps between localized sites. In this simple model the essential randomness is introduced by requiring the energy to vary randomly from site to site. It is shown that at low enough densities no diffusion at all can take place, and the criteria for transport to occur are given.

$$H=-\sum_{\langle i,j\rangle} J_{ij}\hat{b}_i^{\dagger}\hat{b}_j + \sum_j \epsilon_j n_j$$

- Anderson model: weakly interacting electrons hopping on a lattice with random on-site energies
- Single particle tight binding model with random on-site energies
- The eigenstates are spatially localized with exponentially decreasing tails.

- localization of waves in a random medium

- extended states become localized in the presence of disorder

- general phenomenon, from condensed matter (electrons)...
Kramer & MacKinnon, Localization: theory and experiment, Rep. Prog. Phys. 56, 1469–1564 (1993).
Lee & Ramakrishnan, Rev. Mod. Phys. 57, 287 (1985)

...to:

- light waves

D.S. Wiersma et al, Localization of light in a disordered medium, Nature 390, 671-673 (1997).
F. Scheffold et al, Localization or classical diffusion of light?, Nature 398, 206-270 (1999).
M. Störzer et al, Observation of the critical regime near Anderson localization of light, Phys. Rev. Lett. 96, 063904 (2006).
T. Schwartz et al, Transport and Anderson localization in disordered twodimensional photonic lattices, Nature 446, 52-55 (2007).
Y. Lahini et al, Anderson Localization and Nonlinearity in One-Dimensional Disordered Photonic Lattices, Phys. Rev. Lett. 100, 01390 (2008).

- microwaves

R. Dalichaouch et al, Microwave localization by 2-dimensional random scattering, Nature 354, 53-55 (1991).
A. A. Chabanov et al, Statistical signatures of photon localization, Nature 404, 850-853 (2000).

- sound waves

R.L Weaver, Anderson localization of ultrasound, Wave Motion 12, 129-142 (1990).

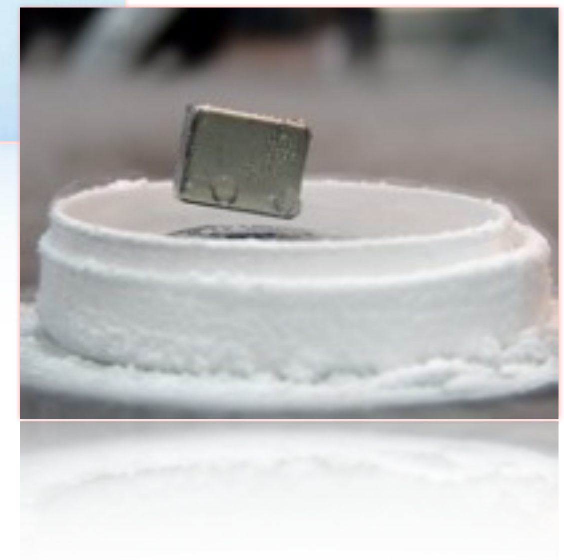
- matter waves (BECs)

J. Billy et al., Direct observation of Anderson localization of matter waves in a controlled disorder, Nature 453, 891 (2008).
G. Roati el al., Anderson localization of a non-interacting Bose-Einstein condensate, Nature 453, 895 (2008).

Still, this is an "approximate" model: in fact electrons are highly interacting quantum objects!

..and many phenomena, as superfluidity and superconductivity, rely on the interactions between the particles.

-> interactions vs disorder



nature Vol 449|18 October 2007|doi:10.1038/nature06180

LETTERS

**Nature of the superconductor–insulator transition in disordered superconductors**

Yonatan Dubi[1], Yigal Meir[1,2] & Yshai Avishai[1,2]

LETTERS

Strong correlations make high-temperature superconductors robust against disorder

ARTI GARG[1,2], MOHIT RANDERIA[3] AND NANDINI TRIVEDI[3]*
[1]Physics Department, Technion - Israel Institute of Technology, Haifa - 32000, Israel
[2]Department of Theoretical Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India
[3]Department of Physics, The Ohio State University, Physics Research Building, 191 W. Woodruff Avenue, Columbus, Ohio 43210, USA
*e-mail: trivedi.15@osu.edu

VOLUME 61, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1988

**Onset of Superfluidity in Random Media**

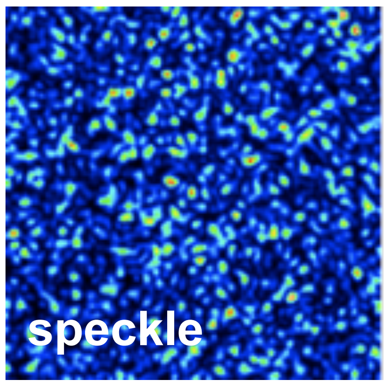
Daniel S. Fisher
*Joseph Henry Laboratories of Physics, Jadwin Hall, Princeton University, Princeton, New Jersey 08544*

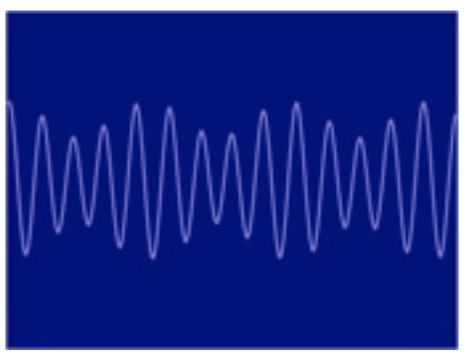
Matthew P. A. Fisher
*IBM Research Division, Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598*

(Received 25 May 1988)

Despite many efforts, the interplay between interactions and disorder remains a challenging task (very difficult to control interactions and disorder at will!!)

## ¿ Quantum gases: quantum simulators ?




J. E. Lye et al. PRL **95**, 070401 (2005)
D. Clément et al. PRL **95** 170409 (2005)
C. Fort et al. PRL **95**, 170410 (2005)
T. Schulte et al. PRL **95**, 170411 (2005)

J. Billy et al., Nature **453**, 891 (2008)

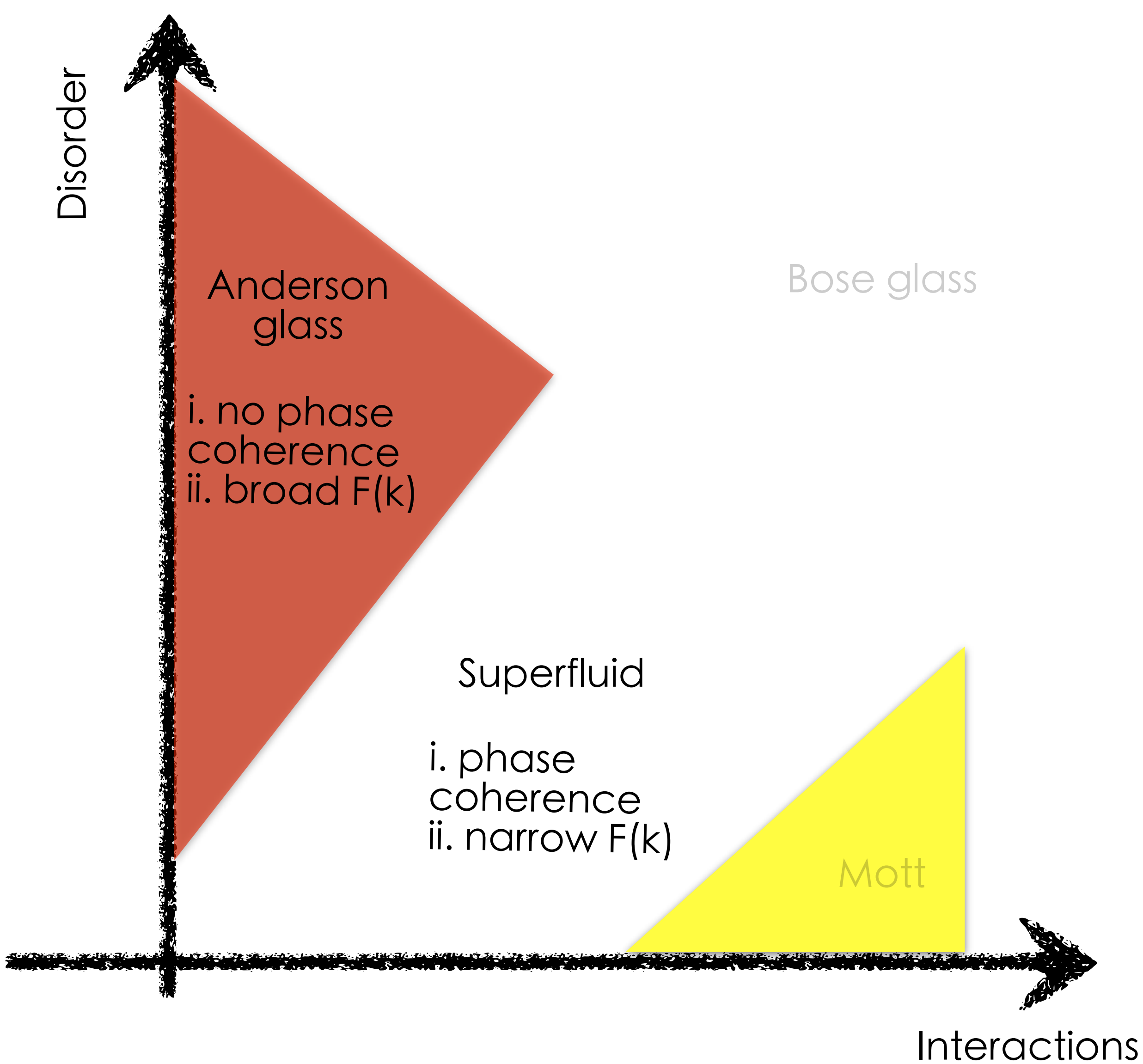
G. Roati et al. Nature 453, 895,898 (2008)

Yong P. Chen, J. Hitchcock, D. Dries, M. Junker, C. Welford, and R. G. Hulet, Phys. Rev. A 77, 033632 (2008)

M. White, M. Pasienski, D. McKay, S. Q. Zhou, D. Ceperley, and B. DeMarco, Phys. Rev. Lett. 102, 055301 (2009)

Our approach is to use a tunable BEC trapped into disordered potentials:

- ☑ BEC into an optical trap
- ☑ Transfer into a fully controllable disordered quasi-periodic lattice
- ☑ Manipulating the scattering length between the atoms (disorder vs interactions)
- ☑ Mapping out the condensate wave-function with and w/o disorder

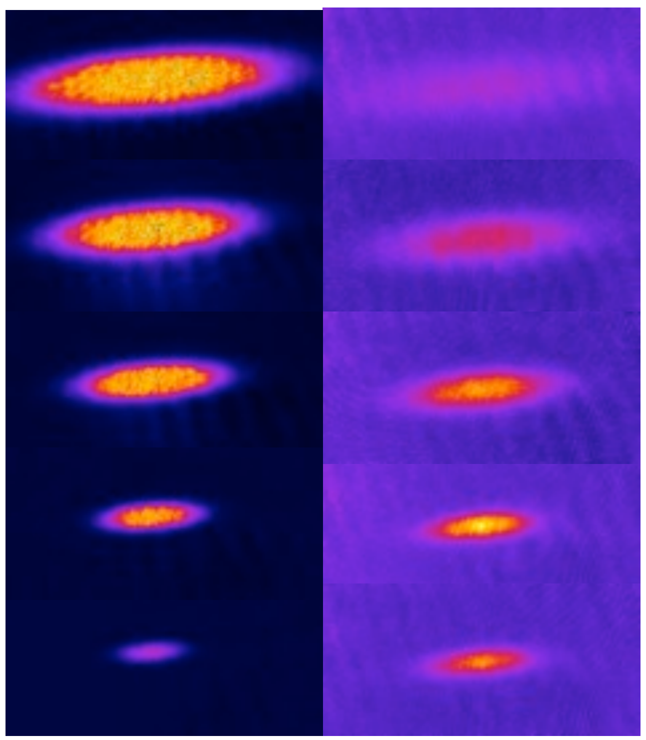



- ☑ A tunable 39 Potassium BEC
- ☑ Our disordered potential: the bichromatic lattice
- ☑ One word on the non-interacting, system: observing Anderson localization.
- ☑ From an uncorrelated glass to a coherent state

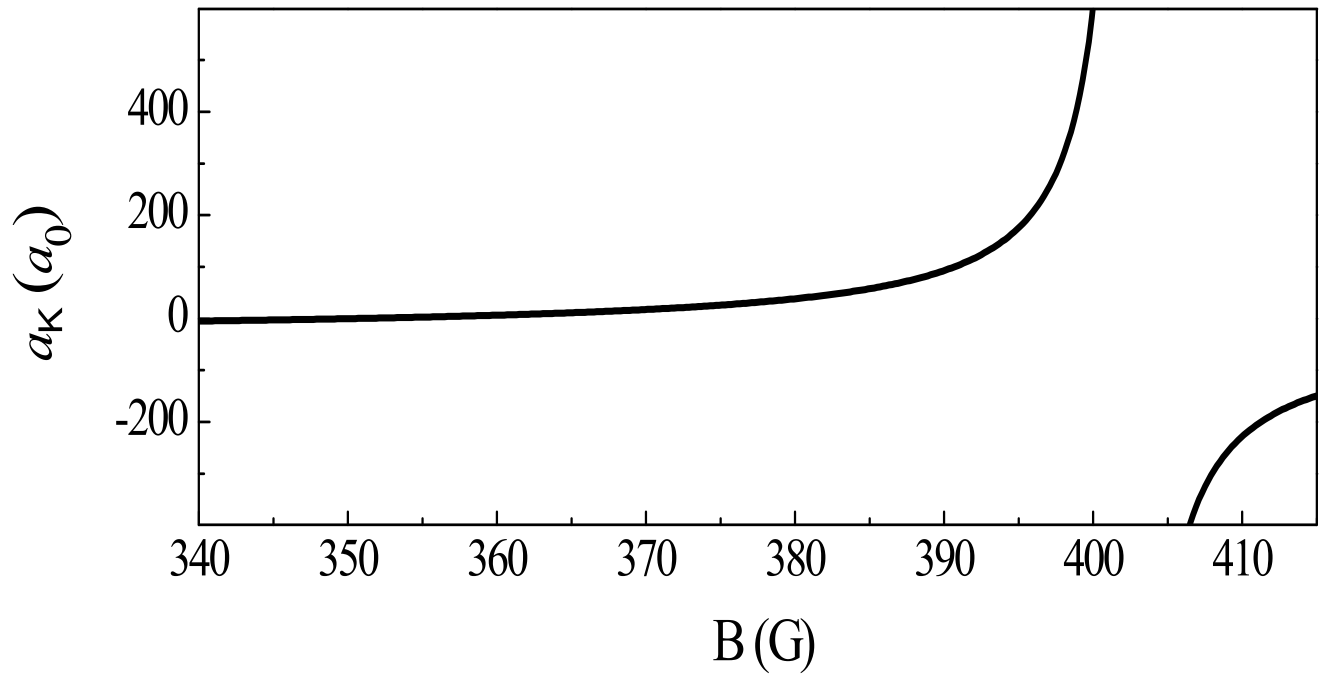
# Cooling potassium to BEC

Sympathetic cooling of $^{39}$K-$^{87}$Rb:

rubidium potassium



BEC of 100000 atoms below 50 nK



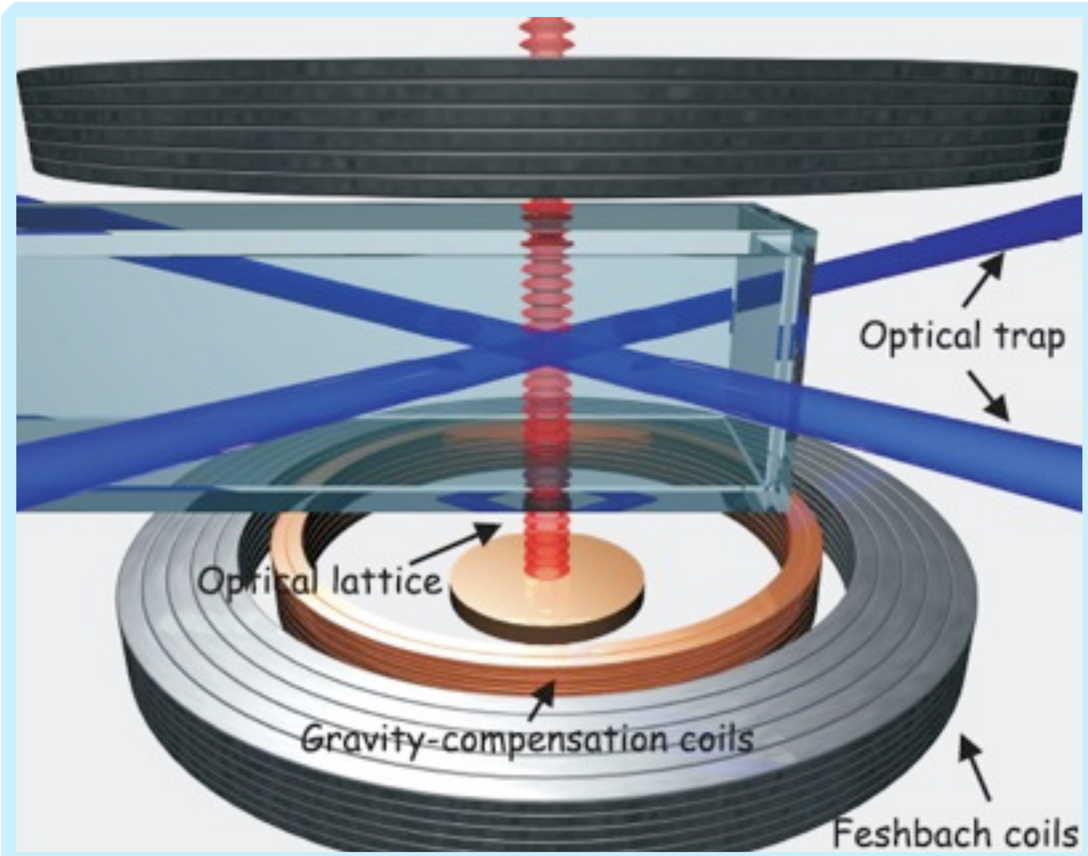

Tuning the interactions via a magnetic Feshbach resonance in a potassium condensate ($^{39}$K)

Feshbach tuning of the interactions (mag. field stability 50 mG -> 0.03 $a_0$ !!)

U < $10^{-4}$ J


G. Modugno, et al. Science 294, 1320 (2001)

G. Roati, et al. PRL 89, 150403 (2002)
G. Roati et al. PRL 99, 010403 (2007)



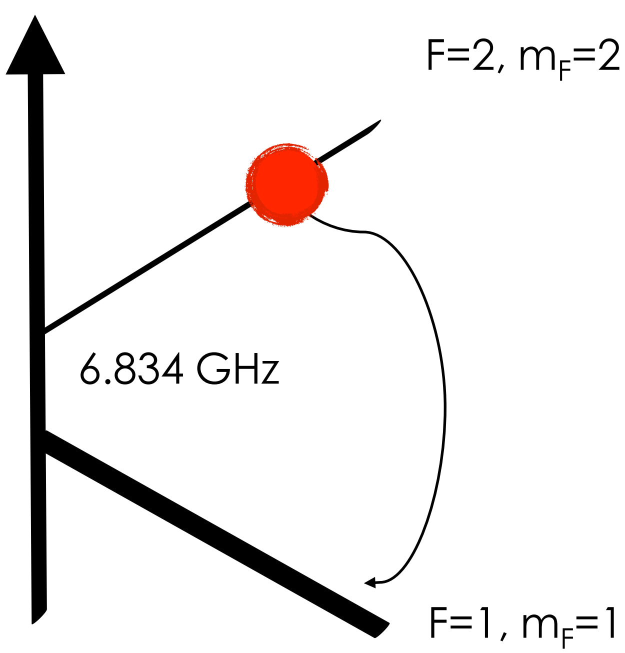

Evaporative+sympathetic cooling in a magnetic trap down to $T \sim 1 \mu K$

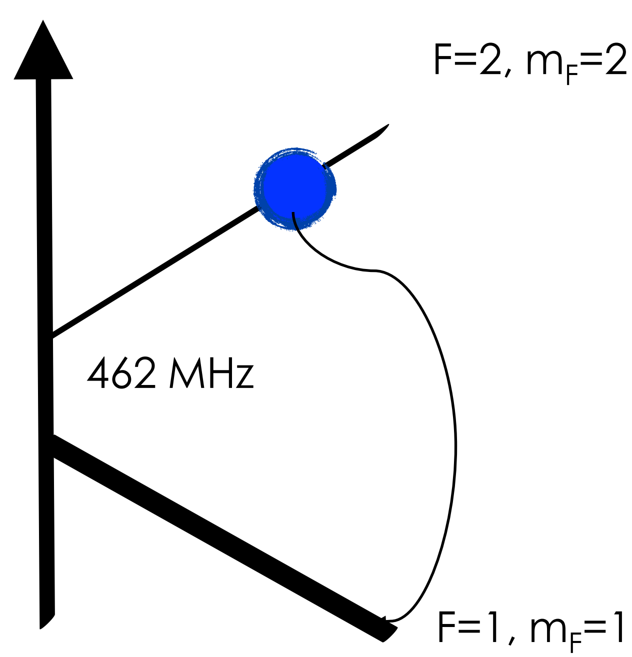
Loading in a crossed beam dipole trap at $\lambda$=1030 nm, P=10 W.

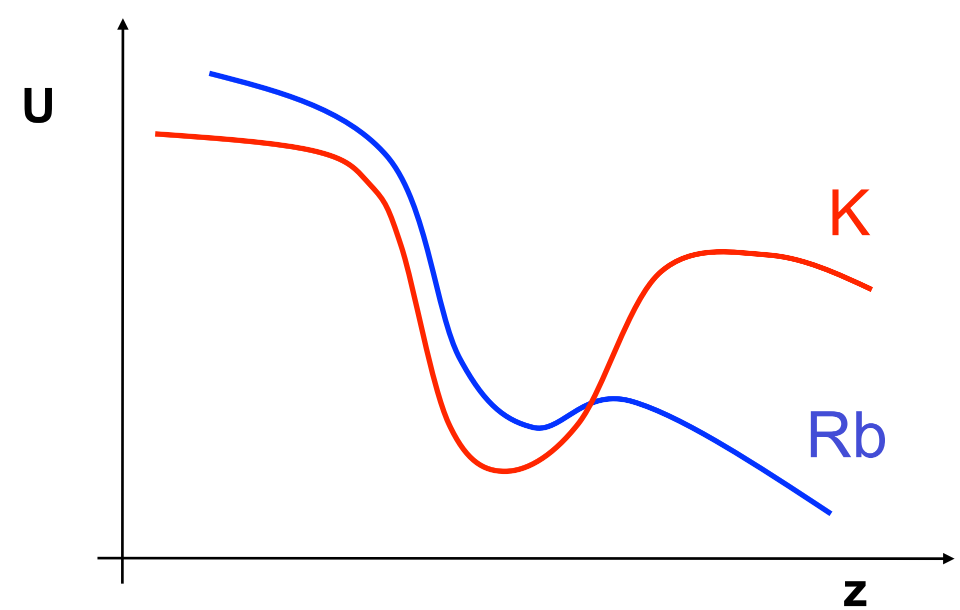
$N_{Rb} \cong 1.5 \times 10^6$ and $N_K \cong 6 \times 10^5$ atoms @1.8 μK

Selective evaporation in the dipole trap

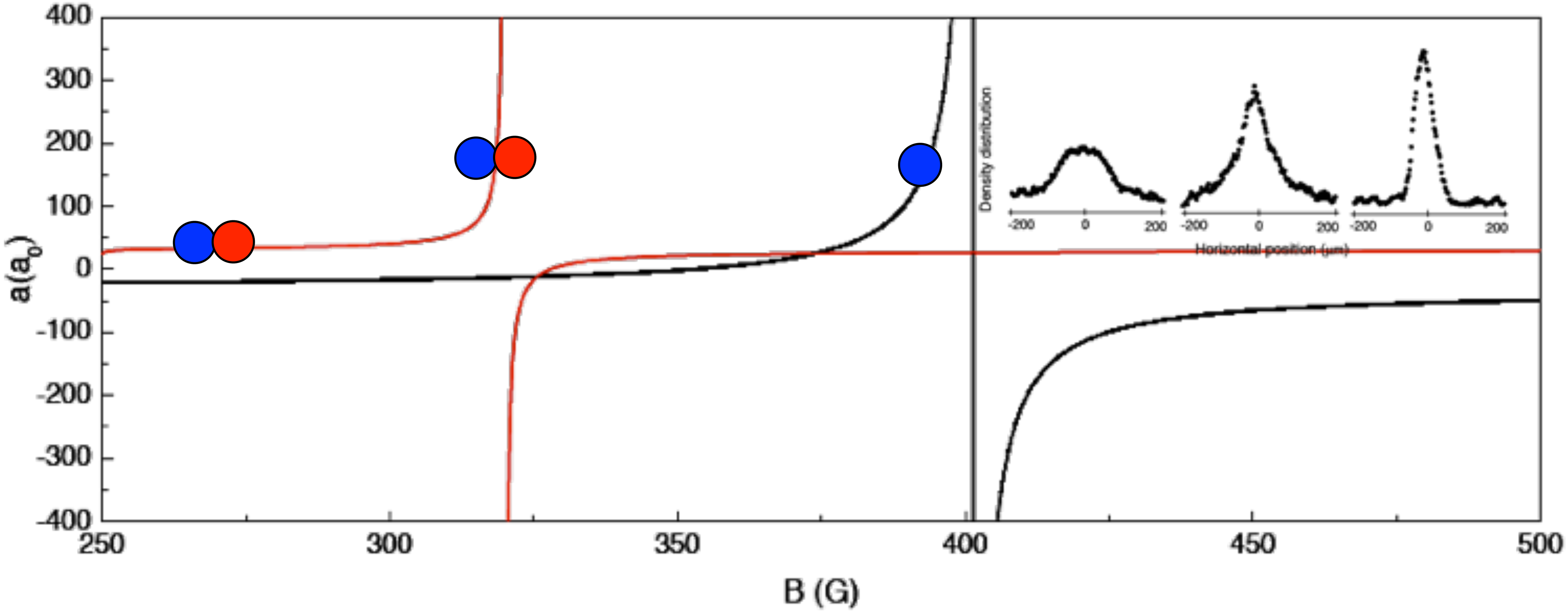
Homogeneous magnetic field: B ~0-1000 G, $dI/I < 10^{-4}$

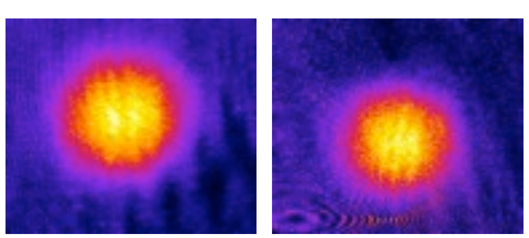


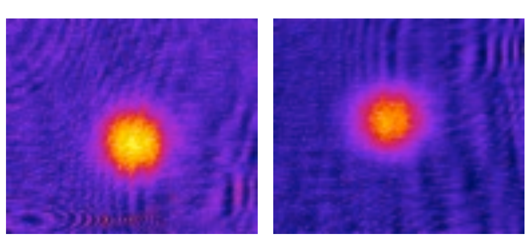



# Potassium BEC



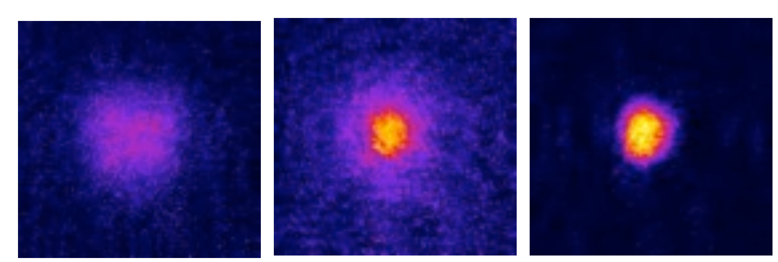



Rb K



Rb K

$^{39}$K BEC



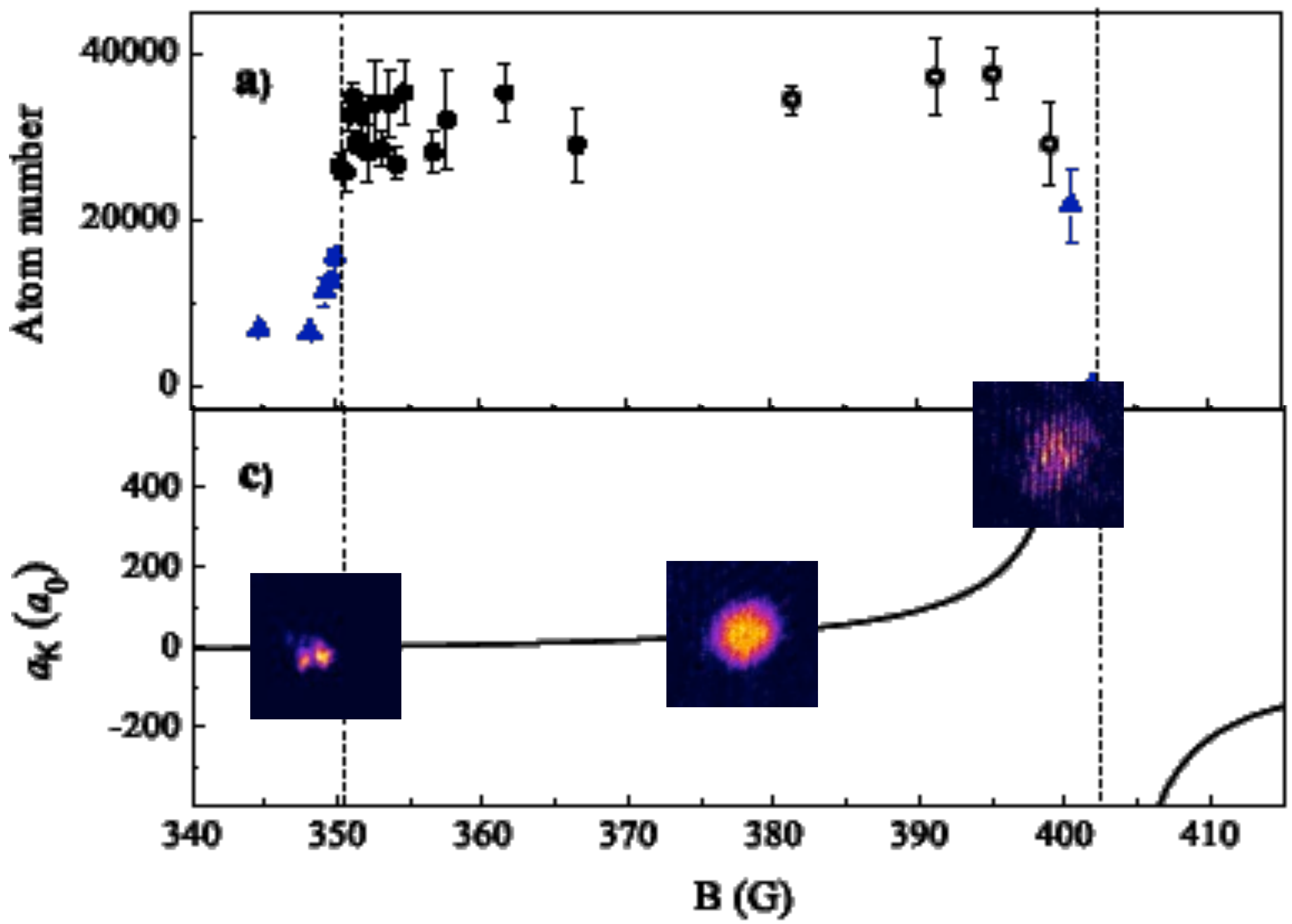
T=1.8 μK
$N_K=6\times10^5$
$a_{kRb}=28\ a_0$
$a_{kK}=-33\ a_0$

T=0.25 μK
$N_K=3.4\times10^5$
$a_{kRb}=150\ a_0$
$a_{kK}=-33\ a_0$

$T_c=0.10$ μK
$N_K=1\times10^5$
$a_{kK}=180\ a_0$

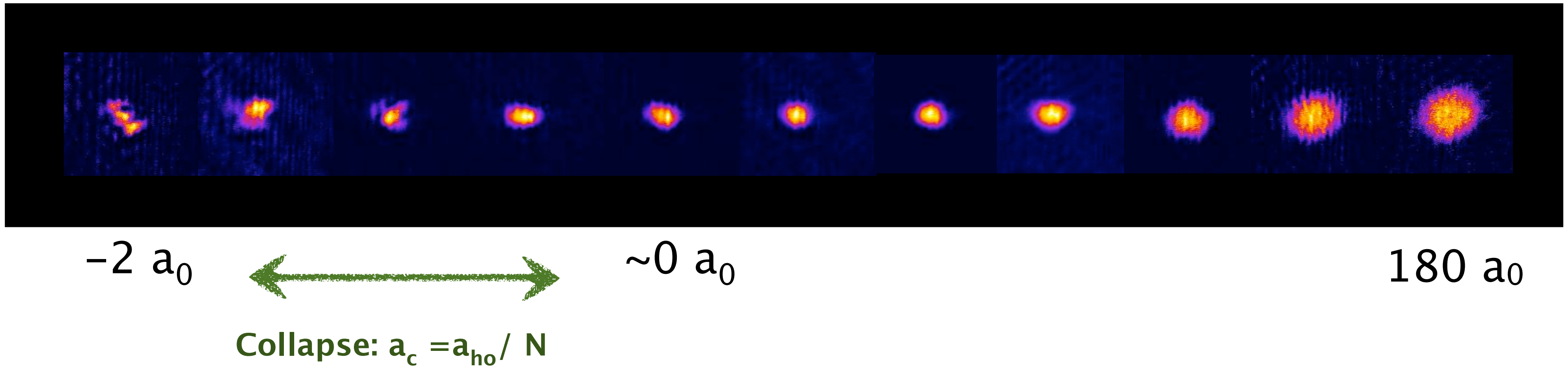
G. Roati et al. PRL 99,010403 (2007)

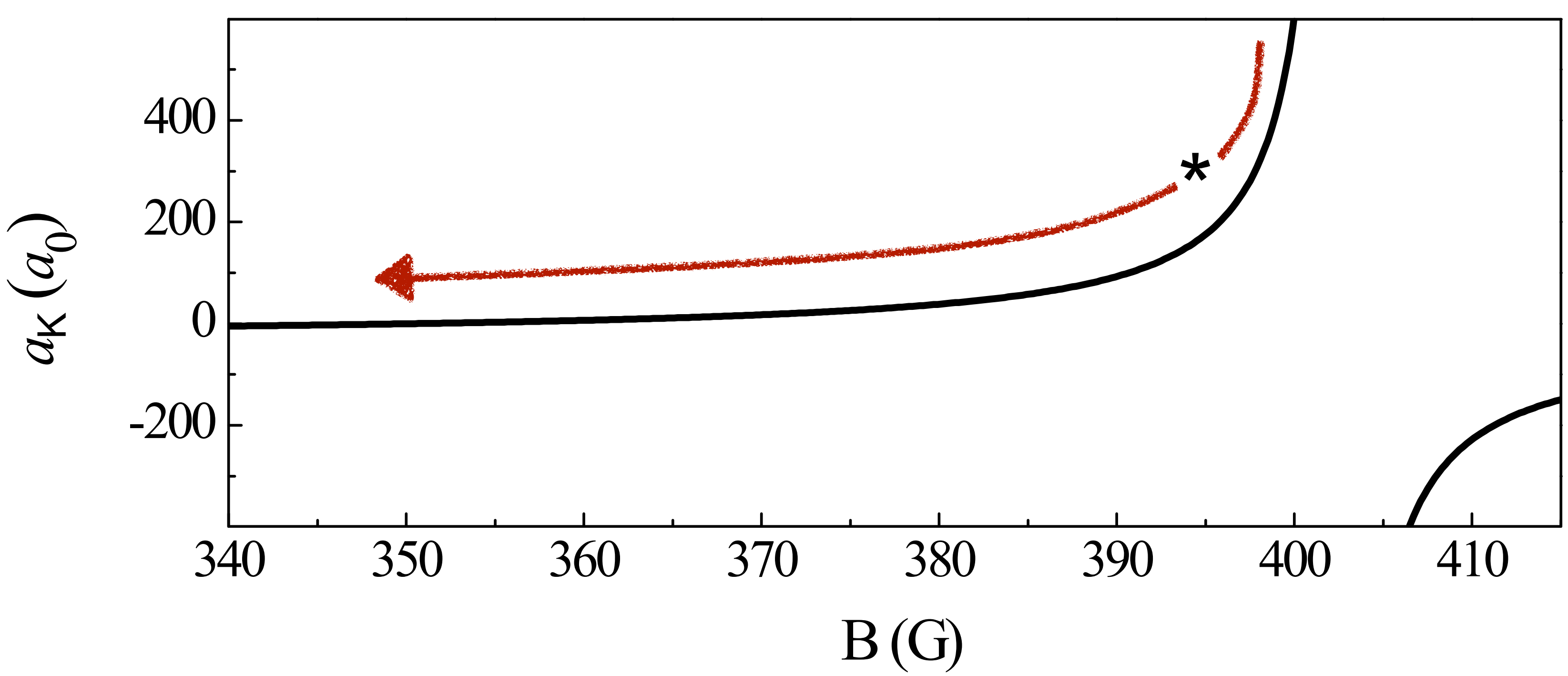
# Tuning the interactions



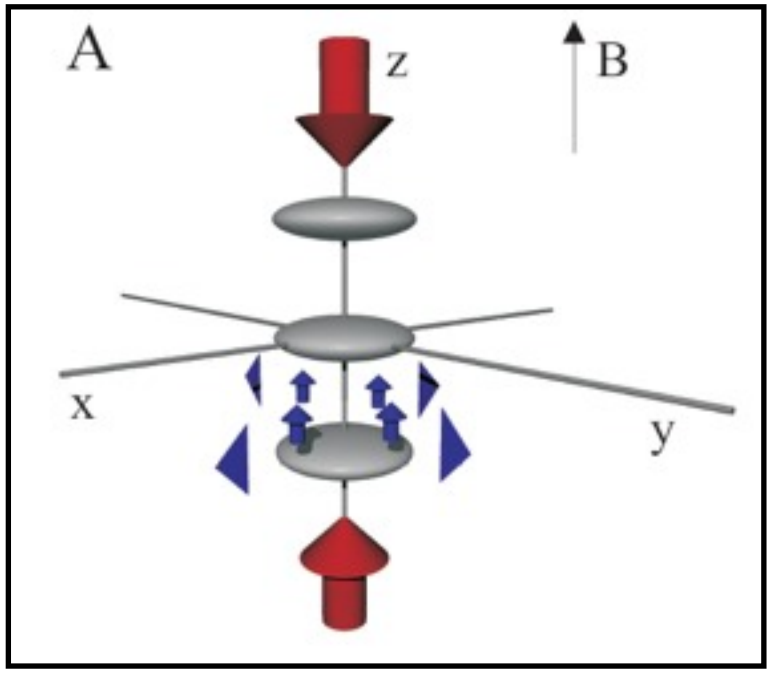

- B > 398.5 G -> 3-body losses due to Feshabach resonance: $K_3 \propto a^4$
- 350.2 G <B<398.5 G -> stable BEC with tunable positive interactions
- B < 350.2 G -> BEC with negative interactions

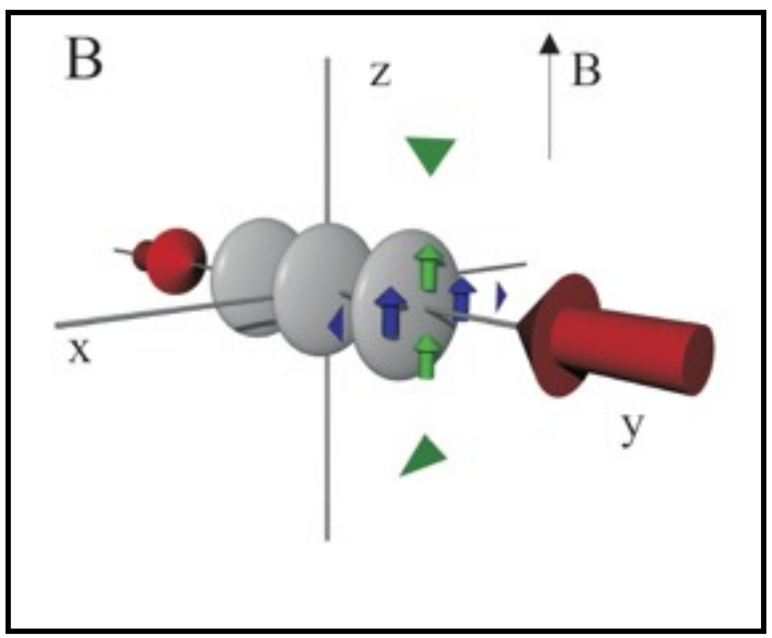
Stable BEC with negative interactions (N,a)
Collapse: $a_c = a_{ho}/ N$

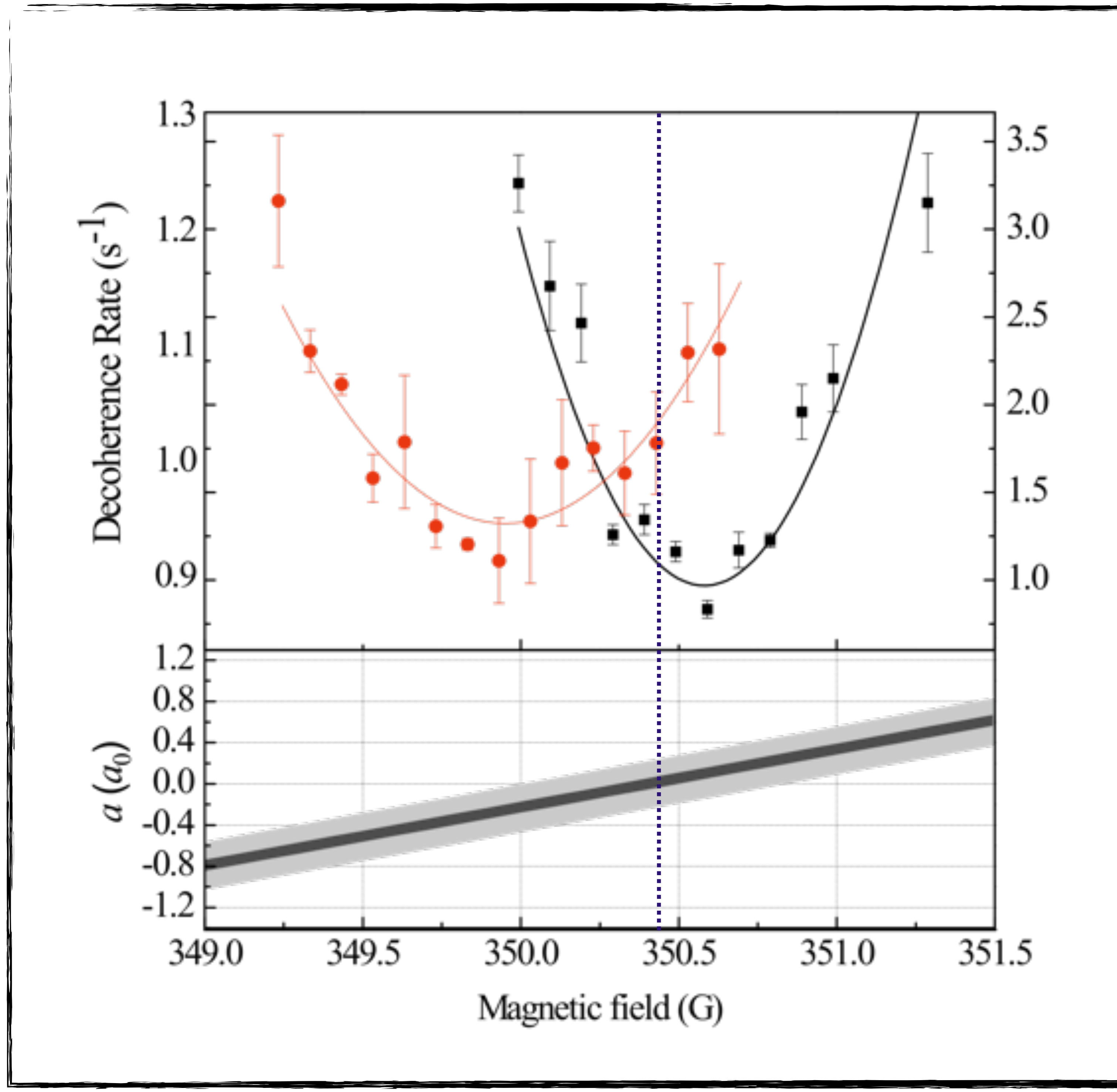



$a_K$=0 -> ground state of the harmonic oscillator, $E_{rel}$ pure kinetic energy $a_{ho} = \sqrt{\dfrac{\hbar}{m\varpi}} = 1.84\ \mu\text{m}$




Observation of the dipolar interactions in 39K

M. Fattori et al. Phys. Rev. Lett. 101, 190405 (2008)
M. Vengalattore, S. R. Leslie, J. Guzman, and D. M. Stamper-Kurn Phys. Rev. Lett. 100, 170403 (2008)
S. E. Pollack, et al. Phys. Rev. Lett. 102, 090402 (2009)

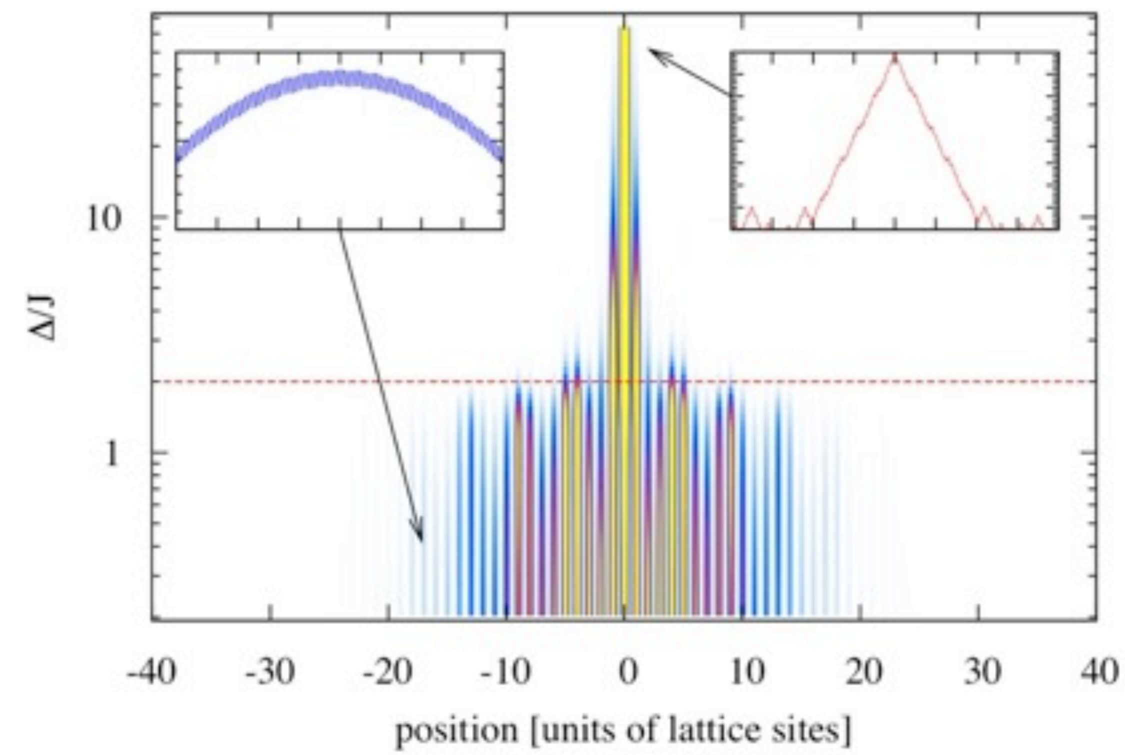
# Quasi-periodic lattice(a=0)

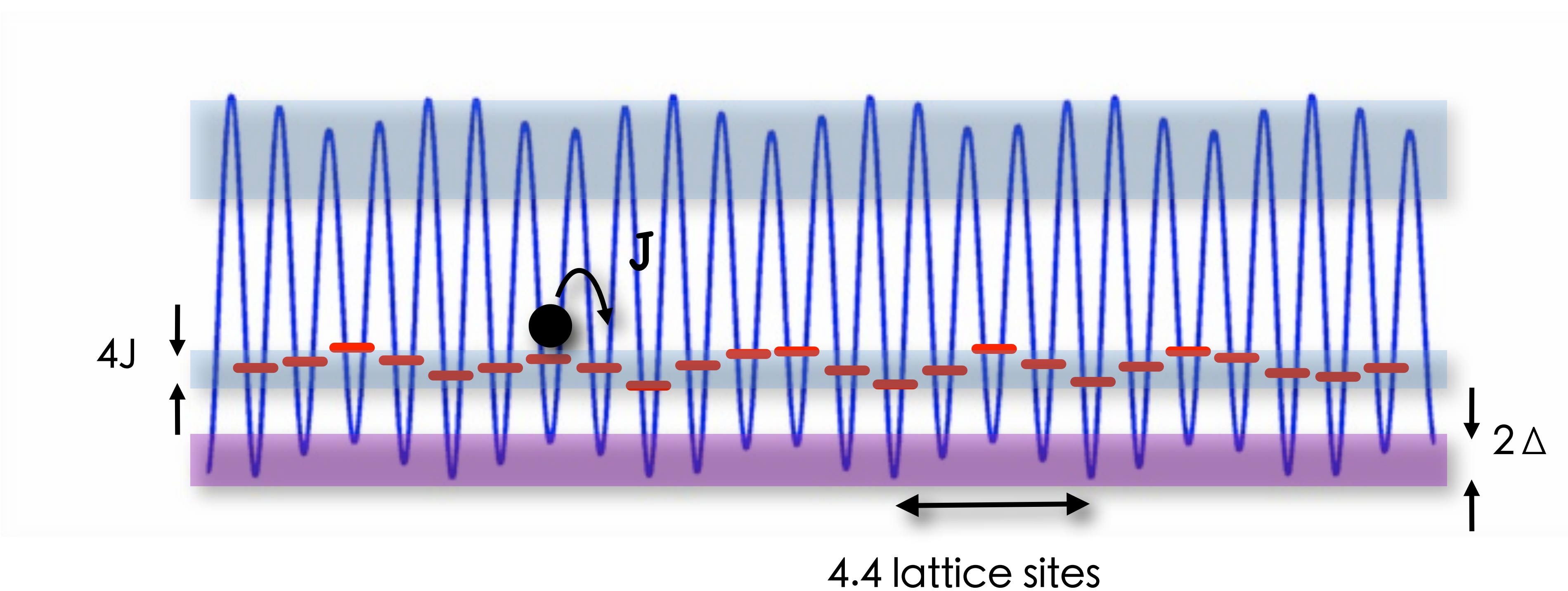
S. Aubry and G. André, Ann. Israel Phys. Soc. 3, 133 (1980).

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

Metal-insulator (exp. localized) transition even in with 1D disorder for $\Delta_C = 2$ J

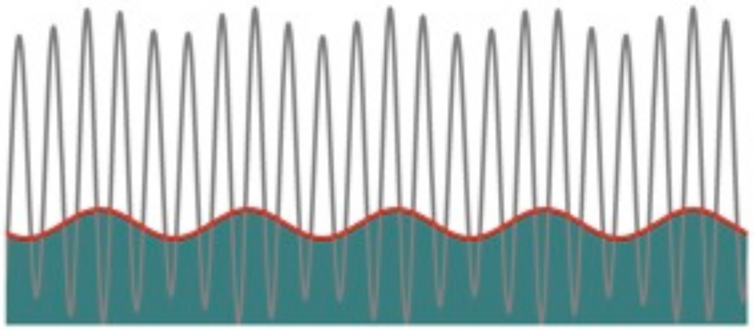
The competition between J (main lattice) and Δ (disorder) defines the physics

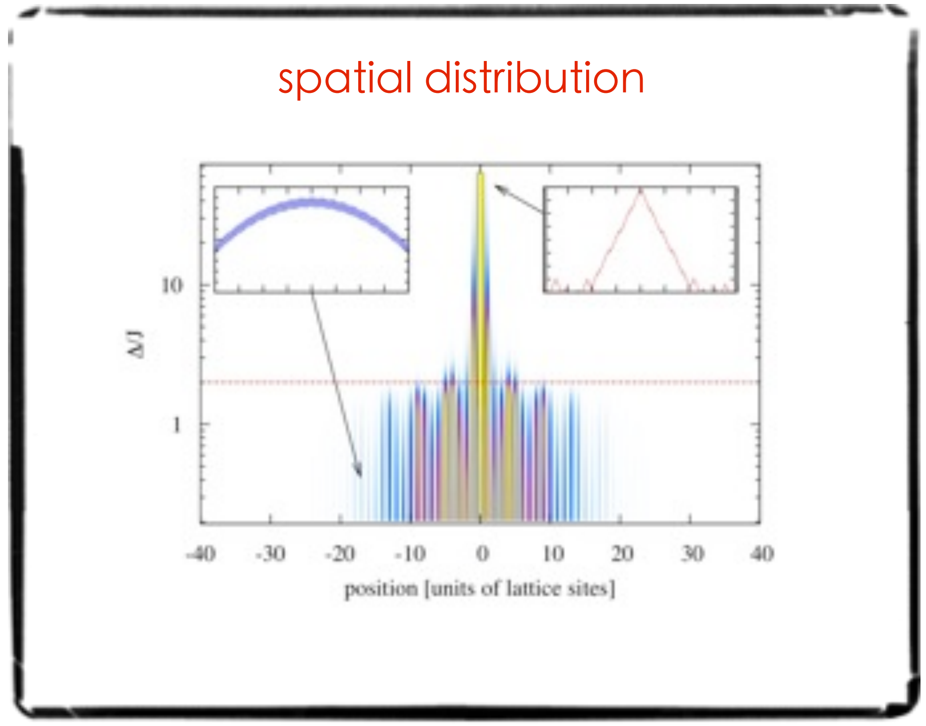


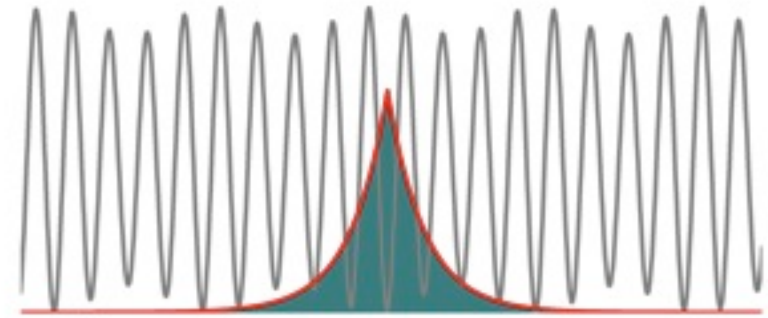




λ1 = 1064.42 nm
λ2 = 866.3 nm

G. Roati et al. Nature 453, 895, 898 (2008)

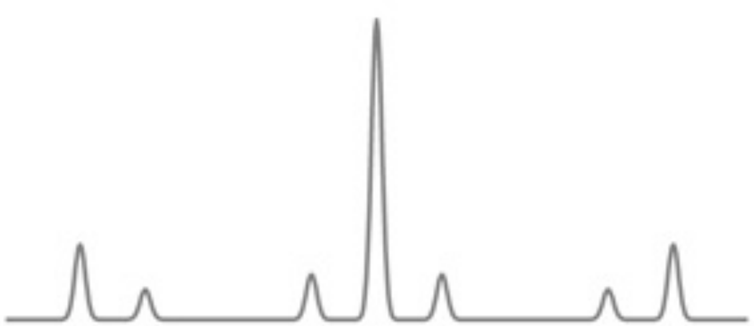


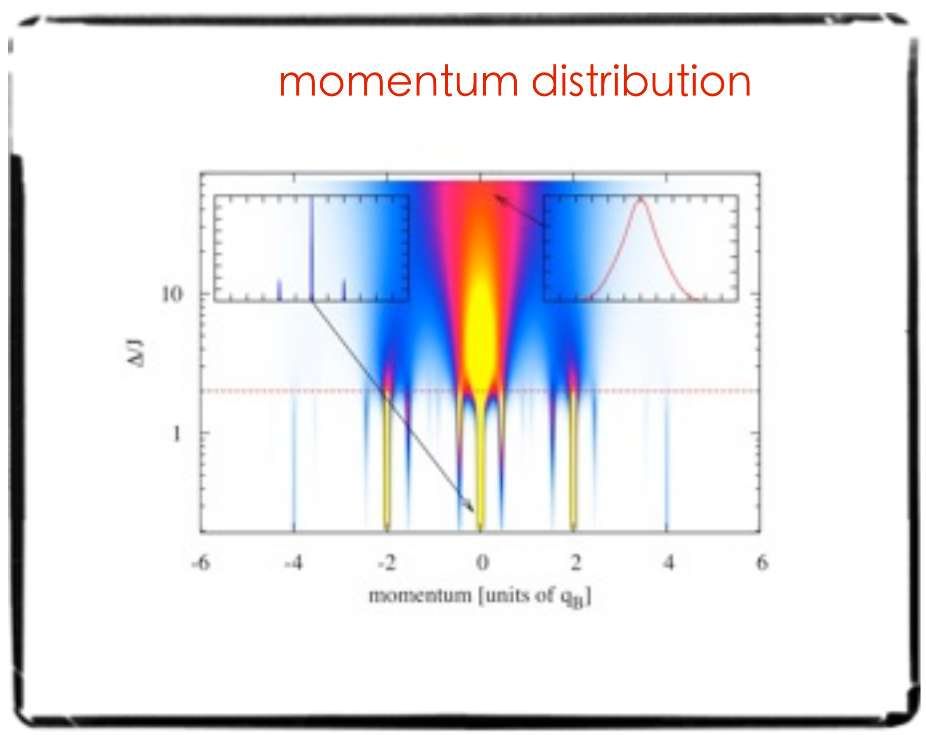


Extended states

Localized states

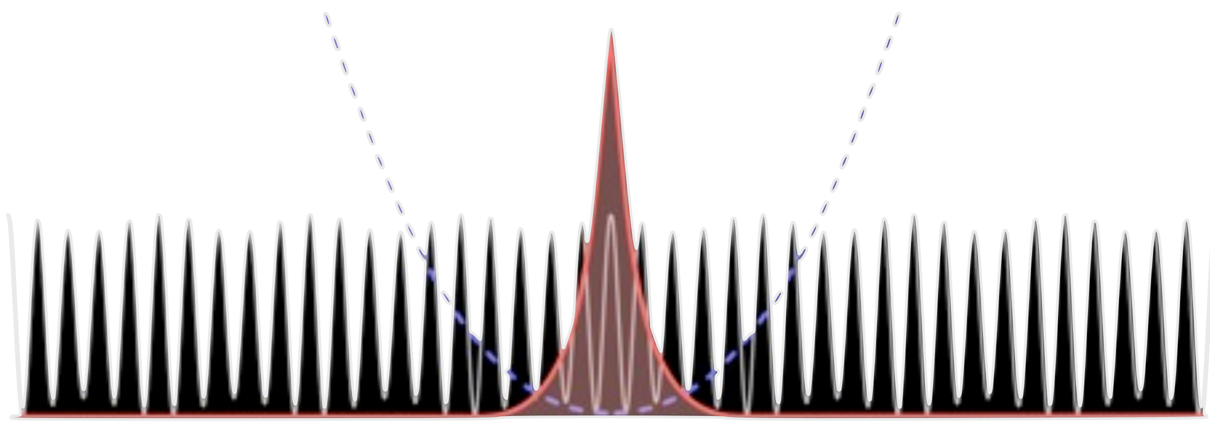




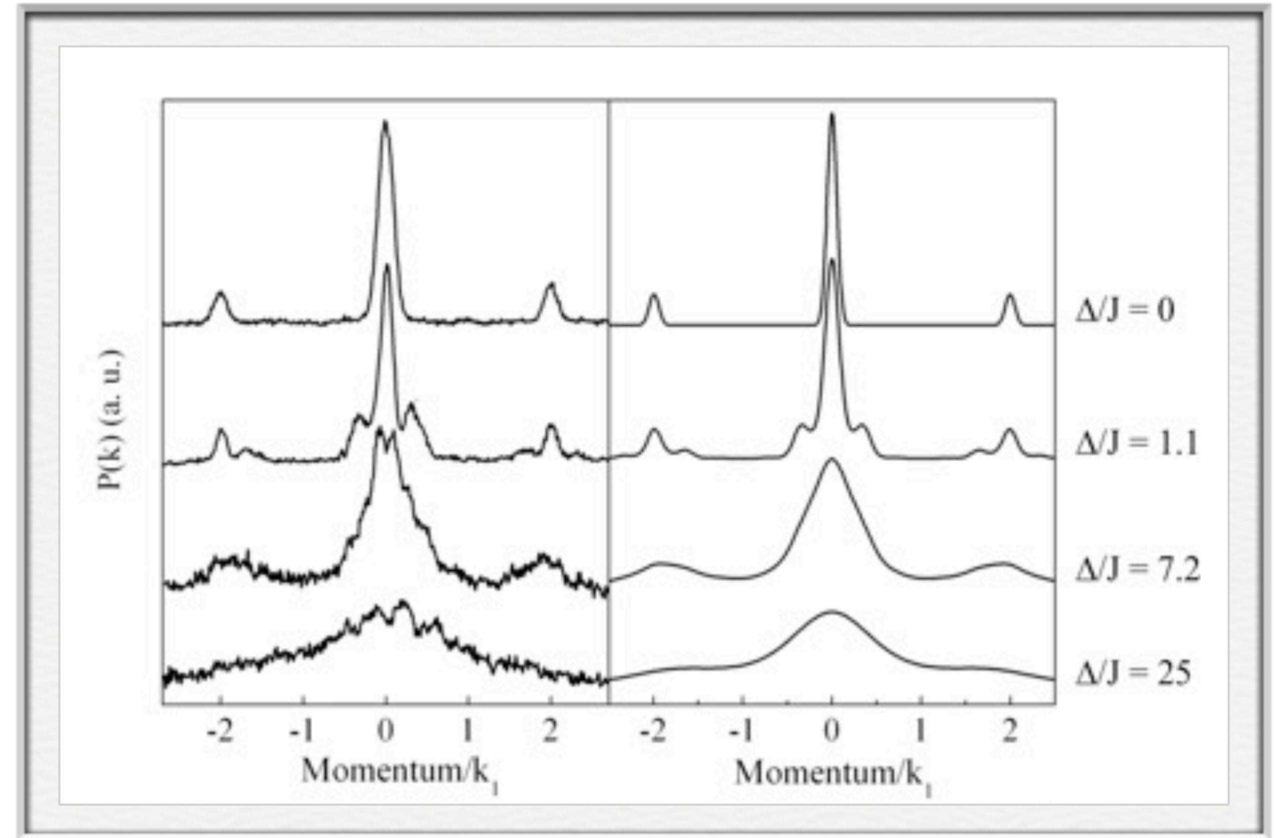

narrow peaks in p(k)

broad peaks in p(k)

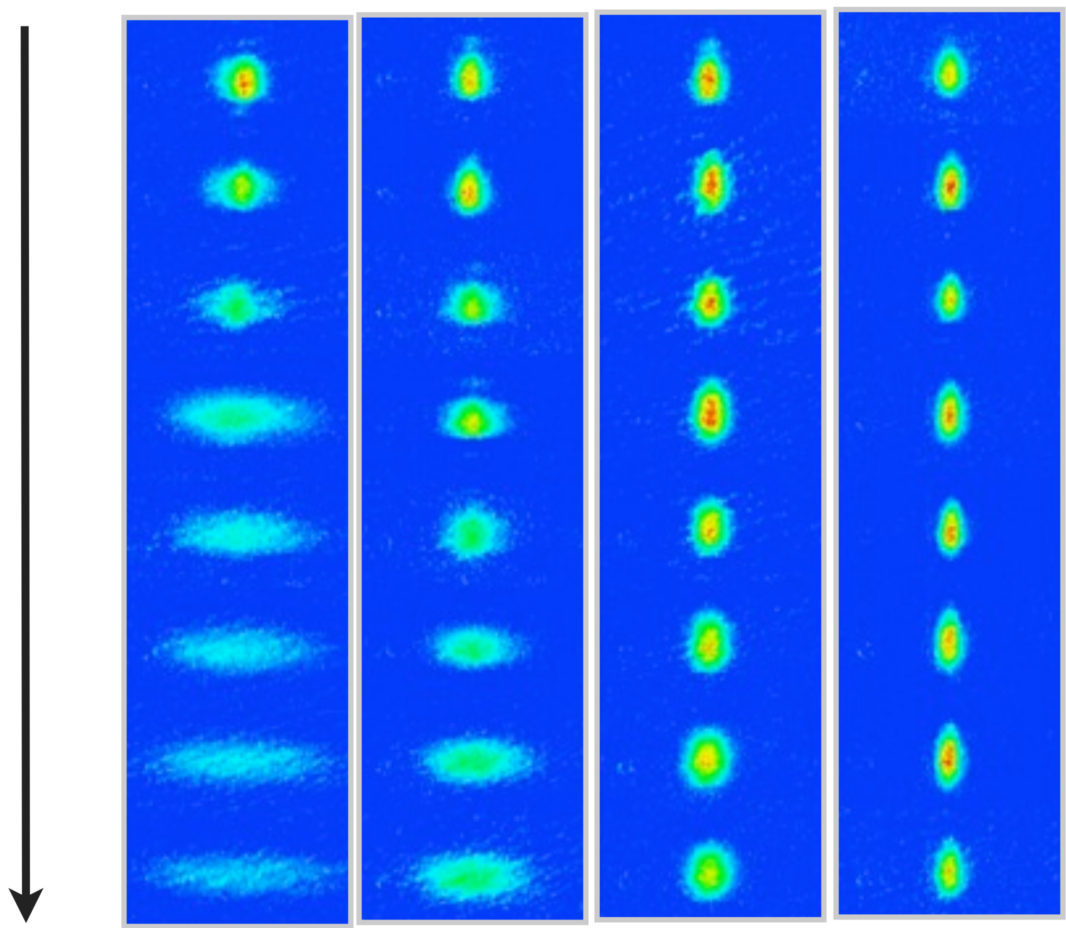
G. Roati et al. Nature 453, 895, 898 (2008)



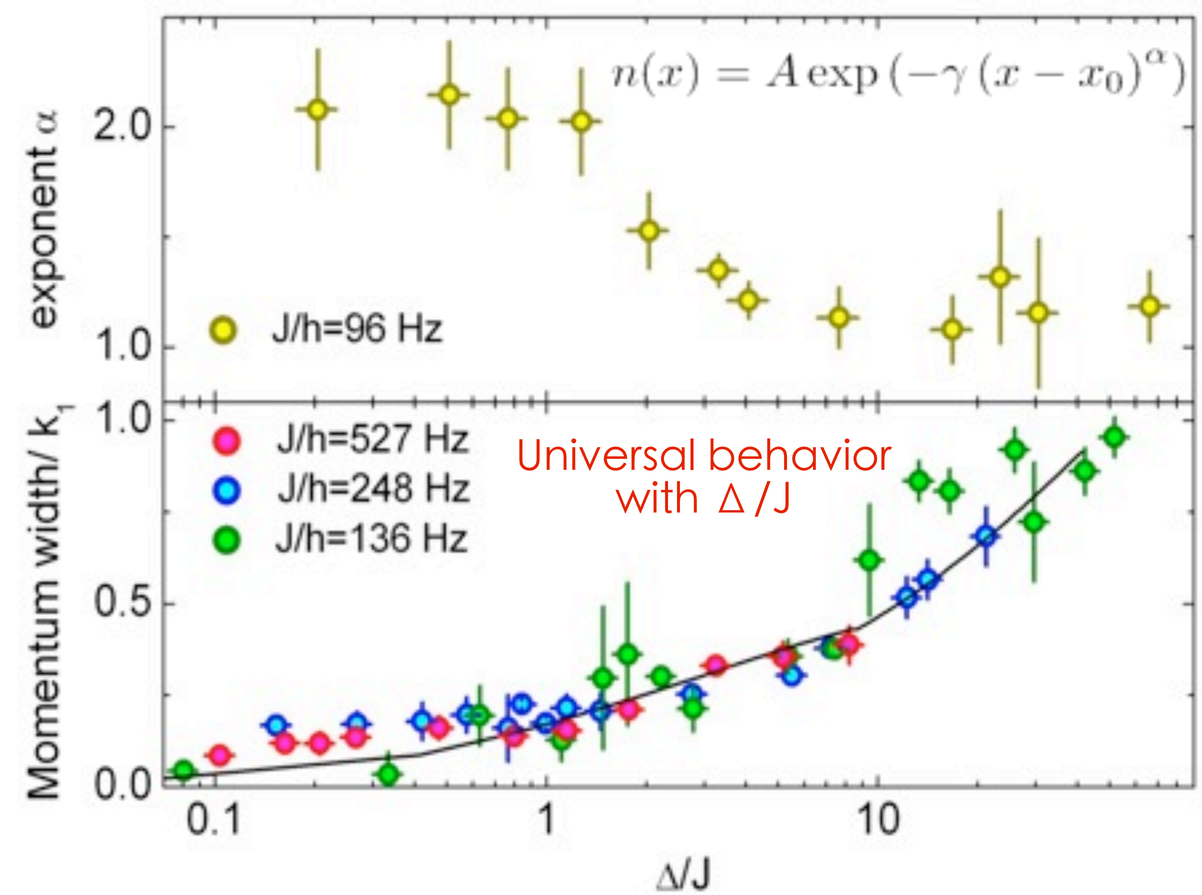
experiment theory



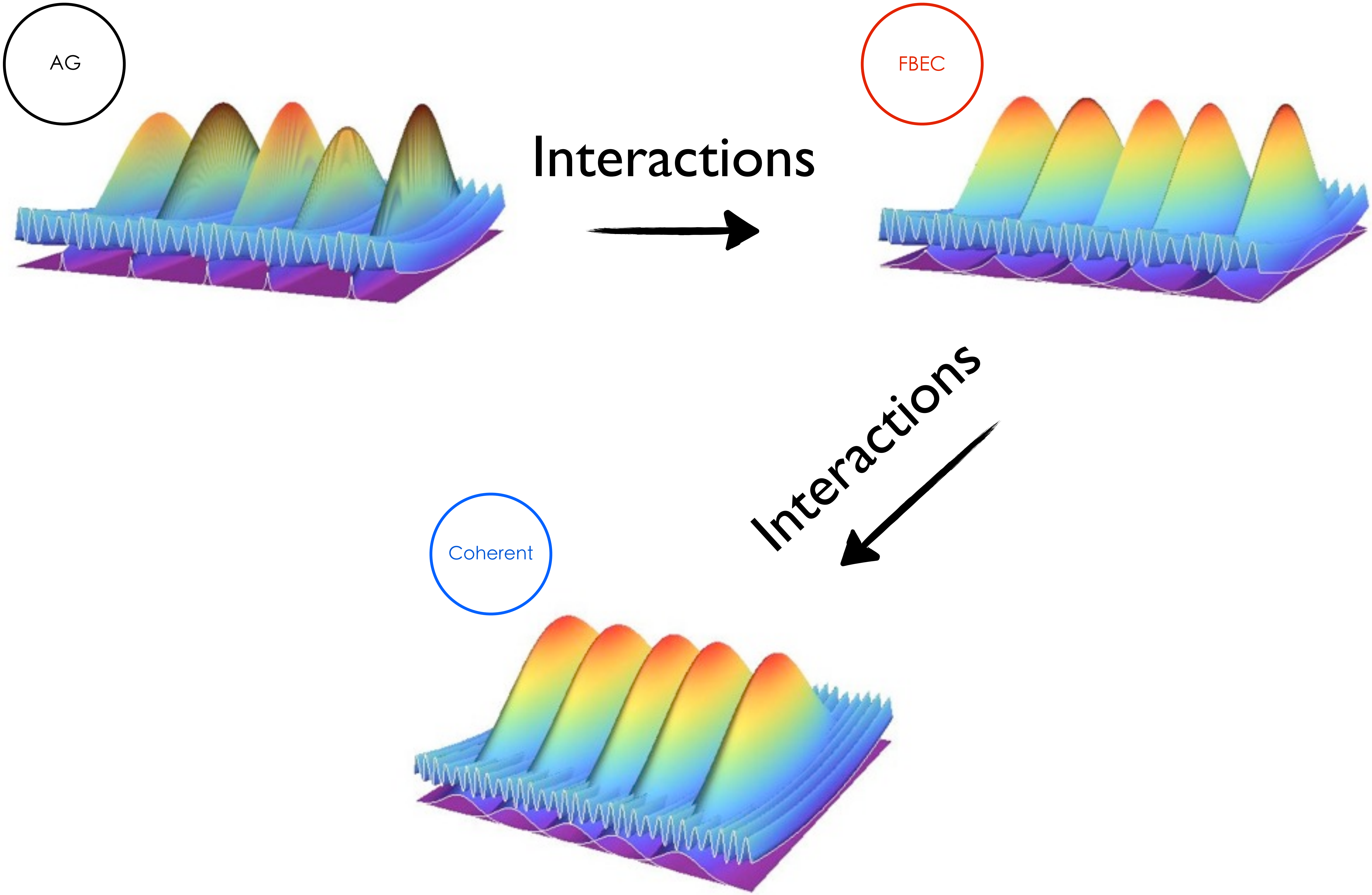

$\langle r^2 \rangle (t) \propto t^2$ $\langle r^2 \rangle (t) \propto \langle r^2 \rangle (0)$

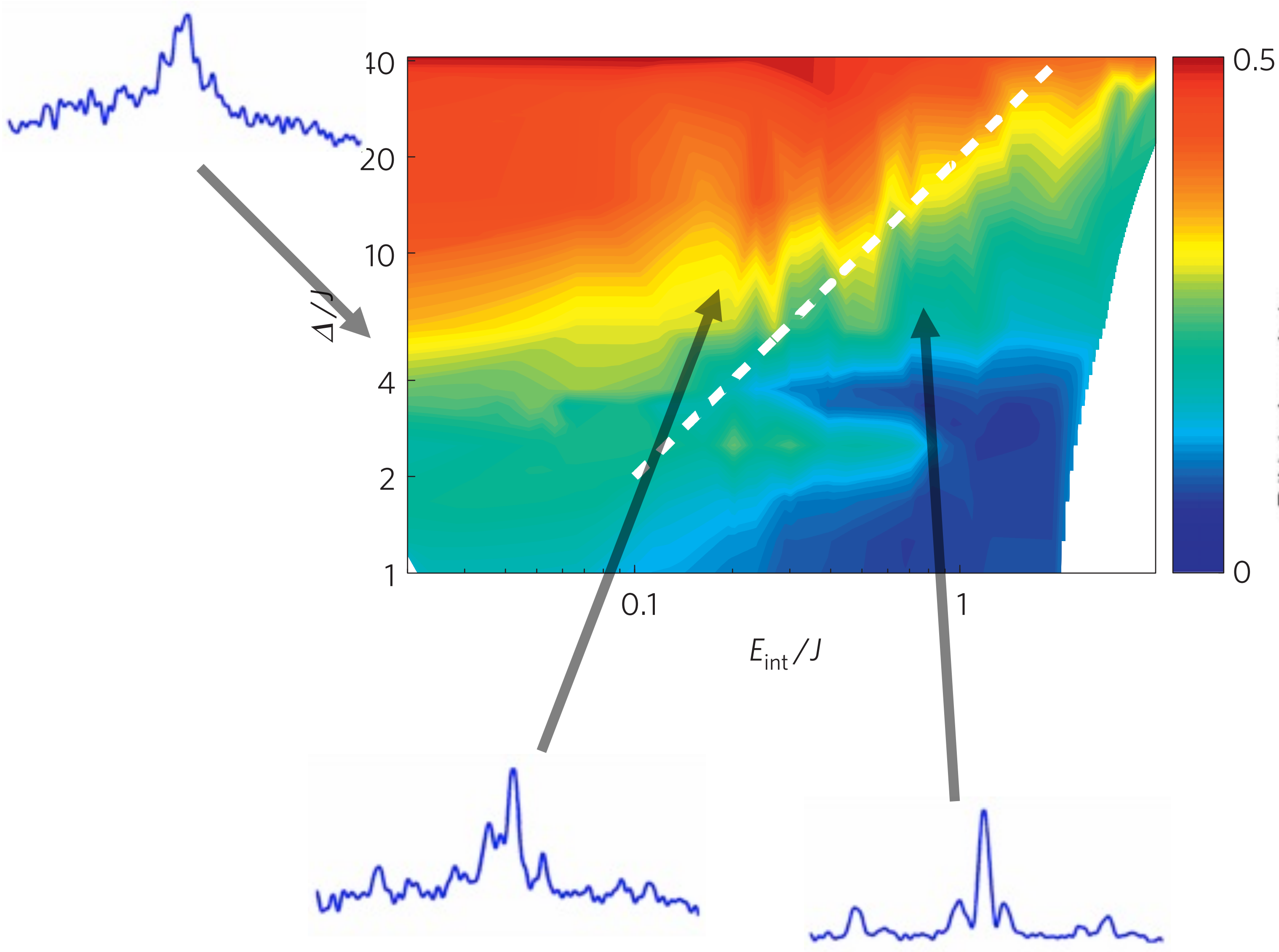


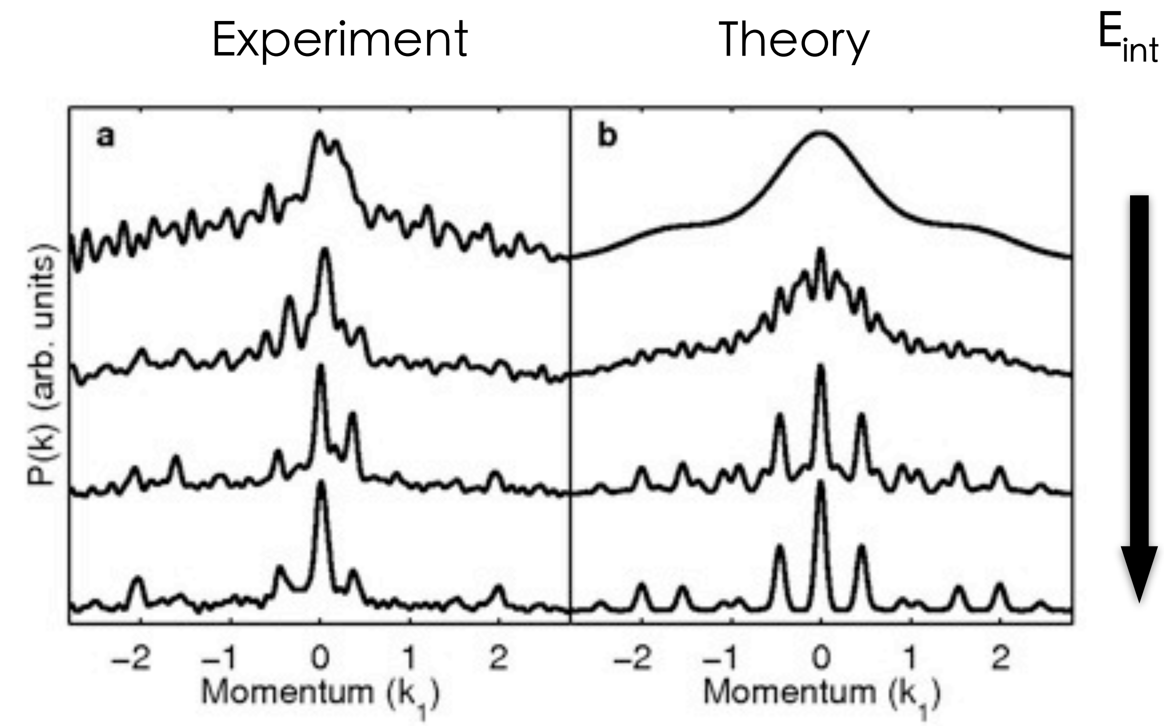
Time $\Delta/J = 0$ $\Delta/J = 1.1$ $\Delta/J = 2.6$ $\Delta/J = 4.3$



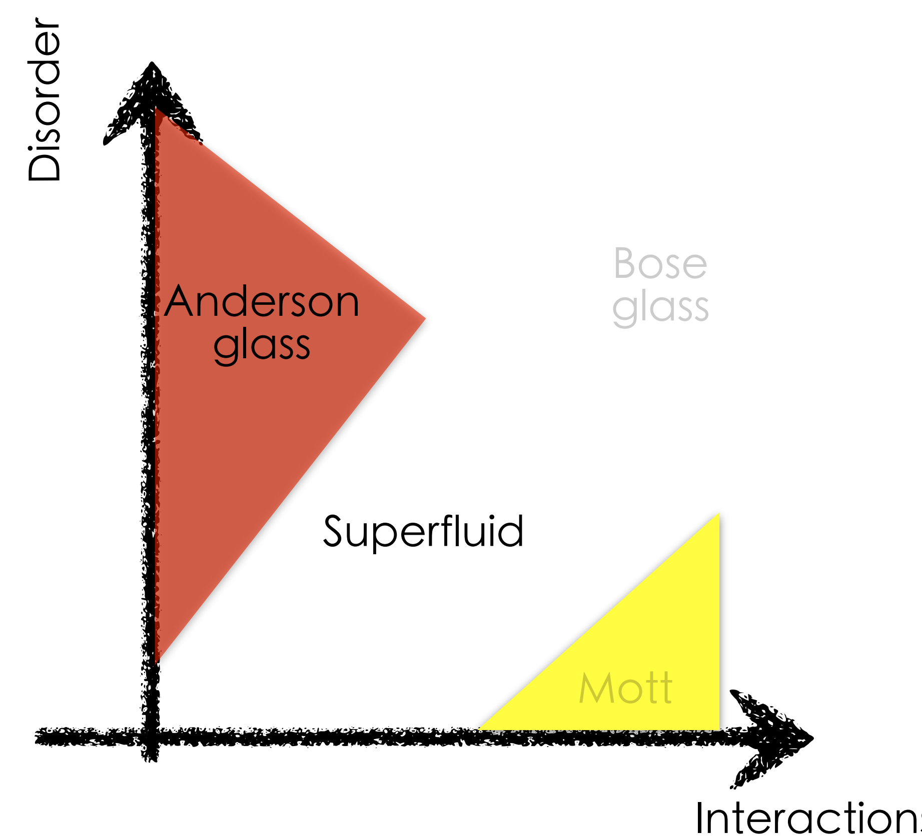
## Adding the interactions: B. Deissler et al. arXiv:0910.5062, Nature physics online 04/11/2010

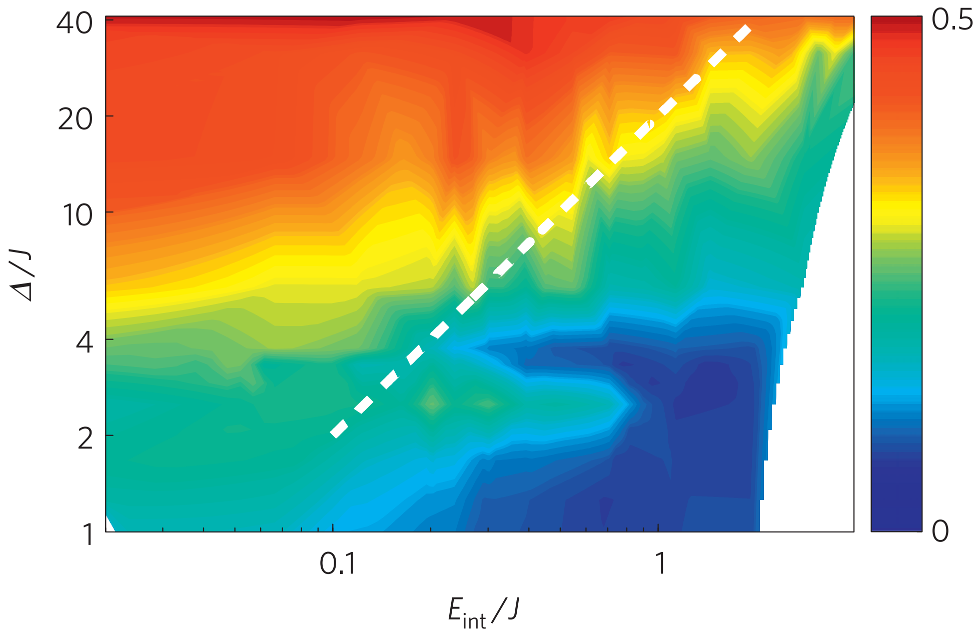


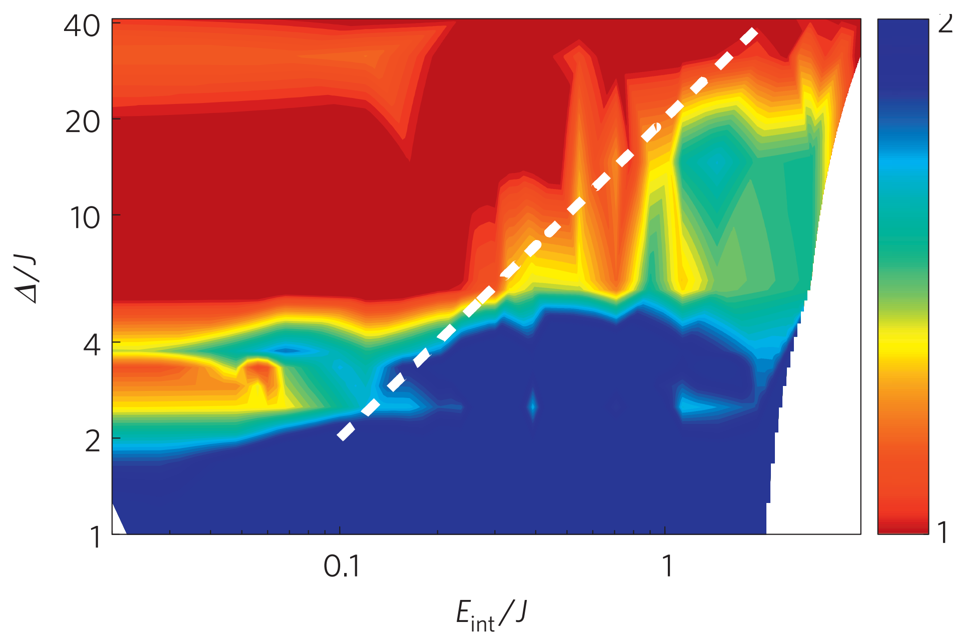


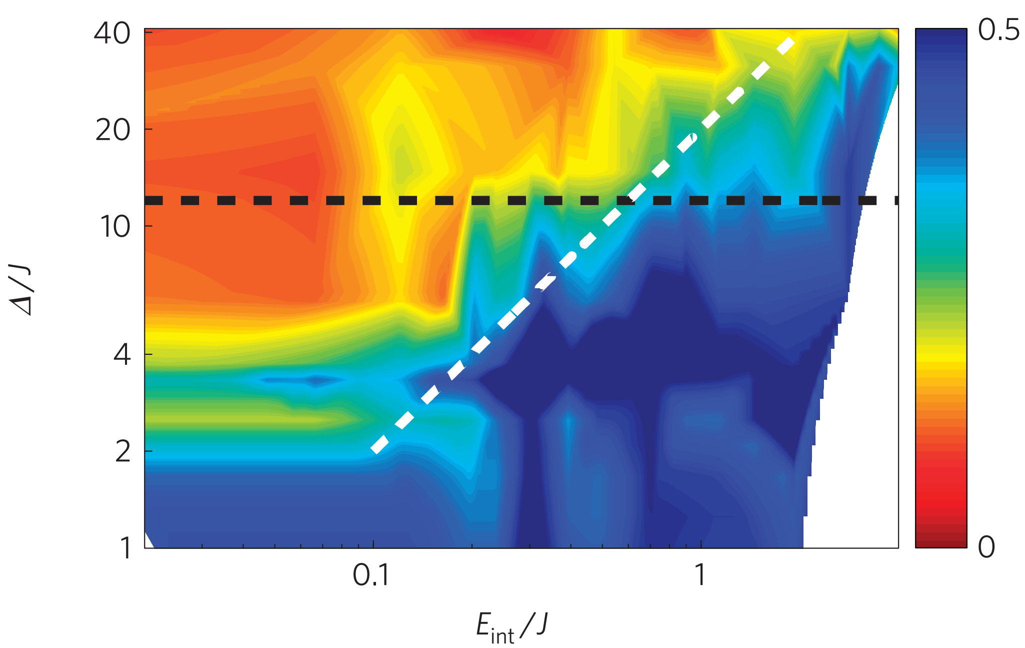




Adding interactions the momentum distribution becomes narrower: transition from a localized to extended state!





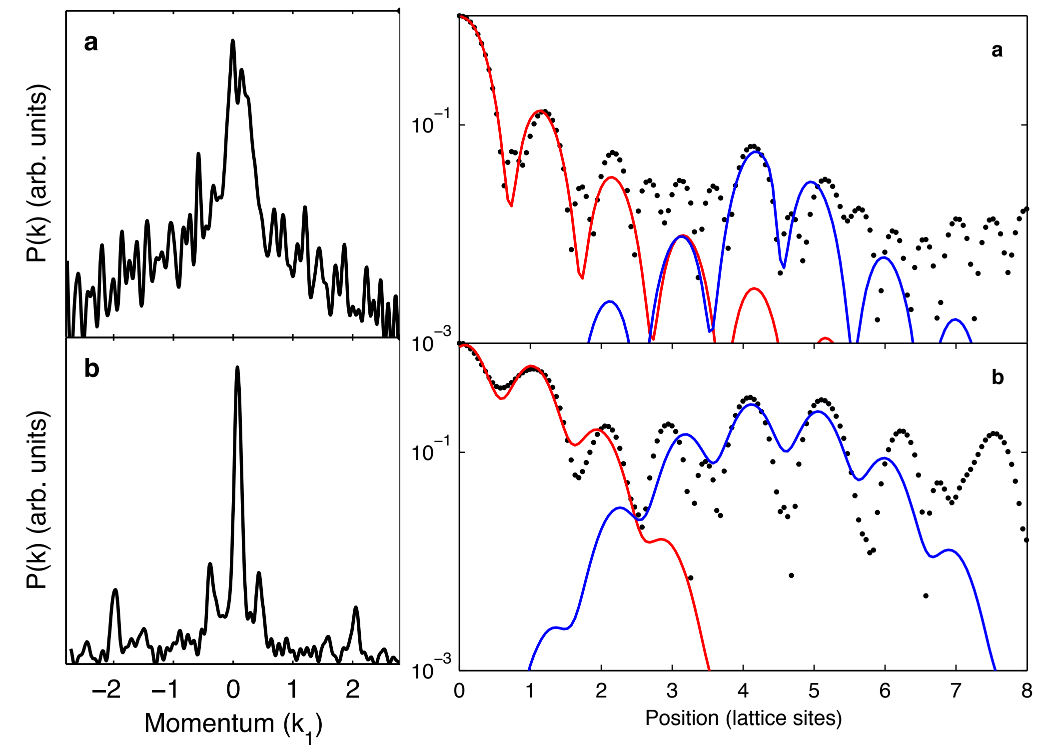




☑ Fourier transform of the momentum distribution f(k):

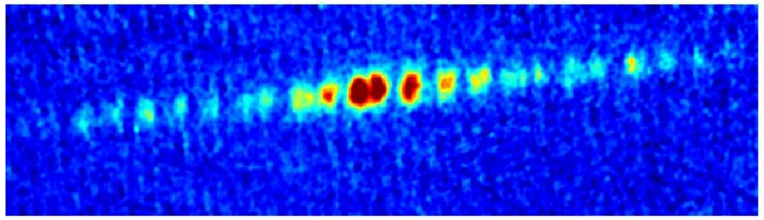
1) $F^{-1}(f(k)^{1/2})$= average local shape of the wavefunction

$$\sum_{i=1,2} A_i \exp\left(-|(z-z_i)/L|^{\alpha}\right)\cdot\left[1+B\cos(k_1(z-z_i)+\phi_i)\right]$$




2) $F^{-1}(f(k))$= correlations (@ 4.4 lattice sites) (Wiener-Khintchine theorem): spatially averaged correlation function

$$f(k) \sim F^{-1}\int G(x', x'+x)dx'$$



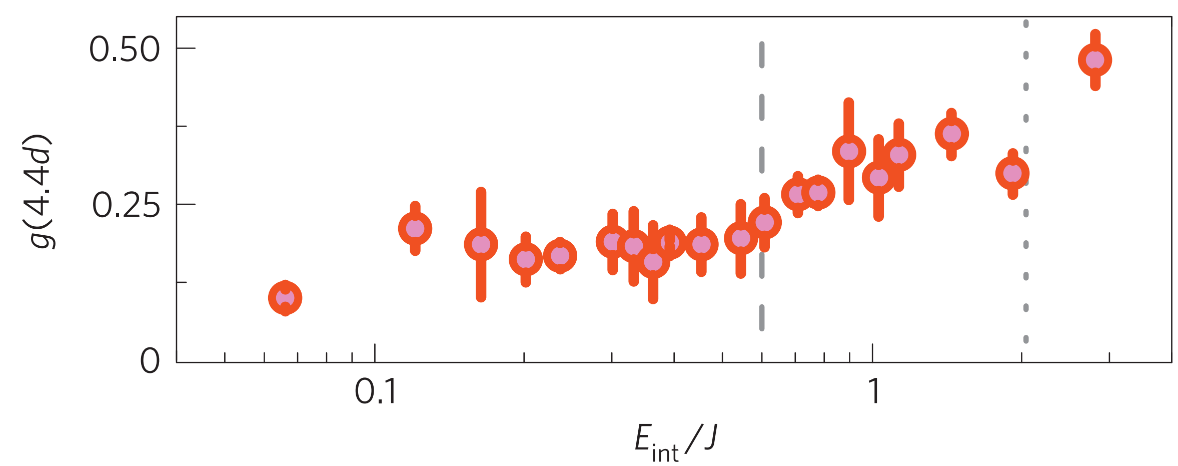
☑ Many copies of the same experimental realization: measuring phase correlation:

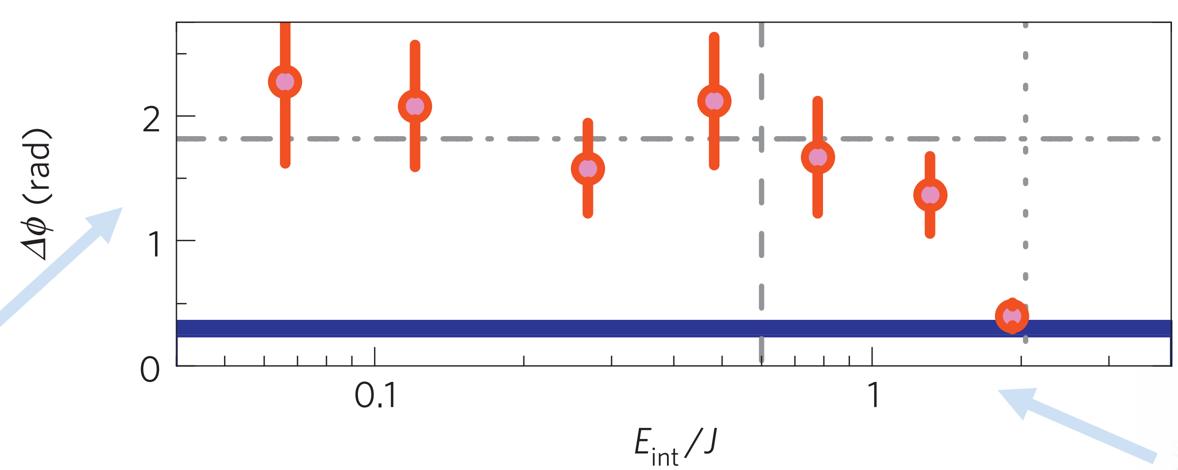
1. Uncorrelated states: low contrast, random phase ( "glassy" regime)

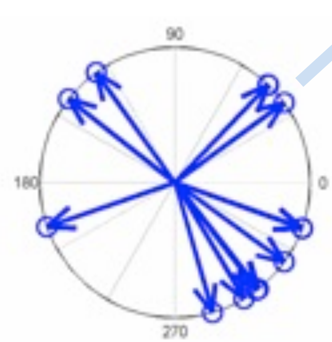
2. Extended single state: maximum contrast and locked phase (coherent regime)

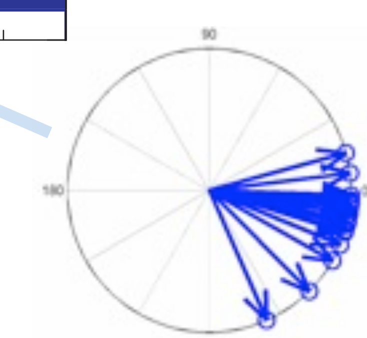
3. "Partially correlated" states: some contrast and not completely random phase (a "fragmented" regime)

$$\Delta/J = 12$$



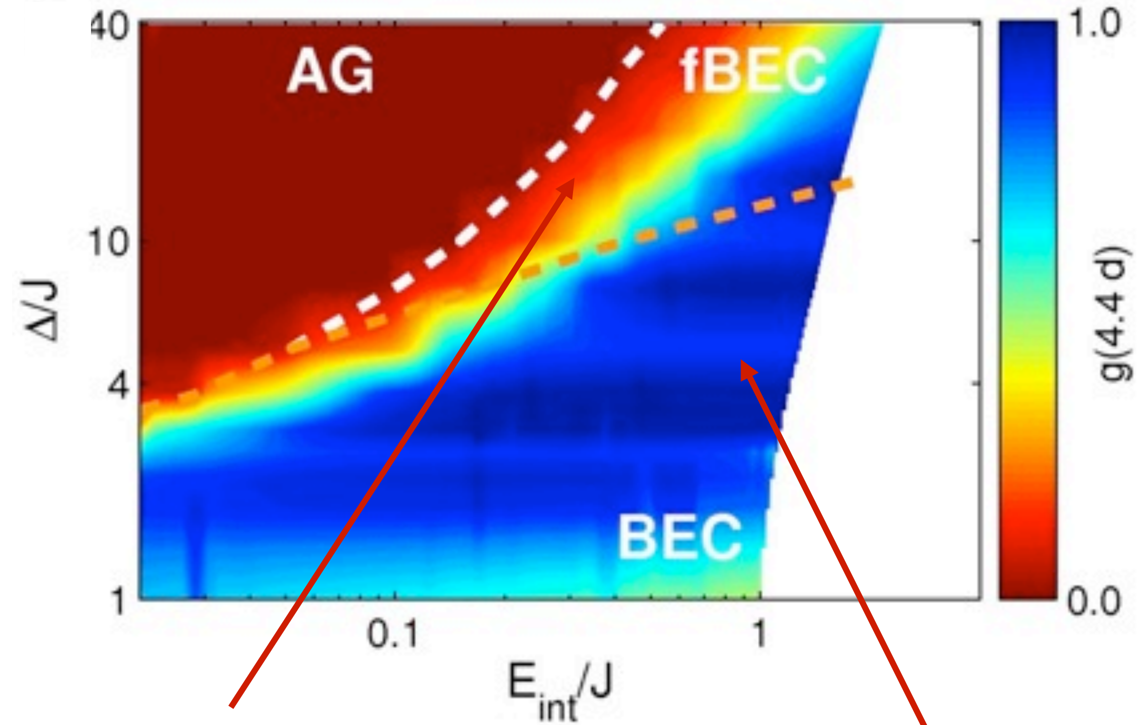



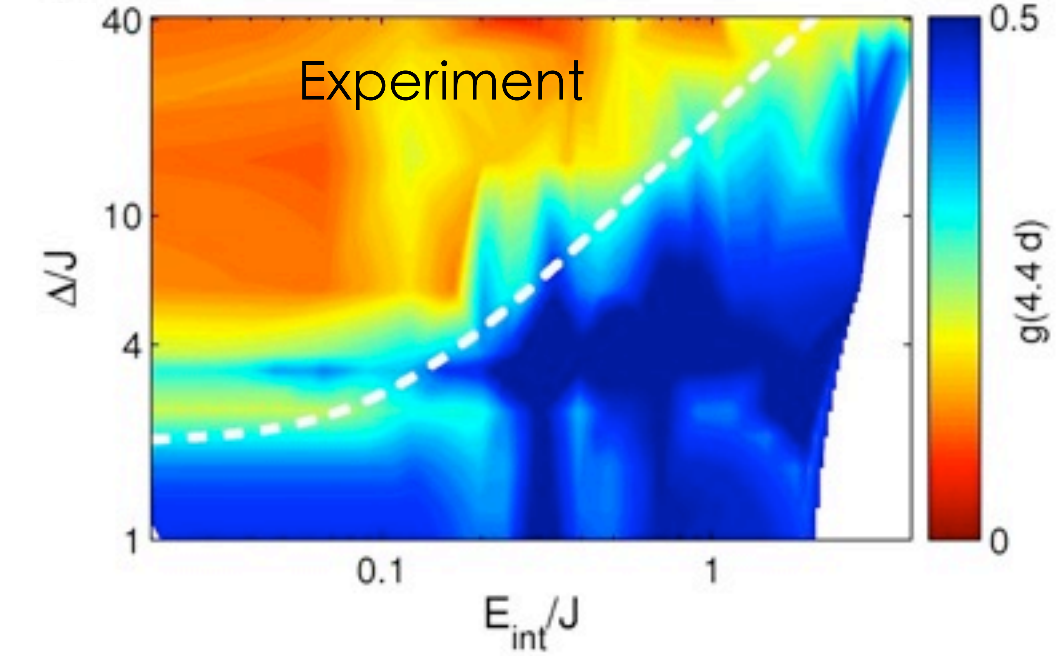



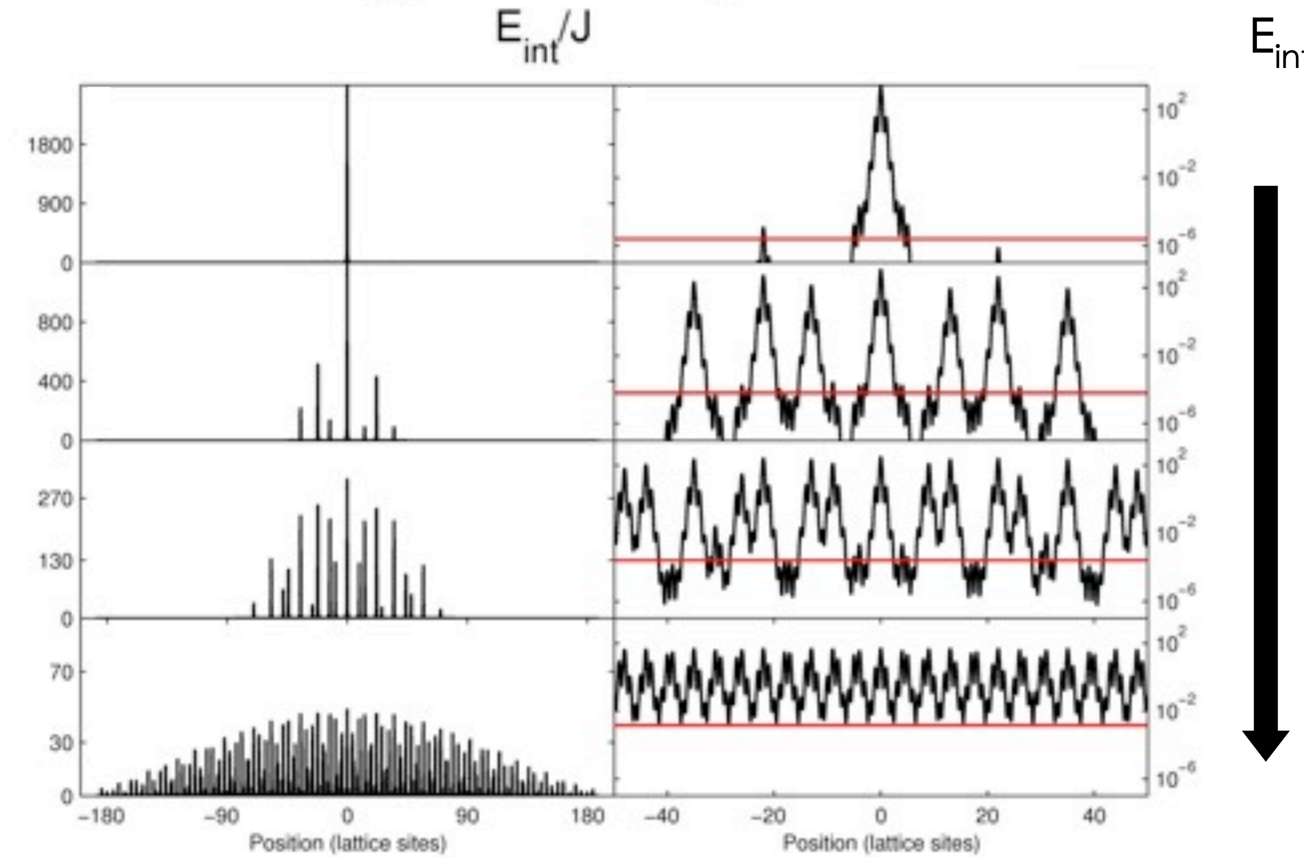



independent
exponentially
localized states

Mean-field calculations by M. Modugno (in preparation)




formation of
fragments

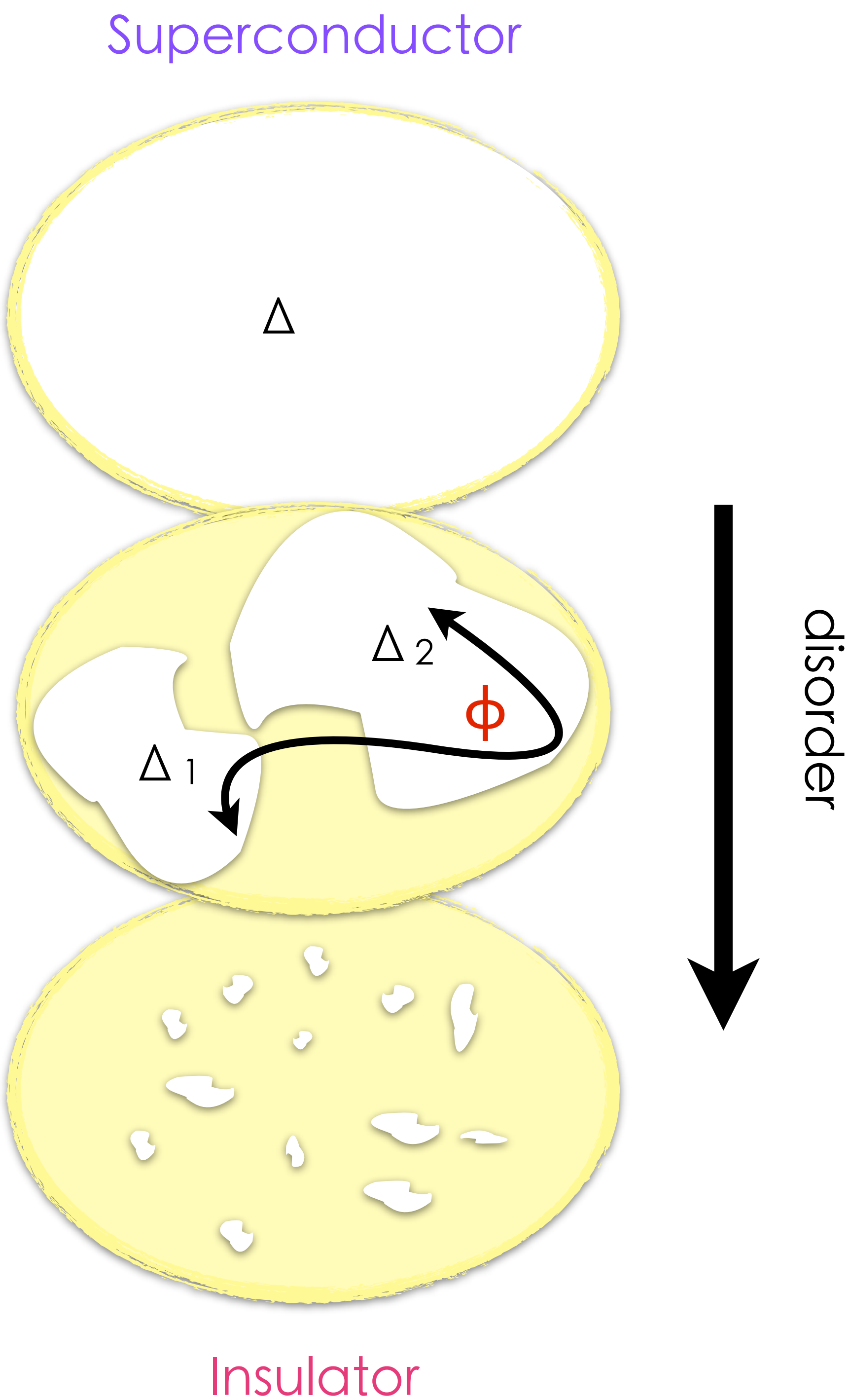
single extended state

Damski et al., PRL **91**, 080403 (2003)
Lugan et al., PRL **98**, 170403 (2007)

# SIT transition

P.W. Anderson demonstrated that superconductivity is stable against some disorder (no magnetic) ( "Anderson theorem" ).

but... 2D disordered superconductors show a transition from a superconducting to an insulator phase (SIT).
The nature of this transition is still under debate.




Disorder "fragments" the order parameter:

-> Islands of superconductivity with defined Δ
-> The system behaves as a bulk superconductor as long as $\Delta \neq 0$, and the phases of $\Delta(r)$ on two sides of the sample are correlated. The correlations are guaranteed by coherent tunnelling of Cooper pairs between the islands


P. W. Anderson. Theory of dirty superconductors, J. Phys. Chem. Solids, 11:26–30, 1959.

Y. Dubi, et al. Nature, 449:876–880, 2007

# Future plans

I. Strongly correlated bosons (1D) in presence of disorder:

a. Expected transition from a SF to Bose glass phase ($U, \Delta >> J$)
b. Probing the excitation spectra (Bragg spectroscopy)
c. Compressibility measurements (Mott vs Bose glass)

II. Fermions in disordered potentials: closer connection to condensed matter problems

a. Competition between EF and disorder strength
b. Fermions in 2D disordered potential (superfluidity vs disorder, MIT)

## 1D highly correlated Bose systems (Rb)

Selected for a Viewpoint in *Physics*
PRL **102,** 155301 (2009) PHYSICAL REVIEW LETTERS week ending 17 APRIL 2009

**Exploring Correlated 1D Bose Gases from the Superfluid to the Mott-Insulator State by Inelastic Light Scattering**

D. Clément,* N. Fabbri, L. Fallani, C. Fort, and M. Inguscio
*LENS, Dipartimento di Fisica, Università di Firenze and INFM-CNR, via Nello Carrara 1, I-50019 Sesto Fiorentino (FI), Italy*
(Received 23 December 2008; revised manuscript received 10 February 2009; published 13 April 2009)

We report the Bragg spectroscopy of interacting one-dimensional Bose gases loaded in an optical lattice across the superfluid to the Mott-insulator phase transition. Elementary excitations are created with a nonzero momentum and the response of the correlated 1D gases is in the linear regime. The complexity of the strongly correlated quantum phases is directly displayed in the spectra which exhibit novel features. This work paves the way for a precise characterization of the state of correlated gases in optical lattices.

## 41K-87Rb Bose-Bose mixture

Selected for a Viewpoint in *Physics*
PRL **103,** 140401 (2009) PHYSICAL REVIEW LETTERS week ending 2 OCTOBER 2009

**Entropy Exchange in a Mixture of Ultracold Atoms**

J. Catani,[1,2] G. Barontini,[1] G. Lamporesi,[1] F. Rabatti,[1] G. Thalhammer,[1] F. Minardi,[1,2] S. Stringari,[3] and M. Inguscio[1,2]
[1]*LENS—European Laboratory for Non-Linear Spectroscopy and Dipartimento di Fisica, Università di Firenze, via N. Carrara 1, I-50019 Sesto Fiorentino—Firenze, Italy*
[2]*CNR-INFM, via G. Sansone 1, I-50019 Sesto Fiorentino—Firenze, Italy*
[3]*Dipartimento di Fisica, Università di Trento and CNR-INFM BEC Center, I-38050 Povo, Trento, Italy*
(Received 11 June 2009; revised manuscript received 16 July 2009; published 28 September 2009)

Recent observations of confinement induced resonances

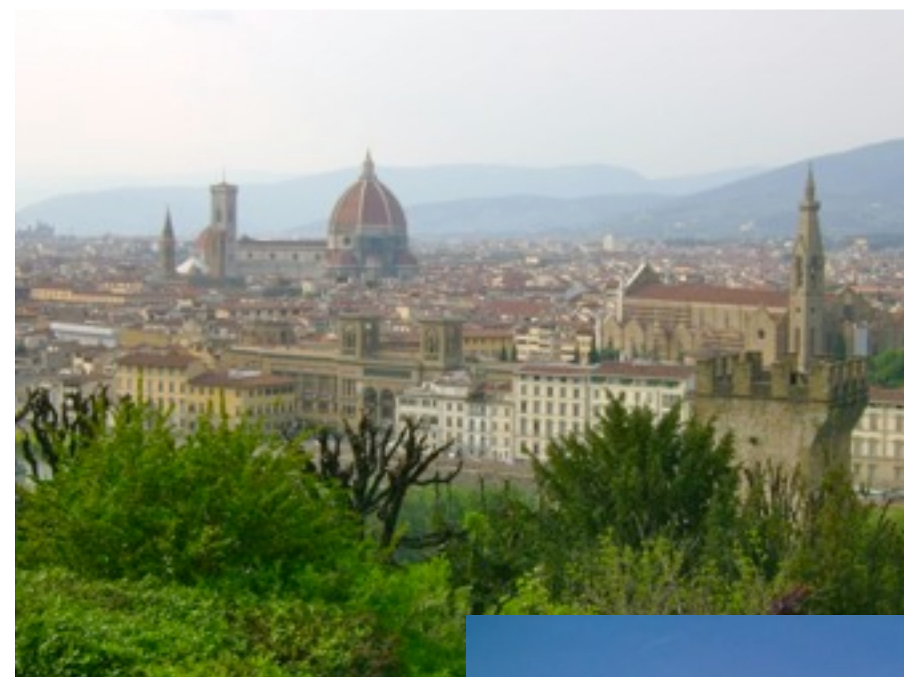
## 39K-87Rb Bose-Bose mixture

ARTICLES
PUBLISHED ONLINE: 13 JULY 2009 | DOI:10.1038/NPHYS1334
nature physics

**Observation of an Efimov spectrum in an atomic system**

**M. Zaccanti[1]*, B. Deissler[1], C. D'Errico[1], M. Fattori[1,2], M. Jona-Lasinio[1], S. Müller[3], G. Roati[1], M. Inguscio[1] and G. Modugno[1]**

ERC starting grant: heteronuclear molecules



## 39K all optical: work in progress

## Ytterbium: work in progress