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Introduction to disordered ultracold quantum gases

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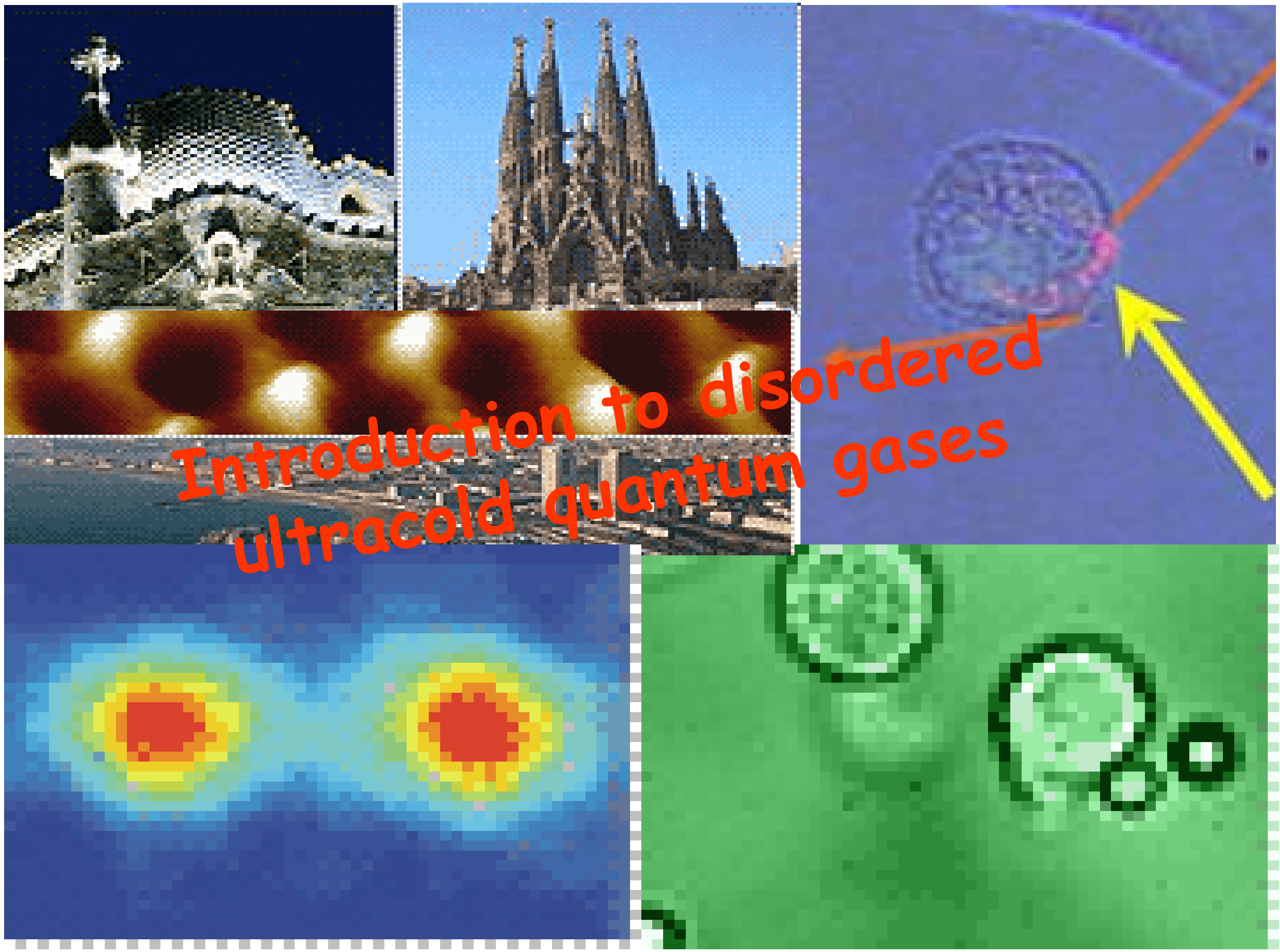

Introduction to disordered ultracold quantum gases

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QT
Quantum Optical Information Technology

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Universität Hannover

Barcelona – Quantum Optics Theory

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Barcelona – Quantum Optics Theory

Collaborations: Theory

MPI Garching – J. I. Cirac
UAB, Barcelona – A. Sanpera (G. Fis. Teor.),
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Univ. Düsseldorf – D. Bruβ
Univ. Paris-Sud, Orsay – G. Shlyapnikov (LPT)
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UAB, Barcelona - V. Ahufinger, J. Mompart, G. Morigi (G. Optica)
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Collaborations: Experiments

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E. Tiemann (IQO)
Univ. Darmstadt - G. Birkl (Darmstadt),
Univ. Siegen - C. Wunderlich
Univ. Hamburg - K. Sengstock, K. Bongs
LENS, Firenze – Massimo Inguscio
Univ. Innsbruck - R. Blatt,
N. Bohr. Inst., Kopenhagen - E. Polzik
ICFO – J. Eschner, M. Mitchel, J. Biegert

Outline

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- Introduction:
  - The concept of quenched disorder
  - Examples (Anderson localization (AL), disordered Bose-Hubbard model, random field Ising model (RFIM), spin glasses (SG))
  - Four ways of creating controlled disorder in ultracold atomic gases
- Anderson localization (single particles):
  - Weak localization and coherent backscattering
  - Localisation in 1D
  - Scaling theory of the "gang of four".
- Anderson localization and disordered weakly interacting Bose gases
  - Bose-Anderson glass
  - Trapped gases and the concept of Lifshits glass
- Random field spin models
  - Imry-Ma argument
  - Random field induced order

The concept of quenched disorder

Very often one considers systems described by a Hamiltonian that depends on a set of parameters μ_i such that:

i) They have "random" or "quasi-random" character (i.e. can be well approximated as a sample of random variables drawn according to some distribution)

ii) They (ergo, also their distribution) remain "frozen" on the time scale of observation of the system (quenched disorder).

iii) Thus, we have to solve the problem for a given realisation of disorder, and then average observables over the disorder:

$$\langle\langle O(\mu_i)\rangle\rangle_{disorder}$$

Examples of quenched disorder

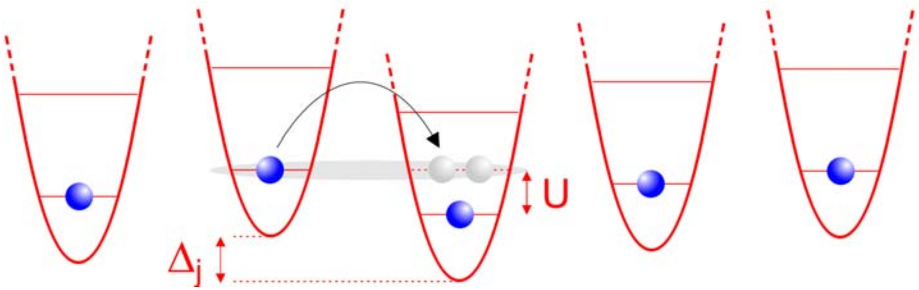
- **Single particle in a random potential (Anderson localization, ε_i – i.e.d.r.v., $p(\varepsilon_i)$ given)**

$$\varepsilon\,\Psi(i) = -t\big(\Psi(i-1) + \Psi(i+1) - 2\Psi(i)\big) - \varepsilon_i \Psi(i)$$

$$H = -t\sum_{\langle ij\rangle}\left(b_j^+ b_i + b_i^+ b_j\right) - \sum_i \varepsilon_i b_i^+ b_i + 2tz\hat{N}$$

- **Disordered Bose-Hubbard model**

$$\hat{H} = -J\sum_{\langle i,j\rangle}\hat{a}_i^\dagger \hat{a}_j + \frac{U}{2}\sum_i \hat{n}_i\left(\hat{n}_i - 1\right) + \sum_i \epsilon_j \hat{n}_j$$



Examples of quenched disorder

- **Random field Ising model (RFIM)**

$$H = -J\sum_{\langle ij\rangle} s_i^z s_j^z - \sum_i h_i s_j^z$$

- **Spin glass (Edwards-Anderson model)**

$$H = -\sum_{\langle ij\rangle} J_{ij} s_i^z s_j^z - \sum_i h_i s_j^z$$

Some "truths" about disordered systems

- Disordered systems are characterized by structurally simple, but **non-linear interactions**, that incorporate **quenched disorder**

- **Disordered systems** often have very many „relevant" states (energy minima, attractors, excitations, etc.)

- Disordered systems exhibit often **long range** correlations in space and time (in particular when interactions themselves are long range)

- Disordered system often incorporate **fractal** structures, **hierarchical** or **ultrametric** structures

- **Quantum** disordered systems are **notoriously** (i.e. much than non-disordered ones) **difficult** to simulate !

Disordered ultracold quantum gases

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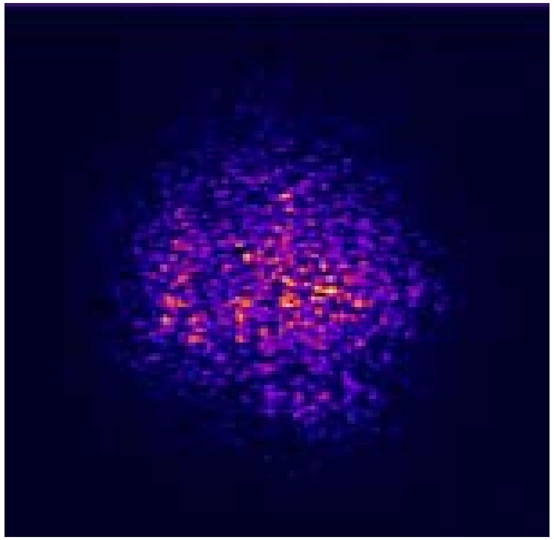
- **Four ways to create random (but controlled) on-site potential**
- **Using optical super-lattices:**
  - Add a disordered lattice(s) created by speckle radiation pattern to the main lattice (in traps PRL's by Florence, Orsay, Hannover…)
  - Add a lattice(s) with incommensurable period (quasi-disorder)
  - papers by us, Roth and Burnett, see also T. Schulte et al. PRL. **95**, 170411 (2005)
- **Quenching auxiliary atoms as random scatterers:**
  - Place auxiliary atoms in a lattice and ramp potential wells up non-adiabatically. For small filling factors, the atoms will be localized at random positions. Super-impose this system of random scatterers with the main lattice – see recent papers of Y. Castin group
- **Employing Feschbach resonances in random magnetic fields:**
  - Disordered interactions - see H. Gimperlein et al., cond-mat/0506572

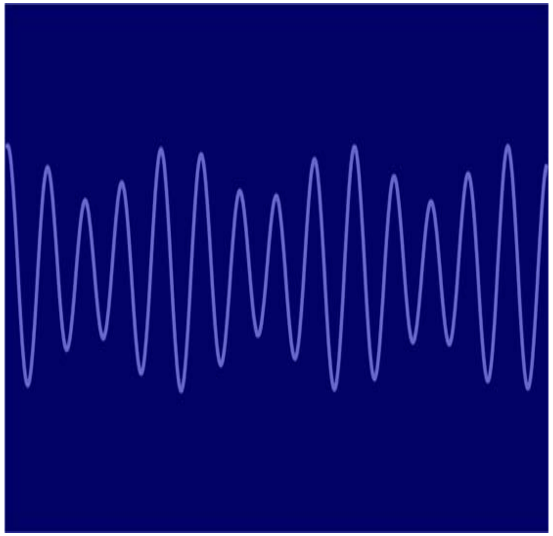
+ Frustarted non-radom!!!

Approach of M. Inguscio *et consortes* to controlled disordered optical potential

speckle pattern



bichromatic lattice



- ✓ random potential
- ✗ large length scale in our set-up (several μm)
  Note, however A. Aspect's group has < 1μm !

J.E.Lye et al. PRL **95**, 070401 (2005)

C. Fort et al. PRL **95**, 170410 (2005)

- ✓ quasiperiodic potential
- ✓ smaller length scale (1 μm or less)

Non-periodic modulation of the energy minima with length scale

$$d = \left(\frac{2}{\lambda_1} - \frac{2}{\lambda_2}\right)^{-1}$$

Quantum Control in Superlattice and Disordered Potentials (Here Mainz, but also NIST, Innsbruck...)

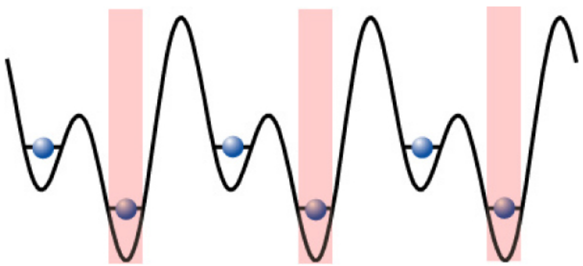
Goals:

1) Generate controllable disordered quantum systems, for quantum simulations of disordered many body systems!

2) Employ quantum parallelism in experiment and theory to efficiently simulate them (see e.g. B. Paredes, F. Verstraete & I. Cirac, *PRL* 95, 140501 (2005))

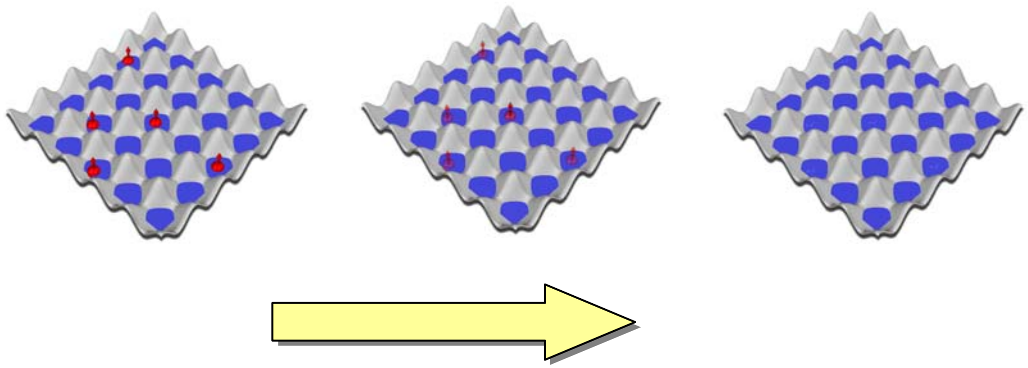
Experimental realizations:

1) *Superlattice potentials for controlled „disorder“*



Superlattice depth and phase controllable (nonrational wavelength factors possible)

2) *Disorder via second atomic species*



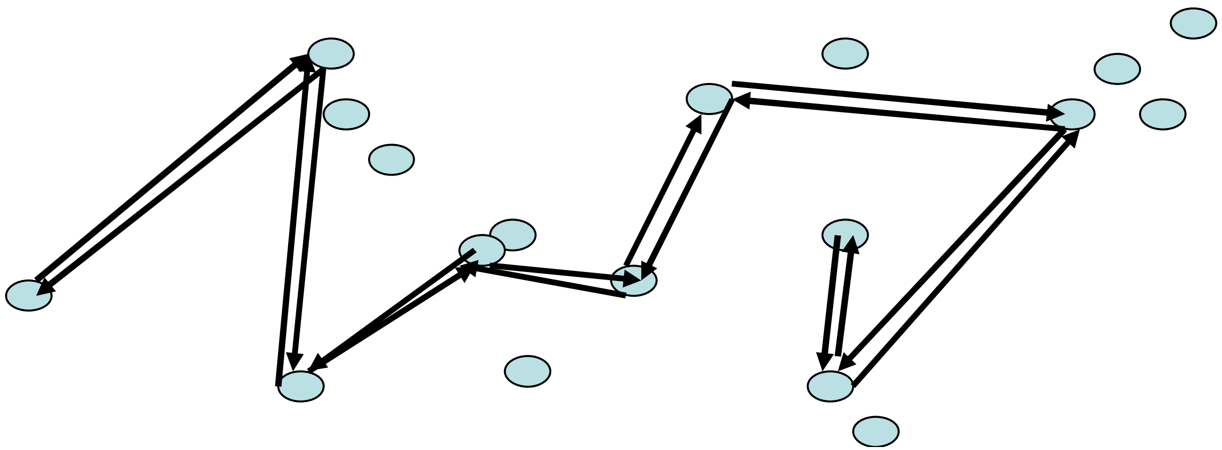
Feshbach resonance

Anderson localization

- **Single particle in a random potential undergoes random scattering events, so that destructive interference counteracts transport**

$$-\varepsilon\ \Psi(i) = -t\sum_{j,nn}\Psi(j) - \varepsilon_i\Psi(i)$$

- **Weak localization – Coherent back scattering**



Anderson localization in 1D

- **If $\varepsilon_i = \varepsilon_{i+q}$, the problem is periodic, and the eigenstates are Bloch waves, and the spectrum has bands+gaps**

$$\varepsilon u(i) = t(u(i+1) + u(i-1)) + \varepsilon_i u(i)$$

- **For arbitrarily small random ε_i, all eigenstates are exponentially localized! For $|\nu\text{-}j| \rightarrow \infty$, we have (where the localization length $l = l(\varepsilon)$):**

$$u_j^\nu \rightarrow \exp(-|\nu - j|/l)$$

Furstenberg theorem

- **Let M_q, q=1,2,… is a set of unimodular matrices (det M_q=1). Under very general conditions**

$$\lim_{q\to\infty} \ln Tr\left(M_q M_{q-1} \ldots M_1\right)/q = \gamma > 0$$

- **In our case**

$$\begin{pmatrix} u_{m+1} \\ u_m \end{pmatrix} = \begin{pmatrix} (\varepsilon - \varepsilon_m)/t & -1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} u_m \\ u_{m-1} \end{pmatrix} \equiv M_m \begin{pmatrix} u_m \\ u_{m-1} \end{pmatrix}$$

Furstenberg theorem

- **In our case**

$$\begin{pmatrix} u_{m+1} \\ u_m \end{pmatrix} = M_m M_{m-1} \ldots M_1 \begin{pmatrix} u_1 \\ u_0 \end{pmatrix} = \mathsf{M}_m(\varepsilon) \begin{pmatrix} u_1 \\ u_0 \end{pmatrix}$$

- **with lnTr[M_m(ε)]/m → γ (Lyapunov exponent).**
Thus, M_m(ε) has an eigenvalues exp(+γm) and exp(-γm). Generically, choosing u_1/u_0, we can always assure u_m→0 exponentially either for m→+∞, or for m→-∞. Choosing appropriate discrete ε we assure that (with *l*=1/γ)

$$u_m^\nu \to \exp(-|\nu - m|/l)$$

Anderson localization – scaling theory

"Gang of four": E. Abrahams, P.W. Anderson, D.C. Licciardello, and T.V. Ramakrishnan, PRL 42, 673(1979)

- **We define a generalized dimensionless "conductance" (Thouless number, sensitivitiy to boundary conditions, superfluid fraction, …) at the scale L**

$$g(L) = \frac{\Delta E(L)}{dE(L)/dN}$$

- **where ΔE(L) is the square root of the disorder averaged squared difference of energy levels caused by replacement of periodic by antiperiodic boundary conditions, and dE/dN is the mean level spacing. The function g(L) is the only relevant quantity when two large cubes of size L are fitted together.**

Anderson localization – scaling theory

- **We consider combining b^d cubes into one block of size bL. We postulate:**

$$g(bL) = f(b, g(L)), \text{ or}$$

$$d \ln g(L)/dL = \beta(g(L))$$

- **For large g (no disorder), we get $g(L) \rightarrow L^{d-2}$, i.e. $\lim_{g\rightarrow\infty} \beta(g) = d-2$.**
  For small g (disorder dominant), we expect exponential localization, $g = g_a e^{-\gamma L}$, i.e. $\lim_{g\rightarrow\infty} \beta(g) = \ln[g/g_a]$.

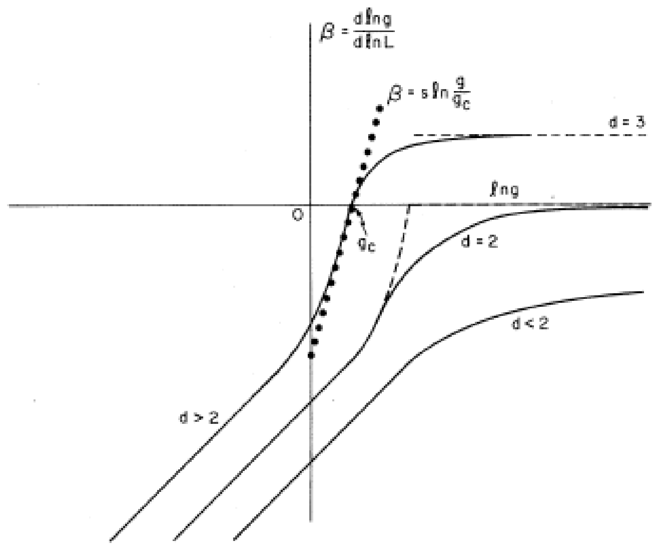
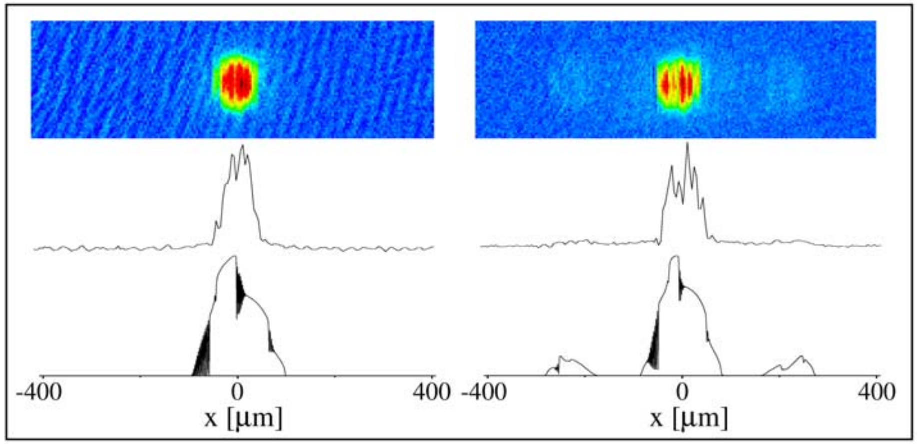


FIG. 1. Plot of $\beta(g)$ vs $\ln g$ for $d > 2$, $d = 2$, $d < 2$. $g(L)$ is the normalized "local conductance." The approximation $\beta = s \ln(g/g_c)$ is shown for $g > 2$ as the solid-circled line; this unphysical behavior necessary for a conductance jump in $d = 2$ is shown dashed.

Routes toward Anderson localization: interplay between disorder and interactions in trapped gases

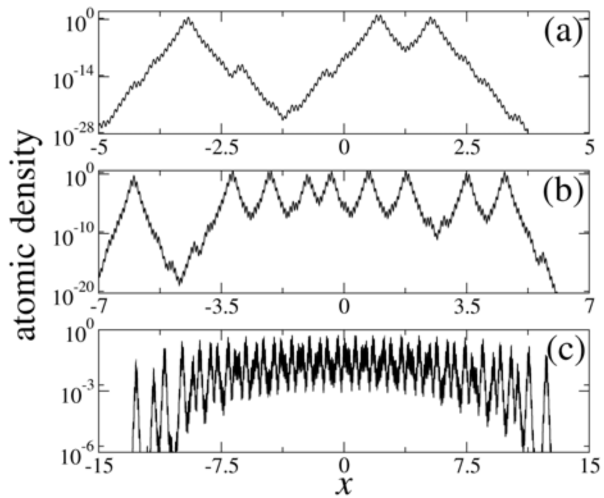
Experiment by T. Schulte et al.

- speckles too "large"
- interactions too "strong"



Theory by T. Schulte et al.

- "quasidisorder"



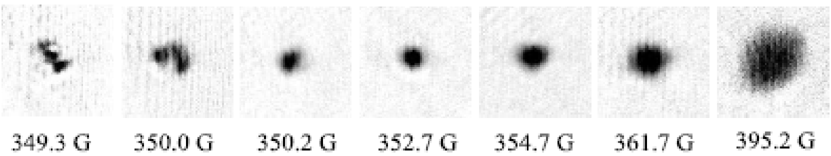
But, observe 11th Commandement:
You shall not block, or obscure the laser access

The quest for Anderson localisation in BEC: Experiments

- Experiments in Orsay/Palaiseau:
  - A. Aspect has speckles with submicron correlation length!!!
  - Plans to see signatures of AL in expansion and excitations
  - Problem: Moving of the labs

- Experiments at LENS:
  - M. Inguscio has BEC of Potassium 39
  - Plans to see signatures of AL in “ideal” gas

- Feshbach resonances on different Rb/K mixtures and K samples: realization of ^{39}K Bose-Einstein condensate with tunable interactions



G. Roati et al. airXiv:cond-mat/0703714v1
M. Zaccanti et al. PRA 74, 041605R (2006)

^{39}K condensate at various magnetic fields in the vicinity of a Feshbach resonance. The size shrinks as the scattering length a is decreased, and the condensate eventually collapses for negative a.

The quest for Anderson localisation in BEC: Theory I

- **Progress in understanding of the interplay disorder-interactions:**

PRL 98, 170403 (2007) PHYSICAL REVIEW LETTERS week ending 27 APRIL 2007

Ultracold Bose Gases in 1D Disorder: From Lifshits Glass to Bose-Einstein Condensate

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(Received 15 October 2006; published 27 April 2007)

We study an ultracold Bose gas in the presence of 1D disorder for repulsive interatomic interactions varying from zero to the Thomas-Fermi regime. We show that for weak interactions the Bose gas populates a finite number of localized single-particle Lifshits states, while for strong interactions a delocalized disordered Bose-Einstein condensate is formed. We discuss the schematic quantum-state diagram and derive the equations of state for various regimes.

- **Progress in understanding of localization effects in expansion and in excitations**
  - **N. Bilas, N. Pavloff, G. Shlyapnikov, L. Sanchez-Palencia**

The quest for Anderson localisation in BEC: Theory II

- **Progress in understanding of the interplay disoreder-interactions:**

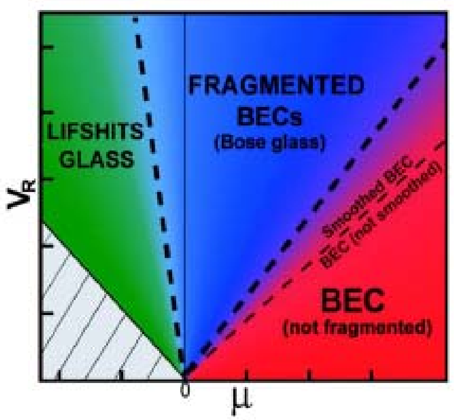


FIG. 1 (color online). Schematic quantum-state diagram of an interacting ultracold Bose gas in 1D disorder. The dashed lines represent the boundaries (corresponding to crossovers) which are controlled by the parameter $\alpha_R = \hbar^2/2m\sigma_R^2 V_R$ (fixed in the figure, see text), where V_R and σ_R are the amplitude and correlation length of the random potential. The hatched part corresponds to a forbidden zone ($\mu < V_{\min}$).

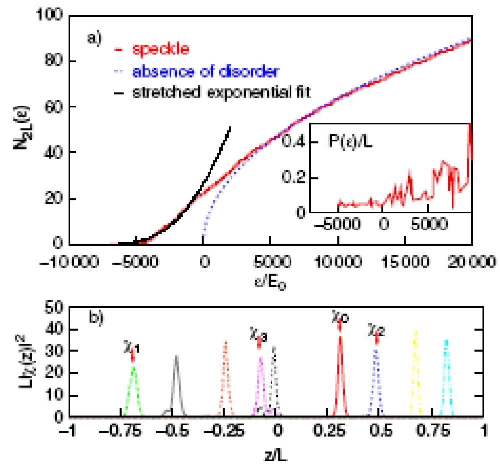


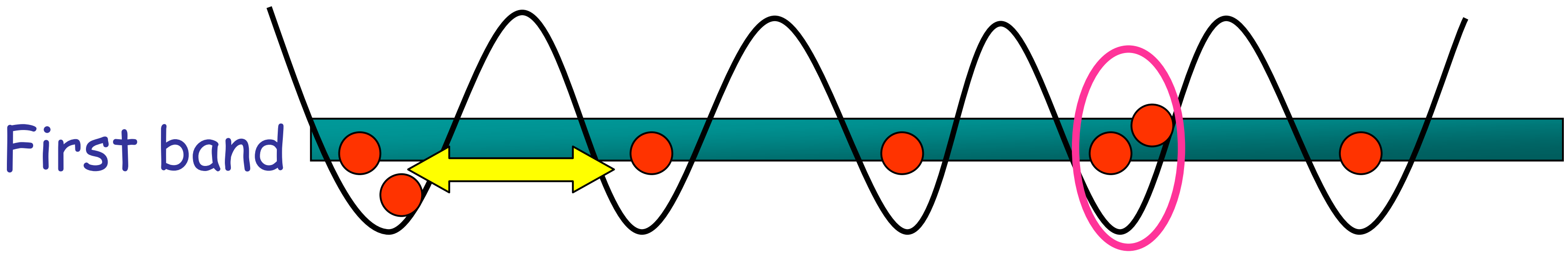
FIG. 2 (color online). (a) Cumulative density of states of single particles in a speckle potential with $\sigma_R = 2 \times 10^{-3}L$ and $V_R = 10^4 E_0$, where $E_0 = \hbar^2/2mL^2$ ($V_{\min} = -V_R$). Inset: Participation length [25]. (b) Low-energy Lifshits eigenstates. For the considered realization of disorder, $\epsilon_0 \simeq -5 \times 10^3 E_0$.

$$|\Psi\rangle = \prod_{\nu \geq 0} (N_\nu !)^{-1/2} (b_\nu^\dagger)^{N_\nu} |\text{vac}\rangle,$$

Lifshits glass

where $b_\nu^\dagger$ is the creation operator in the state $\phi_\nu(\rho)\chi_\nu(z)$

Let us now turn to lattices, but before talkin´ about disorder, let us define remind us about possible orders in an optical lattice with atoms loaded on it.



Tunneling

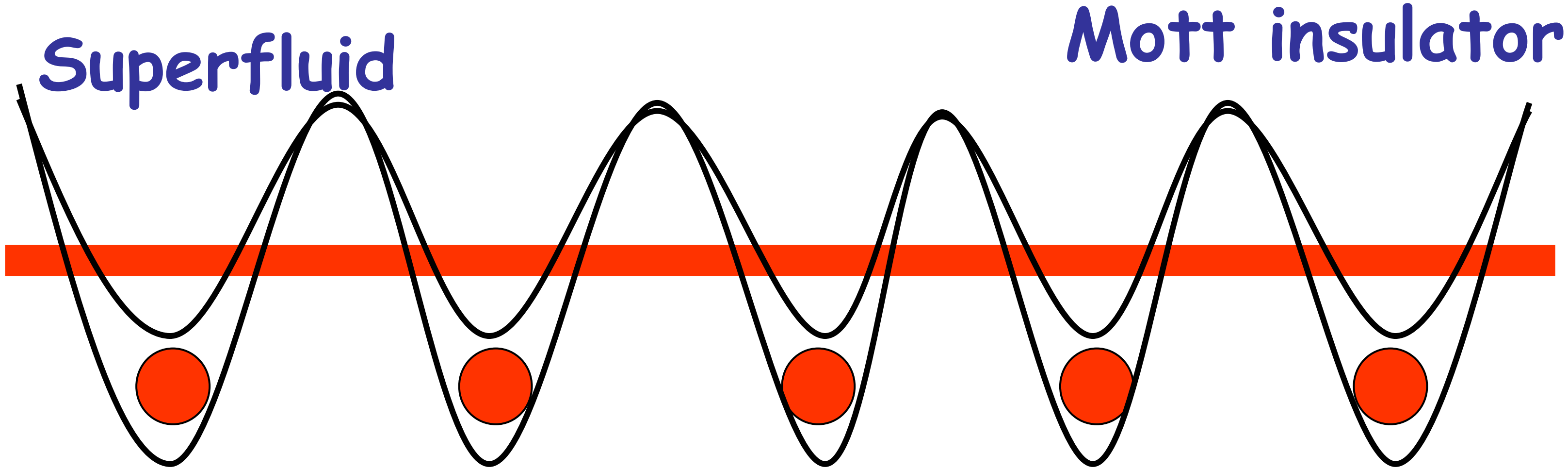
On site interactions

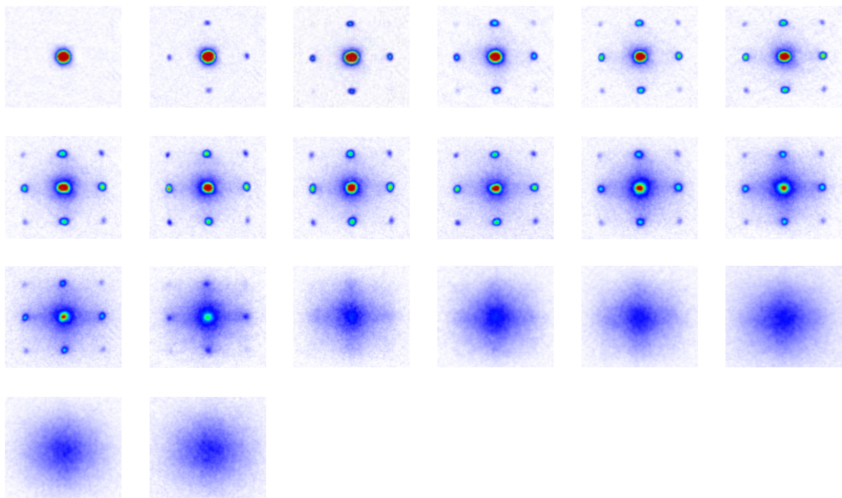
Bose-Hubbard model

$$H = \frac{1}{2} U \sum_i n_i (n_i - 1) - \frac{1}{2} J \sum_{<ij>} b_i^{+} b_j + h.c. + \mu \sum n_i$$

Bose gas in an optical lattice

Idea: D. Jaksch, C. Bruder, J.I. Cirac, C.W. Gardiner and P. Zoller





By courtesy of M. Greiner, I. Bloch, O. Mandel, and T. Hänsch

Anderson localization versus repulsive interactions

- Renormalization group analysis based on bosonization approach in homogeneous systems (T. Giamarchi and H.J. Schulz, PRB 37, 326 (1988) shows that in 1D arbitrarily small disorder localizes (Anderson-Bose glass for bosons), as well as an arbitrarily weak periodic potential (lattice, Mott insulator) – see the wonderfull book of Thierry Giamarchi and refs. therein.

- In higher d we expect competition between superfluid (SF), Mott insulator (MI), and Bose glass (BG) (see the seminal work of M.P.A. Fisher *et al*. PRB 40, 546 (1989).

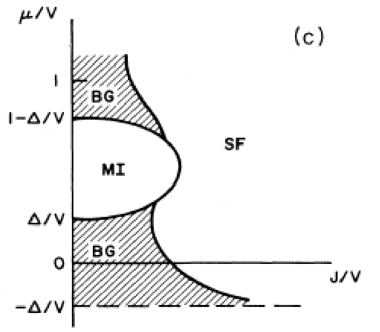


FIG. 2. Possible zero-temperature phase diagrams for the lattice boson model (2.1) with weak bounded disorder, $\Delta/V < \frac{1}{2}$. Figure 2(a), where the transition to superfluidity occurs only from the insulating, gapless Bose glass phase (BG), is argued in the text to be the correct phase diagram.

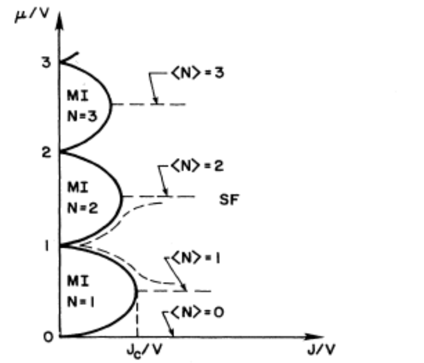
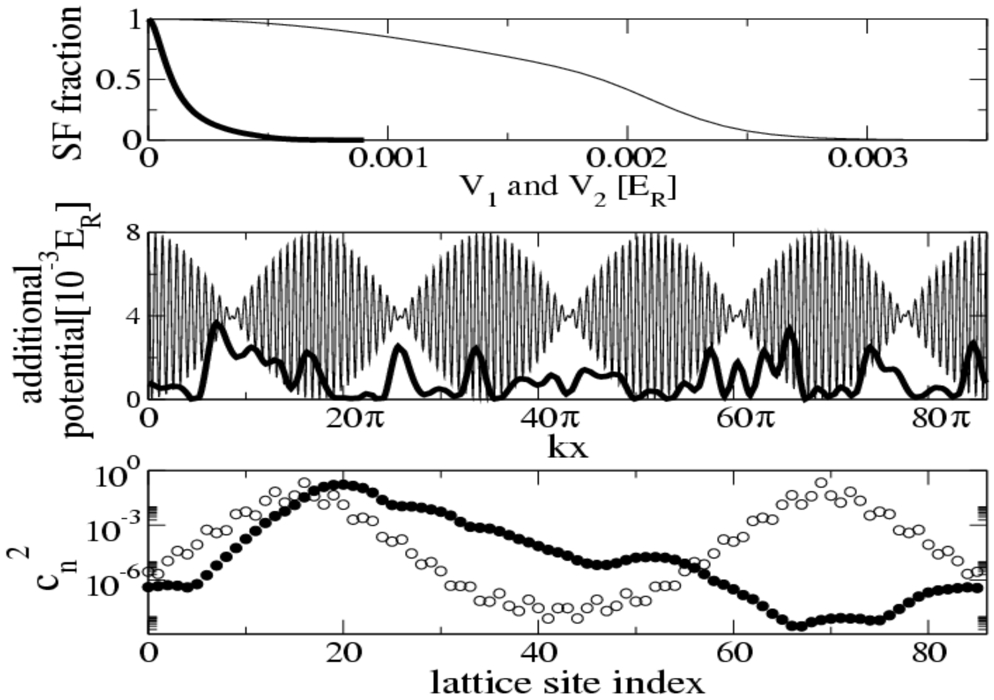


FIG. 1. Zero-temperature phase diagram for the lattice model of interacting bosons, (2.1), in the absence of disorder. For an integer number of bosons per site the superfluid phase (SF) is unstable to a Mott insulating (MI) phase at small J/V.

Creating Anderson glass in a disordered optical lattice

$$H = -\Sigma_{<ij>} (J b^{\dagger}_i b_j + h.c.) + \Sigma_i h_i b^{\dagger}_i b_i + \Sigma_i U n_i (n_i - 1)/2$$



Description:

i) **Bose-Hubbard model with random on-site energies**

ii) **negligible on-site interactions**

iii) **„boost“ method to calculate the SF fraction**

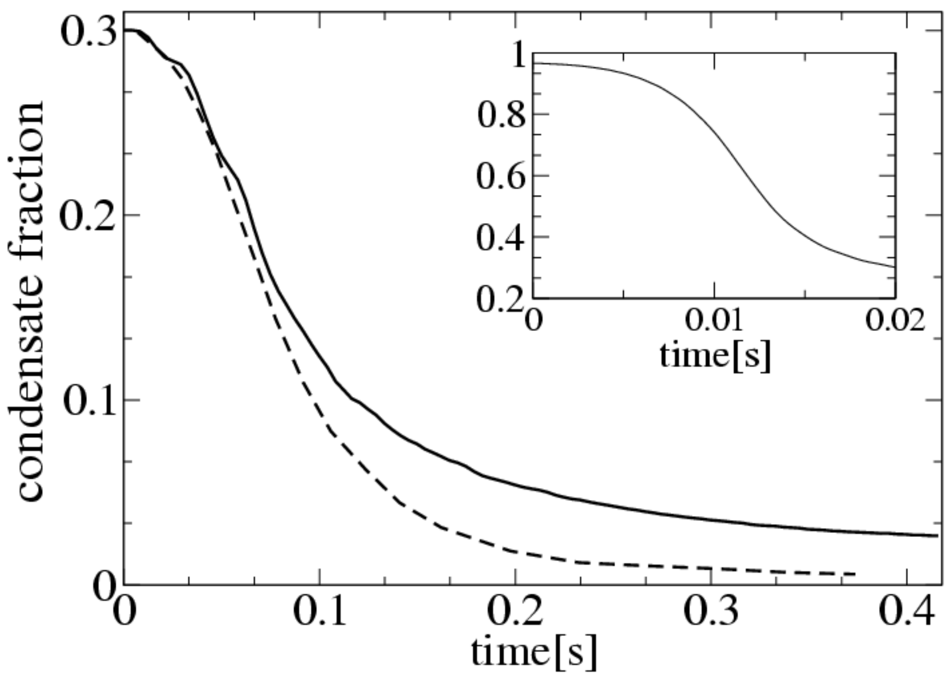
iv) **localization of the condensate wave functions**

B. Damski, J. Zakrzewski, L.Santos, P. Zoller, and M. Lewenstein,

Phys. Rev. Lett. **91**, 080403 (2003)

Bose glass in a disordered optical lattice

$$H = -\Sigma_{<ij>} (J(t) b^{\dagger}_i b_j + h.c.) + \Sigma_i h_i(t) b^{\dagger}_i b_i + \Sigma_i U(t) n_i (n_i - 1)/2$$



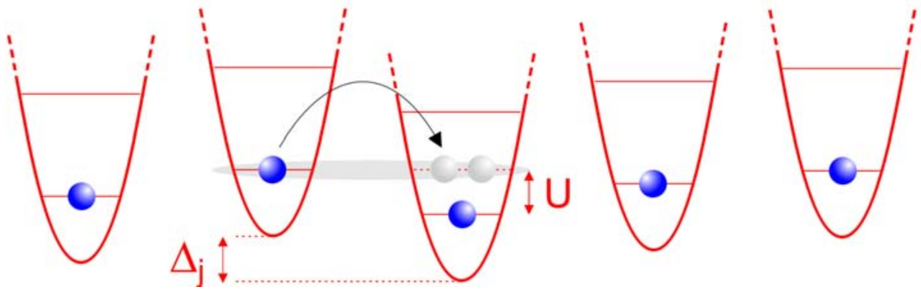
Description:

i) **time-dependent Bose-Hubbard model with random on-site energies**
ii) **growth of the disorder**
iii) **„boost“ method to calculate the SF fraction**
iv) **rapid decrease of the SF and the condensate fraction**

interacting bosons in a disordered optical potential (experiments)

Bose-Hubbard model with bounded disorder in the external potential

$$\hat{H} = -J\sum_{\langle i,j\rangle} \hat{a}_i^{\dagger}\hat{a}_j + \frac{U}{2}\sum_i \hat{n}_i\left(\hat{n}_i - 1\right) +$$



$$\varepsilon_j \in \left[-\Delta/2, +\Delta/2\right]$$

The phase of the system depends on the interplay between these energy terms

hopping energy	interaction energy	disorder
J	**U**	Δ

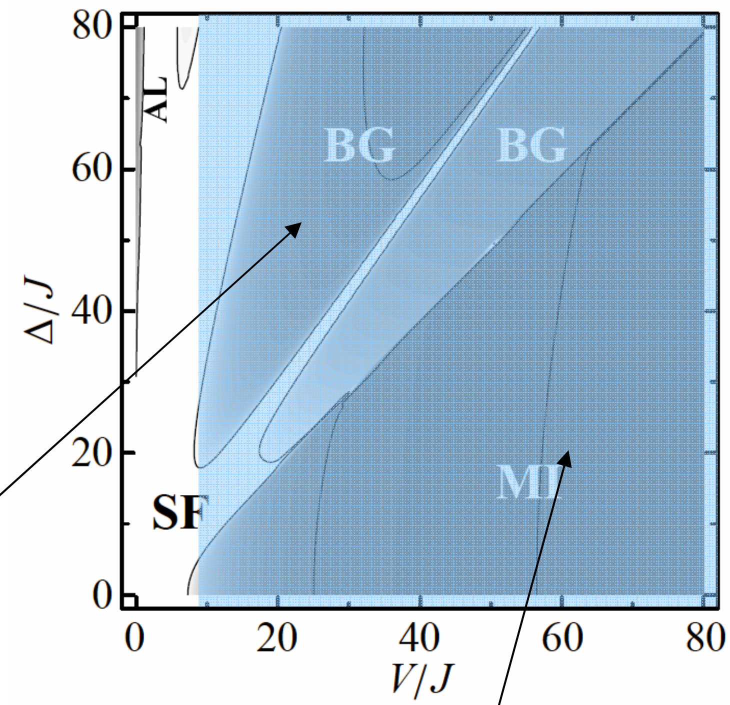
interacting bosons in a disordered optical potential

Phase diagram of 1D – homogeneous system

*(R. Roth and K. Burnett, PRA **68**, 023604 (2003))*

When the amplitude Δ of the disorder is big enough to fill the energy gap of the Mott insulator a new quantum phase appears: the **Bose Glass**

$$\Delta / U \approx 1$$



BOSE-GLASS PHASE (BG)

- No phase coherence
- Low number fluctuations

1. **No gap in the excitation spectrum**
2. Vanishing superfluid fraction
3. **Finite compressibility**

MOTT INSULATOR PHASE (MI)

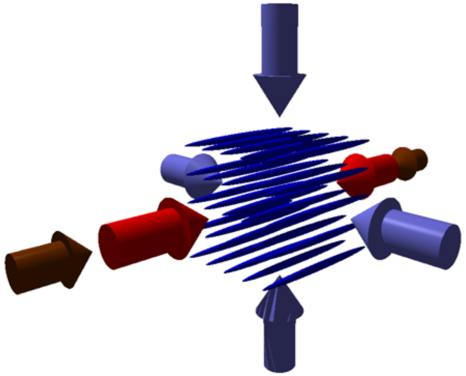
- No phase coherence
- Zero number fluctuations

1. **Gap in the excitation spectrum**
2. Vanishing superfluid fraction
3. **Vanishing compressibility**

strongly interacting bosons in a bichromatic optical lattice

Experimental configuration:1D system **and** 1D disorder

1D atomic systems + two colours along the tubes



Along y,z

λ_1 = 830 nm s_1 = 40

$J_y/h = J_z/h$ = 0.4 Hz

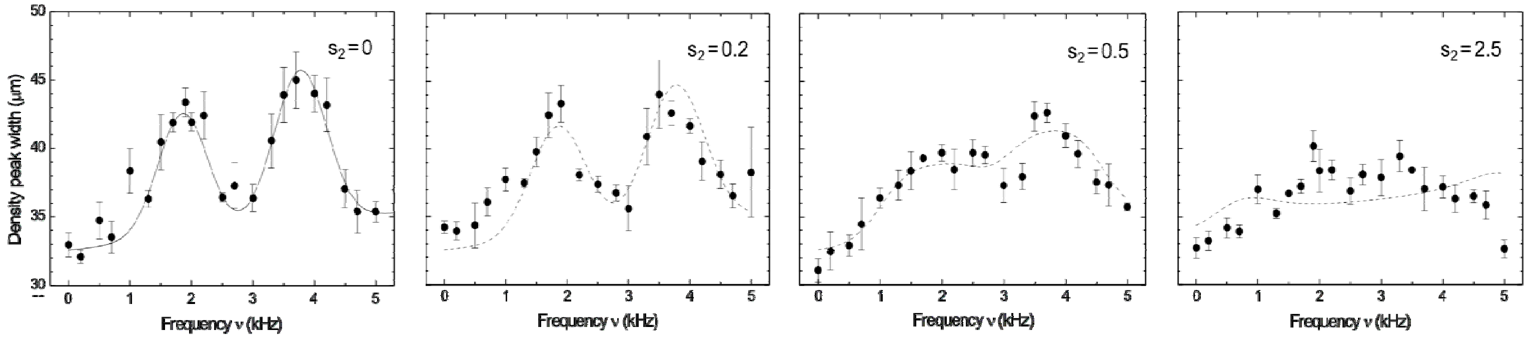
Along x

λ_1 = 830 nm s_1 < 20

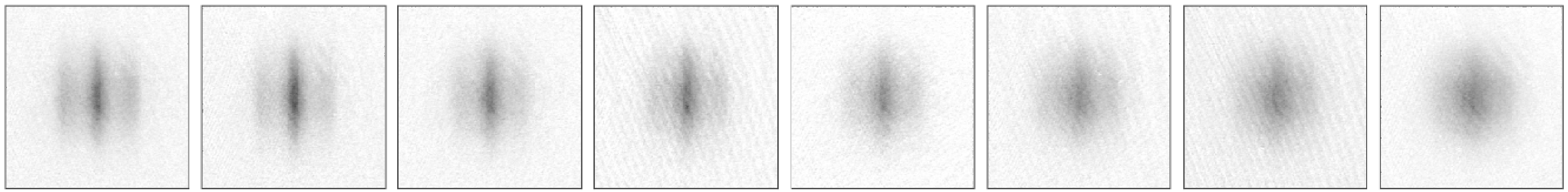
λ_2 = 1076 nm s_2 < 3

Observables:

Excitation spectrum (modulation of the lattice λ_1)



Phase Coherence (density profile after expansion)

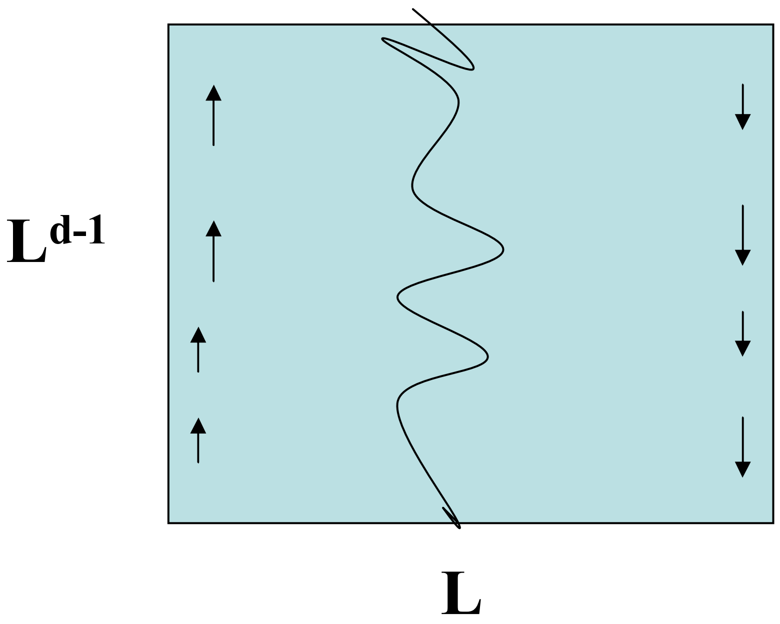


s_1=2 s_1=4 s_1=6 s_1=8 s_1=10 s_1=12 s_1=14 s_1=16

s_2=2.5

Random field spin models – Imry-Ma argument

- Do they magnetize spontaneously? Look at energies of domain (Ising), or Bloch (Heisenberg, XY) walls:



- Ising model $E_{dw} \sim L^{d-1}$

- Heisenberg, or XY model $E_{Bw} \sim L^{d-1} \cdot L \cdot \pi^2/L^2 \sim L^{d-2}$, since $\cos(s_i, s_j) = \cos(\varphi_{ij})$, where $\varphi_{ij} = \pi/L$

Random field spin models – Imry-Ma argument

- **Ergo, Ising model sensitive to boundaries for d>1; models with continuous symmetry sensitive for d>2 (no long range order for d≤2, Mermin-Wagner theorem)**

- **Random field $E_{RF} \sim hL^{d/2}$ ($\langle\langle h_i \rangle\rangle = 0$, $\langle\langle h_i^2 \rangle\rangle = h^2$)**

	pure	random field
	m>0, $0 \leq T < T_c$	m>0, $0 \leq T < T_c$
Ising	d>1	d>2
Cont. Symm.	d>2	d>4

Disorder (random field) induced order

in ultracold gases

Disorder induced order –
Breaking continuous symmetry with disorder

PHYSICAL REVIEW B 74, 224448 (2006)

Disorder versus the Mermin-Wagner-Hohenberg effect: From classical spin systems to ultracold atomic gases

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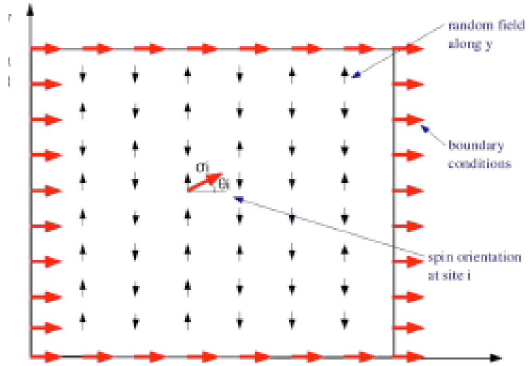
(Received 14 April 2006; revised manuscript received 27 October 2006; published 29 December 2006)

We propose a general mechanism of *random-field-induced order* (RFIO), in which long-range order is induced by a random field that breaks the continuous symmetry of the model. We particularly focus on the case of the classical ferromagnetic *XY* model on a two-dimensional lattice, in a uniaxial random field. We prove rigorously that the system has spontaneous magnetization at temperature $T=0$, and we present strong evidence that this is also the case for small $T>0$. We discuss generalizations of this mechanism to various classical and quantum systems. In addition, we propose possible realizations of the RFIO mechanism, using ultracold atoms in an optical lattice. Our results shed new light on controversies in existing literature, and open a way to realize RFIO with ultracold atomic systems.



PRL 98, 156801 (2007) PHYSICAL REVIEW LETTERS week ending 13 APRIL 2007

Randomness-Induced *XY* Ordering in a Graphene Quantum Hall Ferromagnet

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(Received 2 November 2006; published 10 April 2007)

Valley-polarized quantum Hall states in graphene are described by a Heisenberg O(3) ferromagnet model, with the ordering type controlled by the strength and the sign of the valley anisotropy. A mechanism resulting from electron coupling to the strain-induced gauge field, giving a leading contribution to the anisotropy, is described in terms of an effective random magnetic field aligned with the ferromagnet z axis. We argue that such a random field stabilizes the *XY* ferromagnet state, which is a coherent equal-weight mixture of the K and K' valley states. The implications such as the Berezinskii-Kosterlitz-Thouless ordering transition and topological defects with half-integer charge are discussed.

Ongoing polemics:
I.A. Fomin – G.E. Volovik
on ^{3}He-A in aerogel

Disorder induced order –
Breaking continuous symmetry with disorder

Disorder-Induced Order in Two-Component Bose-Einstein Condensates

A. Niederberger,[1] T. Schulte,[1,2] J. Wehr,[1,3] M. Lewenstein,[1,4] L. Sanchez-Palencia,[5] and K. Sacha[1,6]

We study two-component BEC coupled by ***random real*** Raman coupling

$$
\begin{aligned}
E \;=\; \int \mathrm{dr} \Big[& (\hbar^2/2m)|\nabla\psi_1|^2 + V(\mathbf{r})|\psi_1|^2 + (g_1/2)|\psi_1|^4 \\
& +(\hbar^2/2m)|\nabla\psi_2|^2 + V(\mathbf{r})|\psi_2|^2 + (g_2/2)|\psi_2|^4 \\
& +g_{12}|\psi_1|^2|\psi_2|^2 + (\hbar\Omega(\mathbf{r})/2)\,(\psi_1^*\psi_2 + \psi_2^*\psi_1)\Big], \quad (3)
\end{aligned}
$$

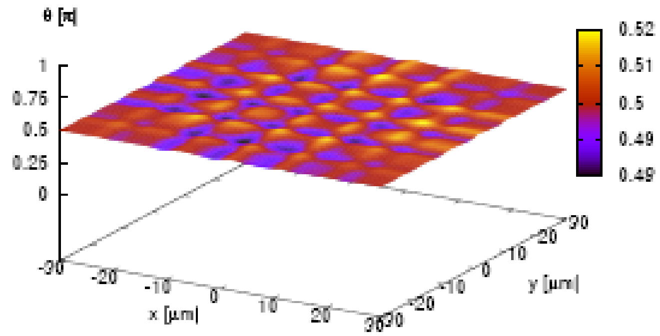

Figure 3: RFIO effect in a 3D two-component BEC trapped in a spherically symmetric harmonic trap with trapping frequency $\omega = 2\pi \times 30$Hz. The total number of atoms is $N = 10^5$, the scattering lengths are the same as in Fig. 2 with quasi-random Raman coupling $\Omega(x,y,z) \propto \sum_{u\in\{x,y,z\}}[\sin(2\pi u/\lambda_R + \varphi_u^1) + \sin(2\pi u/(1.71\lambda_R) + \varphi_u^2)]$ with $\lambda_R = 4.68\mu$m and $\hbar\Omega_R \simeq 5\times10^{-3}\mu$. The plot shows the relative phase θ in the plane $z = 0\mu$m in units of π.

CONCLUSIONS (The Tragedy of Hamlet, by Shakespeare):

- *There are more thing in heaven and earth, Horatio, than are dreamt of in your philosophy.*

Wow!!!

- **See: Ultracold atoms in optical lattices: Mimicking condensed matter and beyond, M. Lewenstein, A. Sanpera, V. Ahufinger, B. Damski, A. Sen (De) and U. Sen, 130 p., over 800 refs., cond-mat/06006771**