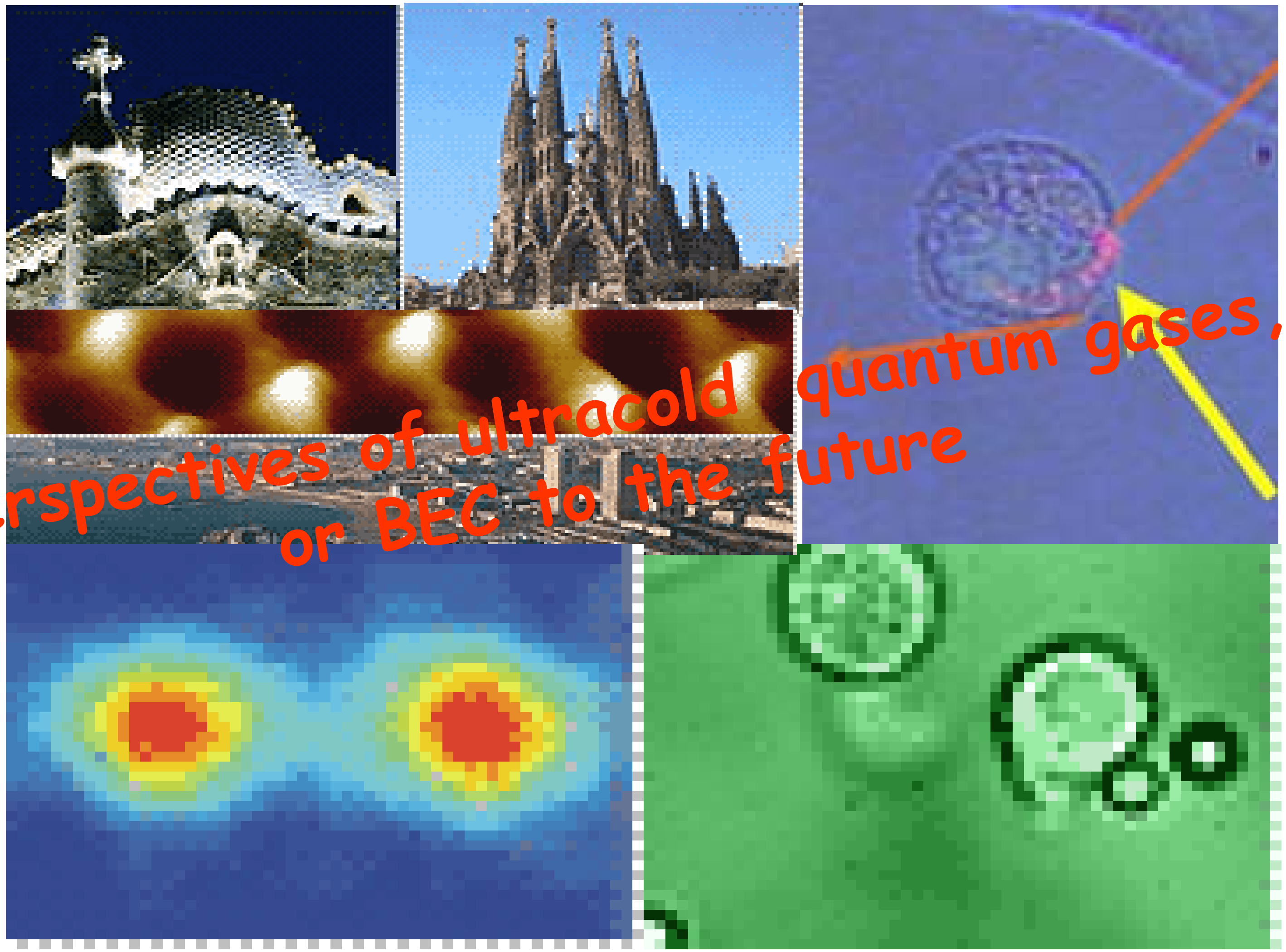
Perspectives of ultracold quantum gases, or BEC to the future



ICFO
Institut de Ciències Fotòniques

*icrea

scala

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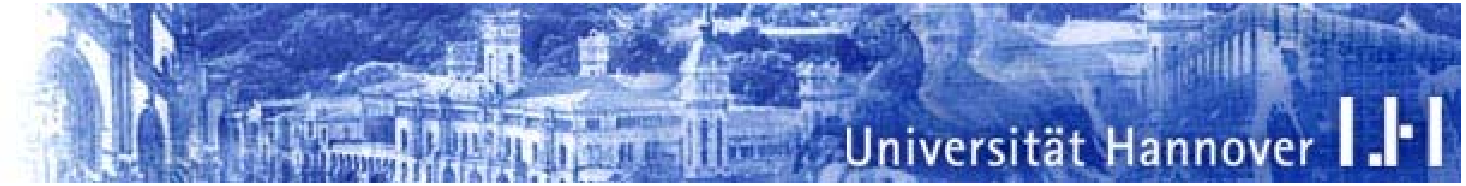

Barcelona – Quantum Optics Theory

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Geza Toth,
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Veronica Ahufinger (ICREA junior, UAB),
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Z. Idziaszek (ten. track, Warsaw),
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M. Baranov (res. assoc., Amsterdam),
P. Pedri (postdoc, Orsay),
O Gühne (postdoc, Innsbruck).
P. Hyllus (postdoc, Hannover)
A.Kantian (PhD, Innsbruck), T. Meyer (PhD, Düsseldorf),
A. Cojuhovschi (PhD, Hannover),

Barcelona – Quantum Optics Theory

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Univ. Siegen - C. Wunderlich
Univ. Hamburg - K. Sengstock, K. Bongs
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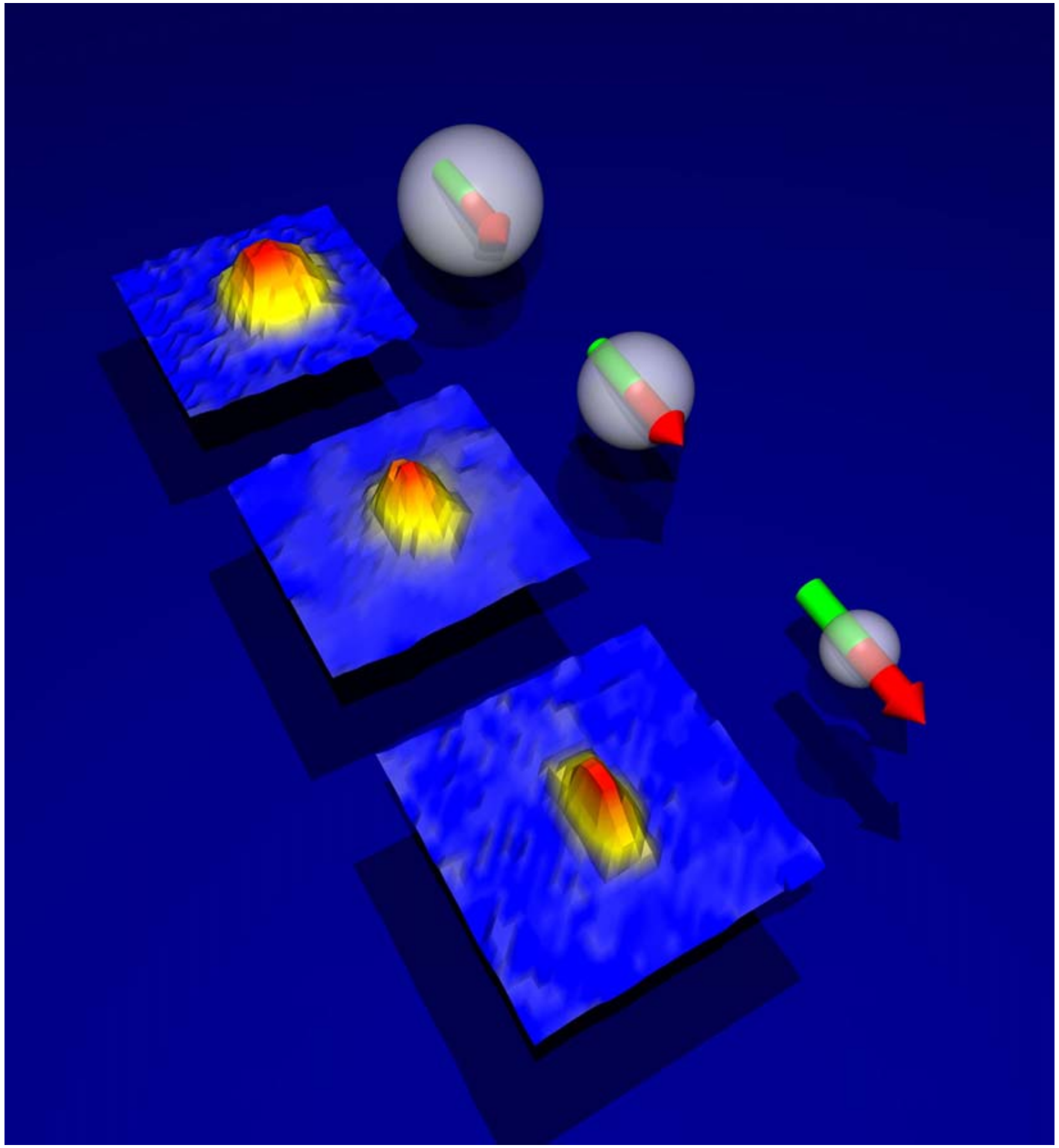
N. Bohr. Inst., Kopenhagen - E. Polzik
ICFO – J. Eschner, M. Mitchel, J. Biegert

Outline

- Introduction: my personal hit list of achievements/open problems
- BCS-BEC crossover
- Ultracold trapped dipolar gases ☻
- Ultracold spinor gases
- Ultracold disordered gases ☻
- Ultracold frustrated gases
- Atom chips and cavity QED
- Experimental methods ☻
- Theoretical methods ☻
- Varia ☻
- New review articles ☻
- Ultracold gases in “artificial” magnetic fields
- Ultracold gases and quantum information
- Ultracold low dimensional gases

Ultracold dipolar gases

Strong dipolar effects in - and Rydberg excitation of - a BEC



Tilman Pfau
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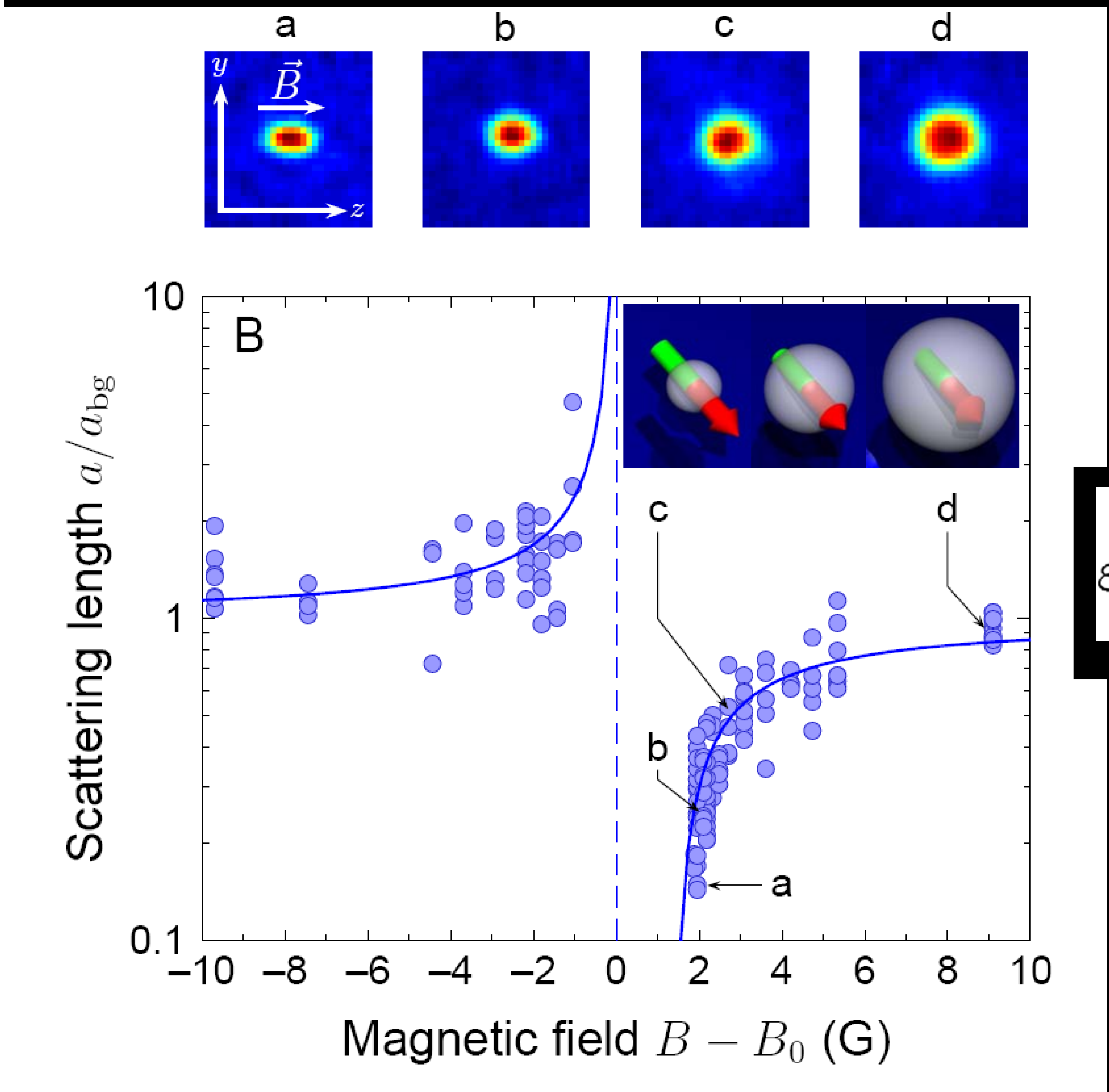
CO.CO.MAT

5. Physikalisches Institut

STUTTGART

Strong dipolar effects

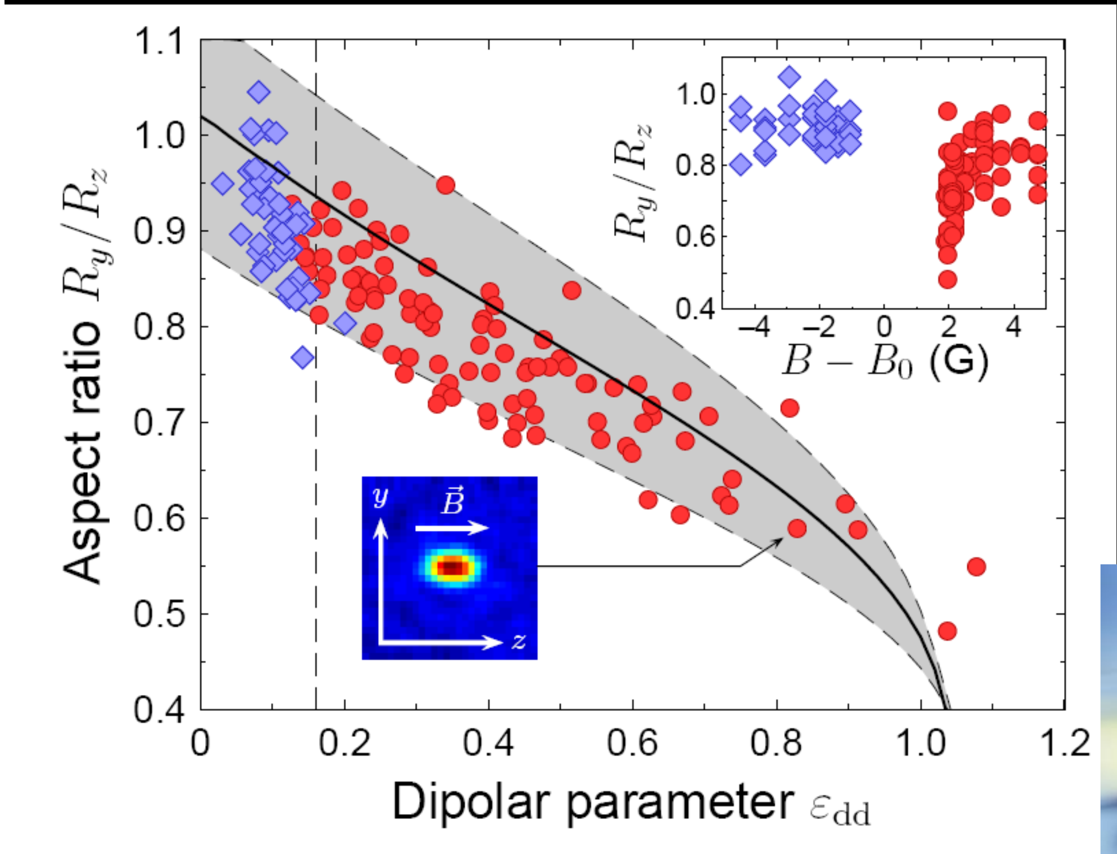


dipolar

$$\varepsilon_{dd} = \frac{\mu_0 \mu^2 M}{12\pi\hbar^2 a}$$

contact

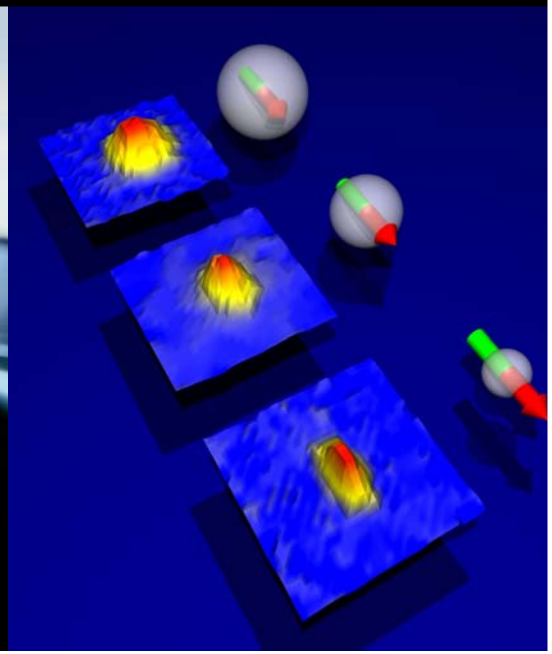
A quantum ferrofluid



dipolar

$$\varepsilon_{dd} = \frac{\mu_0 \mu^2 M}{12\pi\hbar^2 a}$$

contact

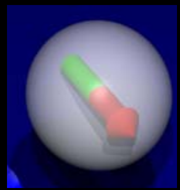


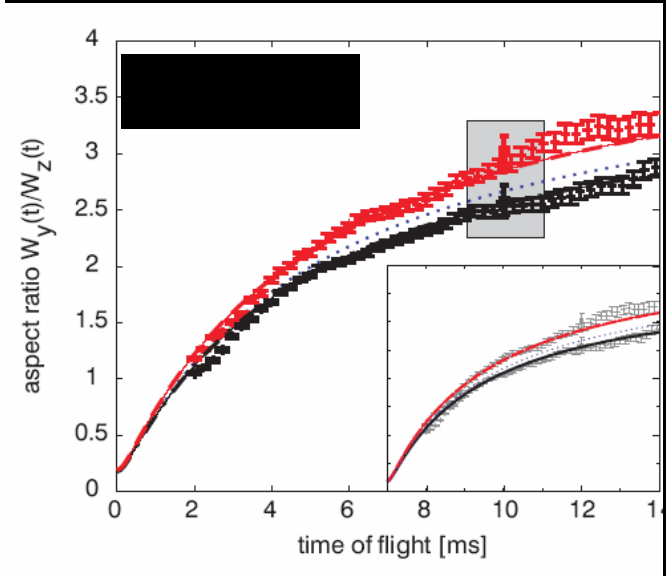
Th. Lahaye et al.; Nature in press

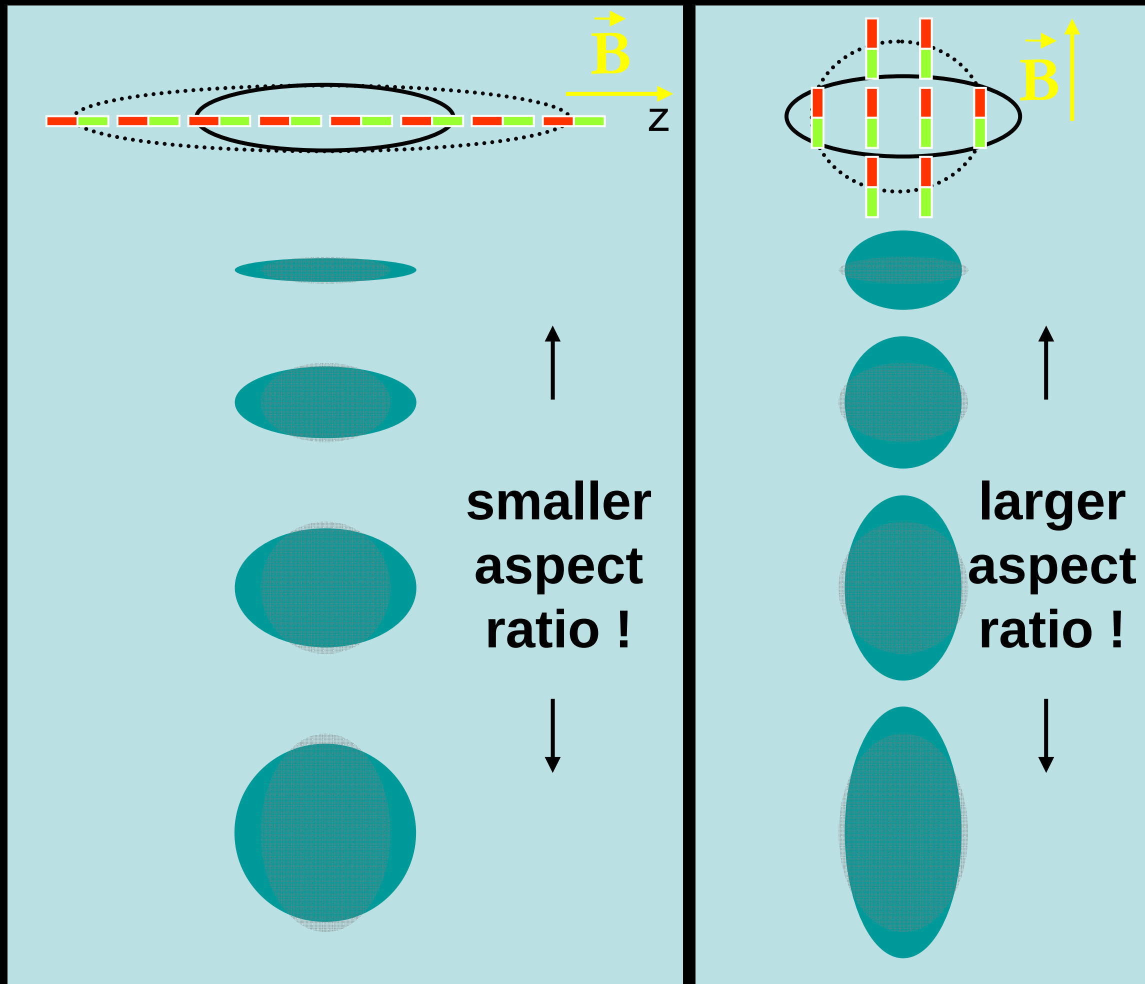
A quantum ferrofluid

First perturbative dipolar effects:

J. Stuhler, A. Griesmaier, T. Koch, M. Fattori, S. Giovanazzi, P. Pedri
L. Santos, T. Pfau
PRL **95**, 150406 (2005)







S. Giovanazzi, A. Görlitz, T.P.
J. Opt. B **5**, 208 (2003)

A quantum ferrofluid

First perturbative dipolar effects:

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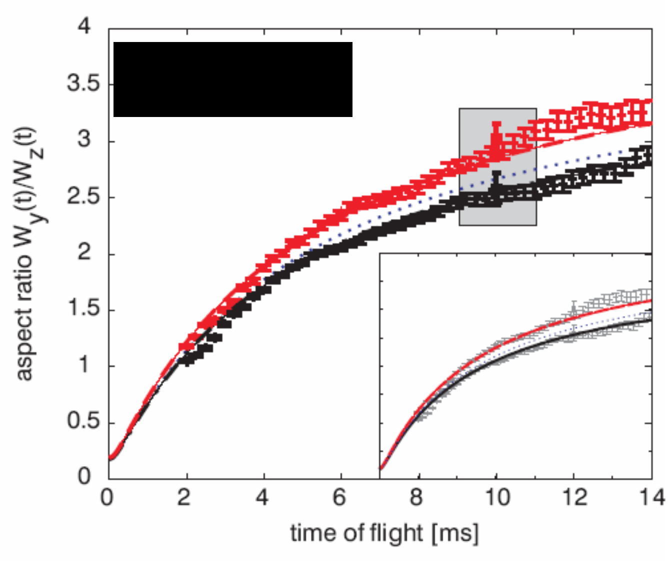
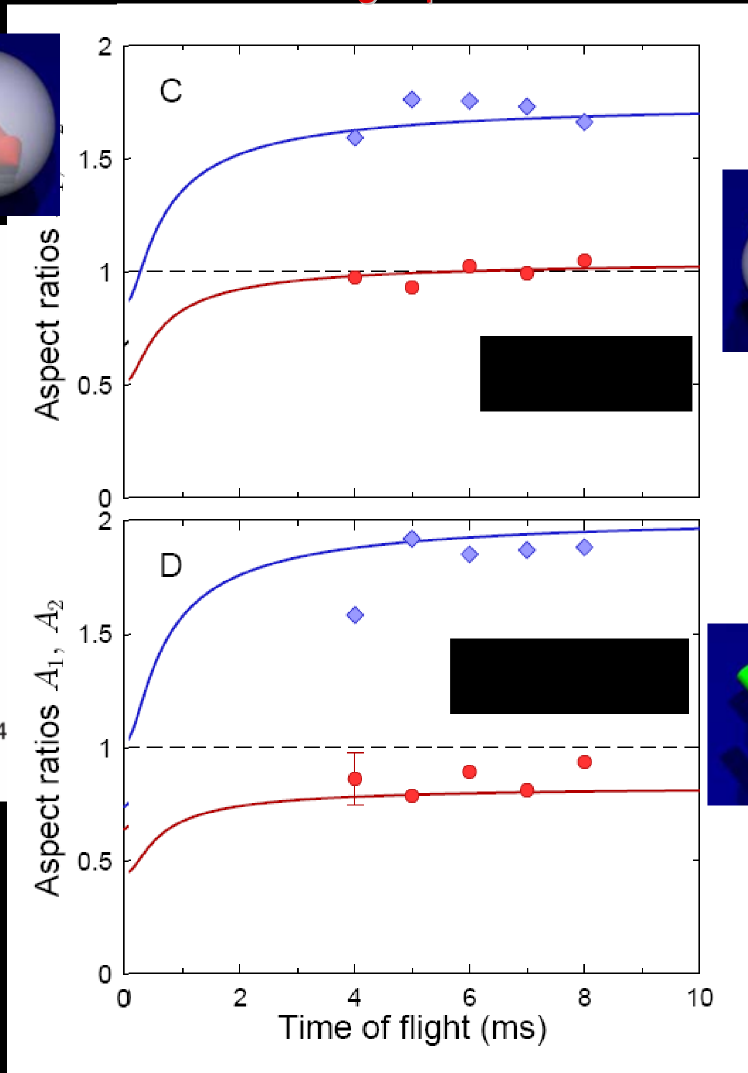
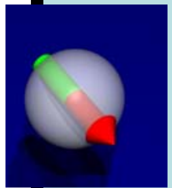
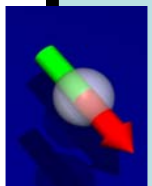
PRL **95**, 150406 (2005)

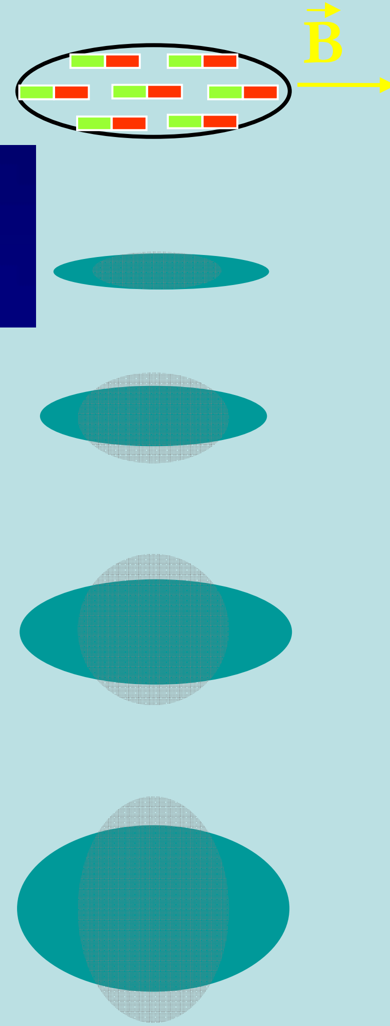


NEW: strong dipolar effects:









Ultracold Heteronuclear Molecules

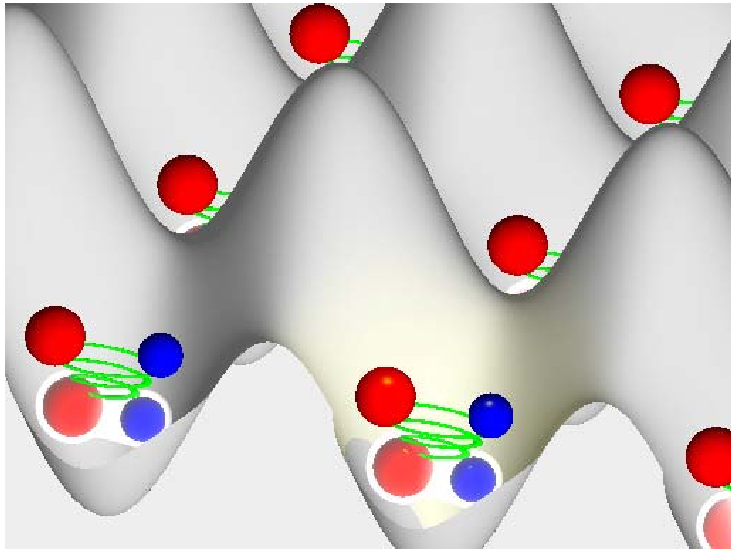
Universität Hamburg

AG Sengstock

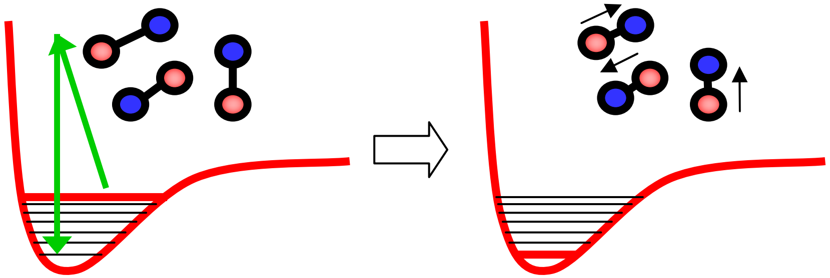
Ultracold chemistry:

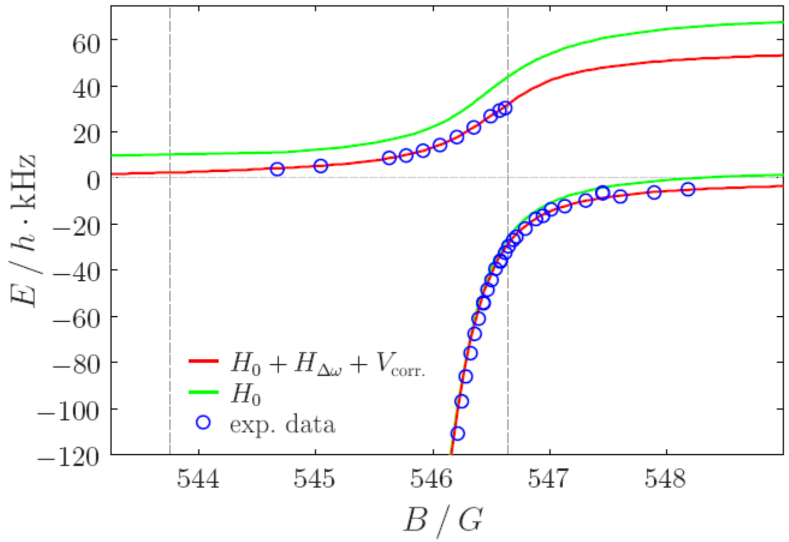
First formation of ultracold heteronuclear molecules in an optical lattice using a $^{40}K/^{87}Rb$ mixture and rf association.

C. Ospelkaus, S. Ospelkaus, L. Humbert, P. Ernst, K. Sengstock and K. Bongs; Phys. Rev. Lett. 97, 120402 (2006)



next step: transfer to low internal state
-> quantum gas with strong dipolar interactions





Binding energy analysis: cond-mat/0703322

Dipolar Bose gas in an optical lattice: Toward quantum memories?

Ch. Menotti, Ch. Trefzger, and M. Lewenstein

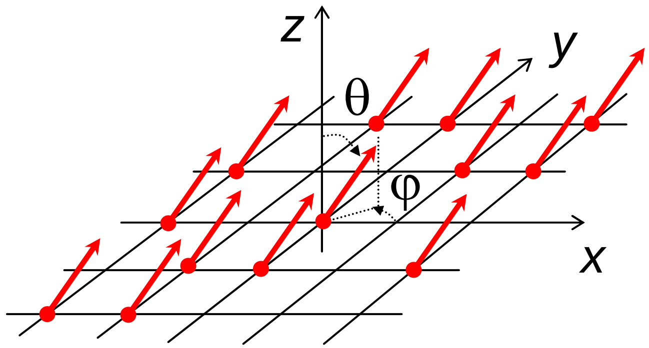
Phys. Rev. Lett. **98**, 235301 (2007)

Dipolar bosons in a 2D optical lattice

– long-range anisotropic interaction

A. Griesmaier, J. Werner, S. Hensler, J. Stuhler, and T.Pfau, Phys. Rev. Lett. 94, 160401 (2005) ;
J. Stuhler, A.Griesmaier, T. Koch, M. Fattori, T. Pfau, S. Giovanazzi, P. Pedri, and L. Santos,
Phys. Rev. Lett. 95, 150406 (2005) .

– many control parameters: U, D, θ, φ



– novel quantum phases
(checkerboard, supersolid)

see e.g.:

G.G. Batrouni and R.T. Scalettar, PRL 84, 1599 (2000);
K. Góral, L. Santos and M. Lewenstein, PRL 88, 170406 (2002);
D.L. Kovrizhin, G. Venketeswara Pai and S. Sihna, EPL 72, 162 (2005);
P. Sengupta, L. P. Pryadko, F. Alet, M. Troyer and G. Schmid, PRL 94, 207202 (2005);

– existence of metastable states?

Extended Bose-Hubbard model

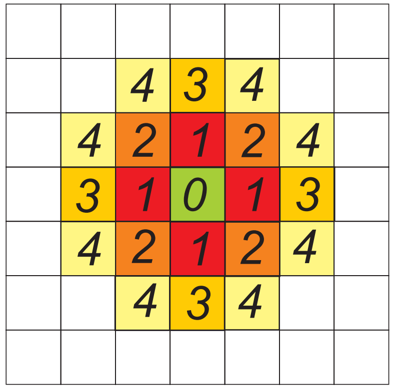
$$H = \sum_i \frac{U}{2} n_i (n_i - 1) + \sum_{\vec{\ell}} \sum_{\langle ij \rangle_{\vec{\ell}}} \frac{U_{\vec{\ell}}}{2} n_i n_j - \frac{J}{2} \sum_{\langle ij \rangle} \left(a_i^+ a_j + a_i a_j^+ \right) - \sum_i \mu n_i$$

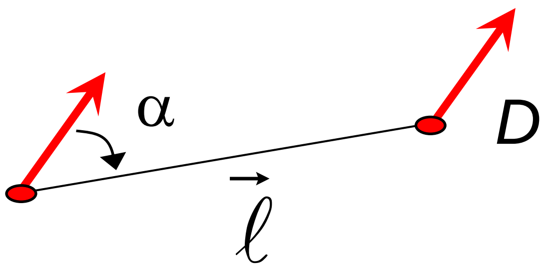
J = tunneling

μ = chemical potential

U = on-site interaction

$U_{\vec{\ell}}$ = dip.-dip. at relative distance $\vec{\ell}$





$$U_{\vec{\ell}} = D^2 \frac{1 - 3\cos(\alpha_{\vec{\ell}})^2}{\ell^3}$$

Dipolar lattice gas: Ground states, metastable state

PRL 98, 235301 (2007) PHYSICAL REVIEW LETTERS week ending 8 JUNE 2007

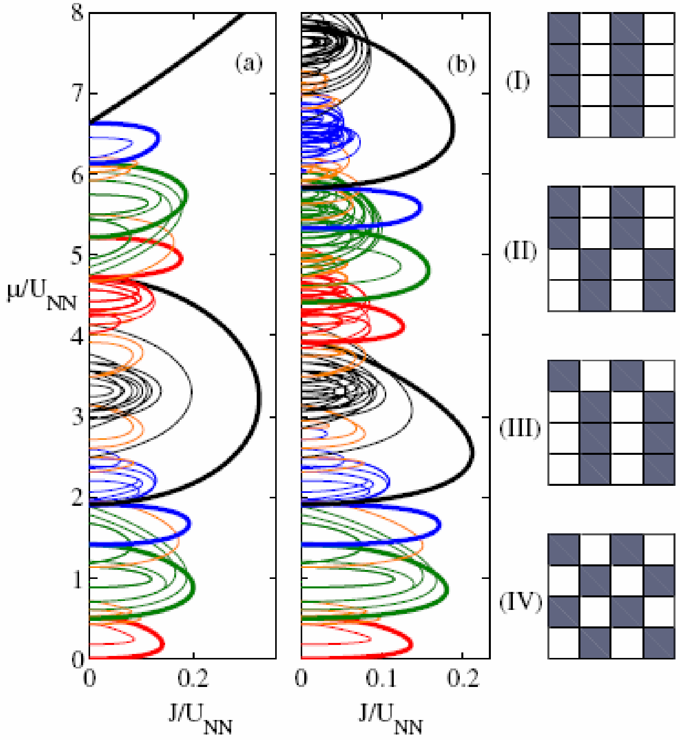


FIG. 1 (color online). Phase diagram for weak and strong dipole-dipole interaction: $U/U_{\rm NN} = 20$ (a) and $U/U_{\rm NN} = 2$ (b). The thick lines are the ground state lobes, found (for increasing chemicals potential) for filling factors equal to all multiples of 1/8. The thin lines of the same color are the metastable states at the same filling factor. The other lines are for filling factors equal to odd multiples of 1/8 [22]; some of the metastable configurations at filling factor 1/2 (I to III) and corresponding ground state (IV).Empty sites are light and sites occupied with 1 atom are dark.

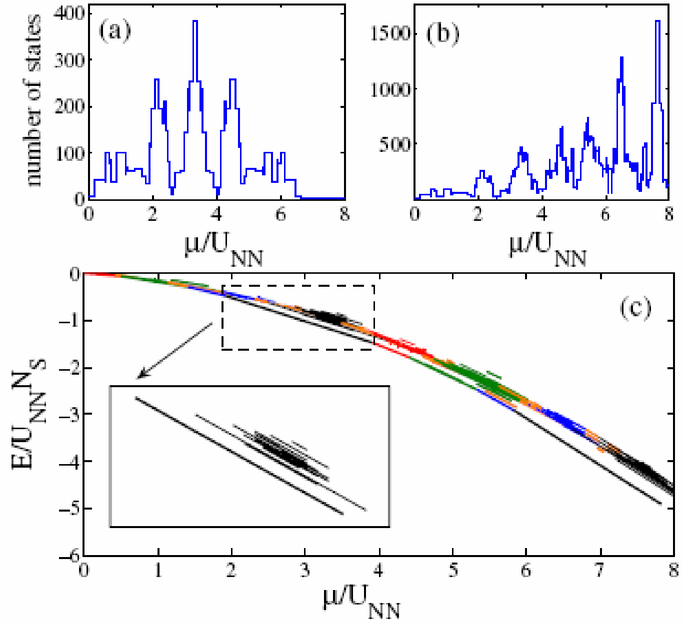


FIG. 2 (color online). Number of metastable states as a function of μ for weak and strong dipole-dipole interaction: (a) $U/U_{\rm NN} = 20$ and (b) $U/U_{\rm NN} = 2$. (c) Energy of the ground (thick line) and metastable states (thin lines) as function of μ for strong dipole-dipole interaction ($U/U_{\rm NN} = 2$). The inset shows the energy levels at filling factor 1/2.

Metastable states: do they play a role in cooling dynamics? Are they reachable?

Dipolar lattice gas: The fate of metastable states

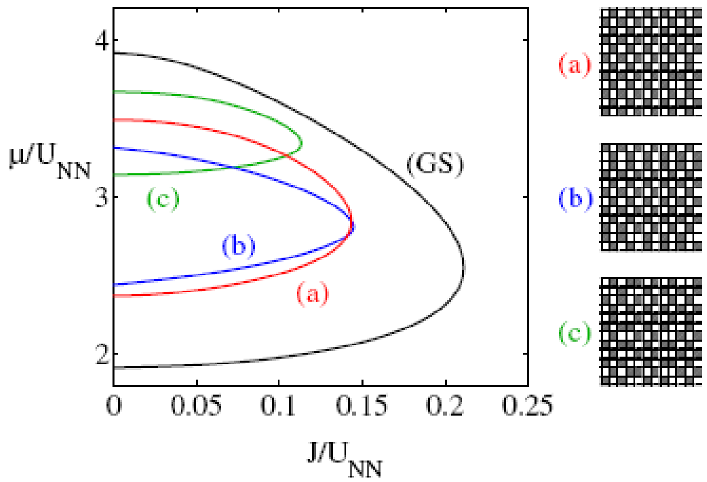


FIG. 3 (color online). Phase diagram for the ground state at filling factor 1/2 and three metastable insulating configurations for $U/U_{\mathrm{NN}} = 2$.

They appear spontaneously and frequently in cooling dynamics!
But, using superlattice techniques they can be "prepared on demand"!
They lifetimes are long, according to generalized instanton theory!
Quantum memories?

They can be unambigiously detected using noise correlations spectroscopy!!!

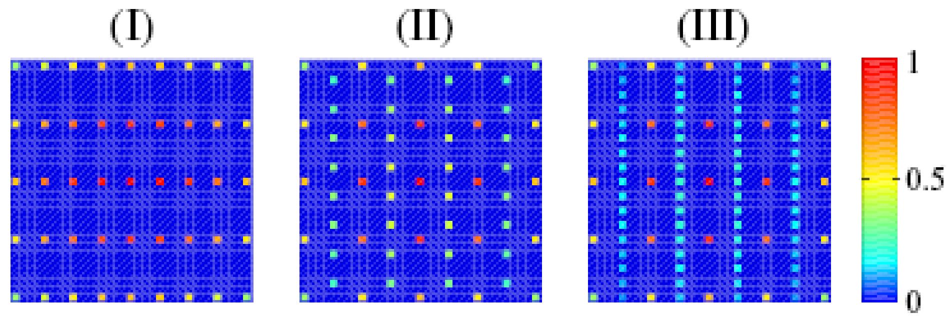
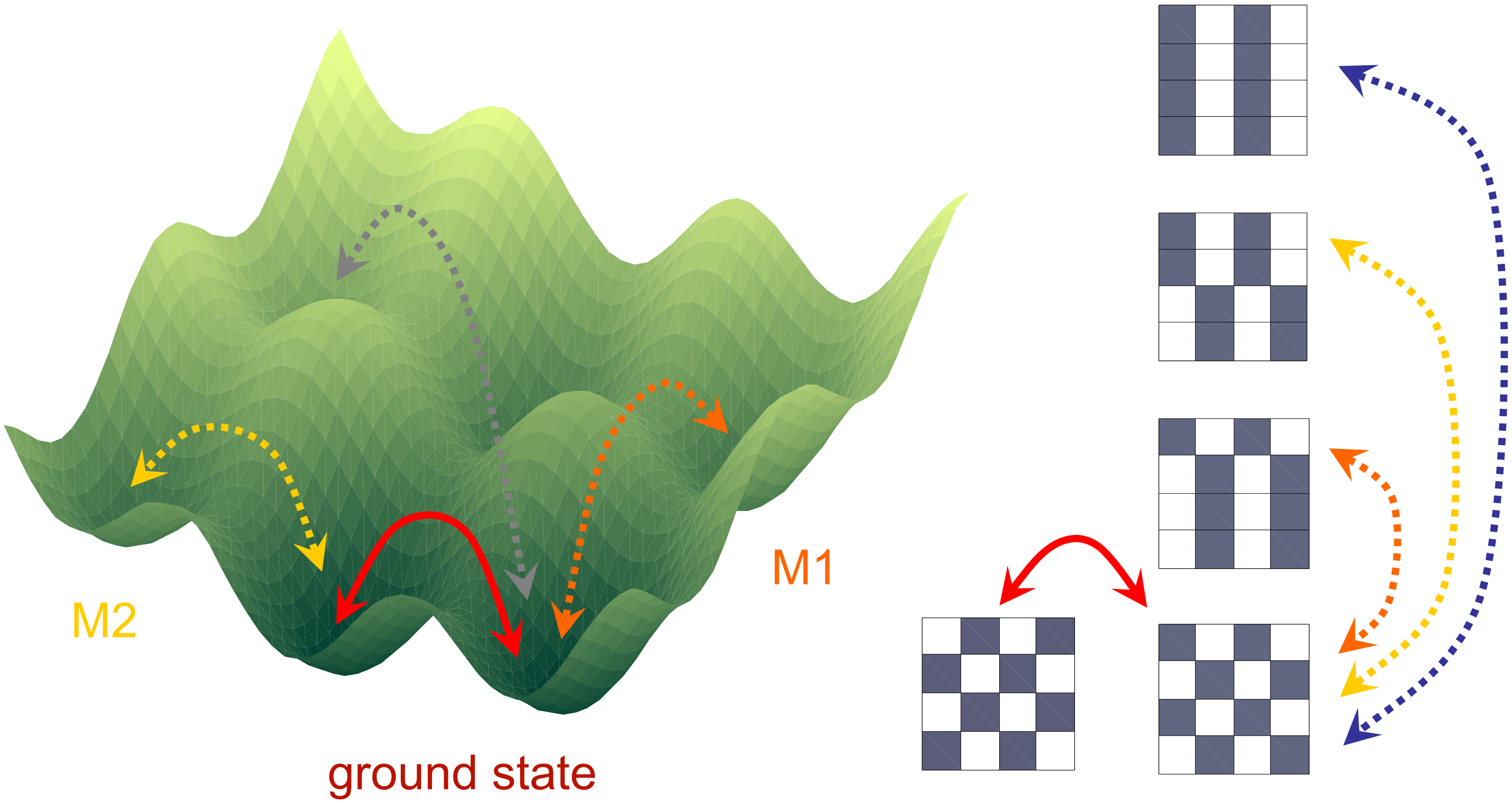
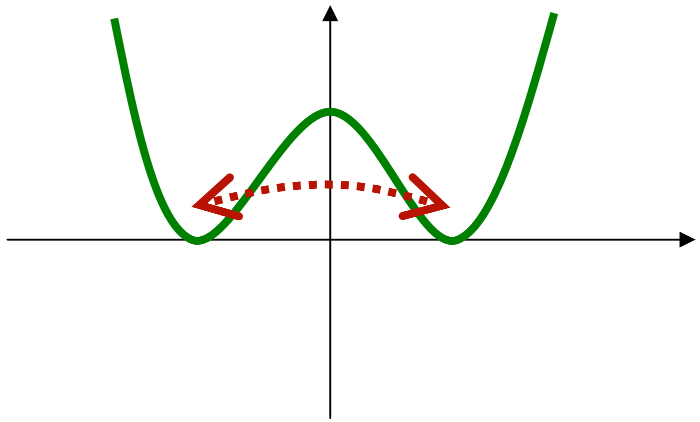


FIG. 4 (color online). Normalized spatial noise correlation patterns for configurations (I) to (III) in Fig. 1 [23].

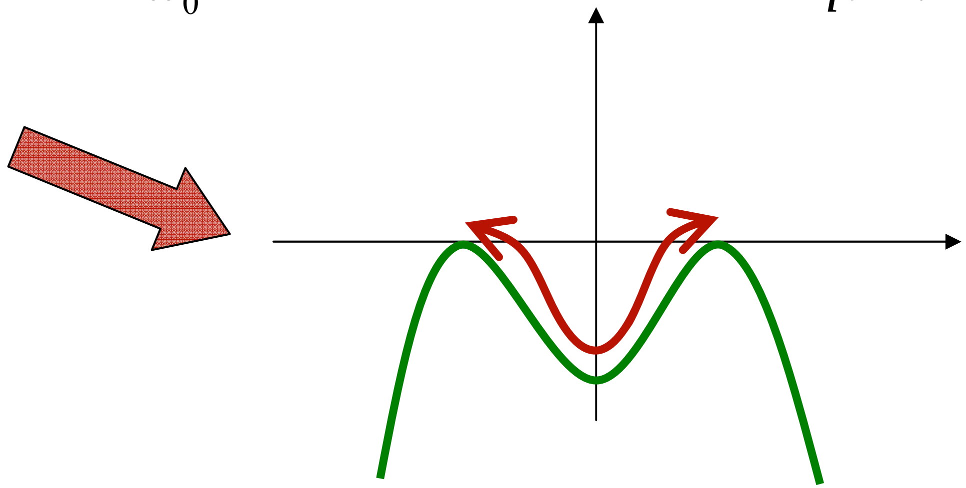
Energy landscape: tunneling events



Path integral in imaginary time

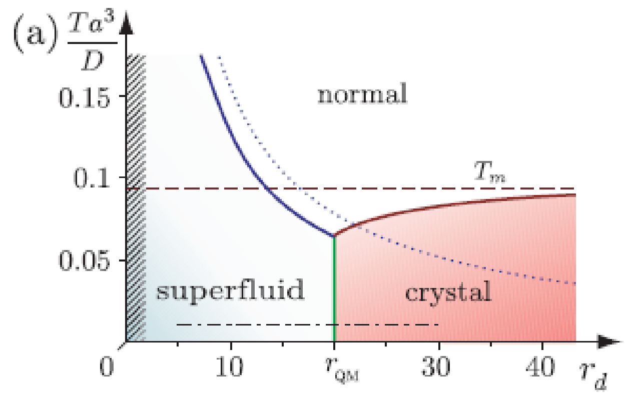


$$T \approx \frac{1}{\omega_0} \exp[S_0] \quad \textit{with} \quad S_0 = \int \frac{L(q)}{dq/d\tau} dq$$



- Our procedure:
  - write the Lagrangian in imaginary time
  - parametrise the transition via a 1-parameter ansatz
  - calculate the action

Wigner crystallisation of trapped dipolar gases



G.E. Astrakharchik, J. Boronat, J. Casulleras, I.L. Kurbakov, and Yu.E. Lozovik
Weakly interacting two-dimensional system of dipoles: limitations of mean-field theory, arXiv:cond-mat/0612691

G.E. Astrakharchik, J. Boronat, I.L. Kurbakov, and Yu.E. Lozovik, Quantum phase transition in a two-dimensional system of dipoles, Phys. Rev. Lett. 98, 060405 (2007).

H.P. Büchler, E. Demler, M. Lukin, A. Micheli, N. Prokof'ev, G. Pupillo, and P. Zoller
Strongly correlated 2D quantum phases with cold polar molecules: controlling the shape of the interaction potential , Phys. Rev. Lett. 98, 060404 (2007).

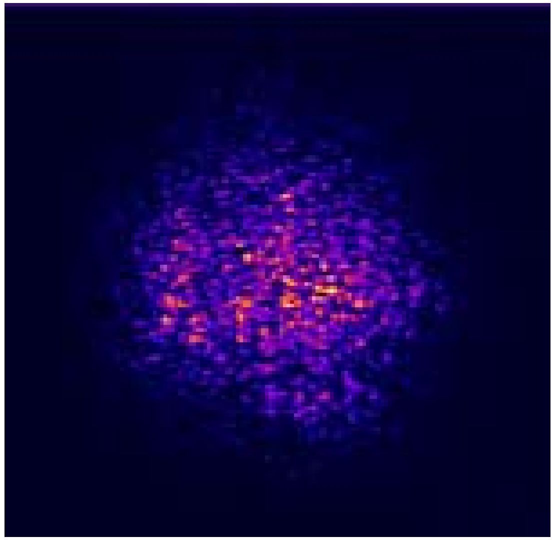
R. Citro, E. Orignac, S. De Palo, and M.-L. Chiofalo, Evidence of Luttinger liquid behavior in one-dimensional dipolar quantum gases, Phys. Rev. A 75, 051602 (2007).

A.S.Arkhipov, G.E.Astrakharchik, A.V.Belikov, Yu.E.Lozovik, Ground-state properties of a one-dimensional system of dipoles, arXiv:cond-mat/0505700.

Ultracold disordered gases

our approach to controlled disordered optical potential

speckle pattern



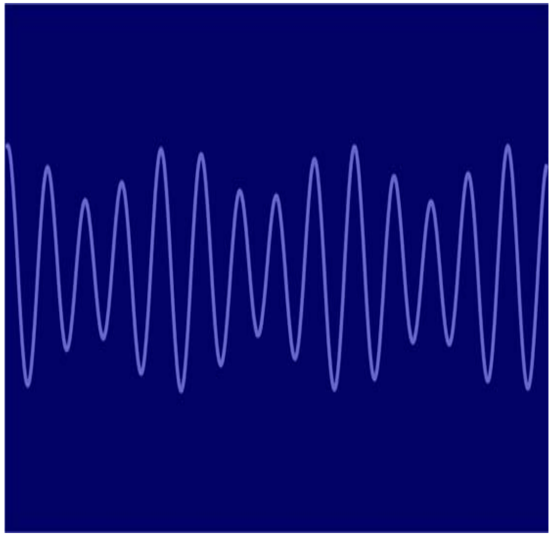
✓ random potential

✘ large length scale in our set-up (several μm)

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

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

bichromatic lattice



✓ quasiperiodic potential

✓ smaller length scale (1 μm or less)

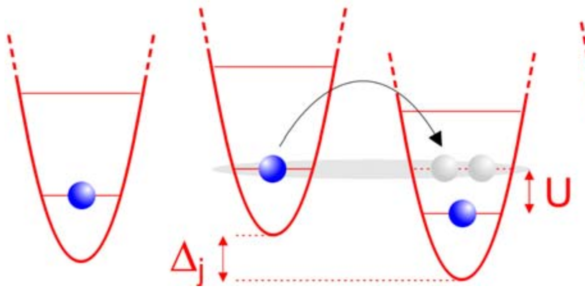
Non-periodic modulation of the energy minima
with length scale

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

interacting bosons in a disordered optical potential

Bose-Hubbard model with bounded disorder in the external potential

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



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

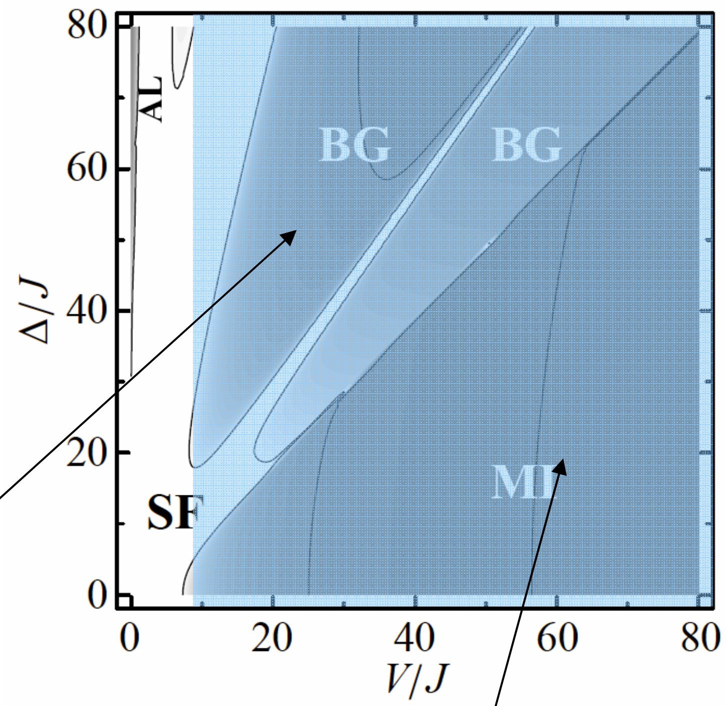
The phase of the system depends on the interplay between these energy terms

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)

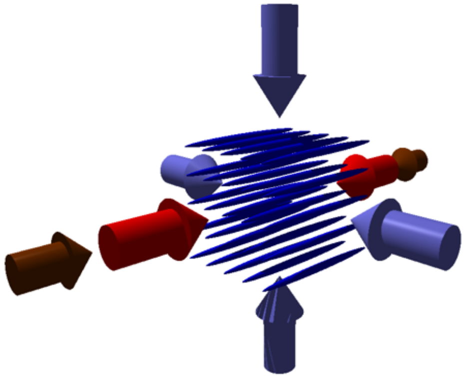
- No phase coherence
- Zero number fluctuations

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

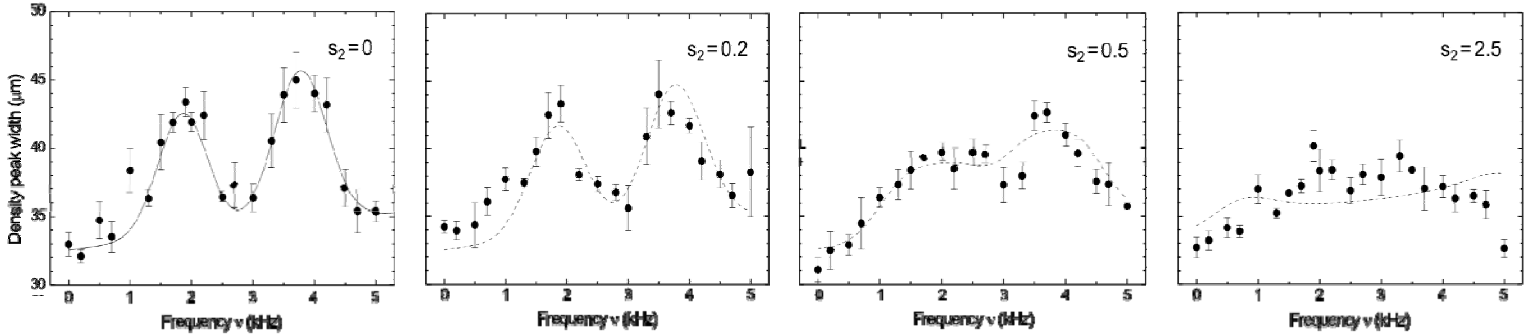
Along x

λ_1 = 830 nm s_1 < 20

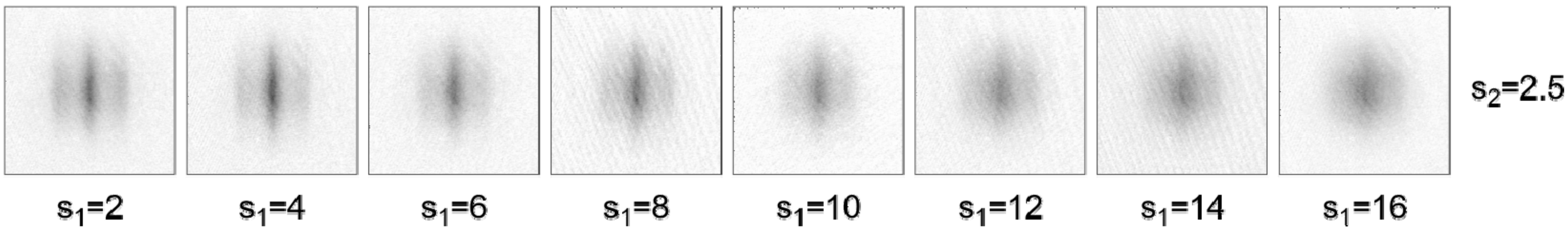
λ_2 = 1076 nm s_2 < 3

Observables:

Excitation spectrum (modulation of the lattice λ_1)



Phase Coherence (density profile after expansion)

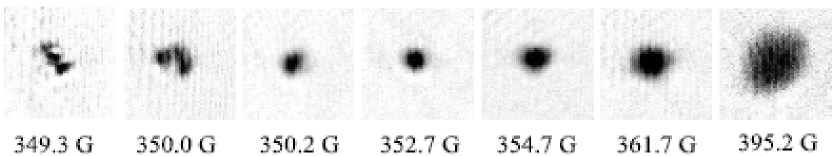


The quest for Anderson localisation in BEC: Experiments

- **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

P. Lugan,[1] D. Clément,[1] P. Bouyer,[1] A. Aspect,[1] M. Lewenstein,[2] and L. Sanchez-Palencia[1]

[1]*Laboratoire Charles Fabry de l'Institut d'Optique, CNRS and Univ. Paris-Sud, Campus Polytechnique, RD 128, F-91127 Palaiseau cedex, France*

[2]*ICREA and ICFO-Institut de Ciències Fotòniques, Parc Mediterrani de la Tecnologia, E-08860 Castelldefels (Barcelona), Spain*

(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**:

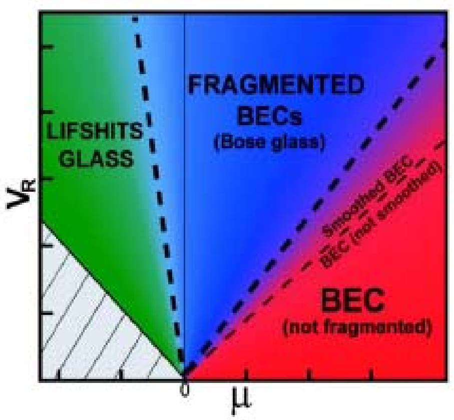


FIG. 1 (color online). Schematic quantum-state diagram of an interacting ultracold Bose gas in 1D disorder. The dashed lines represent the boundaries (corresponding to crossovers) which are controlled by the parameter $\alpha_R = \hbar^2/2m\sigma_R^2 V_R$ (fixed in the figure, see text), where V_R and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

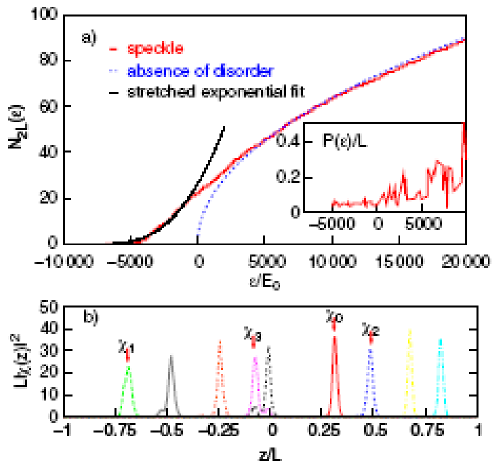


FIG. 2 (color online). (a) Cumulative density of states of single particles in a speckle potential with $\sigma_R = 2 \times 10^{-3} L$ and $V_R = 10^4 E_0$, where $E_0 = \hbar^2/2mL^2$ ($V_{\min} = -V_R$). Inset: Participation length [25]. (b) Low-energy Lifshits eigenstates. For the considered realization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

Lifshits glass

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

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

But, we are still behind…

- **Measurements of critical exponents?!?**

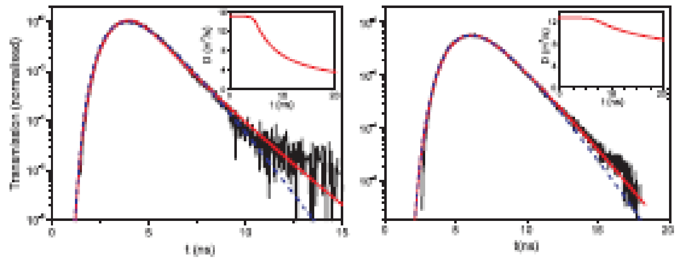


Fig. 1 – Time-of-flight distribution of samples R700 (left; $L = 1.21$ mm, $D = 15\,\mathrm{m^2/s}$, $\tau_{abs} = 1.65$ ns, $\tau_{loc} = 4.8$ ns, $n = 1.55$) and R902 (right; $L = 1.51$ mm, $D = 13\,\mathrm{m^2/s}$, $\tau_{abs} = 1.44$ ns, $\tau_{loc} = 6.9$ ns, $n = 1.23$). For R700, beyond the localisation transition, the distribution can be well fitted assuming a temporally varying diffusion coefficient proportional to $1/t$ at times greater than a localisation time, τ_{loc} as shown in the inset. This implies that the mean-square displacement of photons comes to a halt at a distance corresponding to $L_{loc} = \sqrt{D\tau_{loc}}$. For R902, which is close to the localisation transition, neither classical diffusion nor localisation as used for R700 can fully describe the data. The shown fit assumes a temporal dependence of D shown in the inset as $1/t^{1/2}$, as predicted for the critical regime close to Anderson localisation [10]. This corresponds to a spatial rescaling of $D \propto 1/L$. For comparison, the fit to classical diffusion [9] is given by the dashed line.

EUROPHYSICS LETTERS 15 August 2006

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DOI: 10.1209/epl/i2006-10144-3

Experimental determination of critical exponents in Anderson localisation of light

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PACS. 42.25.Dd – Wave propagation in random media.
PACS. 05.60.-k – Transport processes.
PACS. 42.25.Bs – Wave propagation, transmission and absorption.

Abstract. – Anderson localisation predicts a phase transition in transport, where the diffuse spread of particles comes to a halt with the introduction of a critical amount of disorder. This is due to constructive interference on closed multiple scattering loops which leads to a renormalisation of the diffusion coefficient. This can be described by a slowing-down of diffusion, where the diffusion coefficient decreases with time according to a power law with an exponent a. In the case of strong localisation, where diffusion completely breaks down, the exponent is given by $a = 1$. This is due to the fact that such a dependence of the diffusion coefficient naturally leads to a limited spread of the diffusing particle even at infinite times. In the critical regime approaching the transition, a value of $a = 1/3$ has been predicted, which corresponds to a rescaling of the diffusion coefficient due to the presence of closed loops. Using time-resolved measurements of photon transport in very turbid media, we have determined these scaling exponents experimentally. We find good agreement with theory and determine the critical value of the disorder parameter kl^* to be 4.2(2). Furthermore, we study the critical exponent of the divergence of the localisation length at the transition, where we find $\nu = 1/2$, consistent with the expectation for the exponent of an order parameter.

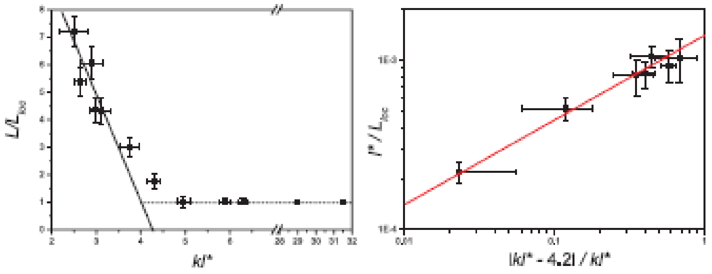

Fig. 3 – The dependence of the inverse localisation length on the critical parameter kl^* normalized to the sample thickness is shown on the left. From a linear extrapolation of the data showing a localisation exponent $a \simeq 1$, we obtain a critical value of $kl^*_c = 4.2(2)$. Due to the finite extent of the sample, the determination of the localisation length is limited experimentally to the sample thickness, such that in the classical limit the curve approaches one corresponding to a correlation length above the transition. On the right, the localisation length is normalized to l^* and plotted *vs.* the critical parameter $|kl^* - kl^*_c|/kl^*$. This allows the determination of the critical exponent $\nu = 0.45(10)$. The straight line in the double logarithmic plot indicates an exponent of $\nu = 0.5$.

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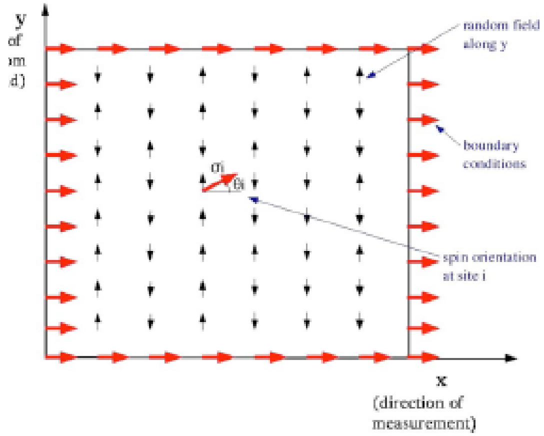
(Received 14 April 2006; revised manuscript received 27 October 2006; published 29 December 2006)

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 – GE. 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

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

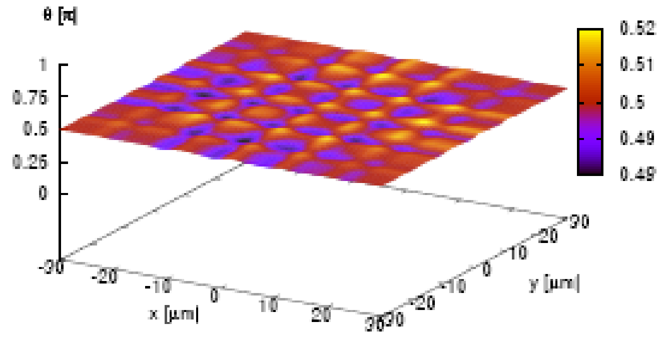


Figure 3: RFIO effect in a 3D two-component BEC trapped in a spherically symmetric harmonic trap with trapping frequency $\omega = 2\pi \times 30$Hz. The total number of atoms is $N = 10^5$, the scattering lengths are the same as in Fig. 2 with quasi-random Raman coupling $\Omega(x,y,z) \propto \sum_{u\in\{x,y,z\}}[\sin(2\pi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

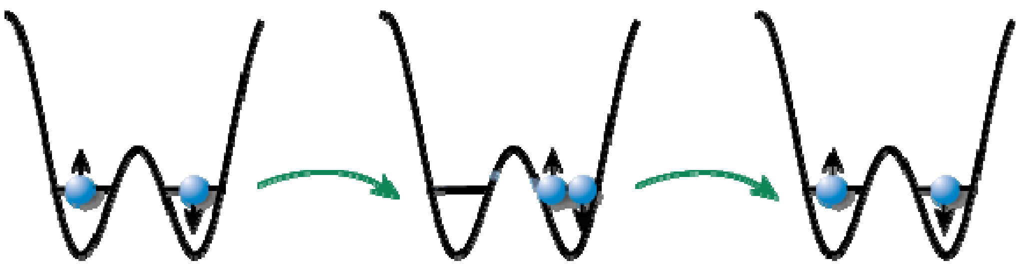
Experimental methods

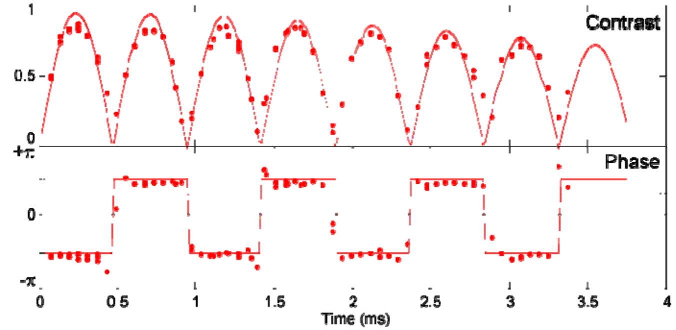
Correlated pair tunneling

Second order hopping processes form the basis of superexchange interactions!
(see e.g. A. Auerbach, Interacting Electrons and Quantum Magnetism)

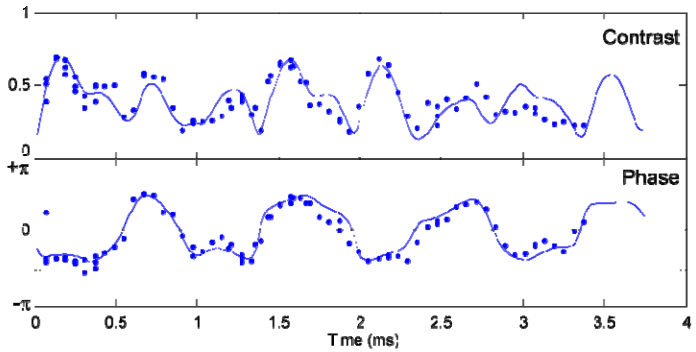
$$J_{ex} \propto \frac{J^2}{U}$$

$$H_{ex} = J_{ex} \vec{S}_i \cdot \vec{S}_j$$





Single atom signal



Complete (1+2 atoms) signal

Controlled exchange interaction between pairs of neutral atoms in an optical lattice

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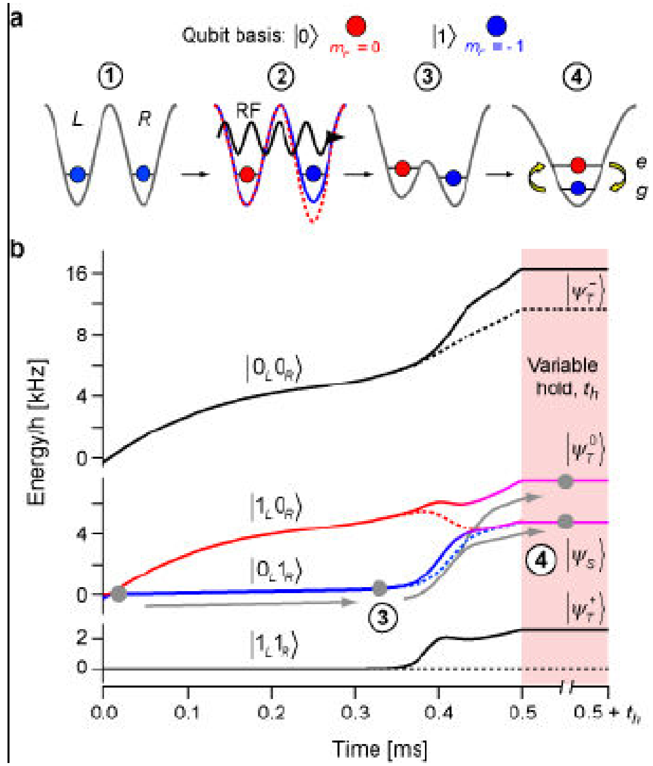
Ultra-cold atoms trapped by light, with their robust quantum coherence and controllability, provide an attractive system for quantum information processing and for simulation of complex problems in condensed matter physics. Many quantum information processing schemes require that individual qubits be manipulated and deterministically entangled with one another, a process that would typically be accomplished by controlled, state-dependent, coherent interactions among qubits. Recent experiments have made progress toward this goal by demonstrating entanglement among an ensemble of atoms[1] confined in an optical lattice. Until now, however, there has been no demonstration of a key operation: controlled entanglement between atoms in isolated pairs. We have used an optical lattice of double-well potentials[2,3] to isolate and manipulate arrays of paired atoms, inducing controlled entangling interactions within each pair. Our experiment is the first realization of proposals to use controlled exchange coupling[4] in a system of neutral atoms[5]. Although ^{87}Rb atoms have nearly state-independent interactions, when we force two atoms into the same physical location, the wavefunction exchange symmetry of these identical bosons leads to state-dependent dynamics. We observe repeated interchange of spin between atoms

Controlled exchange interactions and √SWAP



THE Challenge

Noise interferometry – efficient way of detection of pair correlations

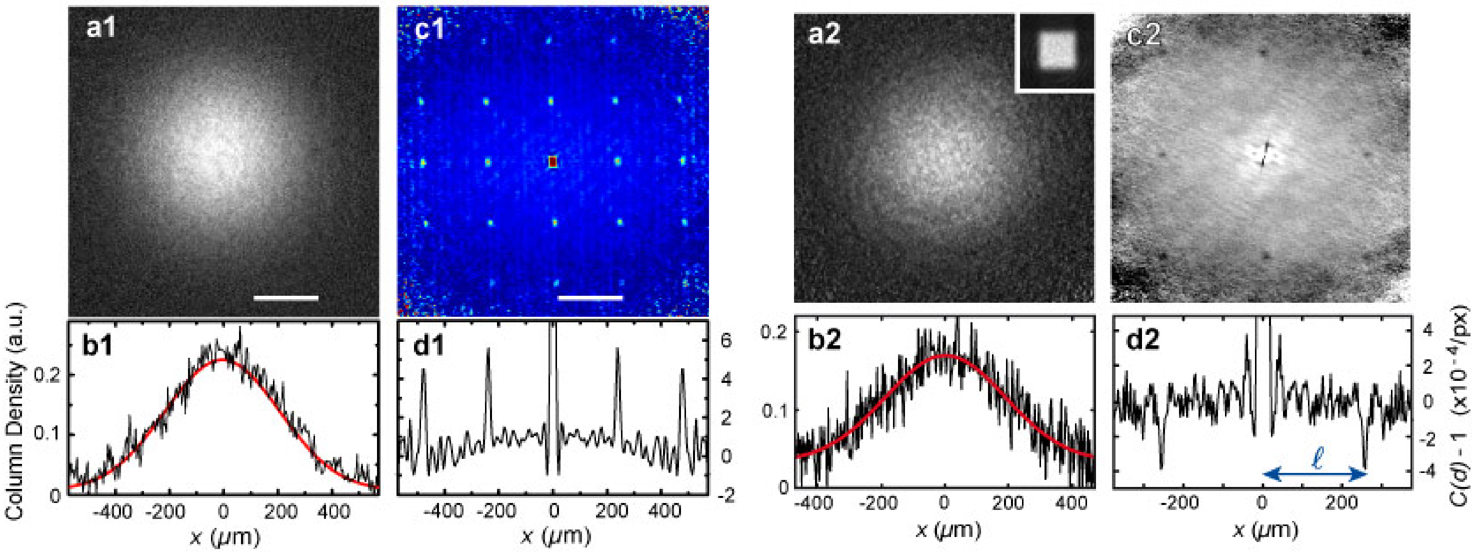
T. Rom, Th. Best, D. van Oosten, U.Schneider, S. Fölling, B. Paredes, and I. Bloch, Nature 444, 733 (2006).

<u>Goals:</u>

1) Be able to detect „exotic“ quantum phases, such as for instance Bose glass, etc.

2) Readout of quantum simulators !!!

Idea (geniale!): Altman, Demler, and Lukin



Atom counting

nature Vol 445 | 25 January 2007 | doi:10.1038/nature05513

LETTERS

Comparison of the Hanbury Brown–Twiss effect for bosons and fermions

T. Jeltes[1], J. M. McNamara[1], W. Hogervorst[1], W. Vassen[1], V. Krachmalnicoff[2], M. Schellekens[2], A. Perrin[2], H. Chang[2], D. Boiron[2], A. Aspect[2] & C. I. Westbrook[2]

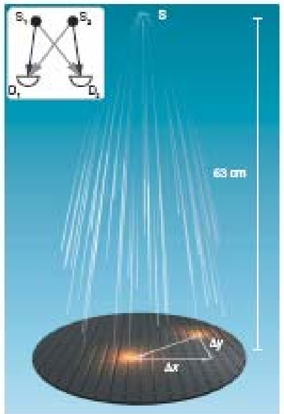


Figure 1 | The experimental set-up. A cold cloud of metastable helium atoms is released at the switch-off of a magnetic trap. The cloud expands and falls under the effect of gravity onto a time-resolved and position-sensitive detector (microchannel plate and delay-line anode) that detects single atoms. The horizontal components of the pair separation Δr are denoted Δx and Δy. The inset shows conceptually the two 2-particle amplitudes (in black or grey) that interfere to give bunching or antibunching: S_1 and S_2 refer to the initial positions of two identical atoms jointly detected at D_1 and D_2.

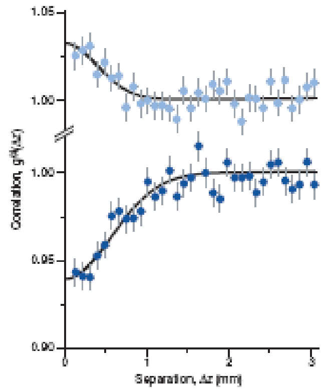


Figure 2 | Normalized correlation functions for $^4He^*$ (bosons) in the upper plot, and $^3He^*$ (fermions) in the lower plot. Both functions are measured at the same cloud temperature (0.5 μK), and with identical trap parameters. Error bars correspond to the square root of the number of pairs in each bin. The line is a fit to a gaussian function. The bosons show a bunching effect, and the fermions show antibunching. The correlation length for $^3He^*$ is expected to be 33% larger than that for $^4He^*$ owing to the smaller mass. We find 1/e values for the correlation lengths of 0.75 ± 0.07 mm and 0.56 ± 0.08 mm for fermions and bosons, respectively.

See also: T. Esslinger using cavity QED mehtods

Read-out for QS of disordered systems

NEWS & VIEWS

NATURE|Vol 445|25 January 2007

ATOMIC PHYSICS

The social life of atoms

Maciej Lewenstein

In a trail-blazing experiment 50 years ago, it was observed that photons from far-off stars bunch up. But it seems there's a more general distinction among free, non-interacting particles: bosons bunch, and fermions 'antibunch'.

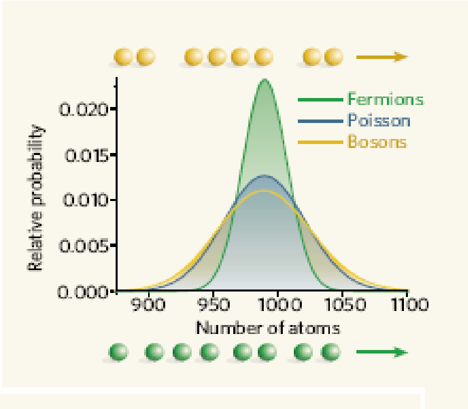


Figure 1 | Bunch, antibunch. Simulated distributions of the number of atoms detected in a certain time-window after 1,000 are released from an atomic trap at low temperature. If the arrival times of the atoms at the detectors were truly random, they would conform to a Poisson distribution (blue). In fact, bosons prefer to bunch, so in the time-window of any one detection event, significantly more or fewer than the mode number can arrive: the counting distribution (red) is broader. For fermions, the converse is true: they antibunch, arriving more regularly spaced than purely randomly, and so produce a taller, narrower counting distribution (green). (Figure courtesy S. Braungardt, U. Sen, A. Sen (De) & R. J. Glauber.)

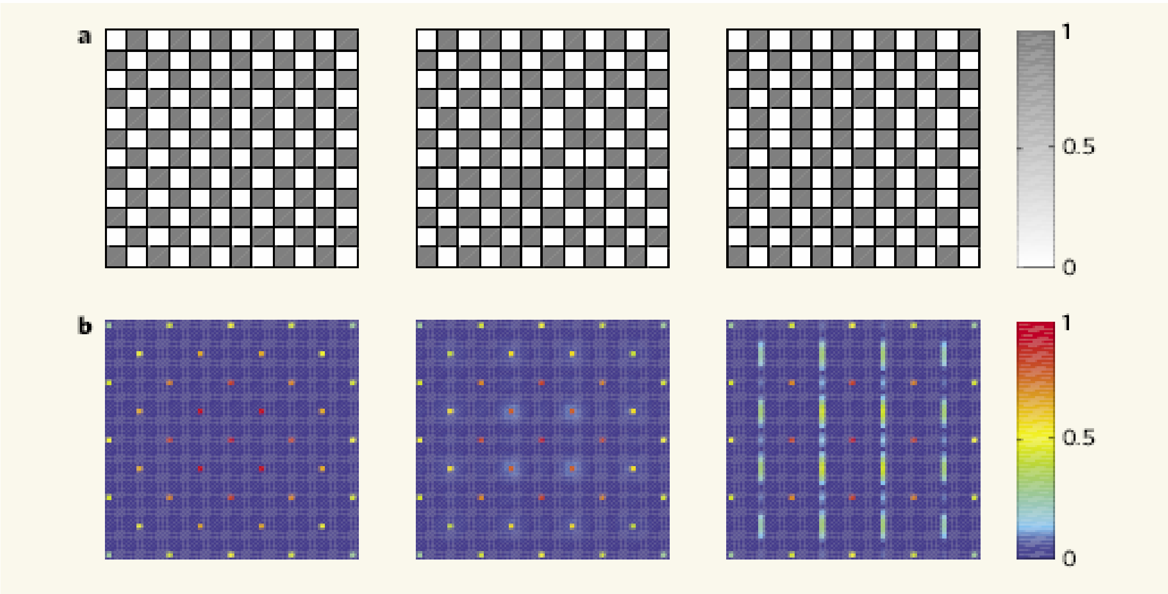


Figure 2 | Noise assessment. 'Noise interferometry' is a particularly efficient way of assessing spatial structures. **a**, A two-dimensional, Bose-gas Mott-insulator state held in an optical lattice, for example, ideally forms a chequer-board state of alternating filled and vacant sites at low temperatures and half filling[10] (left diagram; dark sites indicate presence of an atom). In practice, various kinds of defects occur (adjacent squares filled or unfilled; middle and right diagrams). **b**, Noise interferometry converts this spatial pattern into an easily identifiable interference signal, a characteristic series of peaks equivalent to a bunching behaviour.

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

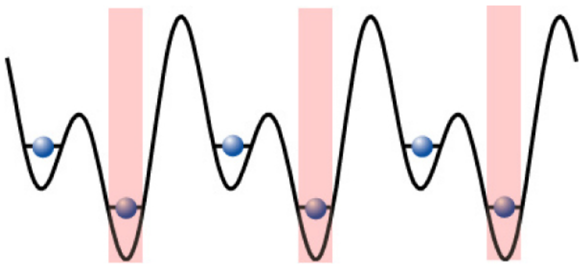
Goals:

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))

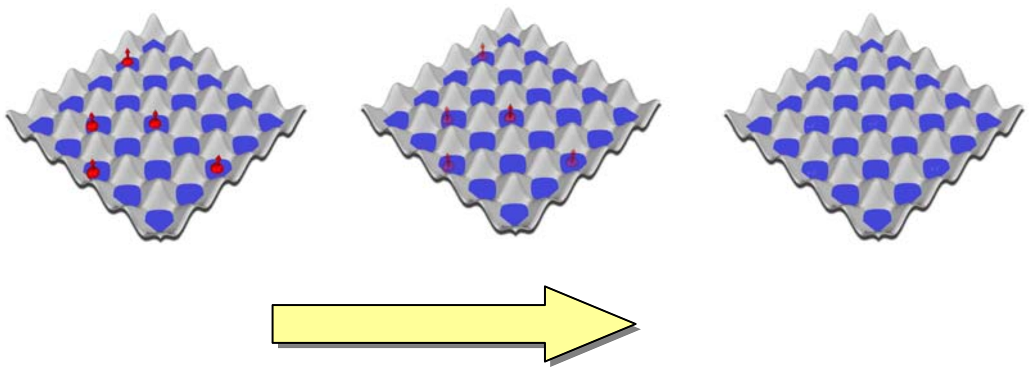
Experimental realizations:

1) *Superlattice potentials for controlled „disorder“*



Superlattice depth and phase controllable (nonrational wavelength factors possible)

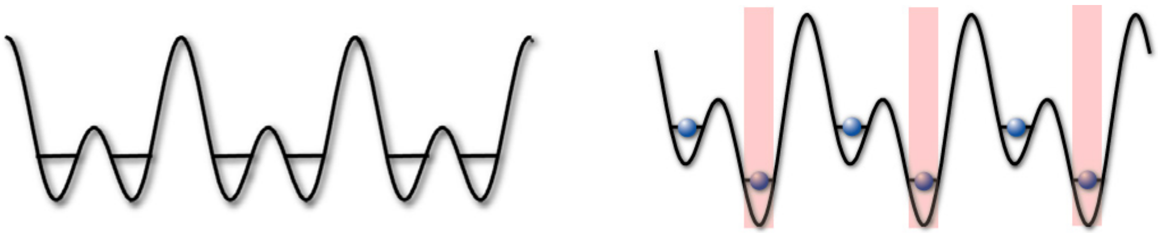
2) *Disorder via second atomic species*



Feshbach resonance

Noise interferometry and superlattices

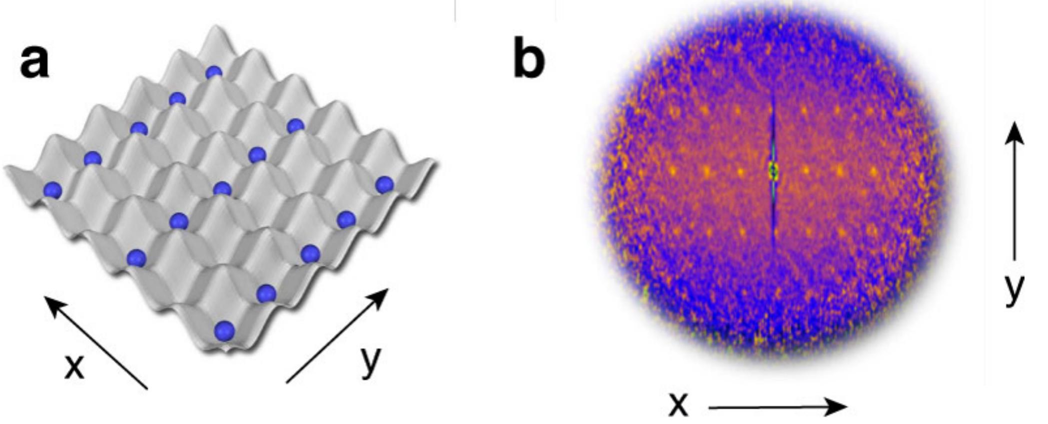
- Optical superlattices formed by a 765 nm lattice and a 1530 nm lattice.
- Highly flexible control of the potential



- High potential for investigating dynamical evolution after state preparation

a) Charge density ordering created via optical superlattices

b) Detection via noise correlations



Detection: New proposals

Scanning tunnelling microscopy for ultracold atoms

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(Dated: June 1, 2007)

We propose a novel experimental probe for cold atomic gases analogous to the scanning tunnelling microscope (STM) in condensed matter. This probe uses the coherent coupling of a single particle to the system. Depending on the measurement sequence, our probe allows to either obtain the *local* density, with a resolution on the nanometer scale, or the single particle correlation function in real time. We discuss applications of this scheme to the various possible phases for a two dimensional Hubbard system of fermions in an optical lattice.

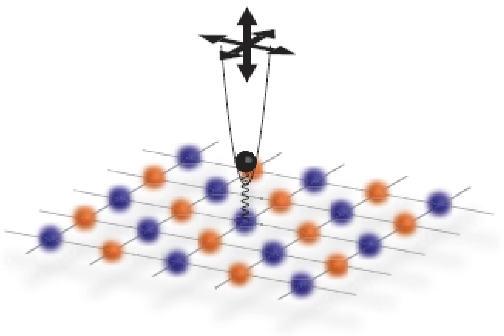
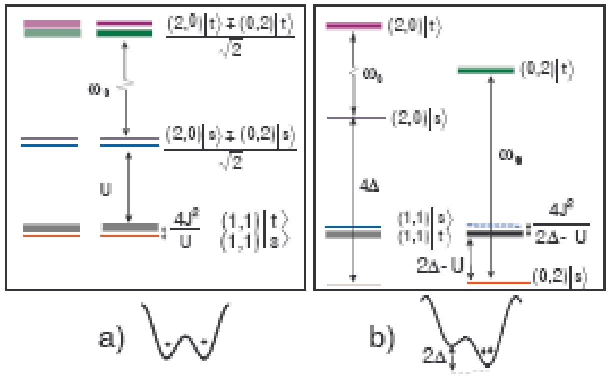


FIG. 1: Sketch of the cold atom tunneling microscope. As an example the application to an anti-ferromagnetic state with alternating spin states labeled by different colors is shown.



Preparation and detection of magnetic quantum phases in optical superlattices

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We describe a novel approach to prepare, detect and characterize magnetic quantum phases in ultra-cold spinor atoms loaded in optical superlattices. Our technique makes use of singlet-triplet spin manipulations in an array of isolated double well potentials in analogy to recently demonstrated quantum control in semiconductor quantum dots. We also discuss the many-body singlet-triplet spin dynamics arising from coherent coupling between nearest neighbor double wells and derive an effective description for such system. We use it to study the generation of complex magnetic states by adiabatic and non-equilibrium dynamics.

Detection: THE proposal I

Quantum nondemolition polatization spectroscopy

PRL 98, 100404 (2007) PHYSICAL REVIEW LETTERS week ending 9 MARCH 2007

Quantum Polarization Spectroscopy of Ultracold Spinor Gases

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(Received 14 August 2006; published 9 March 2007)

We propose a method for the detection of ground state quantum phases of spinor gases through a series of two quantum nondemolition measurements performed by sending off-resonant, polarized light pulses through the gas. Signatures of various mean-field as well as strongly correlated phases of $F = 1$ and $F = 2$ spinor gases obtained by detecting quantum fluctuations and mean values of polarization of transmitted light are identified.

Quantum Faraday effect!!!

$$H=\kappa S_z J_z \,,$$

where

$$J_z=\Sigma_i j_{zi}$$

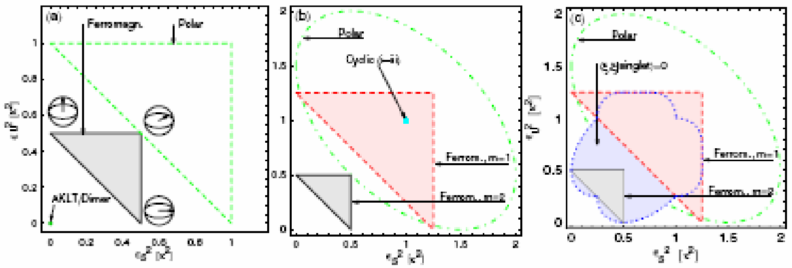

FIG. 1 (color online). Possible combinations of additional fluctuations ϵ_S^2 and ϵ_U^2 imprinted on the light for the ground state phases of the $F = 1$ spinor gas in a uniform trap and in an optical lattice (a) and for $F = 2$ atoms in a uniform trap (b) and in an optical lattice (c). Filled areas denote cases where the mean of $\langle X_S^{out}\rangle$ and/or $\langle \hat{X}_U^{out}\rangle$ is (generically) nonzero. The spheres in (a) illustrate the directions of the spinor for the extremal points of the ferromagnetic phase.

Detection: THE proposal II

Quantum Non-Demolition Detection of Strongly Correlated Systems

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Preparation, manipulation, and detection of strongly correlated states of quantum many body systems are among the most important goals and challenges of modern physics. Ultracold atoms offer an unprecedented playground for realization of these goals. Here we show how strongly correlated states of ultracold atoms can be detected in a quantum non-demolition scheme, that is, in the fundamentally least destructive way permitted by quantum mechanics. In our method, spatially resolved components of atomic spins couple to quantum polarization degrees of freedom of light. In this way quantum correlations of matter are faithfully mapped on those of light; the latter can then be efficiently measured using homodyne detection. We illustrate the power of such spatially resolved quantum noise limited polarization measurement by applying it to detect various standard and "exotic" types of antiferromagnetic order in lattice systems and by indicating the feasibility of detection of superfluid order in Fermi liquids.

$$H=\kappa S_z J_z^{eff},$$

where

$$J_z^{eff}=\Sigma_i\, j_{zi}\cos^2(k_L r_i)$$

Quantum Faraday effect!!!

Detection: THE proposal II

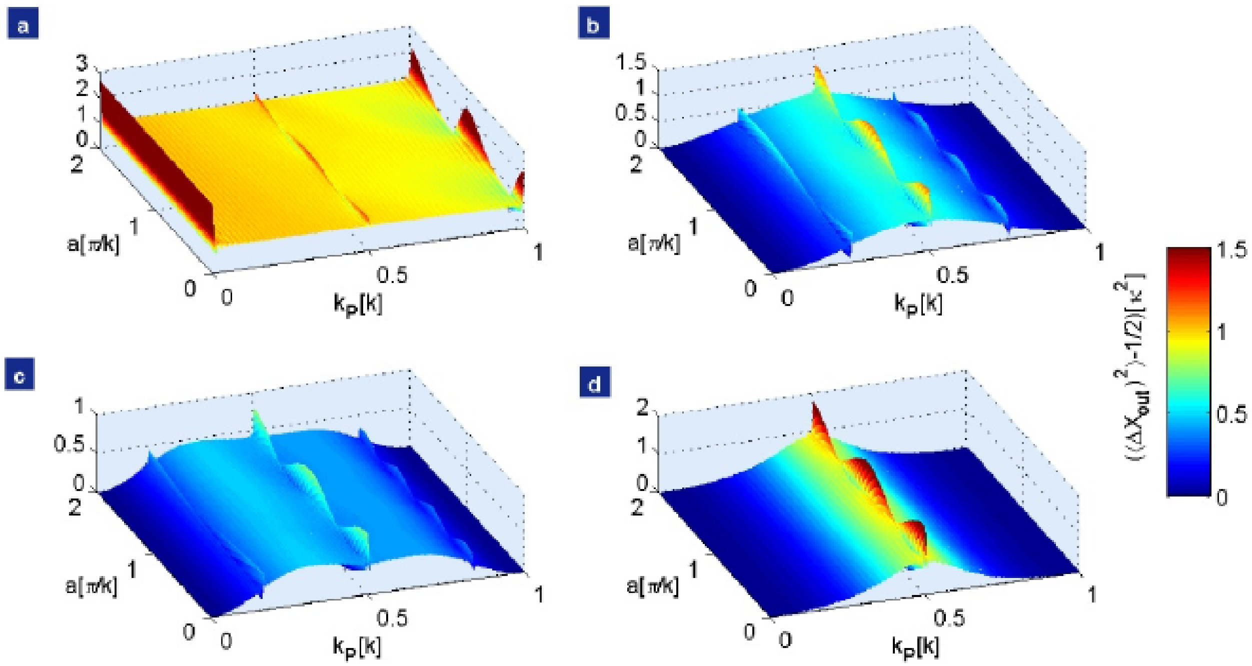


FIG. 3: **Detection of antiferromagnetic states of spin-1 lattice systems.** Fluctuations imprinted on the $\hat{X}$ quadrature of the probe light beam transmitted through a sample of spin-1 atoms in a one-dimensional lattice for (a) unpolarized paramagnetic, (b) dimerized, (c) trimerized, and (d) AKLT states. The dependence on the ratio k_P/k and the shift a permits to distinguish these states unambiguously. The presence of fluctuations at $k_P/k = 0$ signals the unpolarized paramagnetic state. The other three phases can be distinguished in different ways: (i) for $k_P/k = 1/2$ and $a = 0$, the added noise (in units of the shot noise of the probe light) for the dimerized, trimerized, and AKLT states is $4\kappa^2/3$, $8\kappa^2/9$, and $2\kappa^2$, respectively; (ii) at $k_P/k = 1/4, 3/4$, only for the dimerized state the added noise depends on the shift a; and (iii), analogously, at $k_P/k = 1/6, 5/6$ only the additional noise from the trimerized state is a-dependent. The quoted values are for ideally δ-localized atomic wavefunctions, while the figure shows results for extended atomic Wannier functions. This yields an overall decrease of the noise contribution towards larger k_P/k ratios. Except for this decrease, the pattern is repeated for larger k_P/k. Using the exact ground states of spin-1 lattice systems numerically obtained in [30], the fluctuations on the light quadrature present a similar behaviour as the ones here depicted.

Theory methods

Vidal's algorith, MPS, PEPS, TEBD, MERA

THE HERMANN KÜMMEL EARLY ACHIEVEMENT AWARD IN MANY-BODY PHYSICS

The International Advisory Committee of the International Conferences Series on Recent Progress in Many-Body Theories is pleased t o announce that the inaugural, **2007 HERMANN KÜMMEL EARLY ACHIEVEMENT AWARD IN MANY-BODY PHYSICS** is awarded to **Dr. Frank Verstraete** of Universiät Wien, Austria,

Frank Verstraete

"For his pioneering work on the use of quantum information and entanglement theory in formulating new and powerful numerical simulation methods for use in strongly correlated systems, stochastic nonequilibrium systems ,and strongly coupled quantum field theories."

Many-body quantum systems

- Many-body quantum systems are difficult to describe.

$$|\Psi\rangle$$

• • • • • •

$$|\Psi\rangle = \sum c_{i_1 \ldots i_N} |i_1, \ldots, i_N\rangle$$

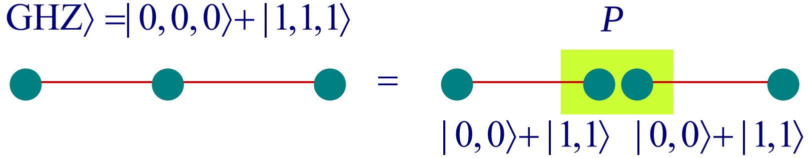
We need 2^N coefficients to represent a state.

- To determine physical quantitites (expectation values) an exponential number of computations is required.

1. Definition

GHZ states:

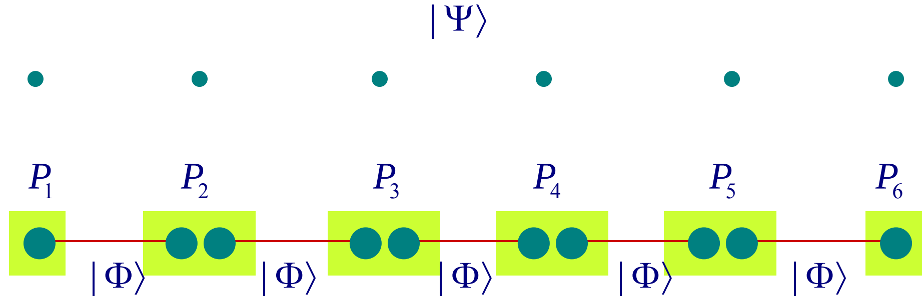
$|\mathrm{GHZ}\rangle = |0,0,0\rangle + |1,1,1\rangle$



where $P = |0\rangle\langle 0,0| + |1\rangle\langle 1,1|$ maps $\mathbb{C}^2 \otimes \mathbb{C}^2 \to \mathbb{C}^2$

1D states:

as:



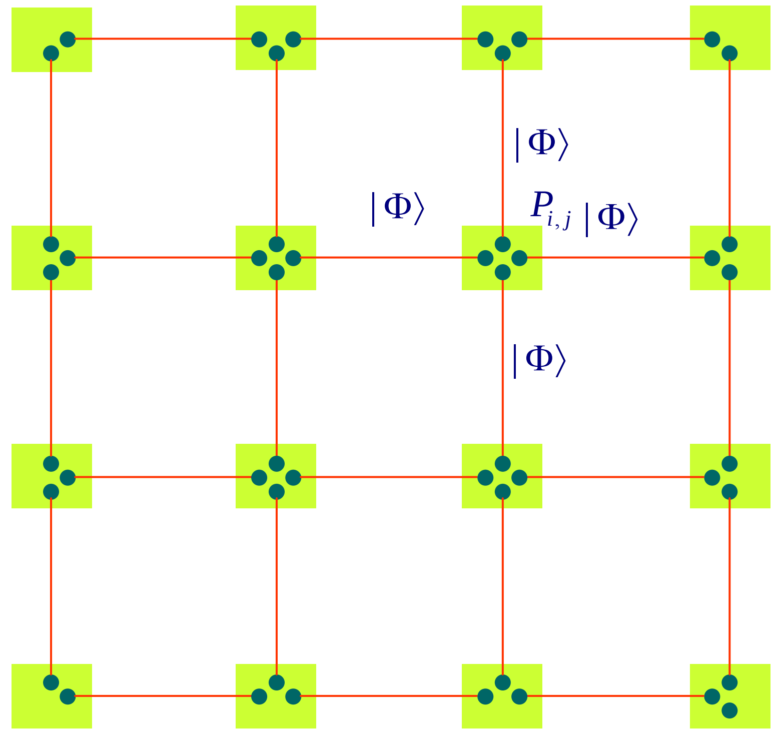
where

- D-dimensional

$|\Phi\rangle = \sum_{m=1}^{D} |m,m\rangle$ are maximally entangled states

$P_k = \sum_{n=1}^{2} |n\rangle\langle \varphi_n^k |$ maps $\mathbb{C}^D \otimes \mathbb{C}^D \to \mathbb{C}^2$

2D states:

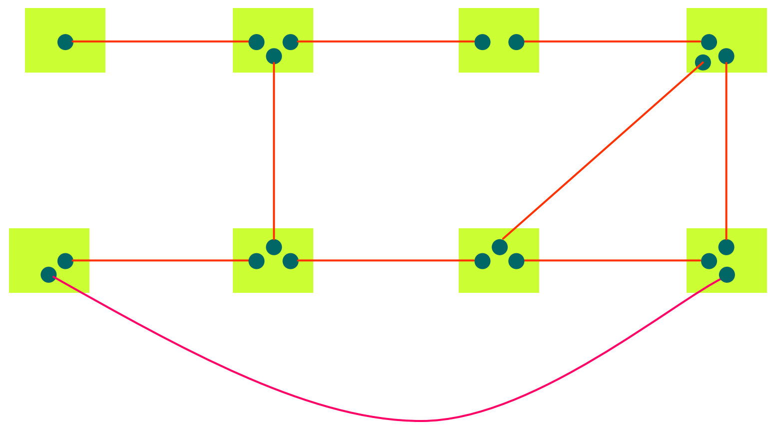


$$P_k = \sum_{n=1}^{2} |n\rangle\langle\varphi_n^k|$$

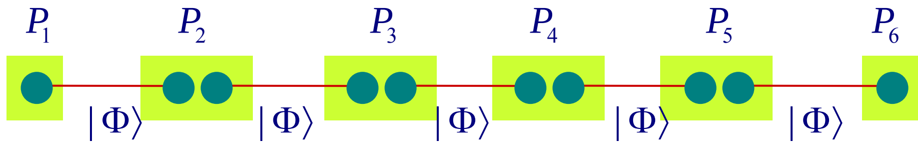
maps

$$\mathbb{C}^D \otimes \mathbb{C}^D \otimes \mathbb{C}^D \otimes \mathbb{C}^D \rightarrow \mathbb{C}^2$$

General:



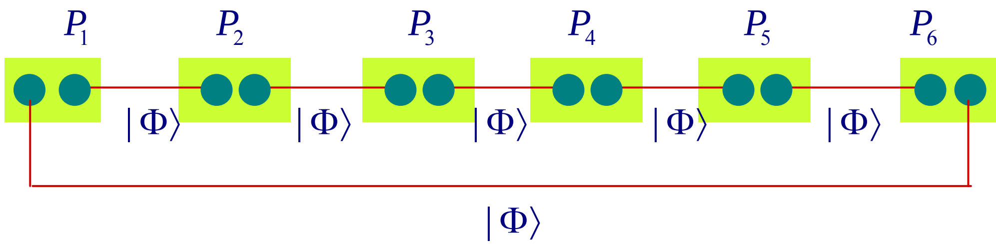
1) Open boundary conditions:



It coincides with DMRG

2) Periodic boundary conditions:

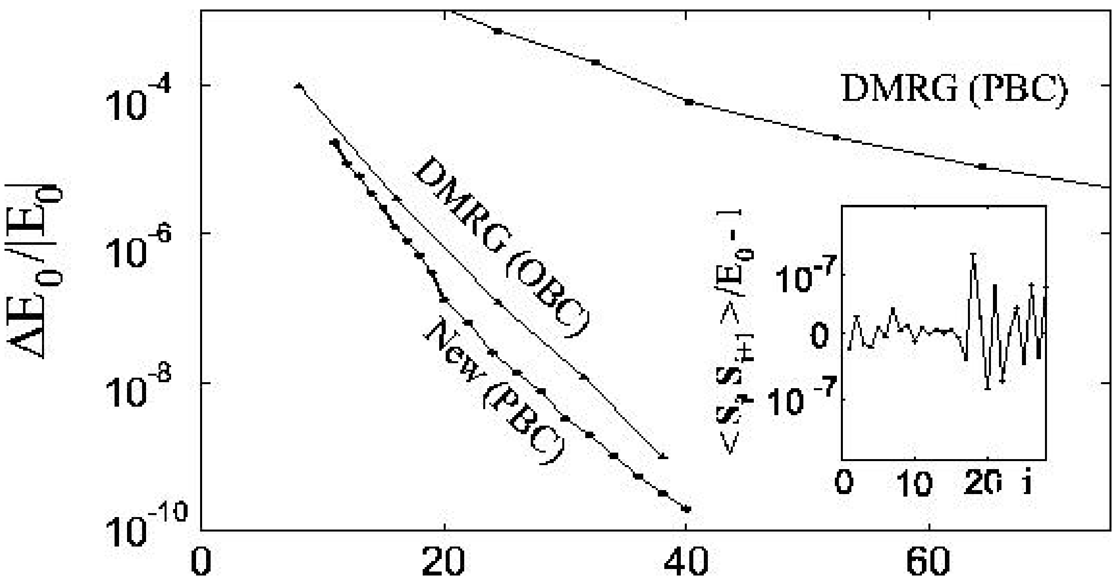
(Verstraete, Porras, Cirac, PRL 2004)



It outperforms DMRG

$$|\Psi\rangle = \sum_{i_1,\ldots,i_N=0}^{1} \mathrm{Tr}\left[A_1^{i_1} A_2^{i_2} \ldots A_N^{i_N}\right] |i_1,\ldots,i_N\rangle$$

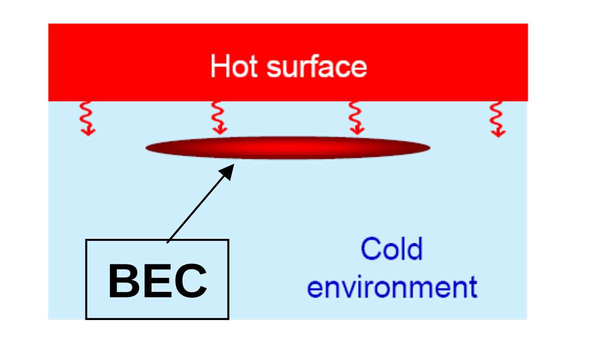
$$H = \sum_{\langle k,j\rangle} \left(\sigma_x^k \sigma_x^j + \sigma_y^k \sigma_y^j + \sigma_z^k \sigma_z^j\right)$$



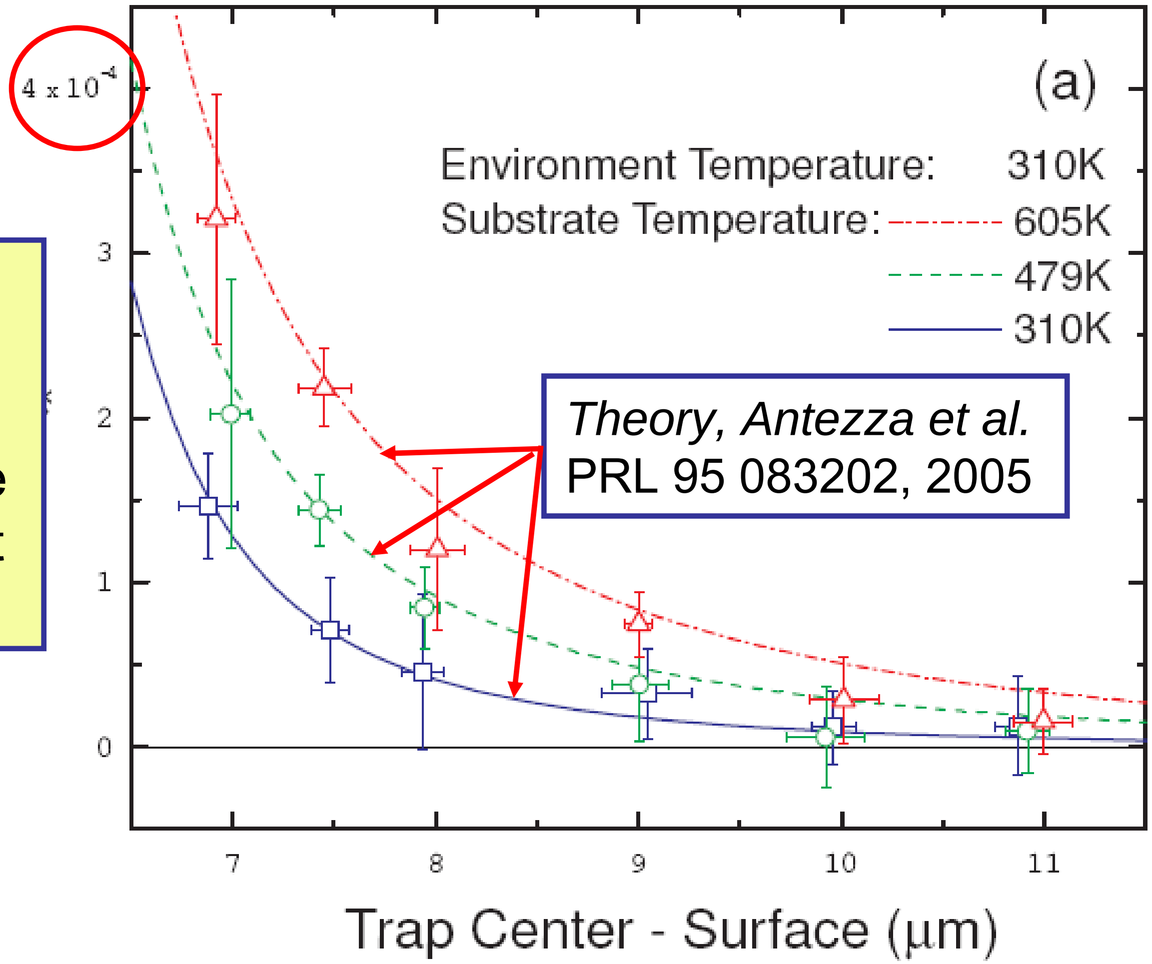
Varia

First measurement of thermal effect on the Casimir-Polder force

(JILA, Obrecht et al. PRL 98, 063201 (2007)



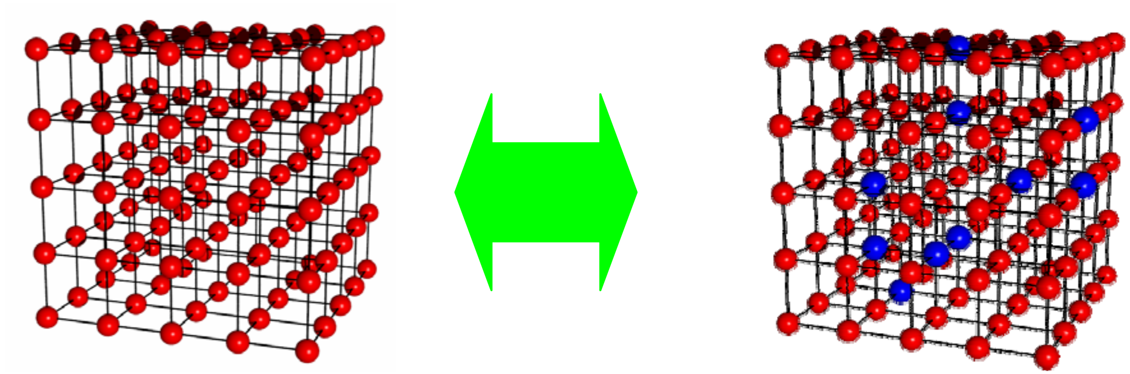
Relative frequency shift of center of mass oscillation of a trapped BEC gas due to the Casimir-Polder force produced by a substrate at different temperatures



Fermi-Bose Mixtures in a 3D Optical Lattice

AG Sengstock

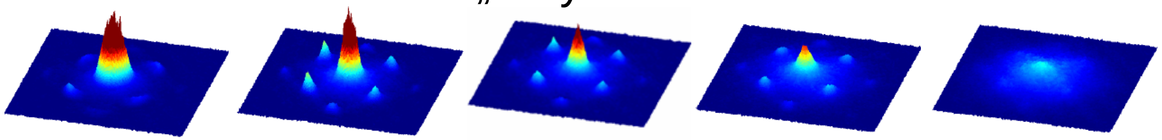
New system: First Fermi-Bose quantum gas mixture in a 3d optical lattice.



^{87}Rb $^{40}K/^{87}Rb$ mixture

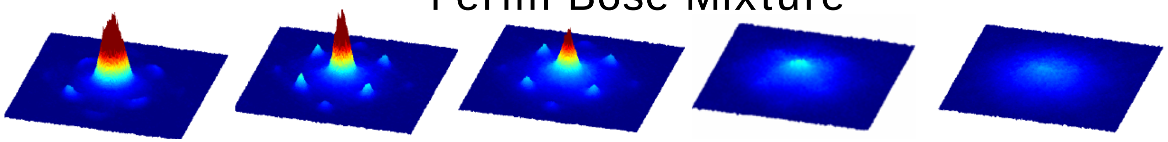
Localization physics: Shift of the "Mott-insulator" transition connected to "fermionic impurities".

„only" bosons



5 E_R 10 E_R 15 E_R 20 E_R 25 E_R

Fermi Bose Mixture



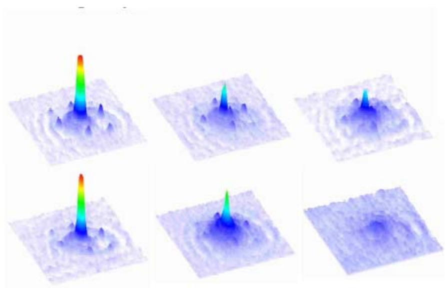
5 E_R 10 E_R 15 E_R 20 E_R 25 E_R

S. Ospelkaus, C. Ospelkaus, O. Wille, M. Succo, P. Ernst, K. Sengstock and K. Bongs; Phys. Rev. Lett. ***96****, 180403 (2006)*

(see also work at ETH Phys. Rev. Lett. 96, 180402 (2006))

Potassium addicts at their best

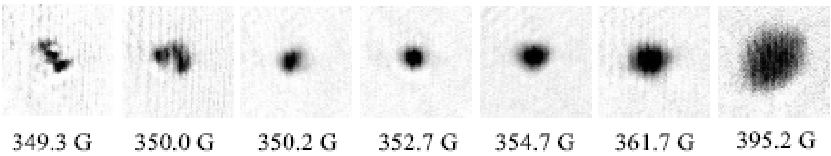
- Degenerate Bose-Bose mixture in a 3D optical lattice:



the superfluid to Mott insulator transition of the heavier ^{87}Rb is affected by a minor fraction of ^{41}K

J.Catani et al. airXiv:0706.2781v1

- 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.

New review articles

My favourite

Advances in Physics
Vol. 00, No. 00, Month-Month 200x, 1–135

Ultracold atomic gases in optical lattices: Mimicking condensed matter physics and beyond

Maciej Lewenstein,
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Anna Sanpera,
ICREA and Grup de Física Teòrica, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain
Veronica Ahufinger,
ICREA and Grup d'Òptica, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain
Bogdan Damski,
Theory Division, Los Alamos National Laboratory, MS-B213, Los Alamos, NM 87545, USA
Aditi Sen(De), and Ujjwal Sen
ICFO-Institut de Ciències Fotòniques, E-08860 Castelldefels (Barcelona) Spain
(Received 00 Month 200x; In final form 00 Month 200x)

We review recent developments in the physics of ultracold atomic and molecular gases in optical lattices. Such systems are nearly perfect realisations of various kinds of Hubbard models, and as such may very well serve to mimic condensed matter phenomena. We show how these systems may be employed as *quantum simulators* to answer some challenging open questions of condensed matter, and even high energy physics. After a short presentation of the models and the methods of treatment of such systems, we discuss in detail, which challenges of condensed matter physics can be addressed with (i) disordered ultracold lattice gases, (ii) frustrated ultracold gases, (iii) spinor lattice gases, (iv) lattice gases in "artificial" magnetic fields, and, last but not least, (v) quantum information processing in lattice gases. For completeness, also some recent progress related to the above topics with trapped cold gases will be discussed.

Covers:

- Introduction (great!)
- Hubbard and spin models
- Methods of treatment
- Ultracold disordered gases
- Ultracold frustrated gases
- Ultracold spinor gases
- Ultracold gases in artificial gauge fields
- Ultracold gases and quantum information
- 135 pages, 823 references

Fermions and all that... (submitted to RMP)

Theory of ultracold Fermi gases

Stefano Giorgini
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Lev P. Pitaevskii
Dipartimento di Fisica, Università di Trento and CNR-INFM BEC Center, I-38050 Povo, Trento, Italy and Kapitza Institute for Physical Problems, ul. Kosygina 2, 117334 Moscow, Russia

Sandro Stringari
Dipartimento di Fisica, Università di Trento and CNR-INFM BEC Center, I-38050 Povo, Trento, Italy

The physics of quantum degenerate Fermi gases in uniform as well as in harmonically trapped configurations is reviewed from a theoretical perspective. Emphasis is given to the effect of interactions which play a crucial role, bringing the gas into a superfluid phase at low temperature. In these dilute systems interactions are characterized by a single parameter, the *s*-wave scattering length, whose value can be tuned using an external magnetic field near a Feshbach resonance. The BCS limit of ordinary Fermi superfluidity, the Bose-Einstein condensation (BEC) of dimers and the unitary limit of large scattering length are important regimes exhibited by interacting Fermi gases. In particular the BEC and the unitary regimes are characterized by a high value of the superfluid critical temperature, of the order of the Fermi temperature. Different physical properties are discussed, including the density profiles and the energy of the ground-state configurations, the momentum distribution, the fraction of condensed pairs, collective oscillations and pair breaking effects, the expansion of the gas, the main thermodynamic properties, the behavior in the presence of optical lattices and the signatures of superfluidity, such as the existence of quantized vortices, the quenching of the moment of inertia and the consequences of spin polarization. Various theoretical approaches are considered, ranging from the mean-field description of the BCS-BEC crossover to non-perturbative methods based on quantum Monte Carlo techniques. A major goal of the review is to compare the theoretical predictions with the available experimental results.

PACS numbers:

Contents

Covers:

- Introduction
- Two-body collision
- Many body theory of uniform gas
- The BCS-BEC crossover
- Trapped interacting Fermi gases
- Dynamics and superfluidity
- Rotations and superfluidity
- Spin polarized Fermi gases and Fermi mixtures
- Fermi gases in optical lattices
- 78 pages, over 350 references

Many body physics… (submitted to RMP)

Many-Body Physics with Ultracold Gases

Immanuel Bloch*

Institut für Physik, Johannes Gutenberg-Universität, D-55099 Mainz, Germany

Jean Dalibard†

Laboratoire Kastler Brossel 24 rue Lhomond, F-75005 Paris, France

Wilhelm Zwerger‡

Physik-Department, Technische Universität München, D-85748 Garching, Germany

(Dated: March 2007)

This article reviews recent experimental and theoretical progress on many-body phenomena in dilute, ultracold gases. Its focus are effects beyond standard weak-coupling descriptions, like the Mott-Hubbard-transition in optical lattices, strongly interacting gases in one dimension or quasi two-dimensional gases in fast rotation. Strong correlations in fermionic gases are discussed in optical lattices or near Feshbach resonances in the BCS-BEC crossover.

Contents

I. INTRODUCTION

The achievement of Bose-Einstein-Condensation (BEC) (Anderson *et al.*, 1995; Bradley *et al.*, 1995; Davis *et al.*, 1995) and of Fermi degeneracy (DeMarco and Jin, 1999; Truscott *et al.*, 2001) in ultracold, dilute gases has opened a new chapter in atomic and molecular physics in which the particle statistics and their interactions, rather than the study of single atoms or photons, are at center stage. For a number of years, a main focus in this field has been to explore the wealth of phenomena associated with the existence of coherent matter waves. Major examples include the observation of interference of two overlapping condensates (Andrews *et al.*, 1997), of long range phase coherence (Bloch *et al.*, 2000) or of quantized vortices and vortex lattices (Abo-Shaeer *et al.*, 2001; Madison *et al.*, 2000a) and molecular condensates with bound pairs of fermions (Greiner *et al.*, 2003; Jochim *et al.*, 2003; Zwierlein *et al.*, 2003). Common to all of these phenomena is the existence of a coherent,

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‡Electronic address: zwerger@ph.tum.de

Covers:

- Introduction
- Optical lattices
- Detection of correlations
- Many body effects in optical lattices
- Ultracold gases in 1D
- 2D quasicondensates
- Bose gases in fast rotation
- BCS-BEC crossover
- Perspectives
- 76 pages, over 600 references

CONCLUSIONS (The Tragedy of Hamlet, by Shakespeare):

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

Wow!!!

Vidal’s algorith, MPS, PEPS, TEBD, MERA

During his still brief career as a theoretical physicist Frank Verstrate has left a a massive imprint on the field of many-body physics that will influence the subject in the future. He was the first to realize that the insights from entanglement theory could give rise to very powerful numerical simulation methods that apply to a broad range of phenomena, both in quantum and classical systems. His outstanding work includes:

The discovery that all numerical RG methods for 1D systems can be reformulated as variational methods in the class of matrix product states.
A demonstration that the ground states of local 1D hamiltonians can effectively be represented by matrix product states, even for critical s ystems.
Exploitation of quantum parallelism to simulate exponentially many realizations of random many-body systems in parallel.
Generalizations of matrix product states to higher dimensions through the concept of projected entangled pair states (PEPS).
A generalization of the Jordan-Wigner transformation to higher dimensions and to graphs.Generalizations of matrix product states to higher dimensions through the concept of projected entangled pair states (PEPS).
Construction of exactly solvable critical quantum systems in 2D whose entropy of entanglement obeys a strict area law.