

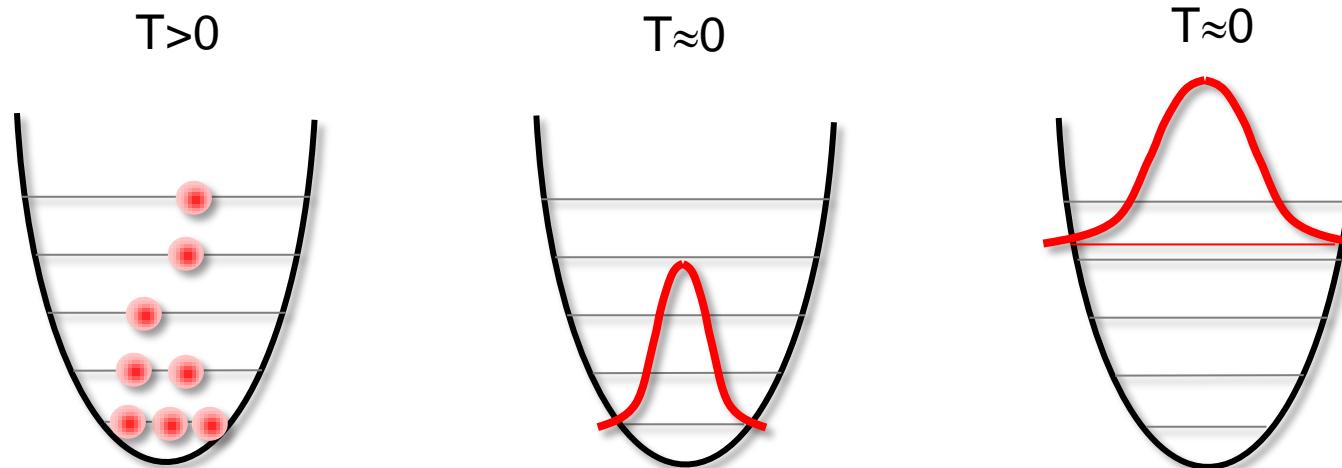
Fisica a molti corpi con gas quantistici di atomi e di molecole

Giovanni Modugno

Dipartimento di Fisica e Astronomia, and LENS, Università di Firenze



Weakly interacting Bose-Einstein condensates

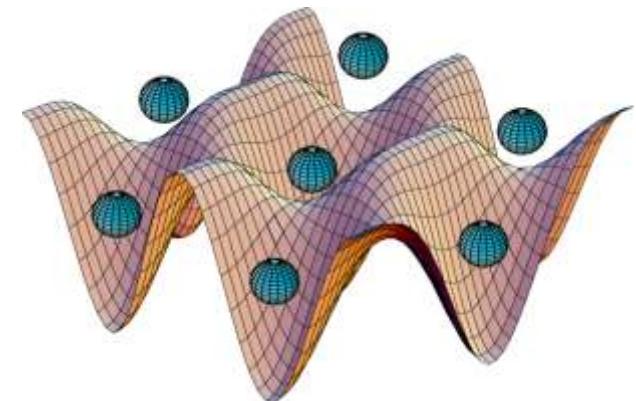


The atom-atom interaction allows to study

- superfluidity
- correlated quantum phases
- strongly entangled states

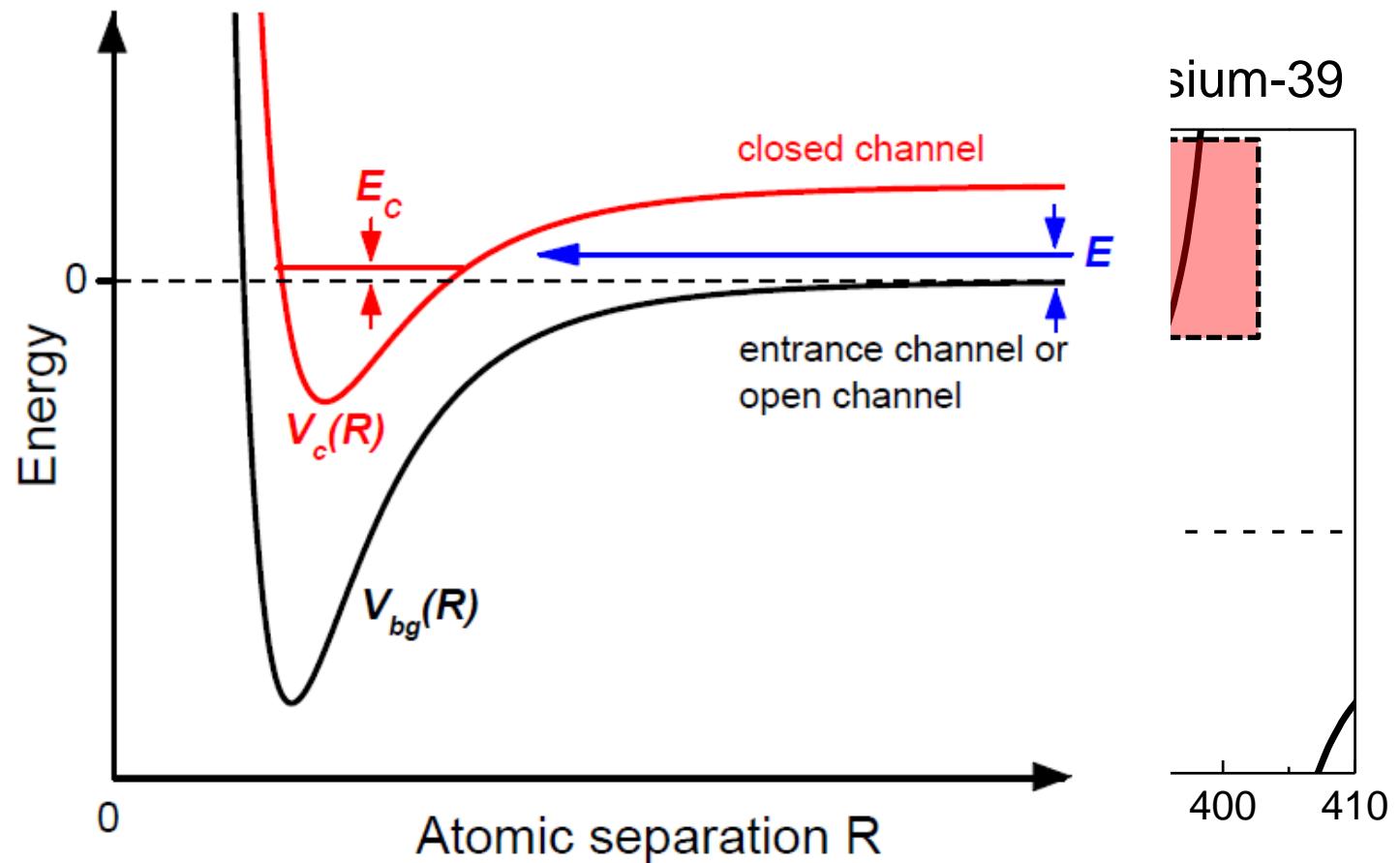
But at the same time it forbids

- the study of very low energy phenomena
- the implementation of ultraprecise interferometers



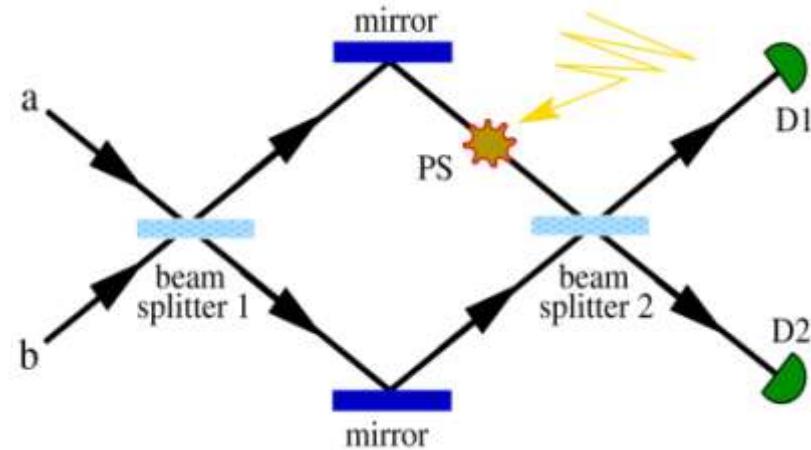
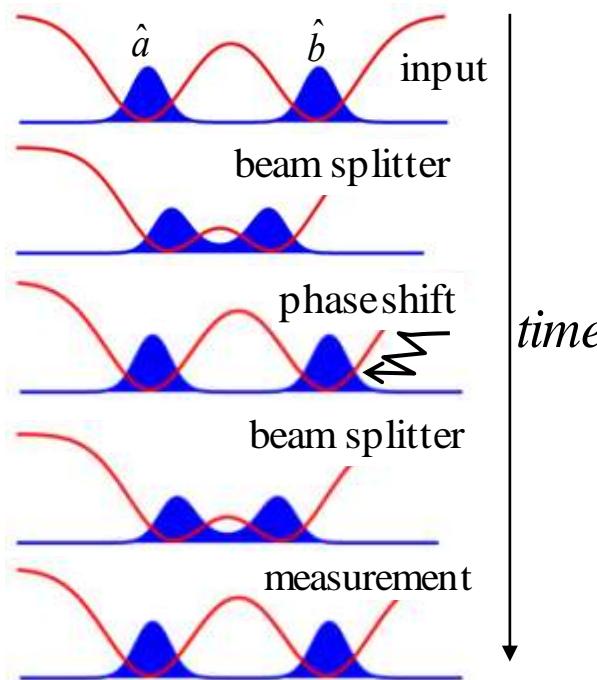
Two-body interaction in atomic systems

$$E_{\text{int}} = \frac{4\pi\hbar^2}{m} an + E_{dd}$$



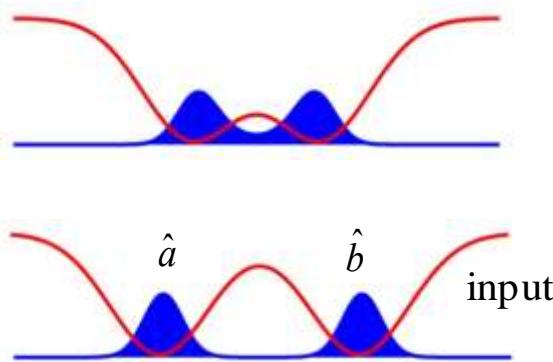
Atom interferometry with Bose-Einstein condensates

The atomic analogous of the optical Mach-Zehnder interferometer



- Very appealing for the measurement of local fields
- Atoms have a mass: high sensitivity detection of forces, rotations
- Atoms have a naturally strong nonlinearity (atom-atom interaction)

Atom interferometry in a trap



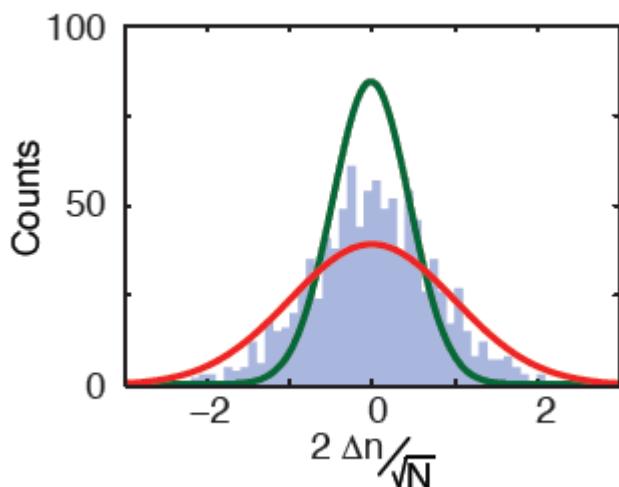
The interaction can be exploited to prepare entangled input states

Coherent state \rightarrow shot noise limit

$$|\Psi\rangle_0 \approx \bigotimes_{l=1}^N (|a\rangle_l + |b\rangle_l) \rightarrow \quad \Delta\vartheta/\vartheta \approx 1/\sqrt{N}$$

NOON state \rightarrow Heisenberg limit

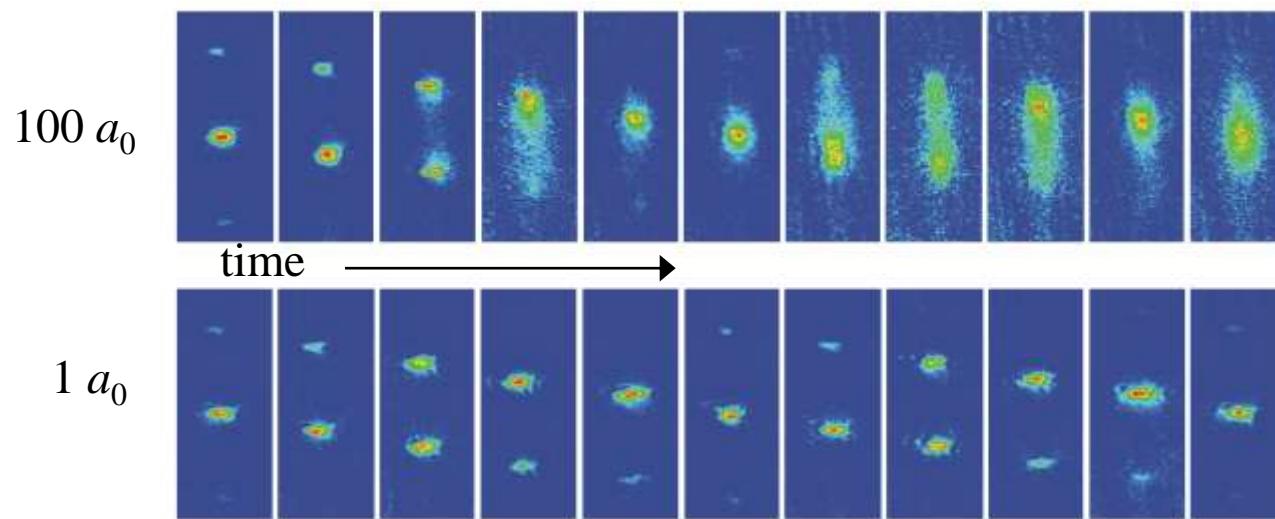
$$|\Psi\rangle_{NOON} \approx (|a\rangle_0 + |b\rangle_N) + (|a\rangle_N + |b\rangle_0) \rightarrow \quad \Delta\vartheta/\vartheta \approx 1/N$$



Squeezed states $\rightarrow \Delta\vartheta/\vartheta \approx \xi/\sqrt{N}$

The same interaction provides decoherence of the interferometer

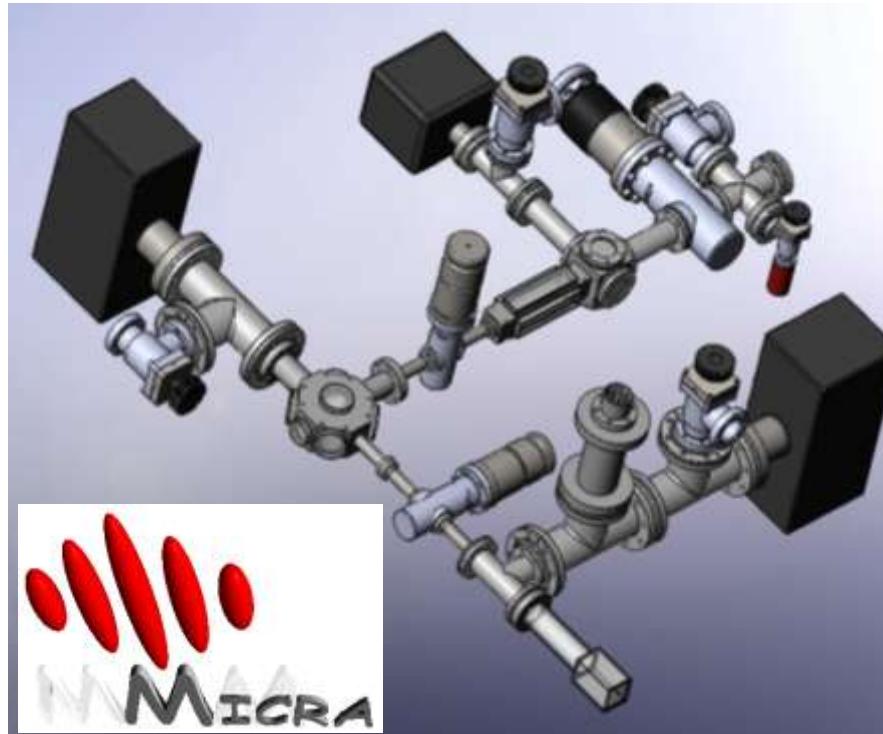
A lattice interferometer



Our strategy:

- 1) Employ a Bose-Einstein condensate: maximal coherence, minimal size
- 2) Use a large nonlinearity to create appropriate entangled input states
- 3) Cancel the nonlinearity to operate the interferometer

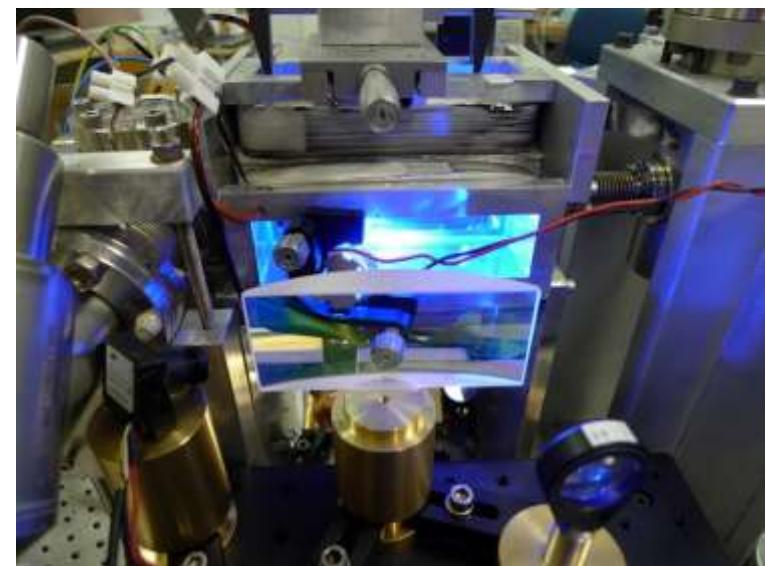
A novel set-up for potassium-39 BECs



2009



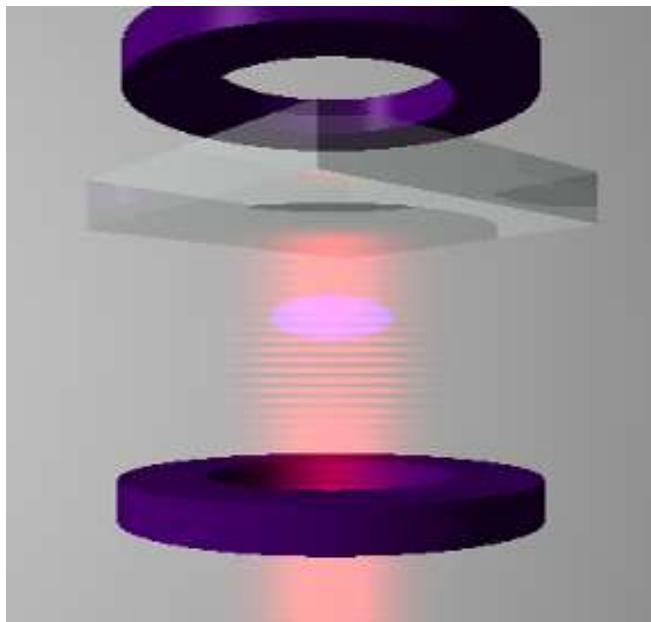
2010



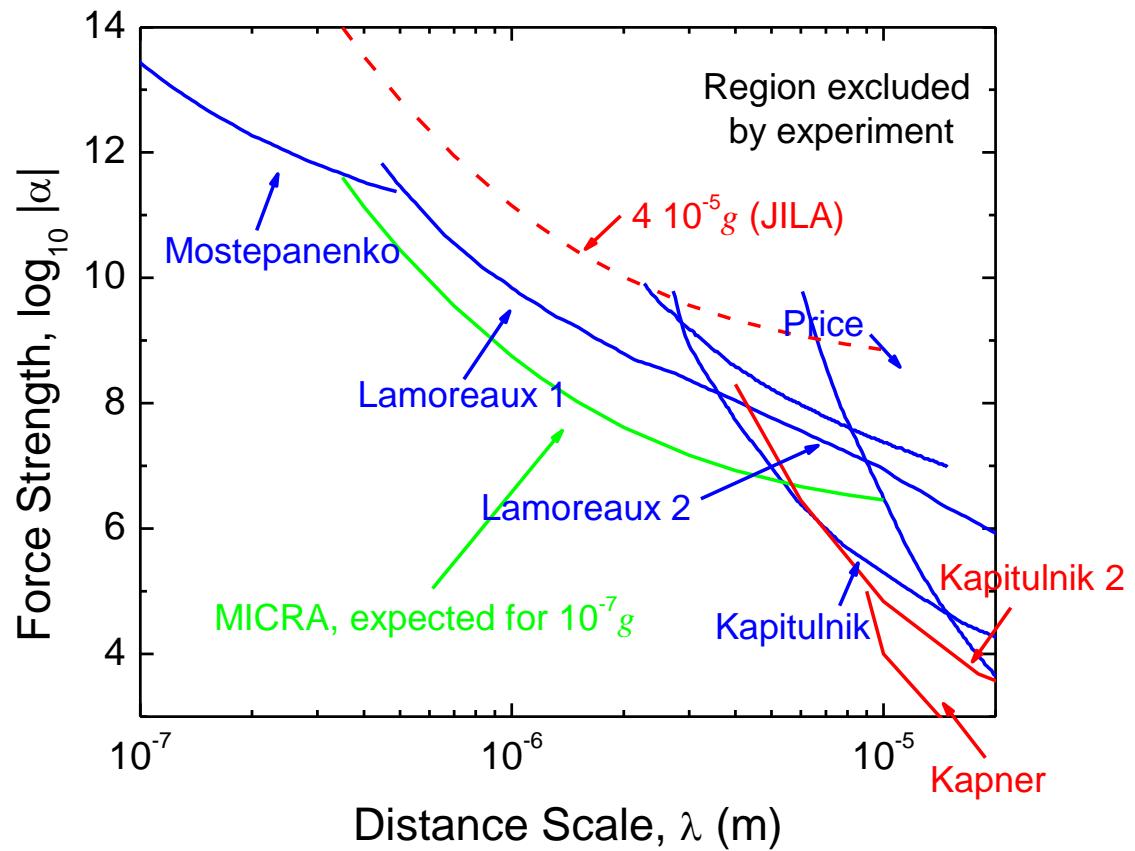
- improved control of magnetic fields
- high resolution imaging
- high repetition rate

FIRB Futuro in Ricerca: Marco Fattori (INFN) + Luca Pezzè (CNR- Trento)

Search for non-newtonian gravitational forces



$$U_G = - \int dV \frac{Gm\rho}{r} \left(1 + \alpha e^{-r/\lambda}\right)$$

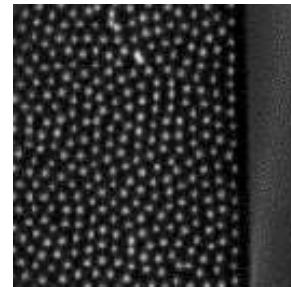


Disorder physics with ultracold atoms

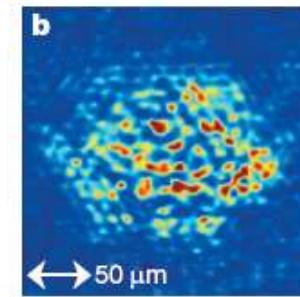
Disorder is ubiquitous in nature. Even if weak, it tends to inhibit transport.



Superfluids in
porous media



Superconducting thin
films



Light propagation in
random media

Still much has to be understood:

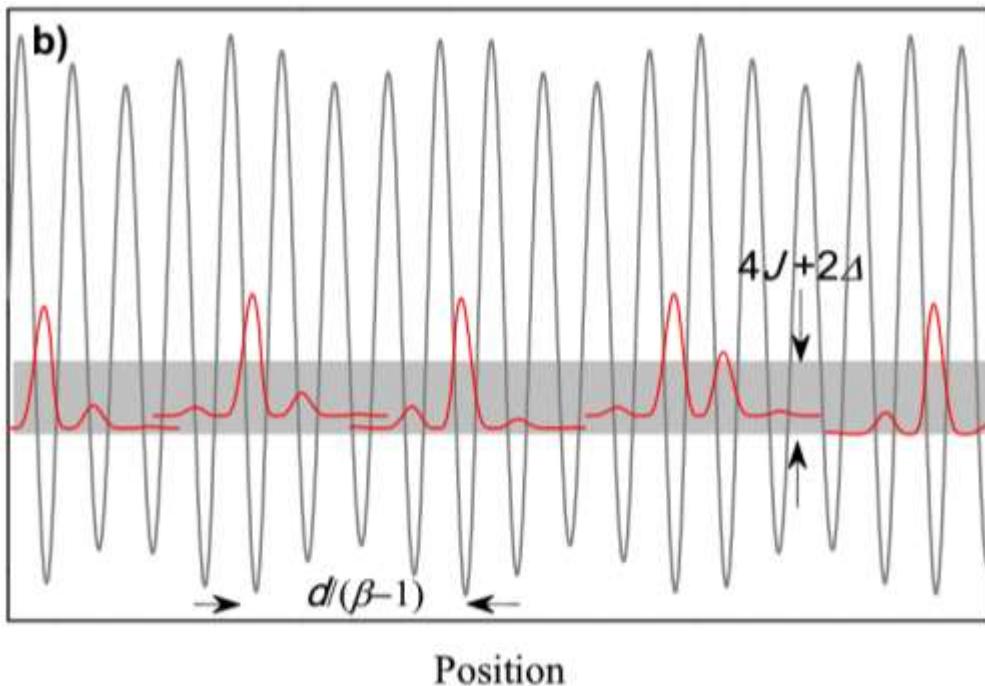
- Single-particle localization and dimensionality
- interplay of disorder and interactions
- strongly correlated systems

Bose-Einstein condensates in disordered potentials are very useful:

- massive particles
- tunable nonlinearity
- large control over disorder and dimensionality

Anderson localization in quasiperiodic lattices

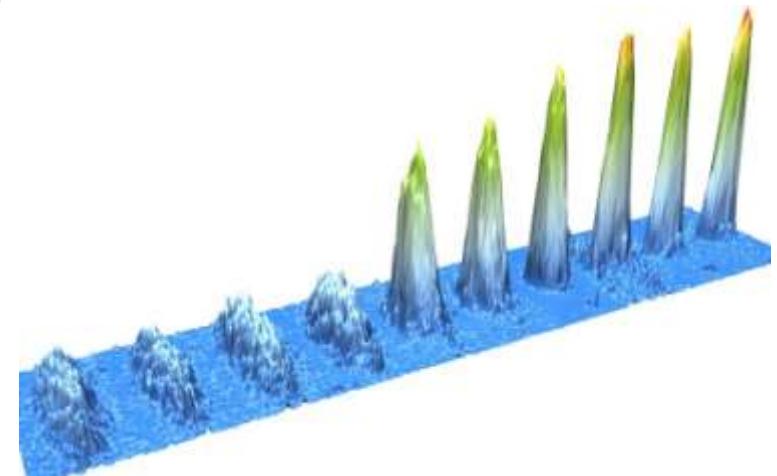
Energy



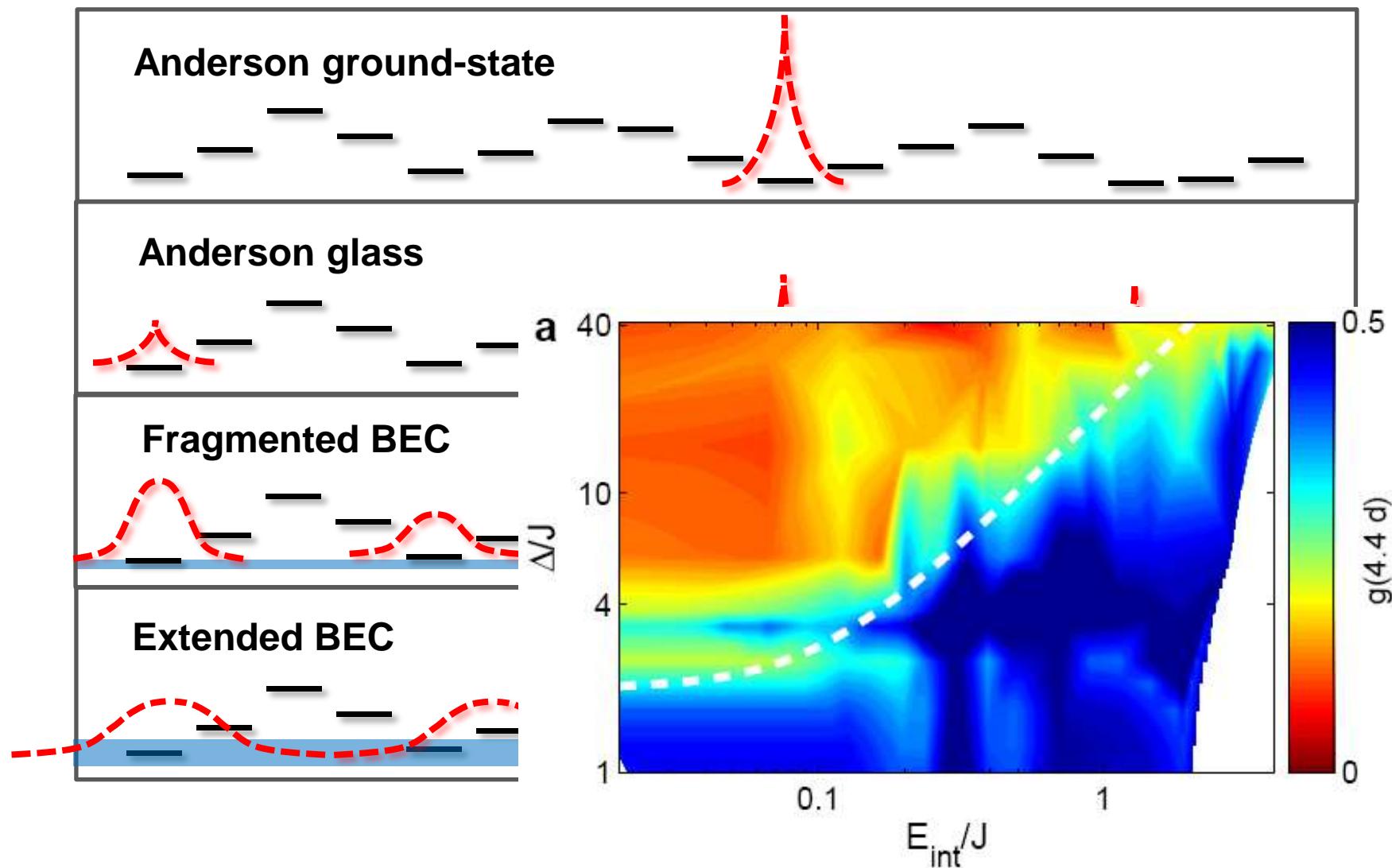
A realization of the Aubry-Andr   (or Harper) model

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

Anderson localization is observable in both spatial and momentum analysis

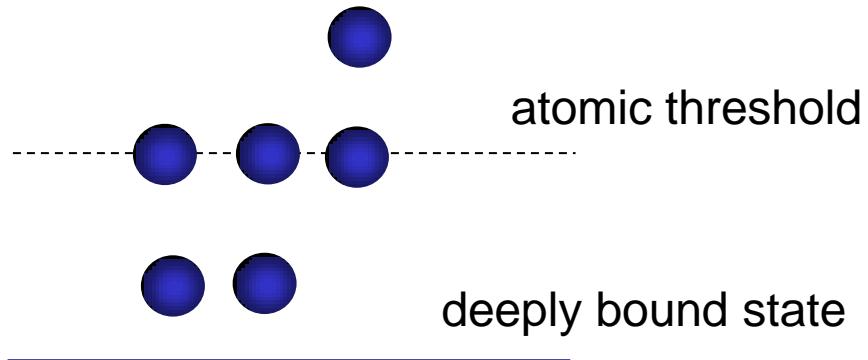


Delocalizing effect of a repulsive interaction

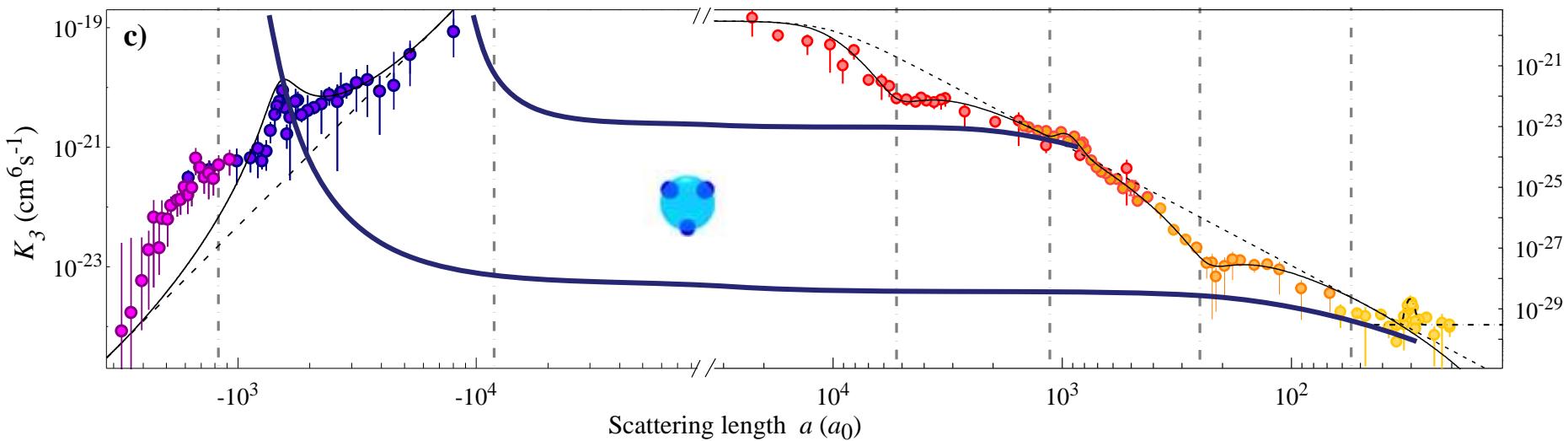


Three-body physics in BECs

Three-body recombination is the first step in the collisional decay of a BEC ...

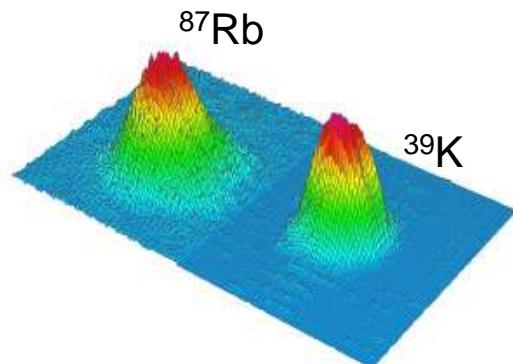


... but also carries information of the underlying few-body (Efimov) states



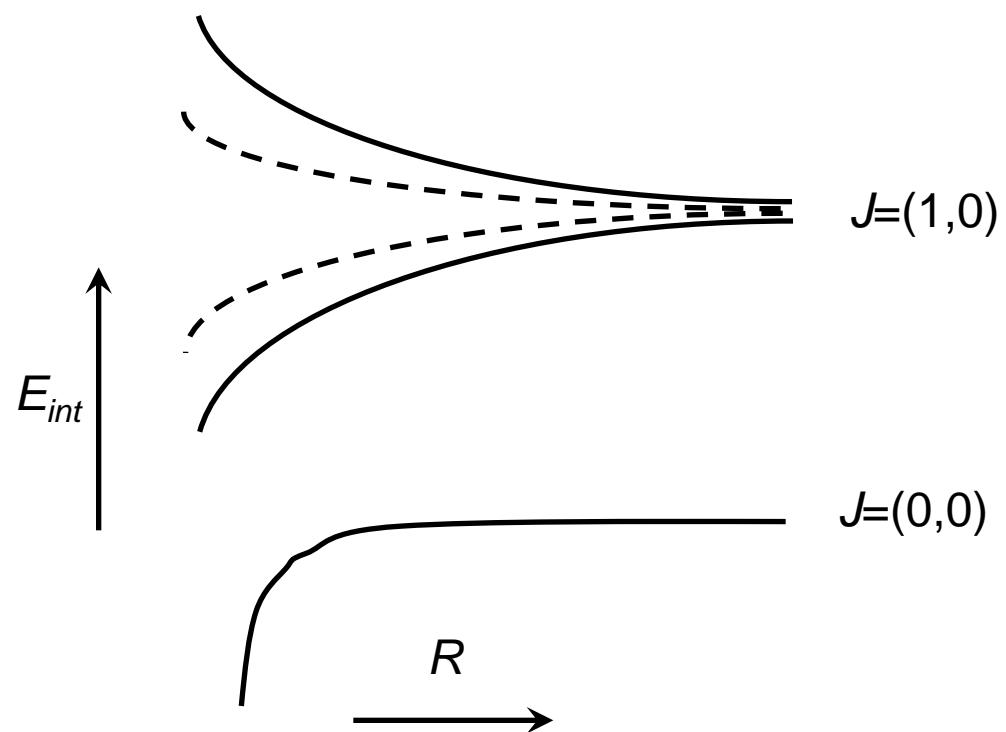
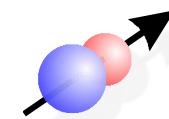
... and can allow to have large effective three-body interactions

Strong tunable dipolar interactions in quantum gases



Feshbach resonance

$d=0.7\text{D}$



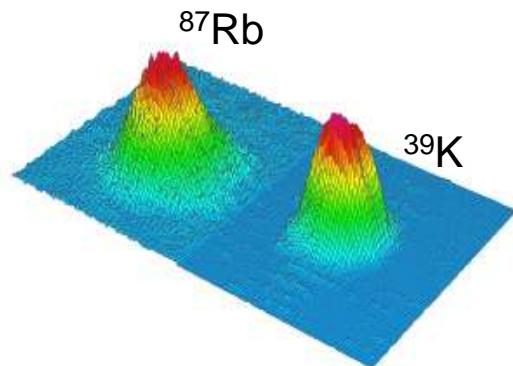
A schematic diagram showing two pairs of spheres (blue and red) connected by dashed lines representing a chain. The distance between the centers of the spheres is labeled R . The dipole moment of the left sphere pair is labeled d_1 and the dipole moment of the right sphere pair is labeled d_2 .

$$V = \frac{\mathbf{d}_1 \cdot \mathbf{d}_2}{R^3} - \frac{3(\mathbf{d}_1 \cdot \mathbf{R})(\mathbf{d}_2 \cdot \mathbf{R})}{R^5}$$

A schematic diagram showing three spheres (one blue, one red, one blue) arranged in a triangle. The blue spheres represent ^{87}Rb atoms and the red sphere represents a ^{39}K atom. Dipole moments are indicated by arrows pointing outwards from the spheres.

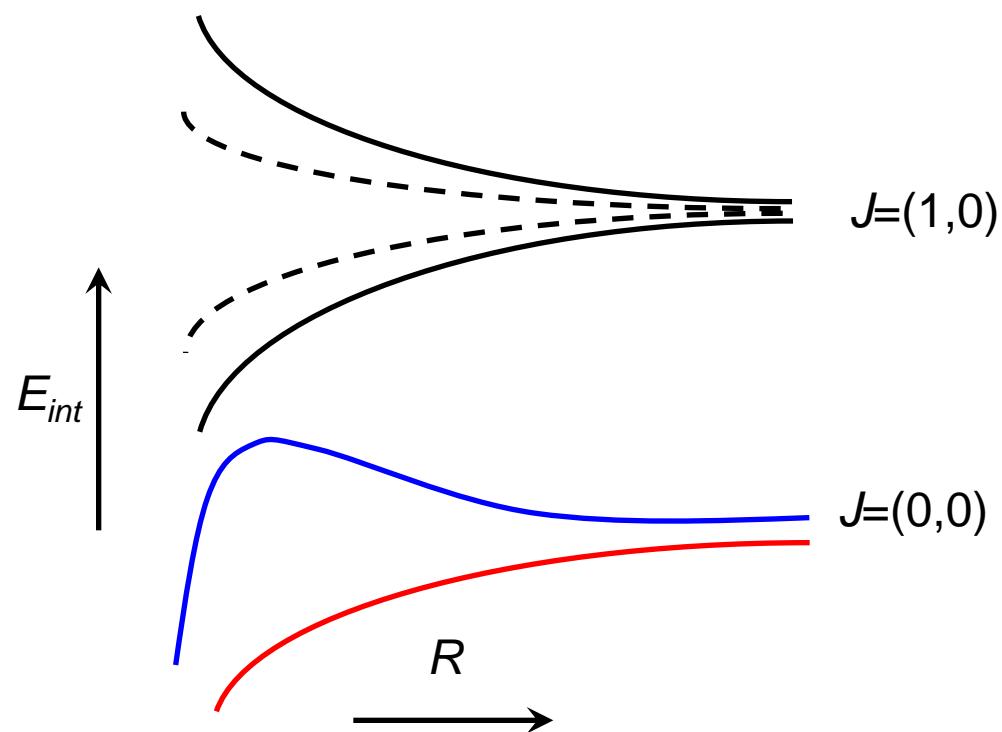
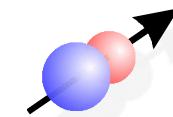
$$V = -\frac{d^4}{6BR^6}$$

Strong tunable dipolar interactions in quantum gases



Feshbach resonance

$d=0.7\text{D}$



A schematic diagram showing two pairs of spherical particles (blue and red) arranged along a horizontal dashed line. The distance between the centers of the two pairs is labeled R . Each pair has a dipole moment \mathbf{d}_1 and \mathbf{d}_2 represented by arrows originating from the center of each sphere. The angle between the two dipoles is labeled θ .

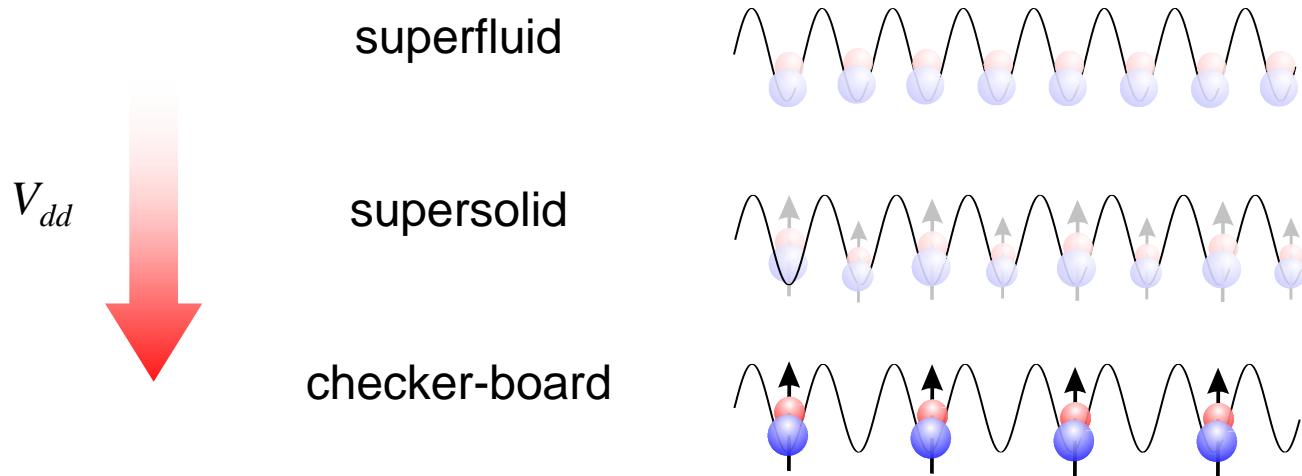
$$V = \frac{\mathbf{d}_1 \cdot \mathbf{d}_2}{R^3} - \frac{3(\mathbf{d}_1 \cdot \mathbf{R})(\mathbf{d}_2 \cdot \mathbf{R})}{R^5}$$

A schematic diagram showing two pairs of spherical particles (blue and red) arranged along a horizontal dashed line. The distance between the centers of the two pairs is labeled R . Each pair has a dipole moment \mathbf{d} represented by an arrow originating from the center of each sphere. The angle between the two dipoles is labeled θ . A vector \mathcal{E} is shown perpendicular to the plane defined by the two dipoles.

$$V = d^2(\mathcal{E}) \frac{(1 - 3 \cos^2 \theta)}{R^3}$$

Strong tunable dipolar interactions in quantum gases

Long-range nature of the dipolar interaction: novel quantum phases

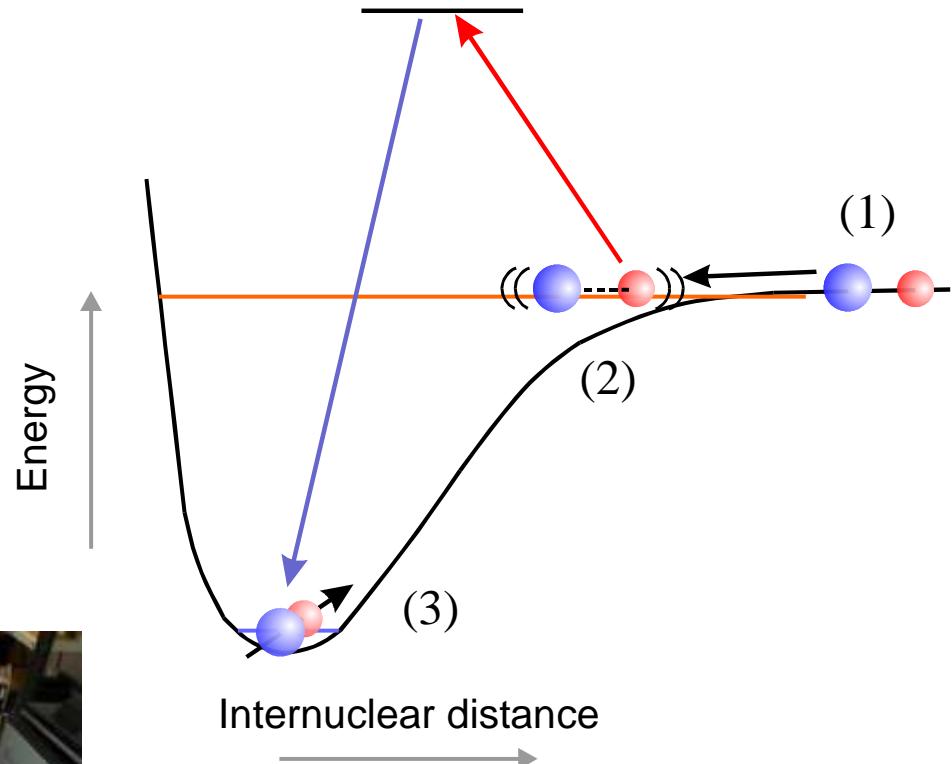
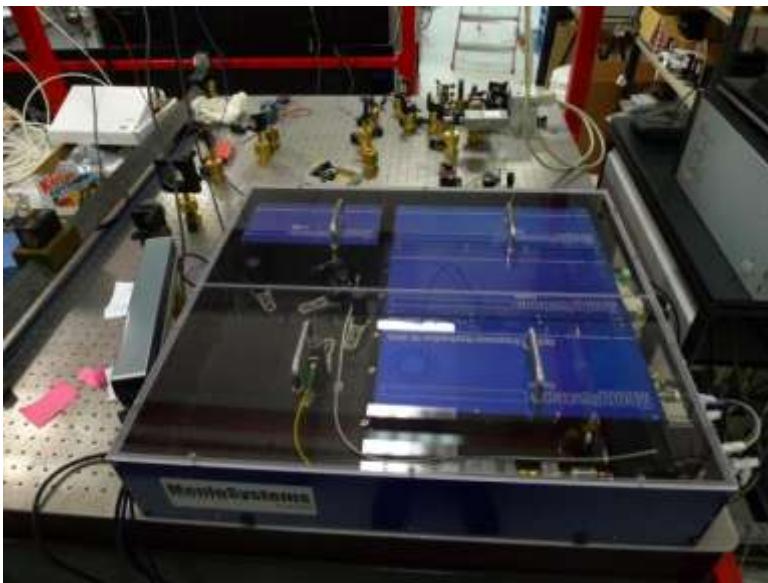


- simulation of spin lattice hamiltonians
- lattices of quasi-2D systems: quantum phases of dimers or chains
- three-body interactions larger than two-body one
- ...



How to produce ultracold polar dimers?

- 1) Take an ultracold quantum degenerate atomic mixture
- 2) Associate a weakly-bound molecular quantum gas
- 2) Transfer it optically to deeply bound states ($v=0, J=0$)



The team

Massimo Inguscio

coll.: Chiara Fort, Leonardo Fallani, ...

Michele Modugno - Bilbao

Benjamin Deissler

Giacomo Roati - CNR

Marco Fattori

Matteo Zaccanti (Innsbruck)

Chiara D'Errico (MIT)

Dimitris Trypogeorgos (Oxford)

Mauro Mozzoni

Manuele Landini (Uni Trento)

Eleonora Lucioni

Luca Tanzi (Uni Milano)

Stefano Ferrari (Uni Milano)

