Doing condensed matter physics with the ultracold atomic gases

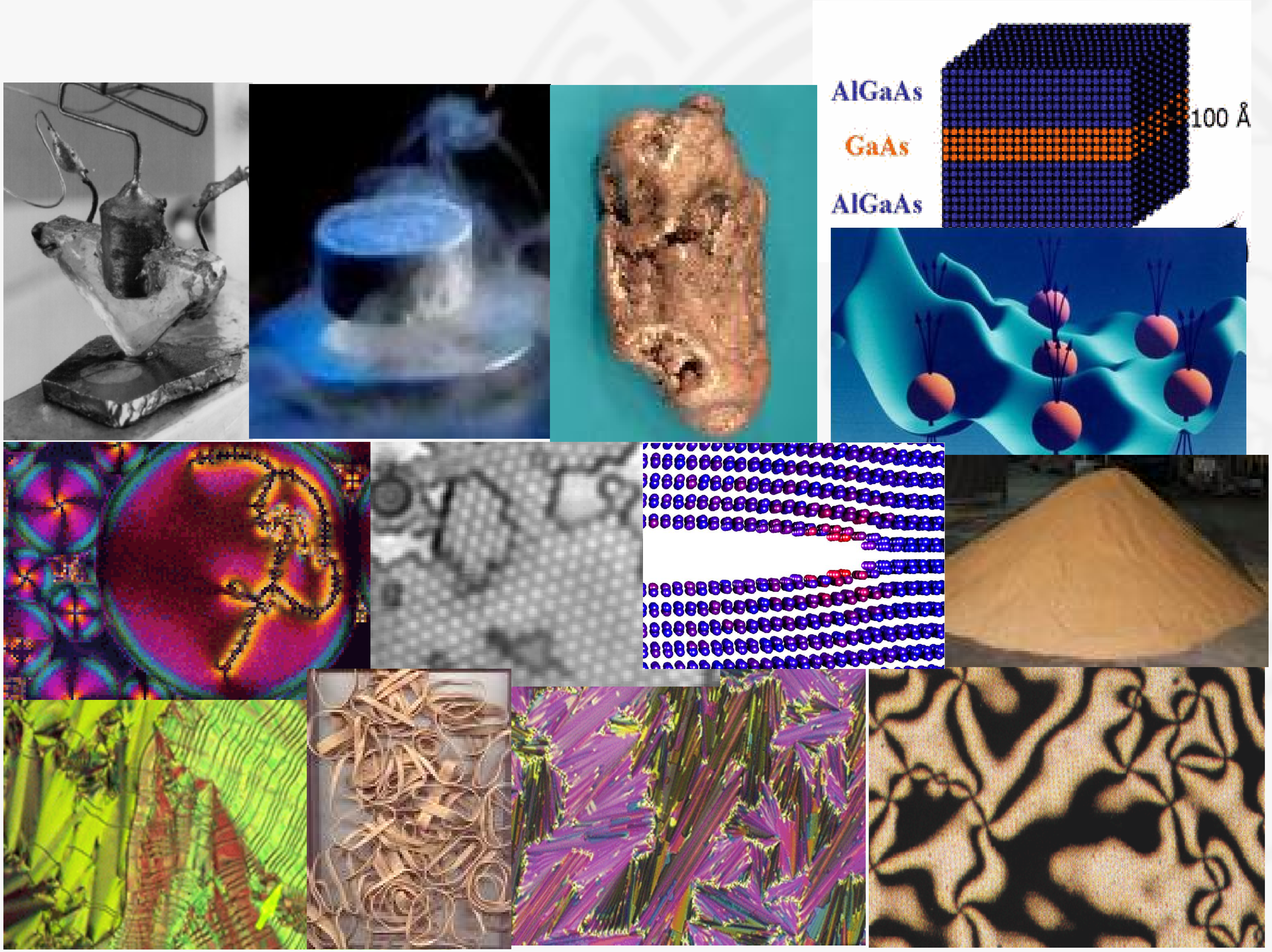
Victor Gurarie

University of Wyoming, Feb 26 2010

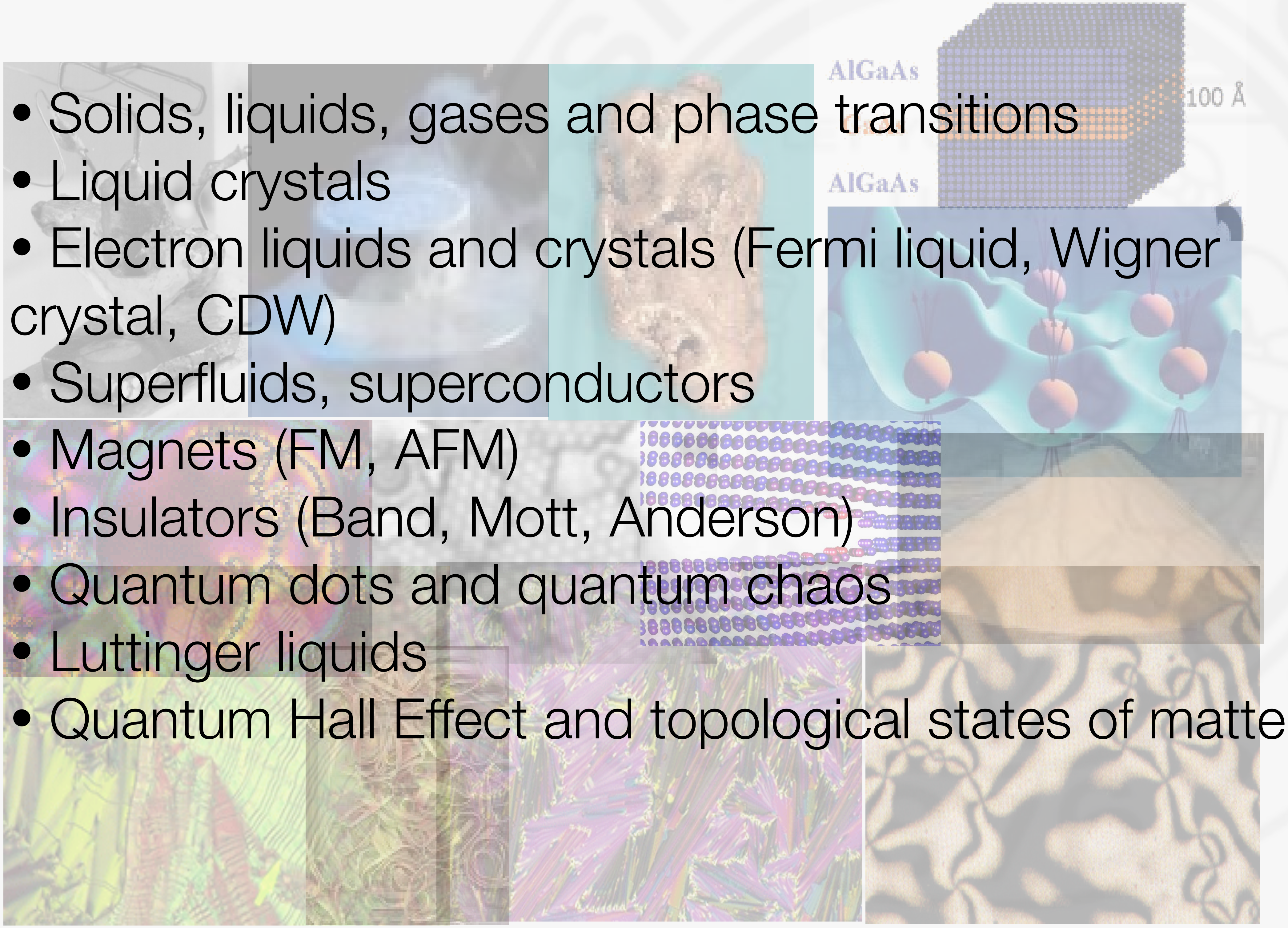
Outline

- Condensed matter and atomic physics
- Early days: BEC (mid 90s)
- Big breakthrough: modeling condensed matter physics with cold atoms (1998-2003)
- Modern developments (2003 on)

Condesed Matter Physics

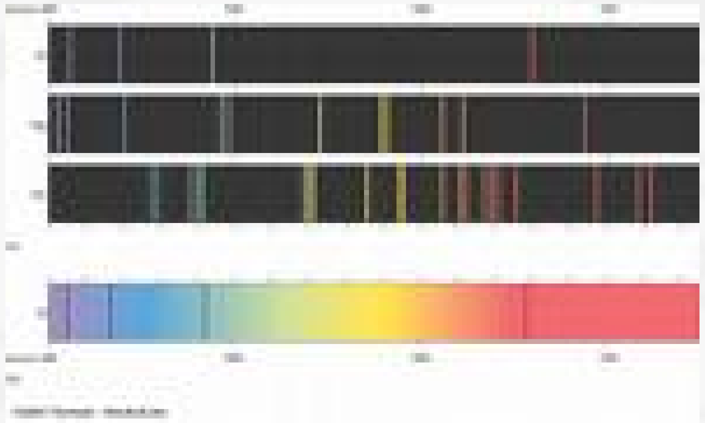


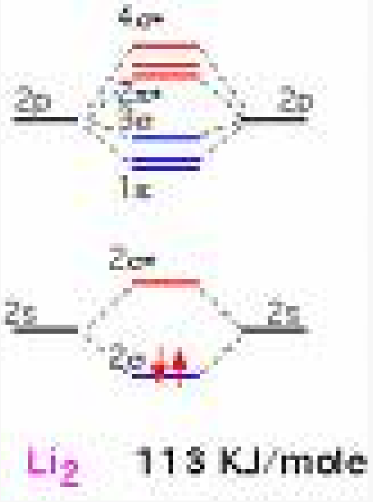
Condesed Matter Physics

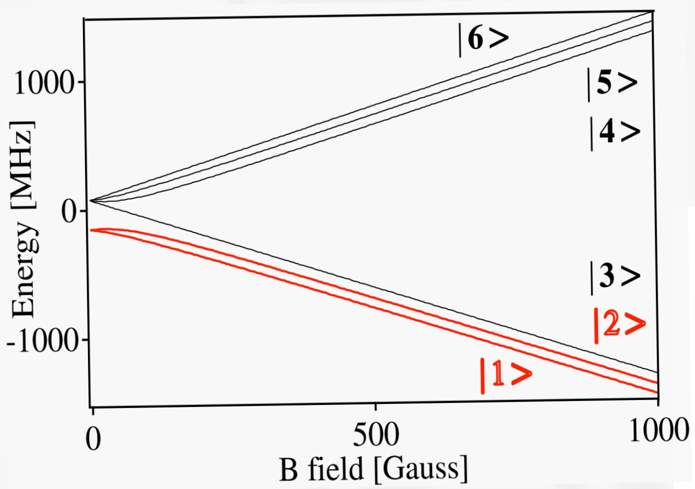


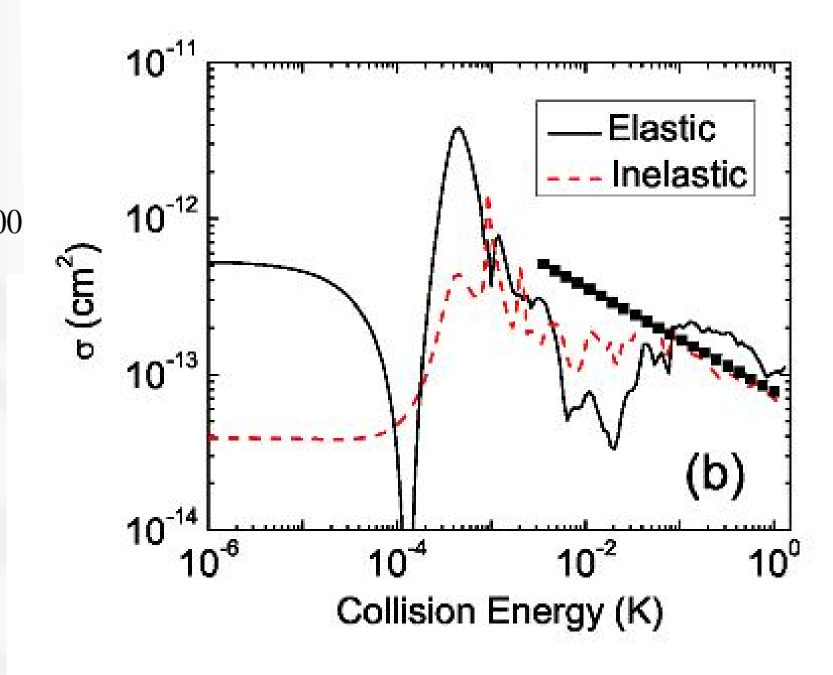
- Solids, liquids, gases and phase transitions
- Liquid crystals
- Electron liquids and crystals (Fermi liquid, Wigner crystal, CDW)
- Superfluids, superconductors
- Magnets (FM, AFM)
- Insulators (Band, Mott, Anderson)
- Quantum dots and quantum chaos
- Luttinger liquids
- Quantum Hall Effect and topological states of matter

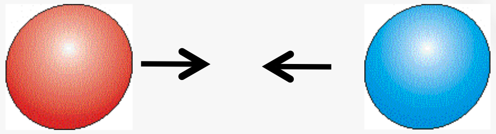
Atomic Physics (naive view of a condensed matter theorist)





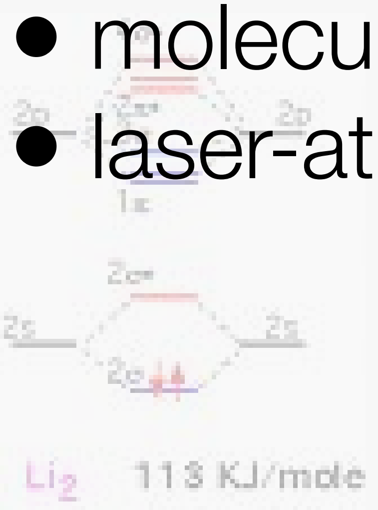


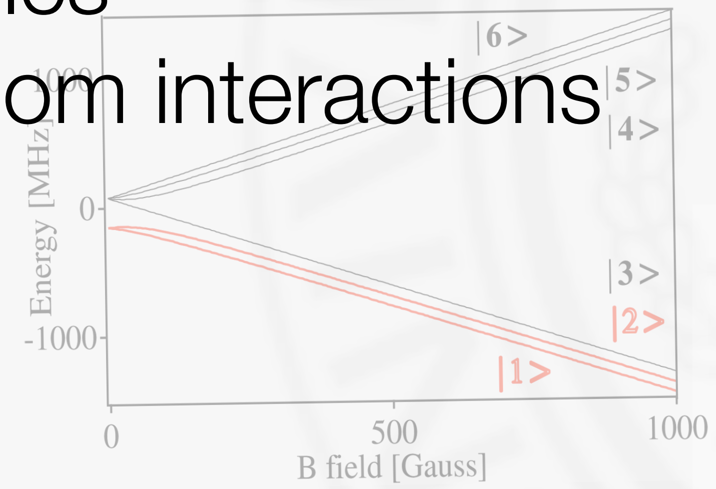


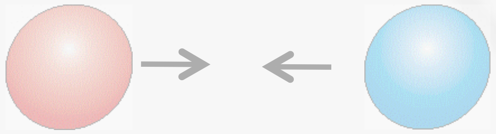


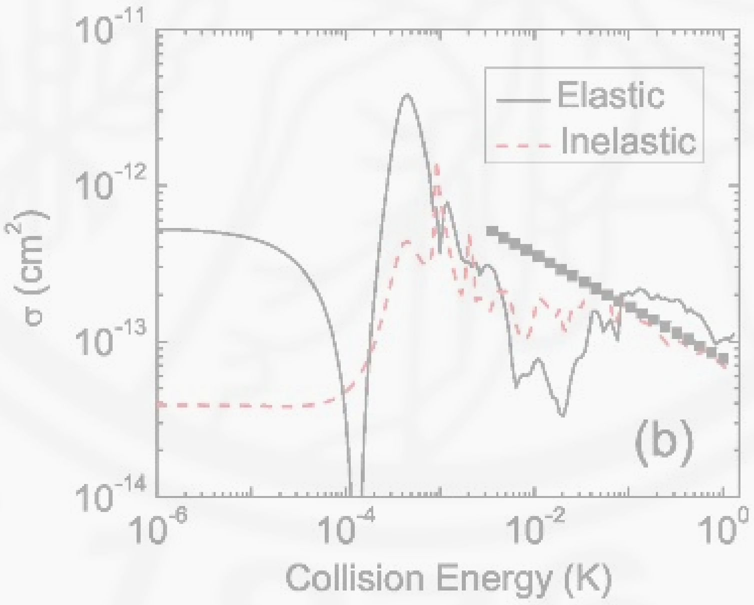
Atomic Physics (naive view of a condensed matter theorist)

- precision spectroscopy
- atomic collisions
- molecules
- laser-atom interactions









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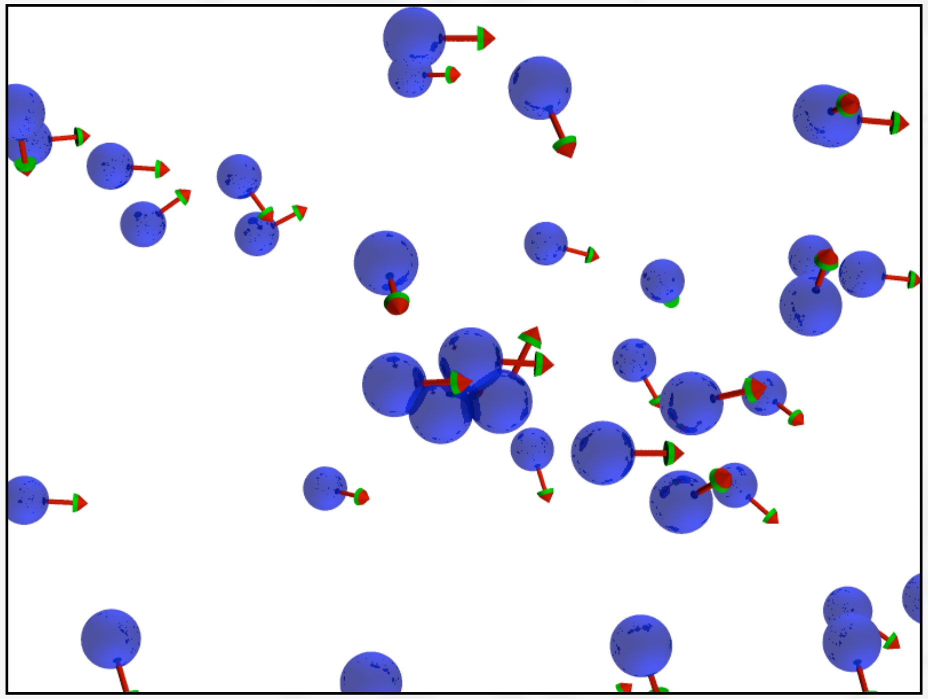
Dilute atomic gases

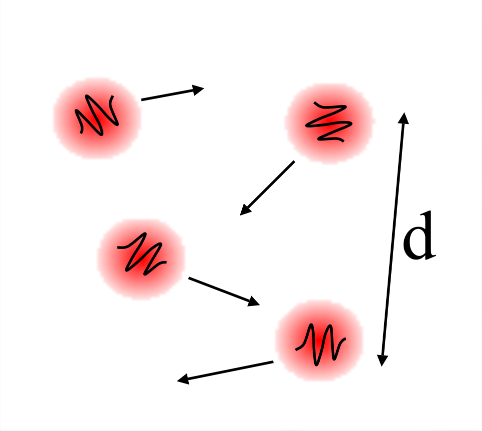
Density ~ 10^{12} cm^{-3} ⇔ d~10^4 Å, mfp = $1/(n\,\boldsymbol{\sigma})$ ~ 10cm



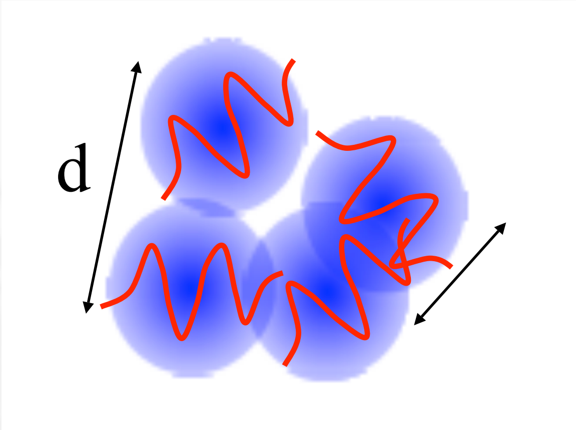
This is but an ideal gas...

Degenerate atomic gases

hot



classical ideal Boltzmann gas



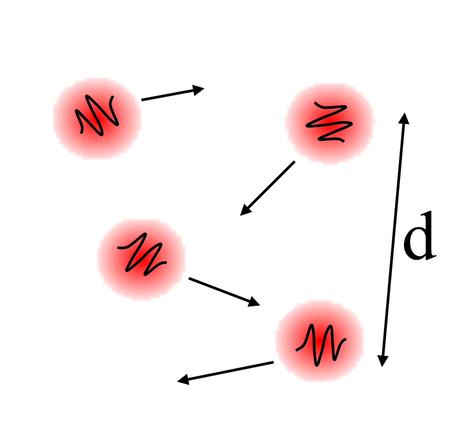
cold

degenerate quantum gas

$$\lambda_{dB} \sim \frac{h}{\sqrt{mT}}$$

Degenerate atomic gases

hot



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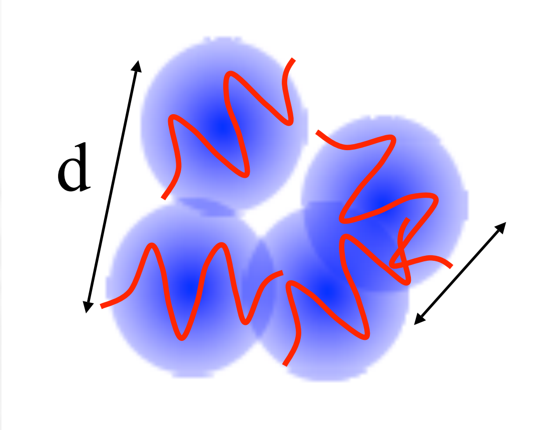

cold

degenerate quantum gas

$$\lambda_{dB} \sim \frac{h}{\sqrt{mT}}$$

$$\frac{h}{\sqrt{mT_d}} \sim d$$

Electron gas in a metal: $T_d \sim 10^4$ K

Dilute atomic gas: $T_d \sim 10^{-6}$ K

Cooling of atomic gases

Steven Chu, Claude Cohen-Tannoudji, Bill Phillips

Nobel Prize 1997

For development of methods to trap and cool atoms with laser light

Cooling of atomic gases

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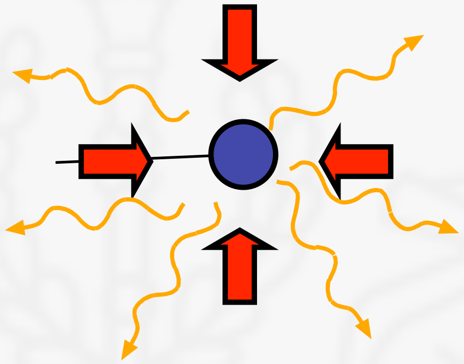

Laser (Doppler) cooling

1997
Chu,
Cohen-Tannoudji,
Phillips

300 K to 1 mK
~10^9 atoms

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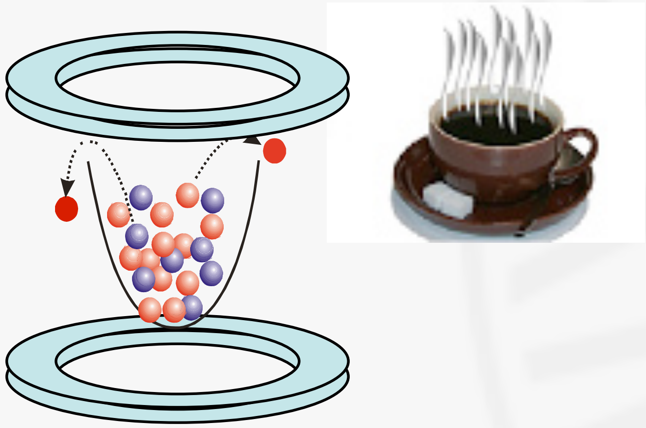
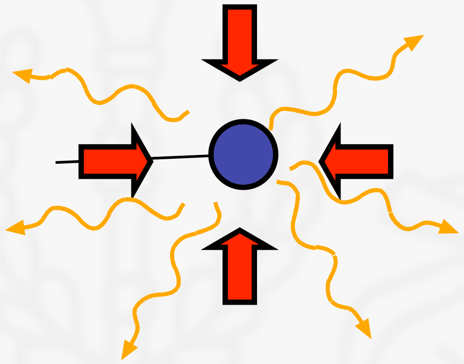


Evaporative cooling



Laser (Doppler) cooling

1997
Chu,
Cohen-Tannoudji,
Phillips

1 mK to 1 μK
~10^8 → 10^6 atoms

300 K to 1 mK
~10^9 atoms

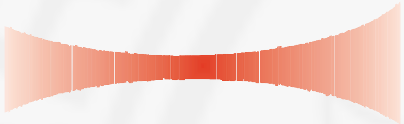
T

Imaging atomic gases

Time of flight measurements

Imaging atomic gases

Time of flight measurements



Imaging atomic gases

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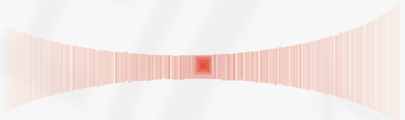
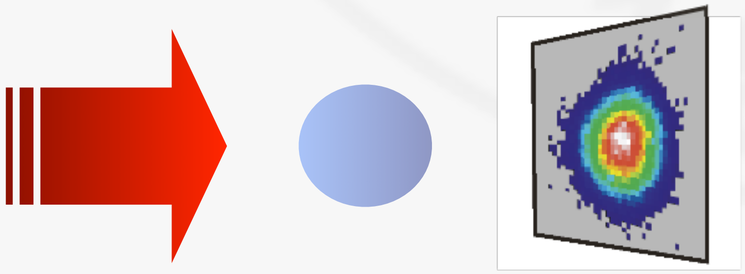


probing w/ resonant laser



shadow image

$$n(r,t) \approx n_i\left(\hbar k = mr/t\right)$$

Degenerate (very) weakly interacting gases $T < T_d$

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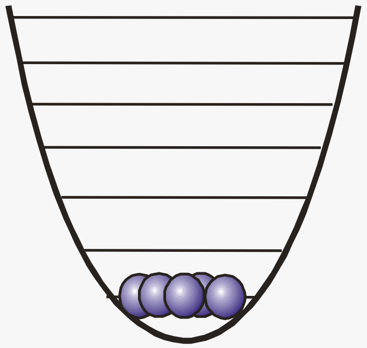
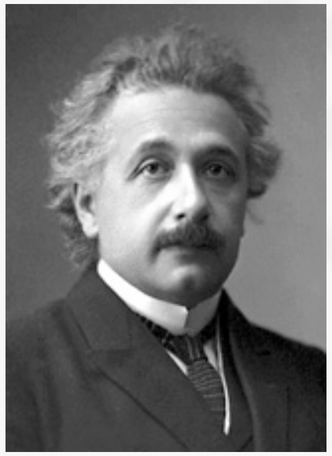
Bosons:

- Integer spin
- Symmetric wave function

Bose condensate



Bose



Einstein

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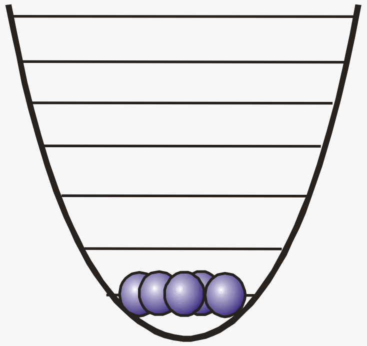
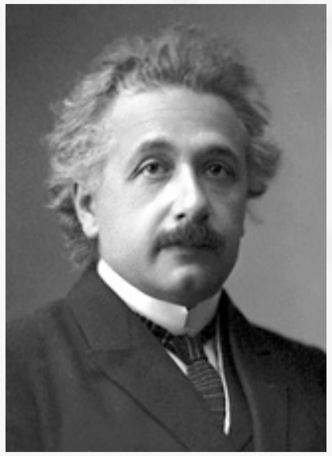


Bose

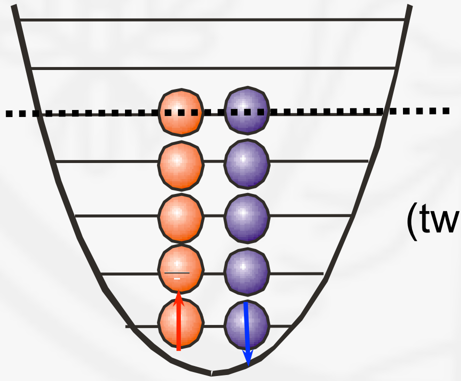


Einstein

Fermions:

- Half-integer spin
- Antisymmetric wave function

Degenerate Fermi gas: “Fermi condensate”

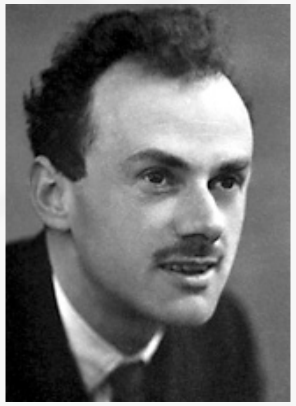


$E_F = k_B T_F$

(two iso-spin states)

Fermi

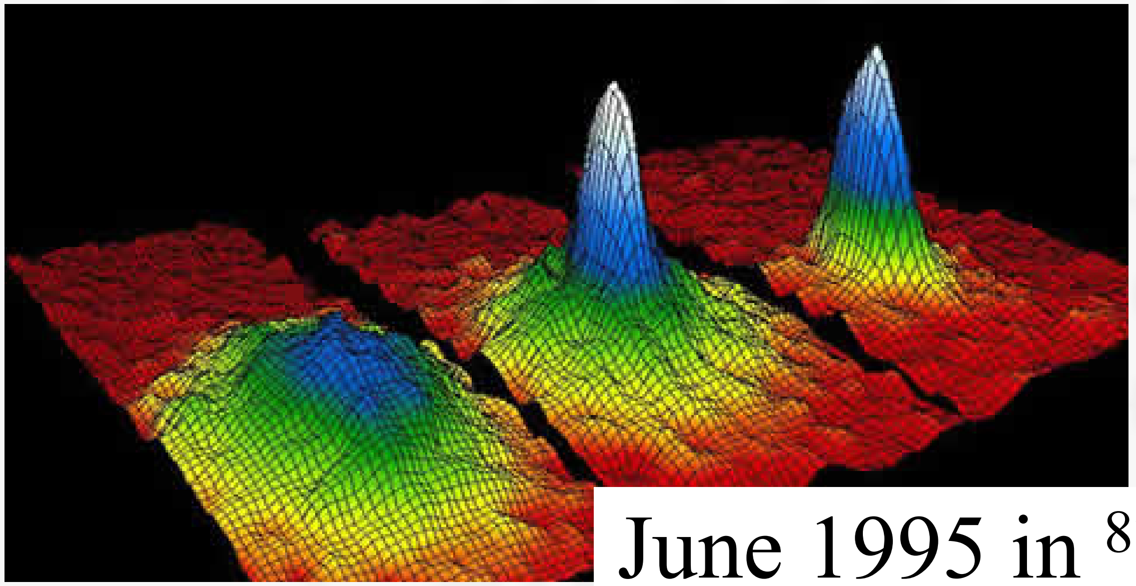
Dirac



First BEC (^{87}Rb)

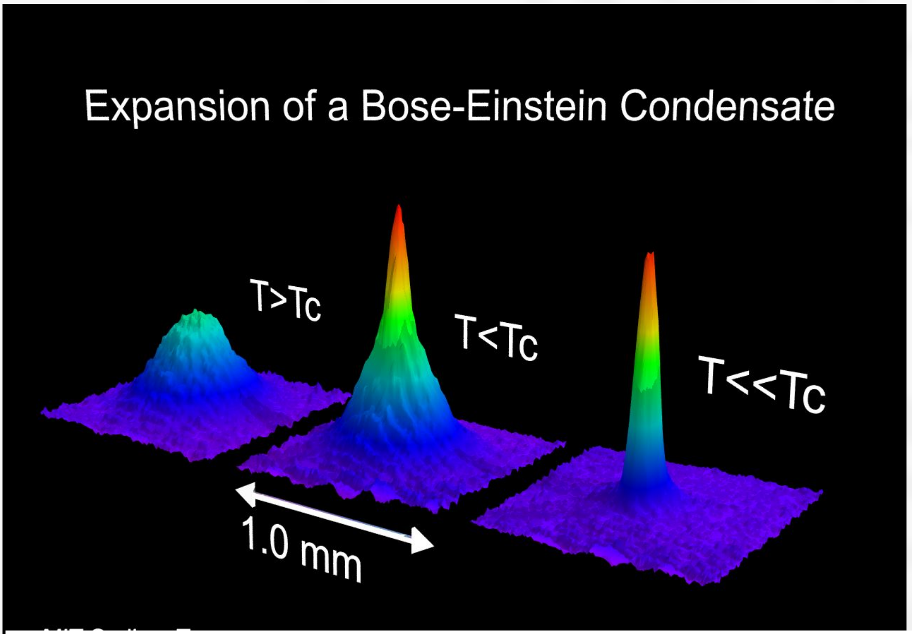
2001

Cornell Wieman

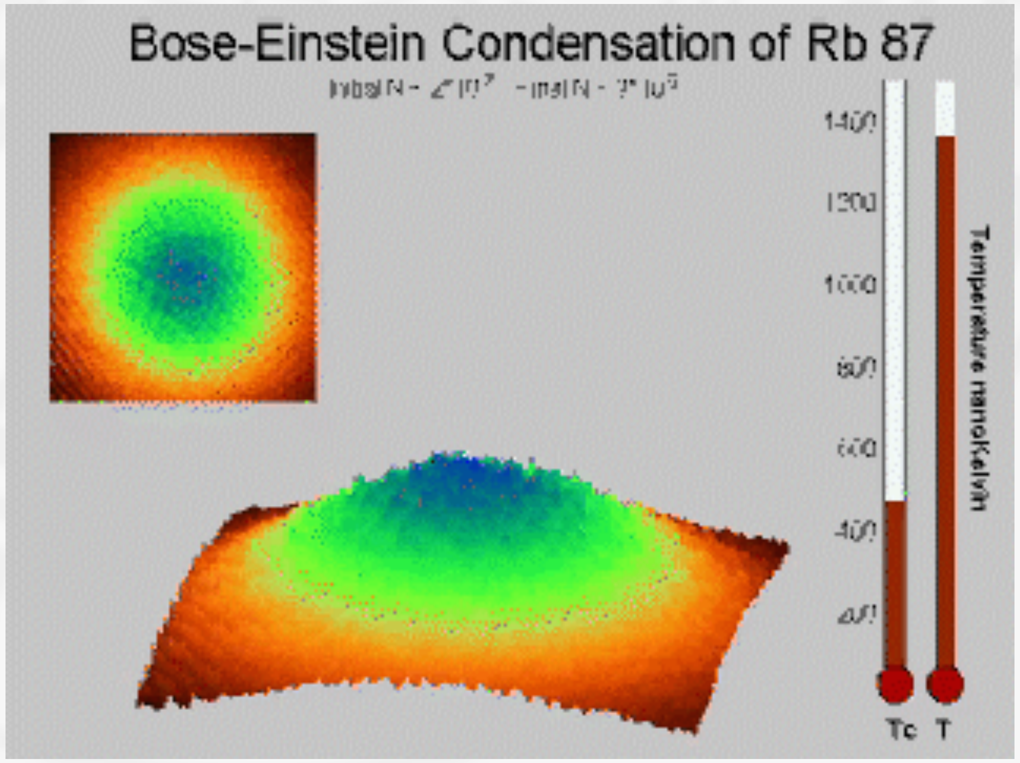


June 1995 in ^{87}Rb

Ketterle



September 1995 in ^{23}Na



BEC experiments, late 90s

Late 90s: “Dark ages” of cold atoms (various BEC experiments)

Ketterle ’97:
Will two ballistically expanding BECs interfere?

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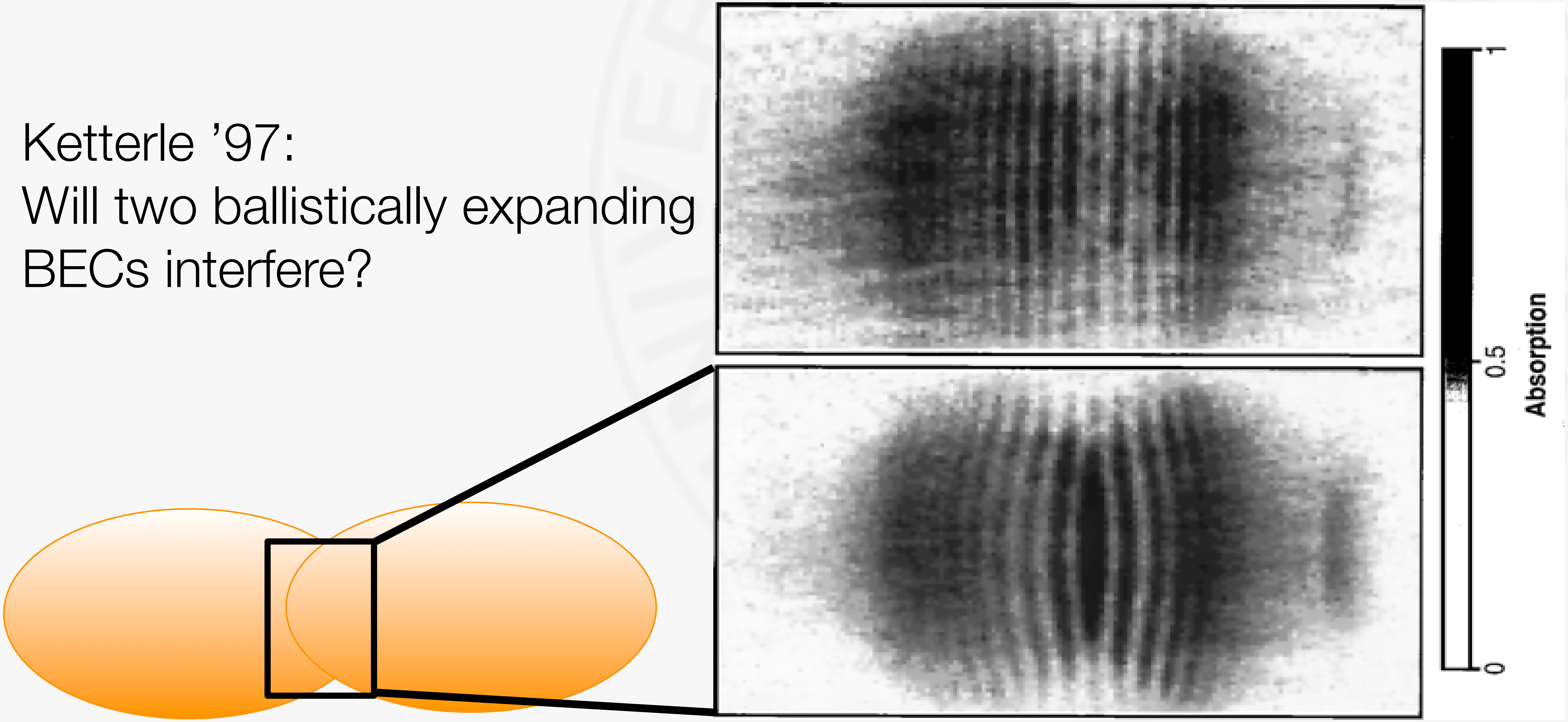

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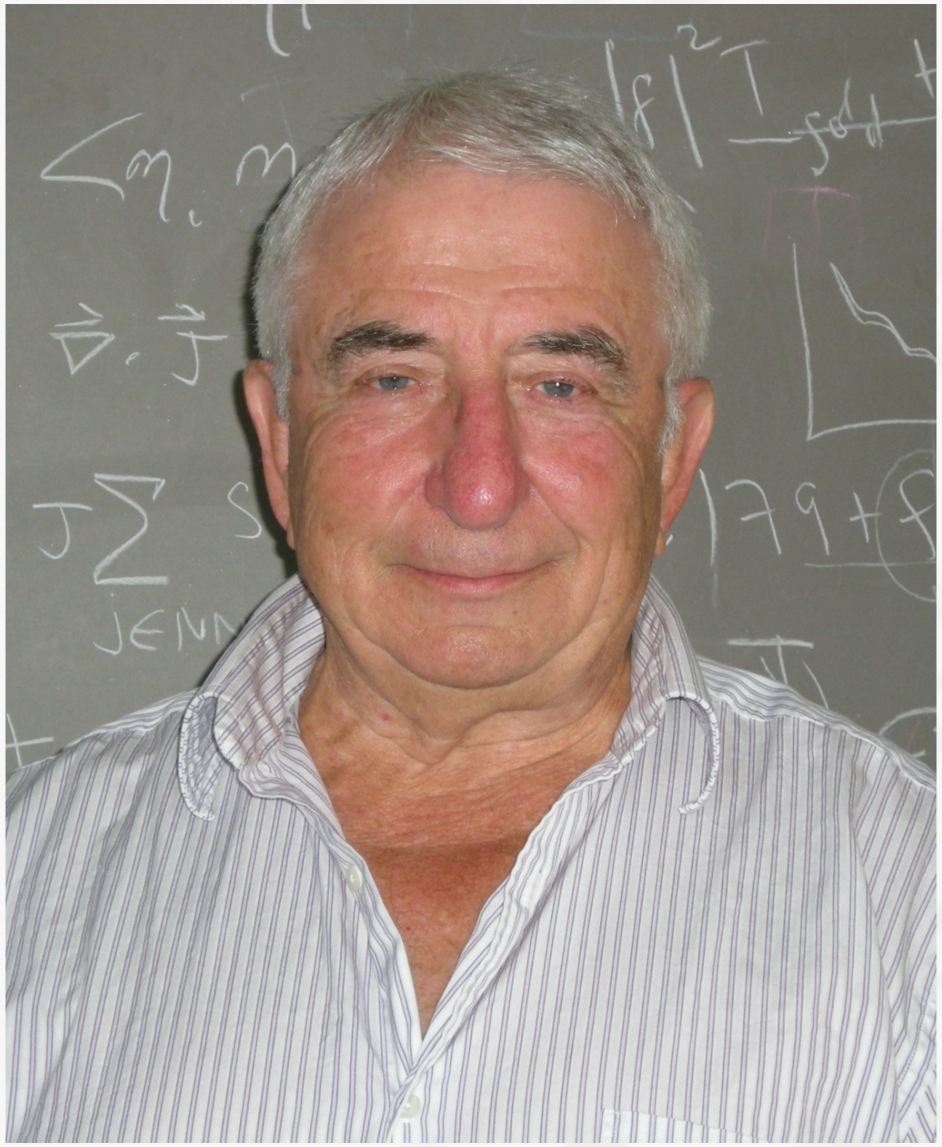
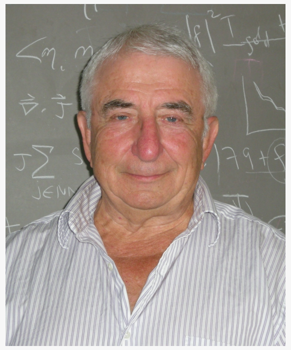
Superfluid - Mott insulator transition



S. Doniach, 1981



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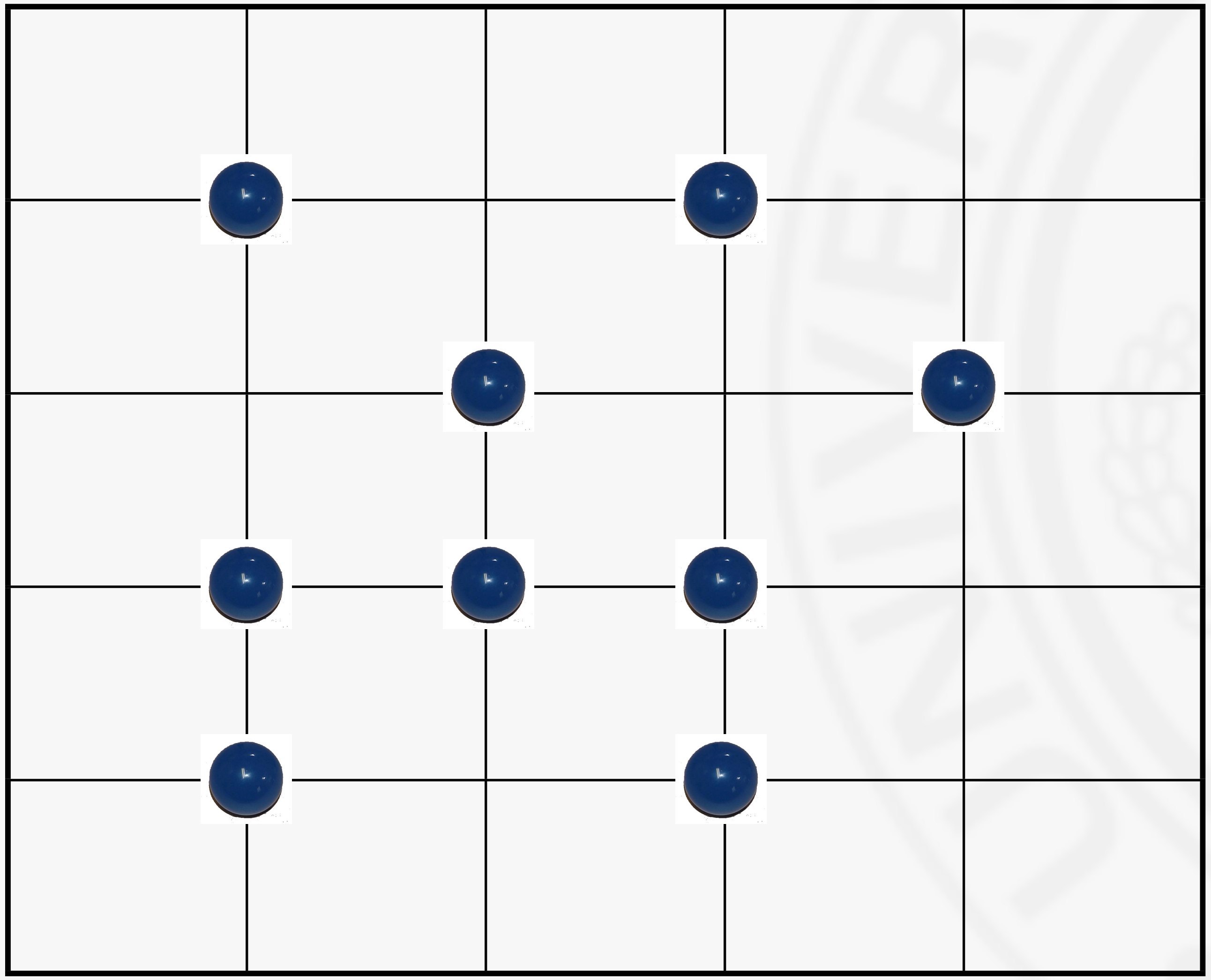

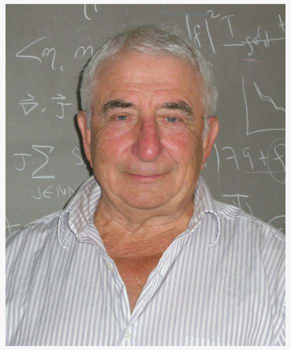

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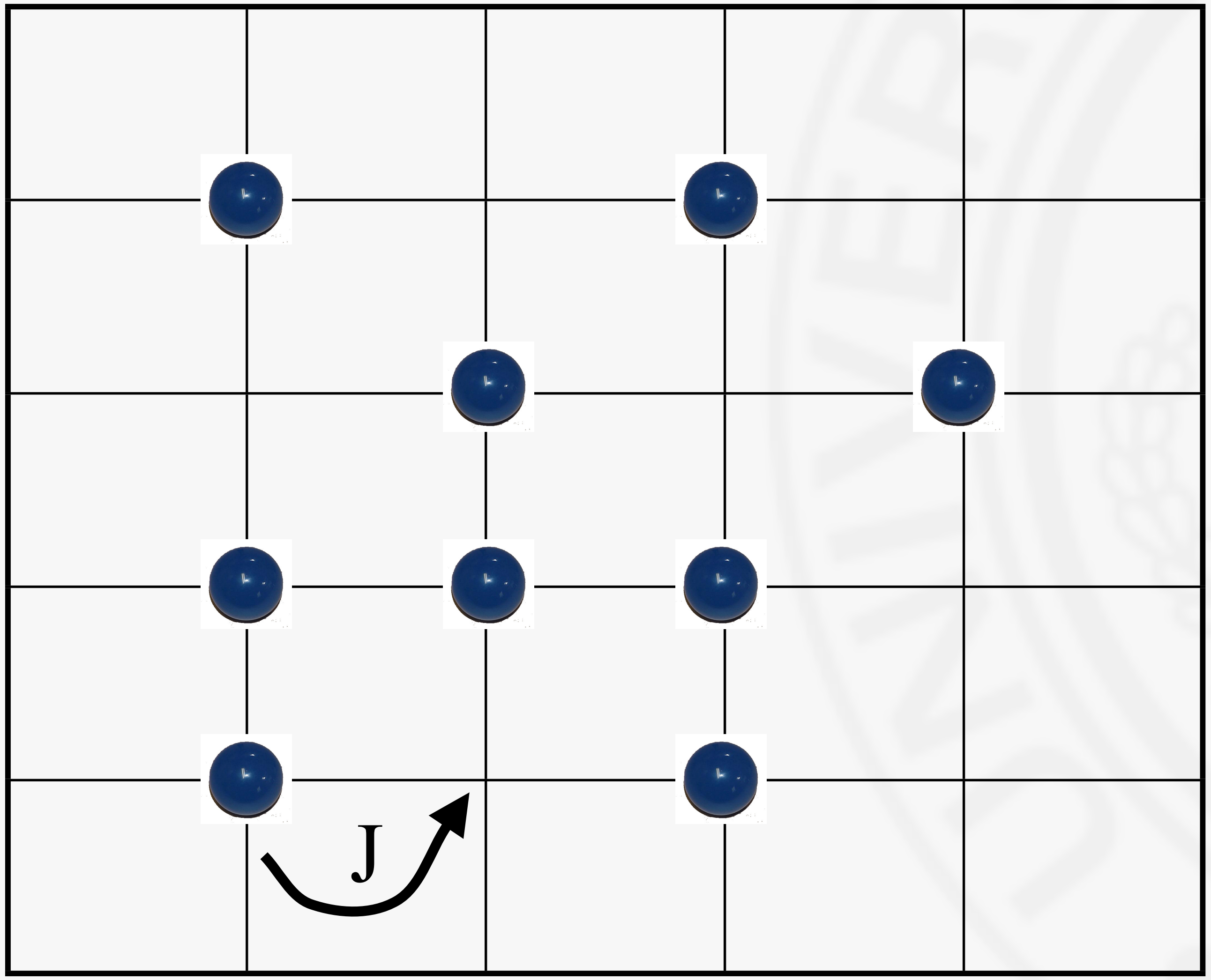

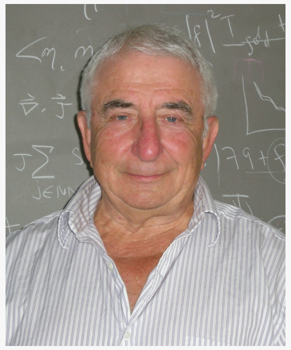

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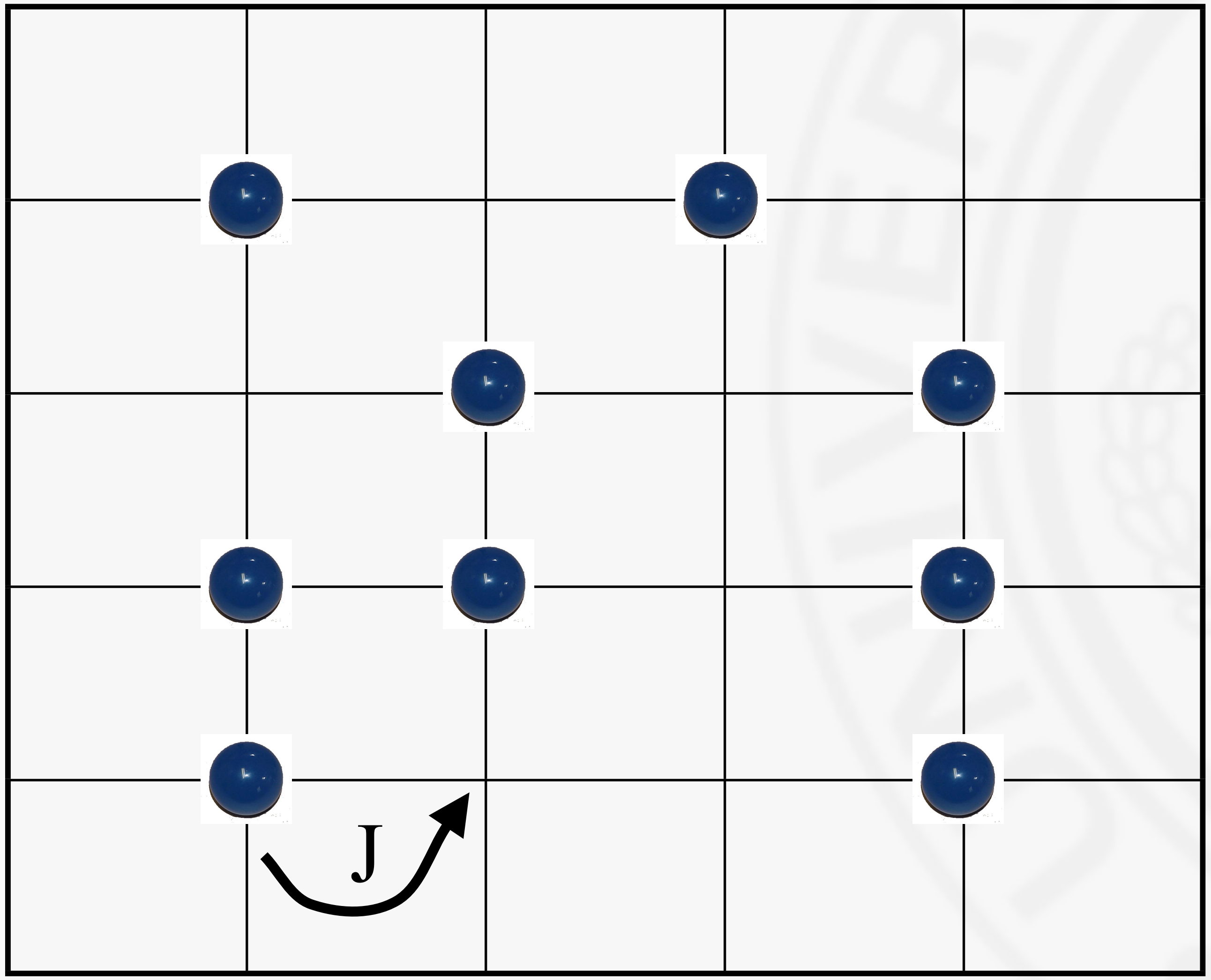

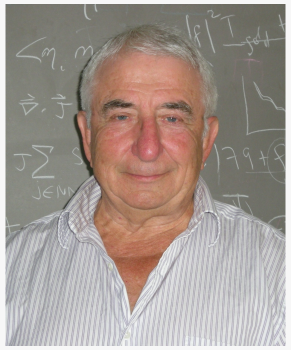

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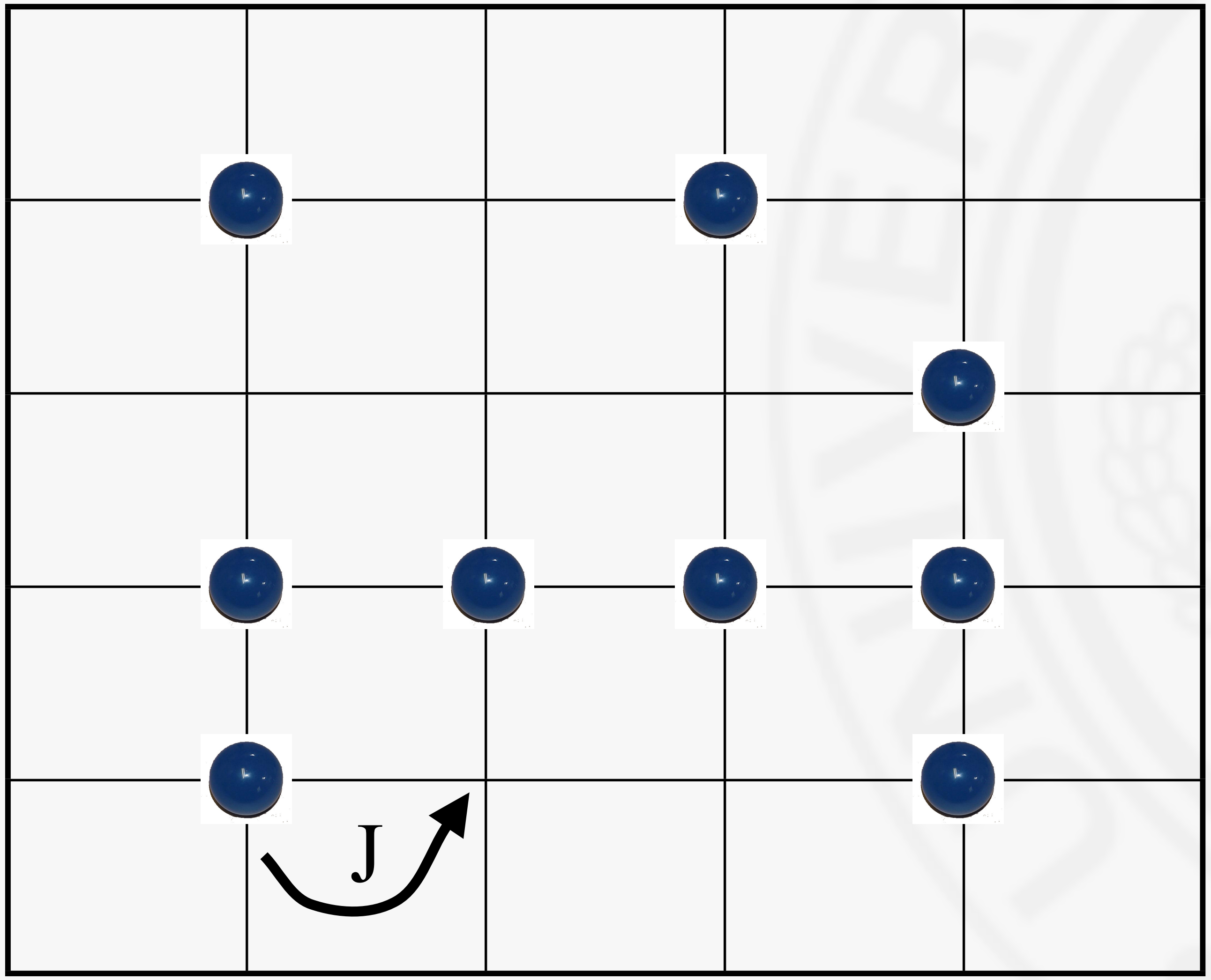

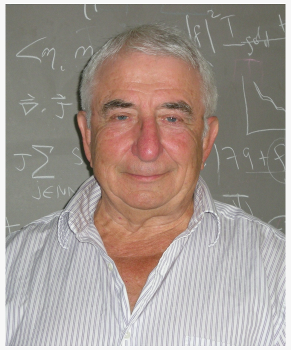

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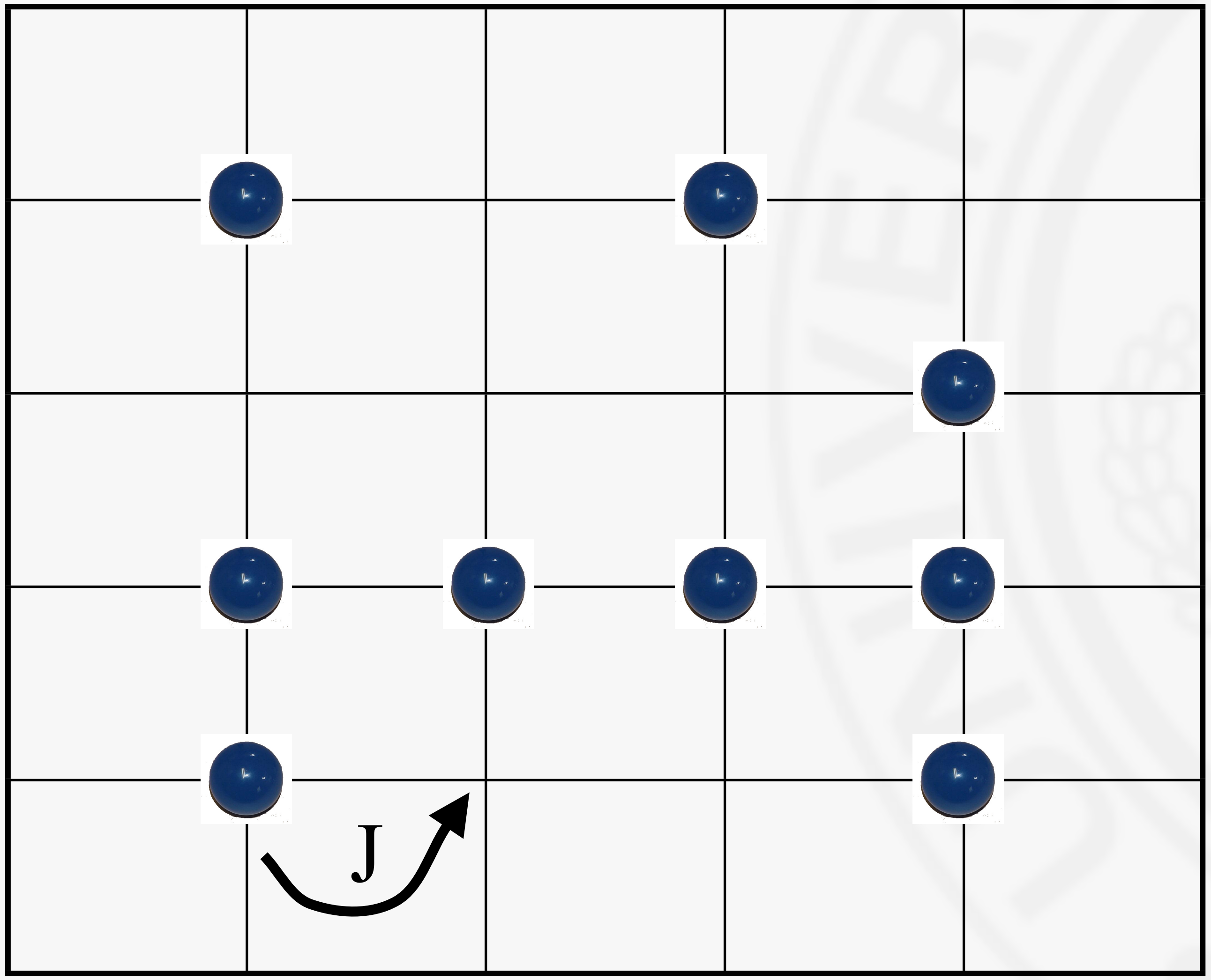
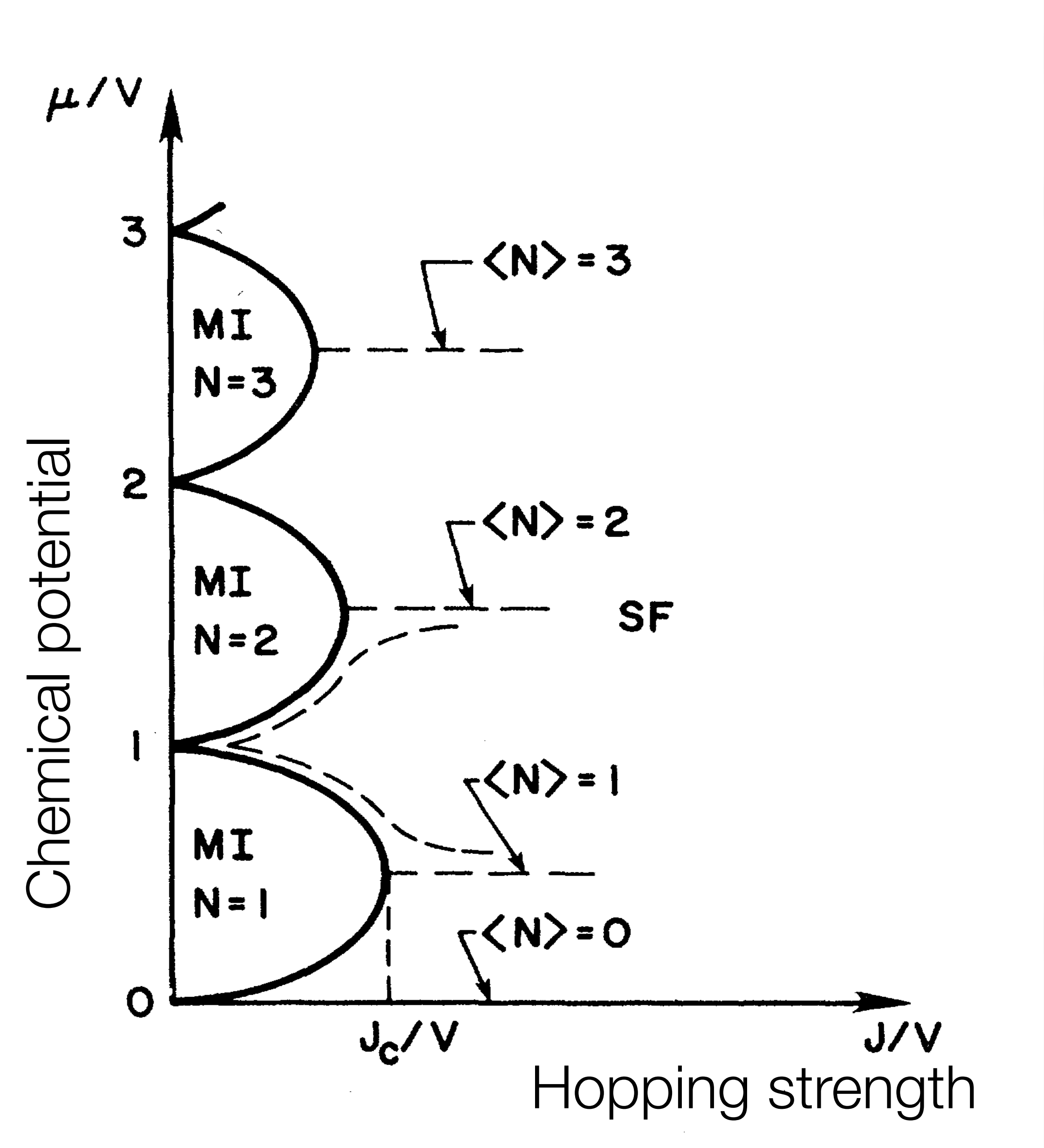
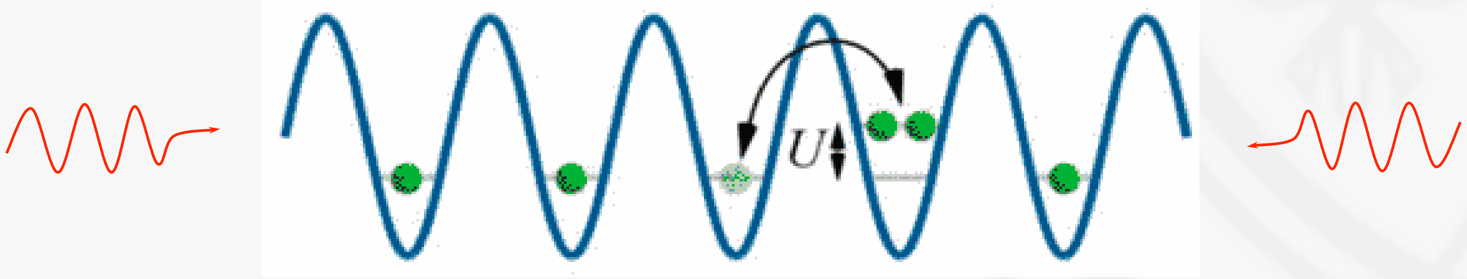




MPA Fisher, P Weichman, G Grinstein, DS Fisher, PRB (1988)

Cold atom realization of the superconductor-Mott insulator transition

Theoretical proposal, D. Jaksch, et al (1998).
This transition can be observed if one puts some bosonic atoms on an optical lattice



Interfering laser beams

ac-Stark effect
(red-detuned, attractive)

Cold atom realization of the superconductor-Mott insulator transition

Experimental realization
M. Greiner, I. Bloch, T. Esslinger, T. Hansch (2001)

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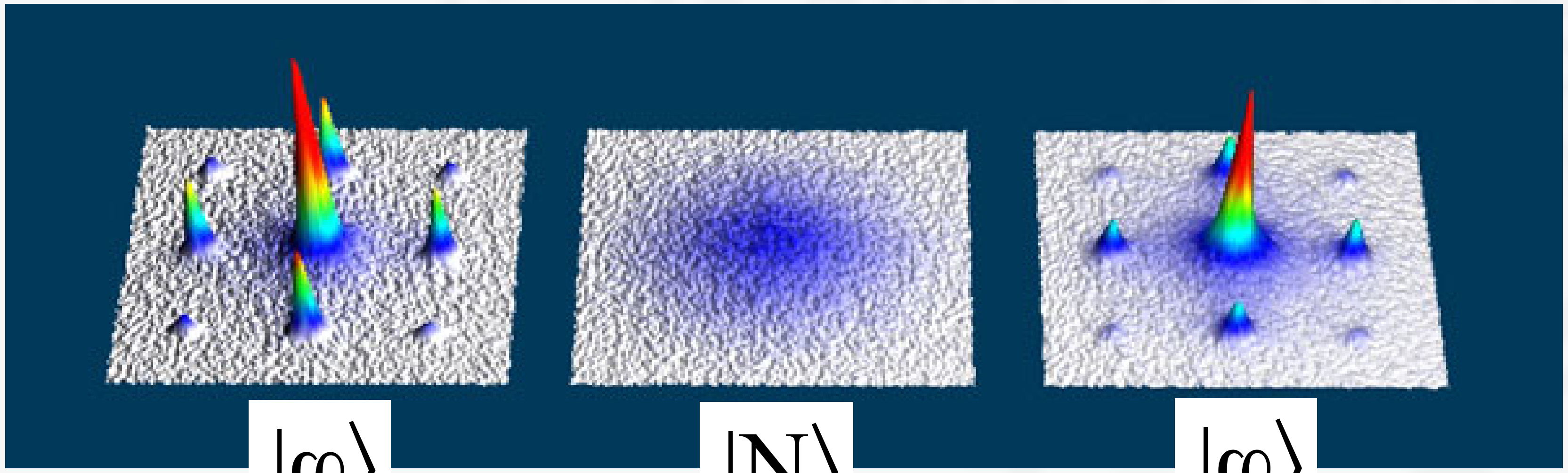
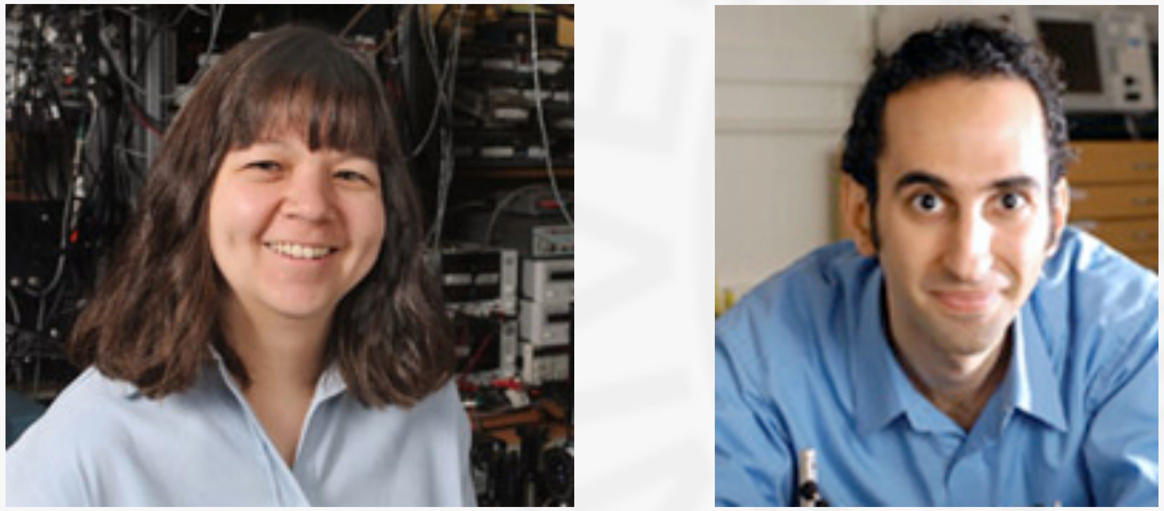
Time of flight measurement



$|\varphi\rangle$ SF $\quad$ $|N\rangle$ MI $\quad$ $|\varphi\rangle$ SF

Degenerate Fermi gas

D. Jin and B. DeMarco, Boulder, (1999)



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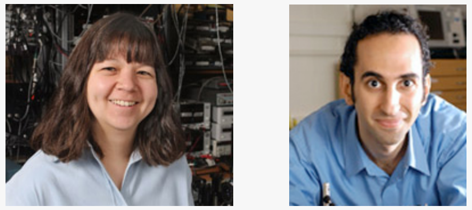
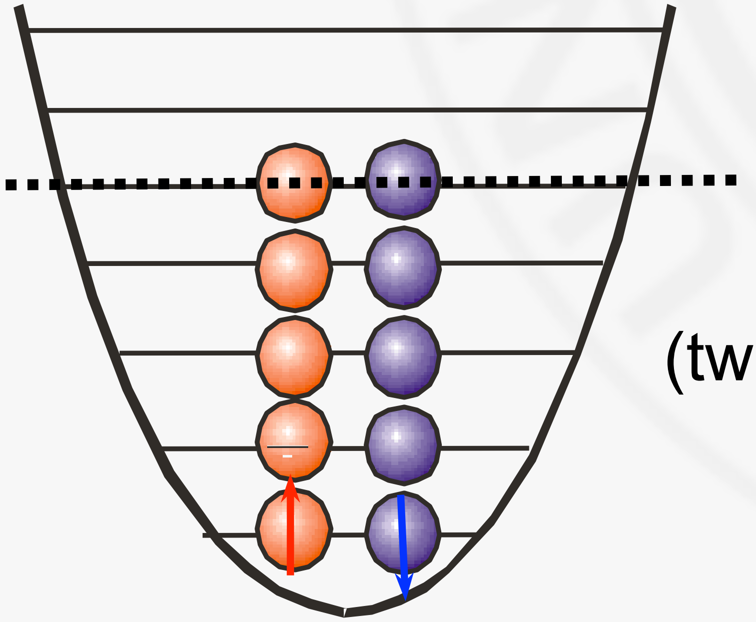


D. Jin and B. DeMarco, Boulder, (1999)

- Fermions do not interact at low T: difficult to cool
- Sympathetic cooling



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(two iso-spin states)

Feshbach resonance (tunability of interactions)

Exploits the natural tendency of alkaline atoms to try to form molecules

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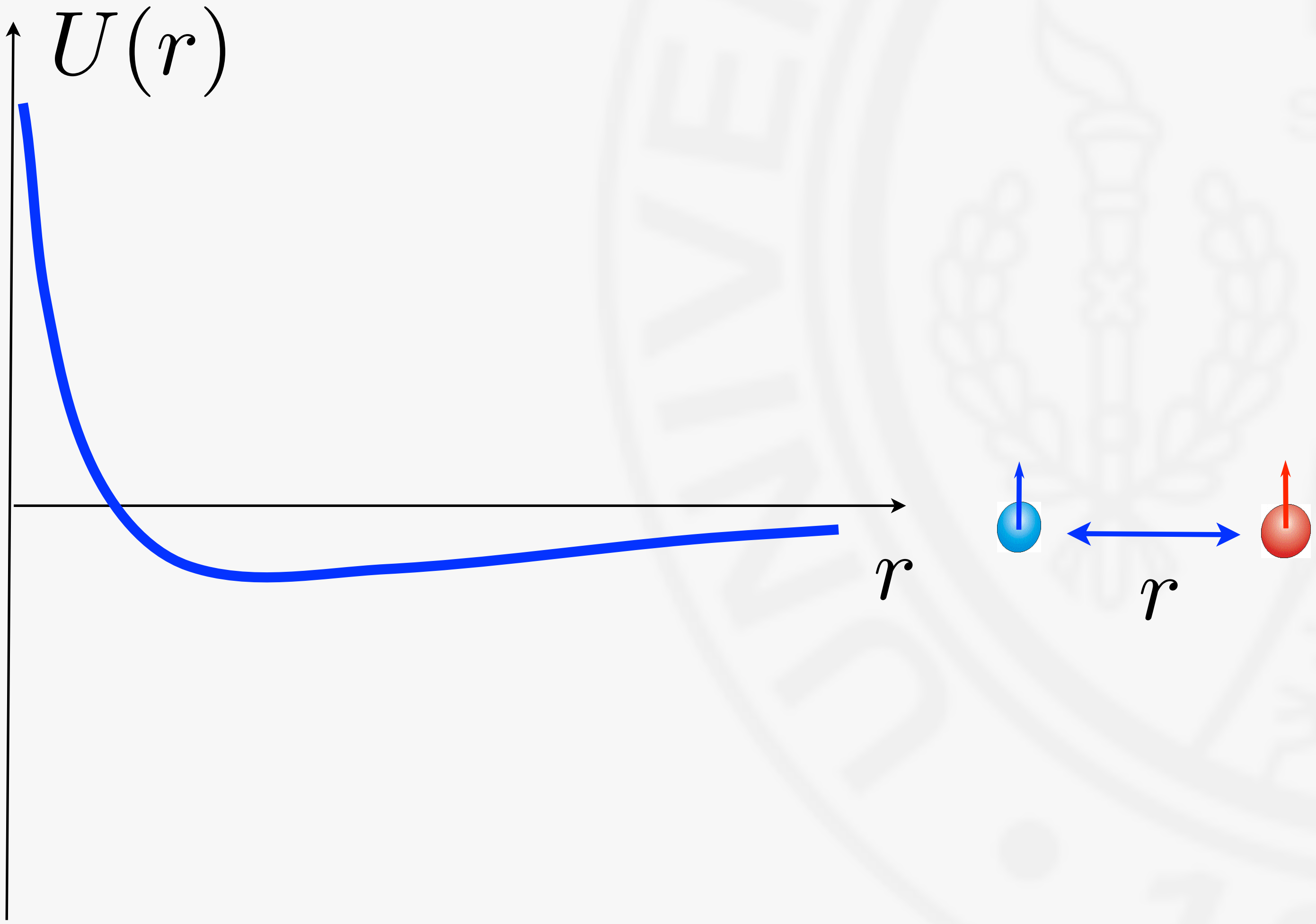

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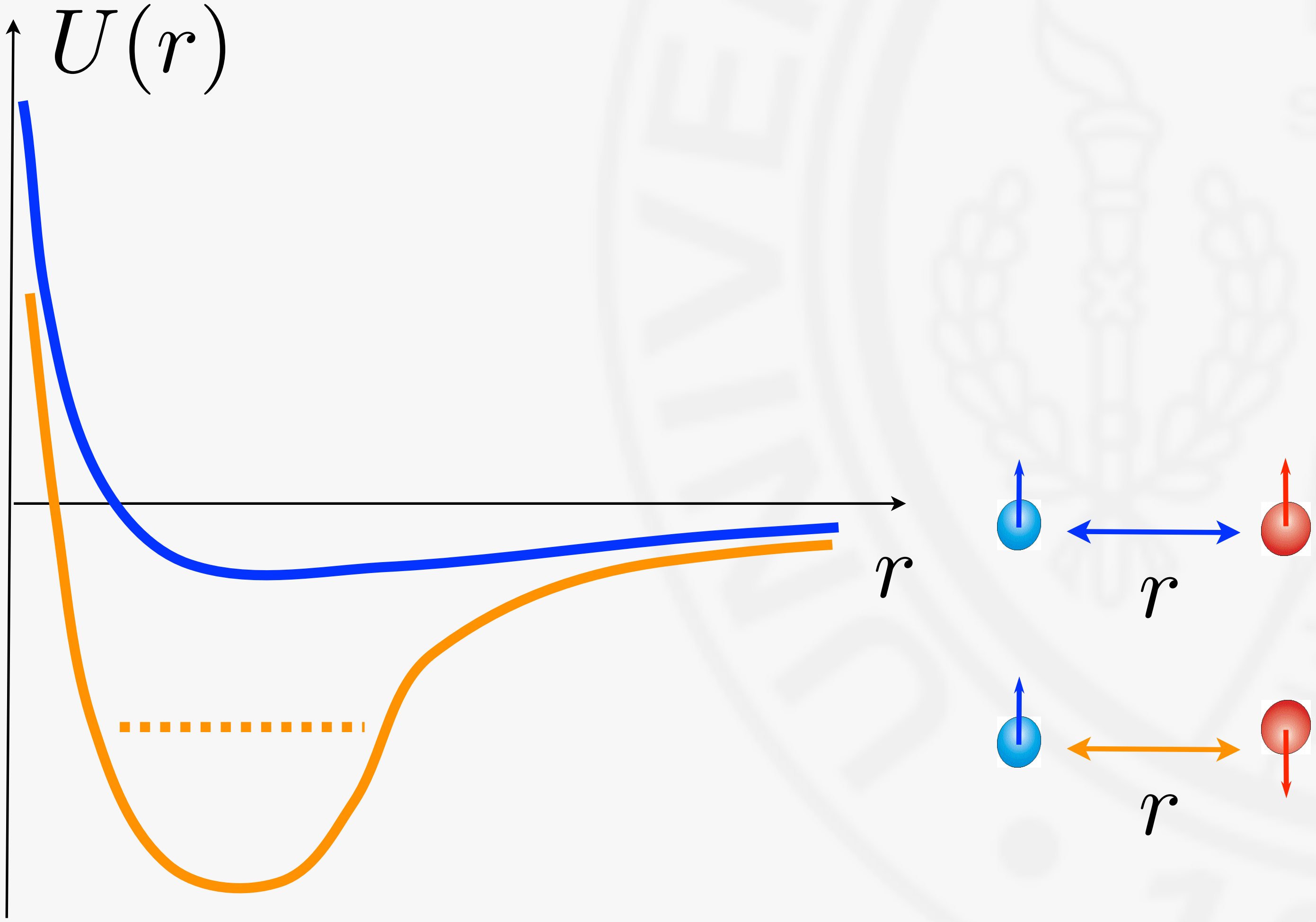

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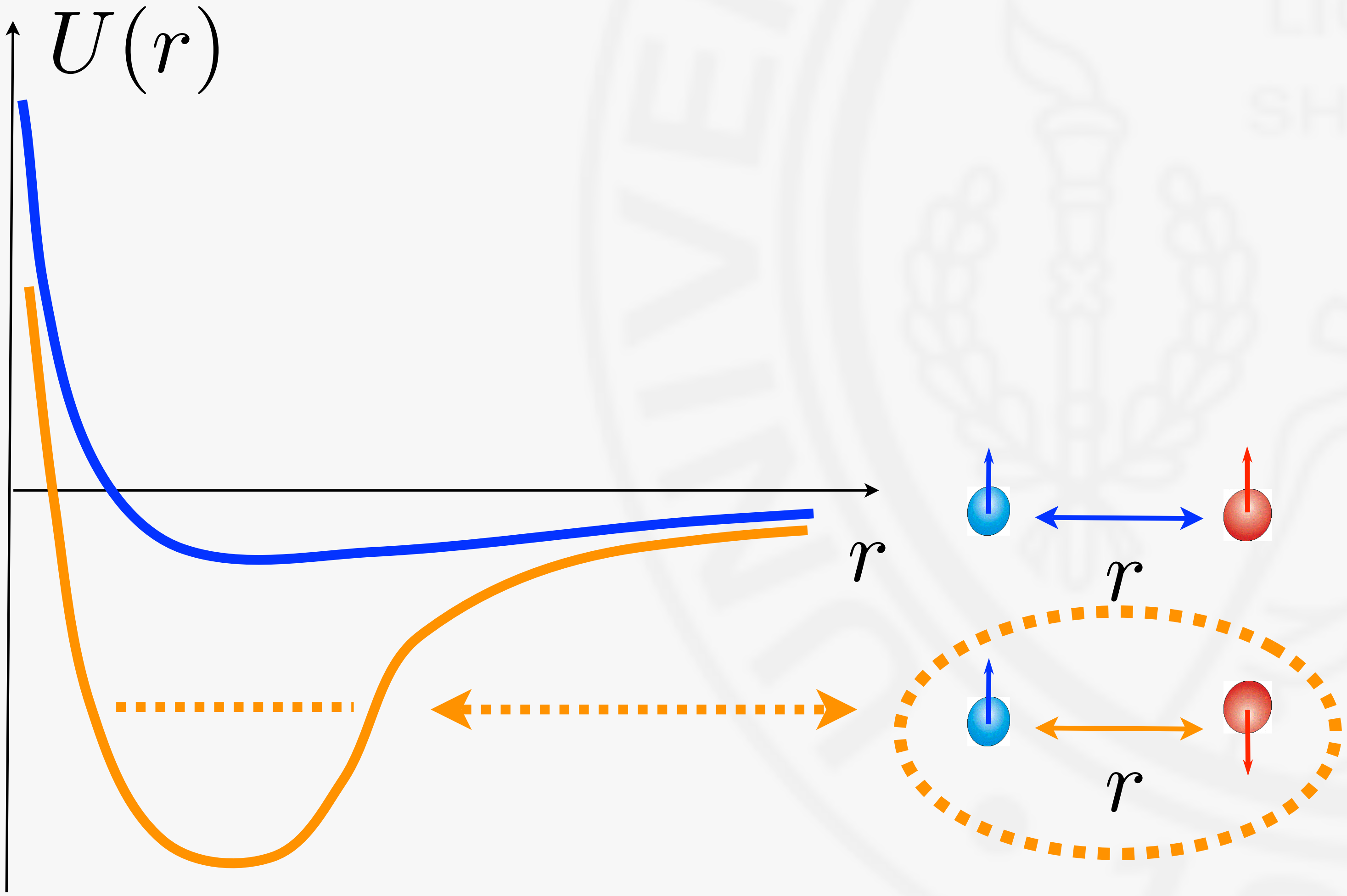

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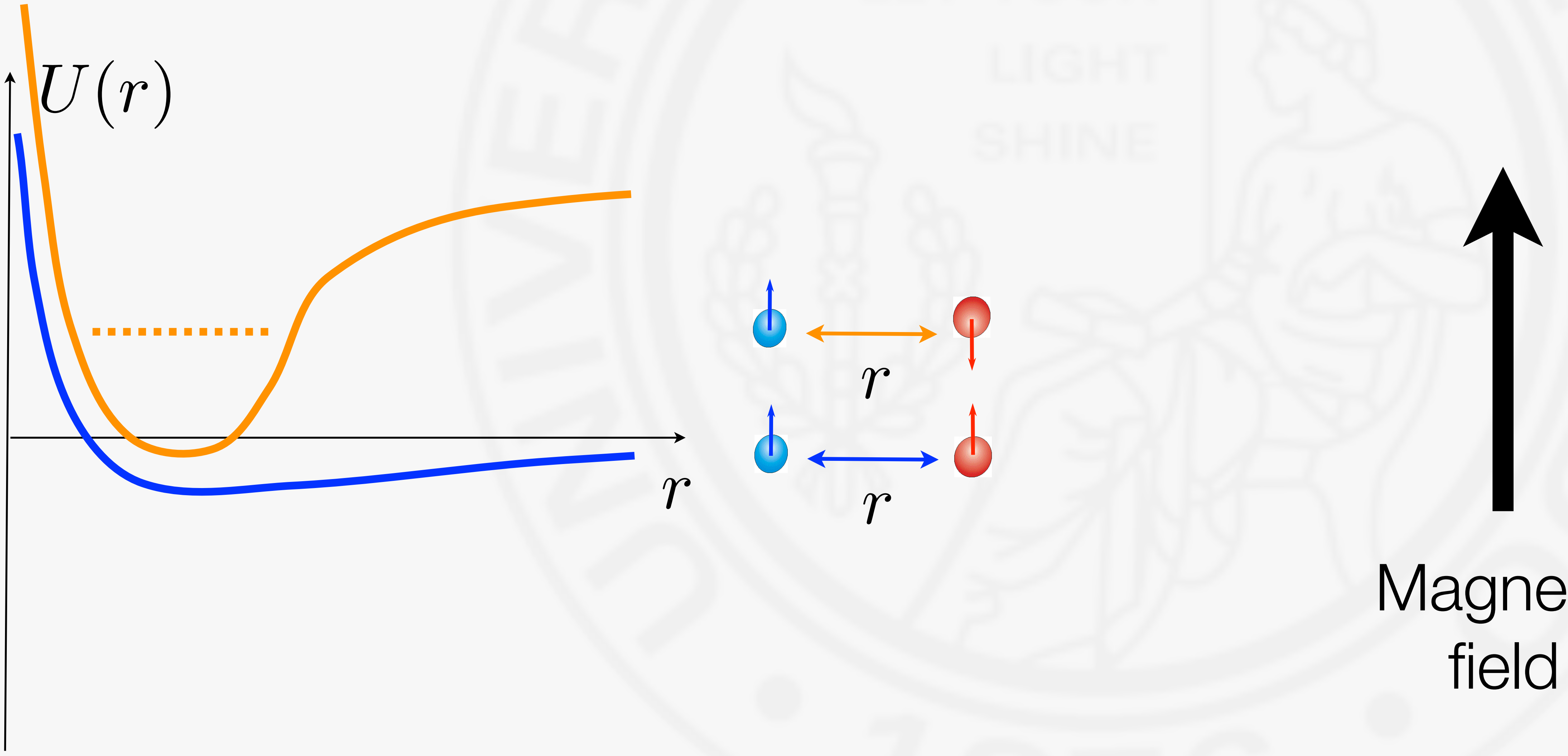

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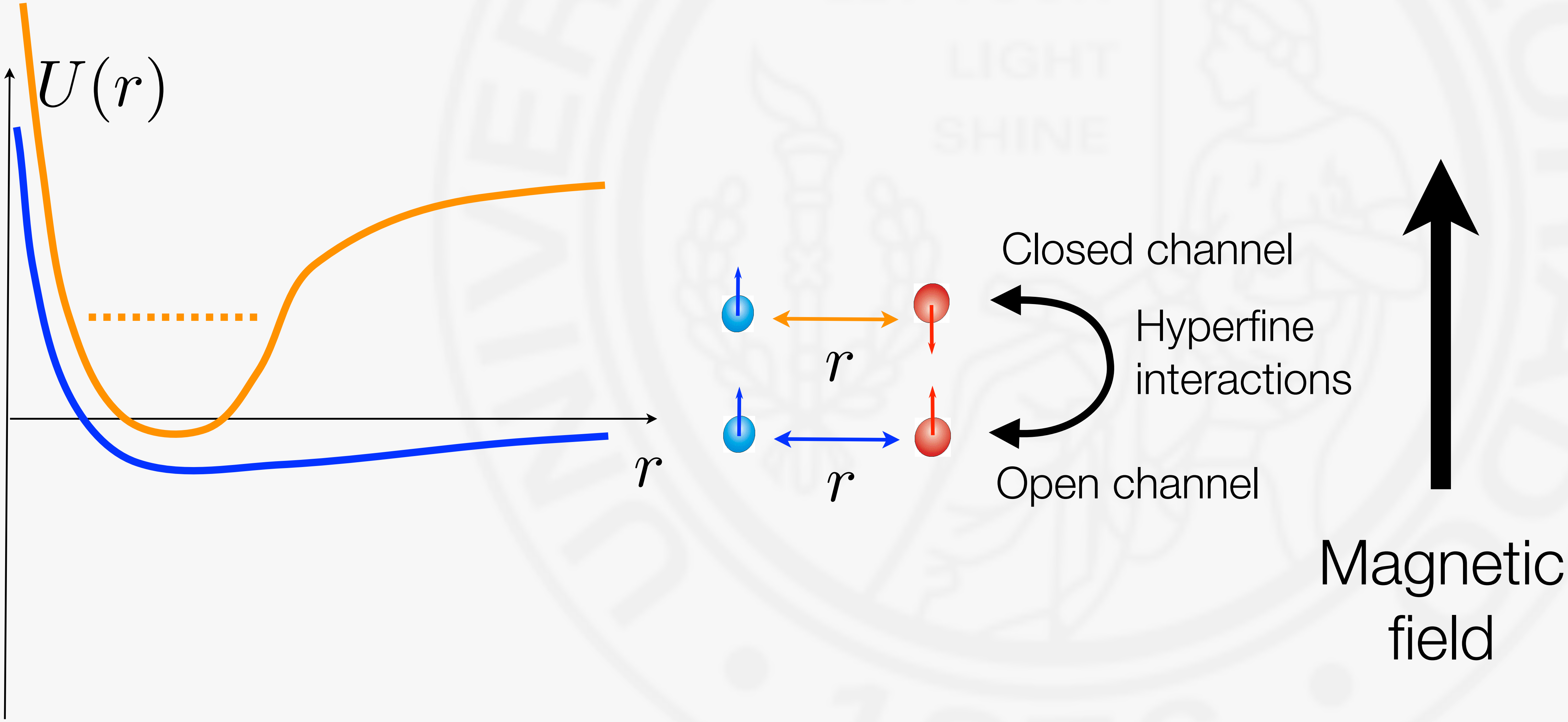

Closed channel

Hyperfine interactions

Open channel

Magnetic field

Feshbach resonance (tunability of interactions)

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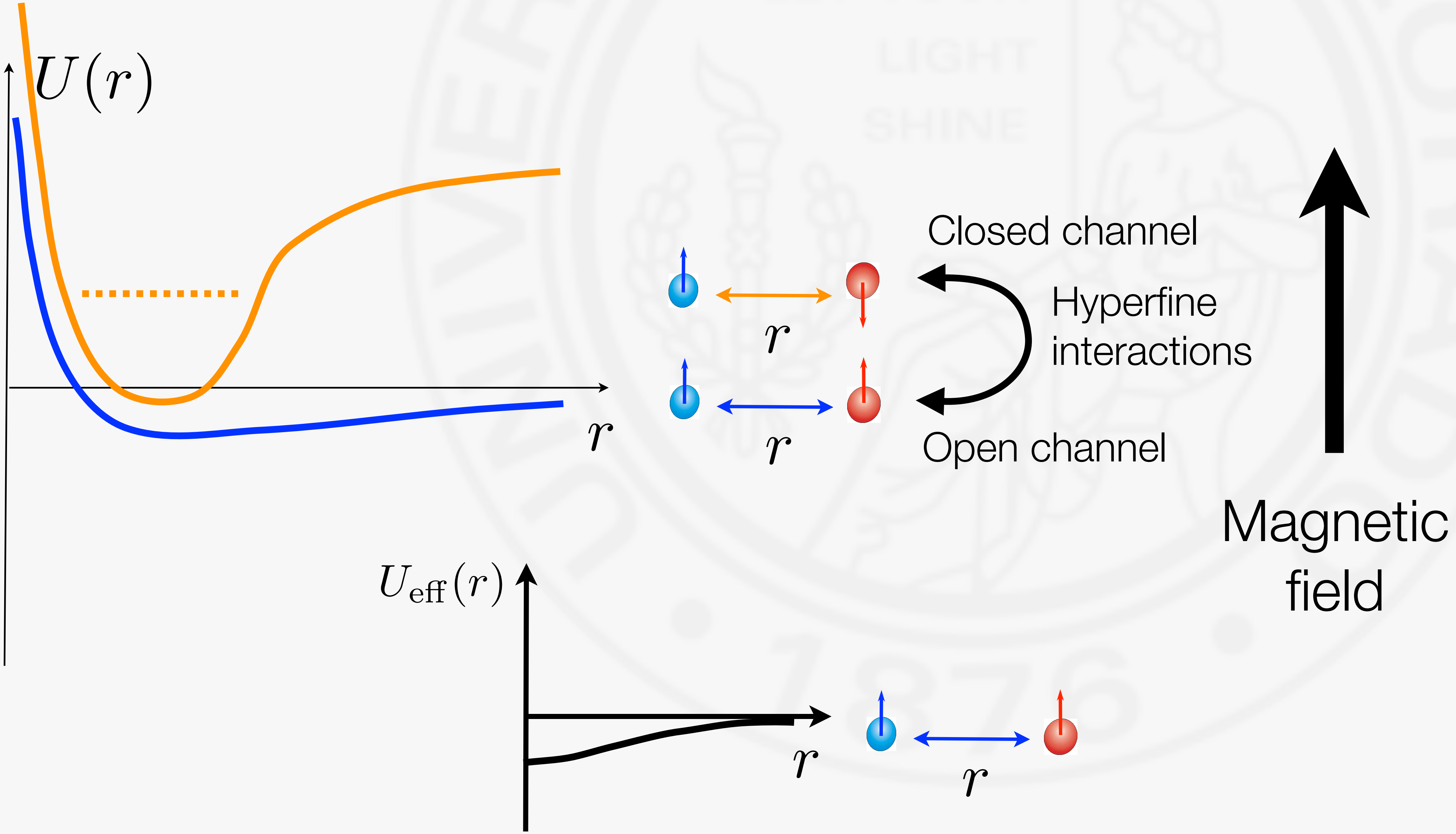

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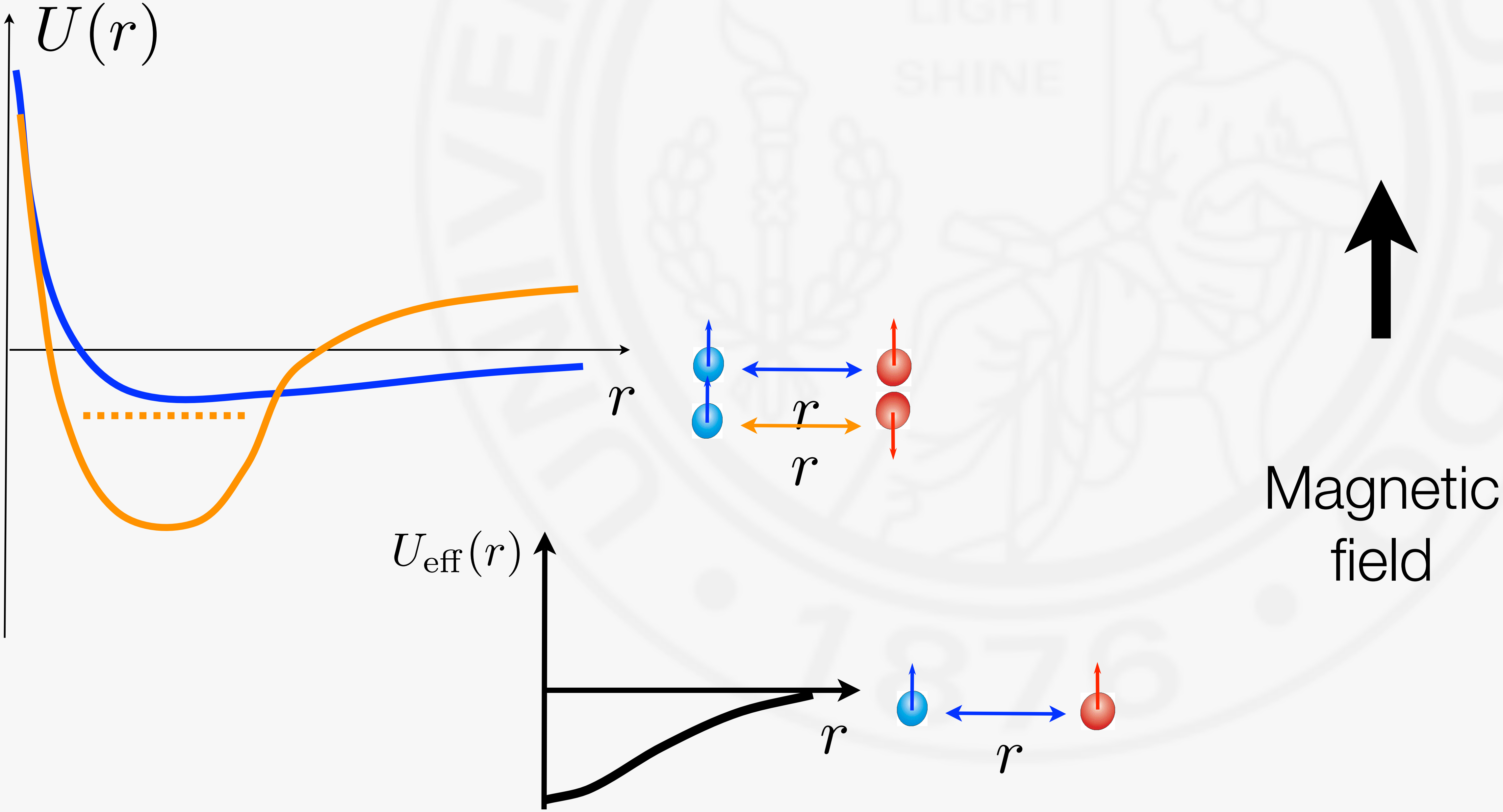
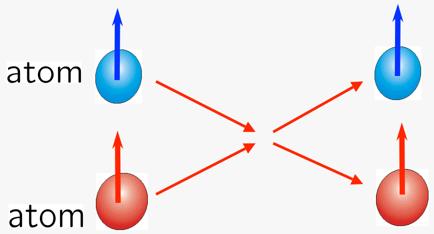
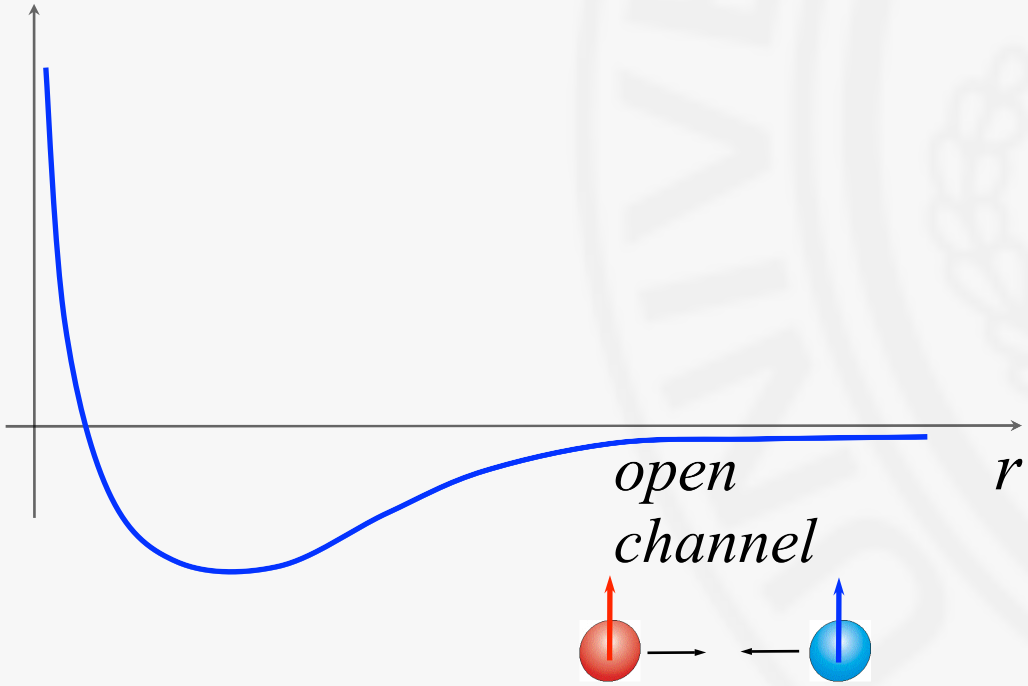


Feshbach resonance (tunability of interactions)

Ketterle (1998)



$U_{eff}(r) \sim a_{bg}\delta^3(r)$



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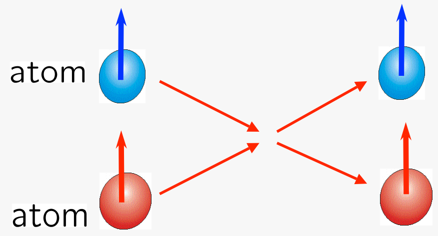
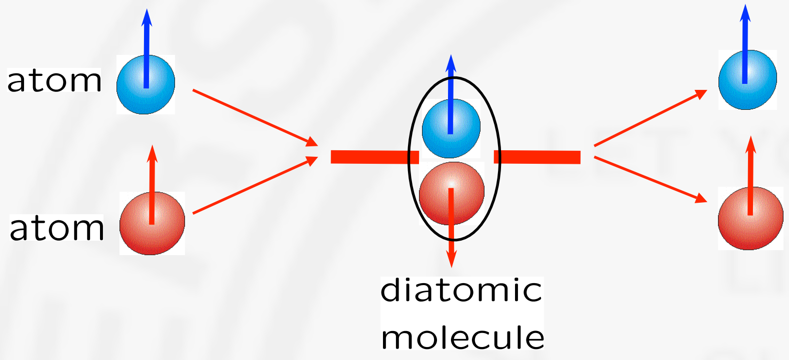
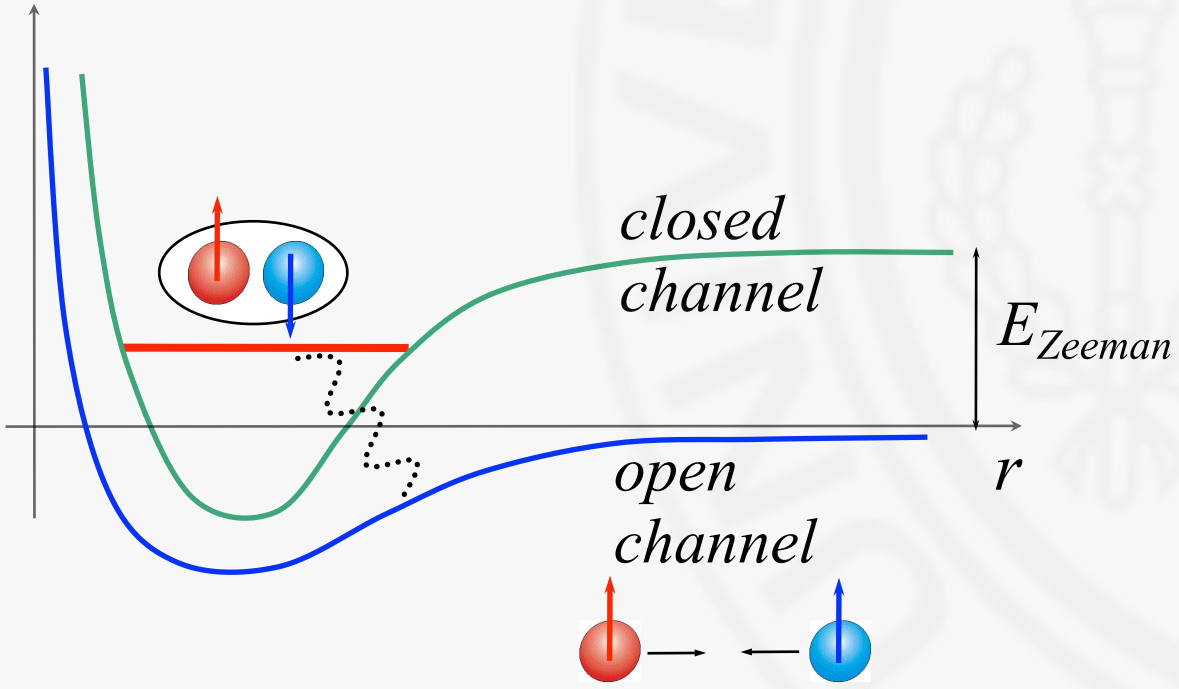




Ketterle (1998)

$U_{eff}(r) \sim a_{bg}\delta^3(r)$



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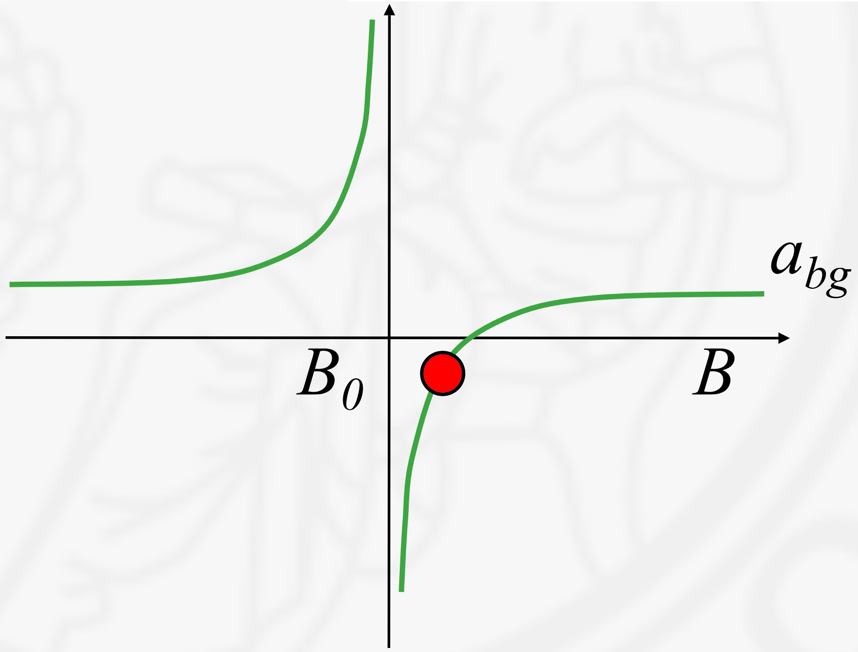

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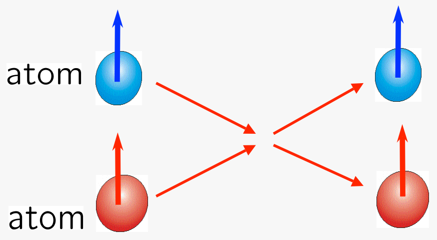

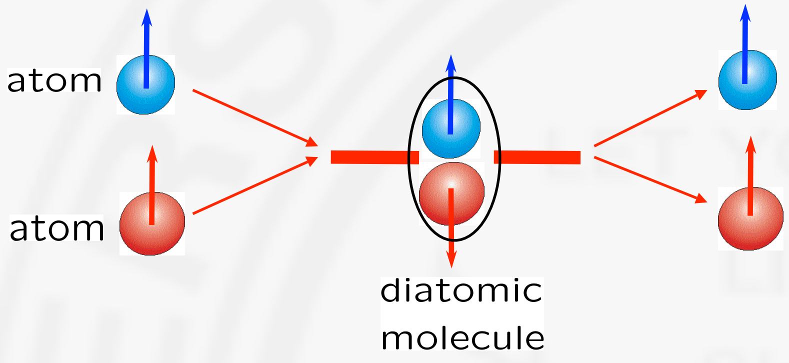

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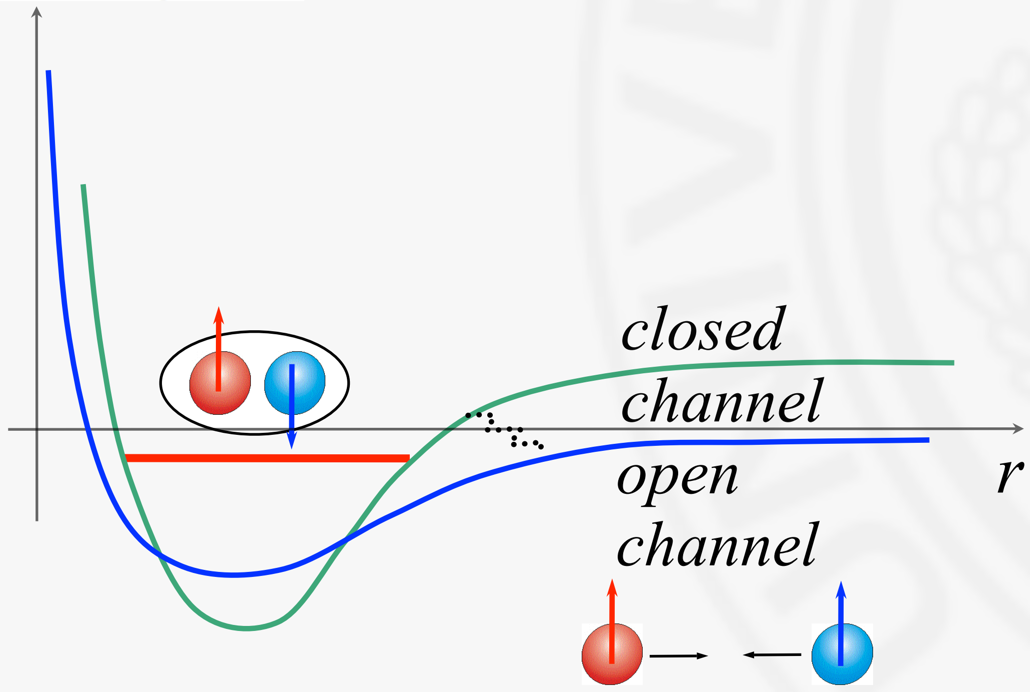

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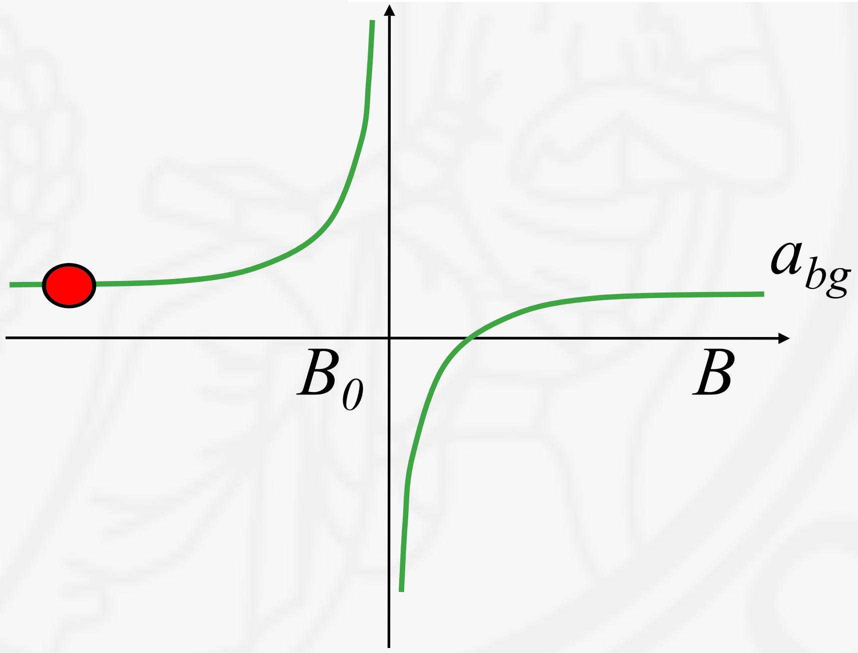

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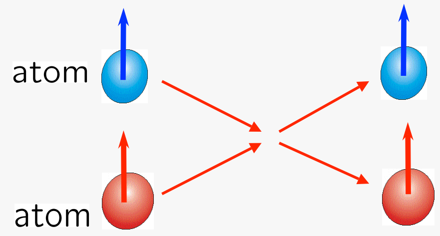

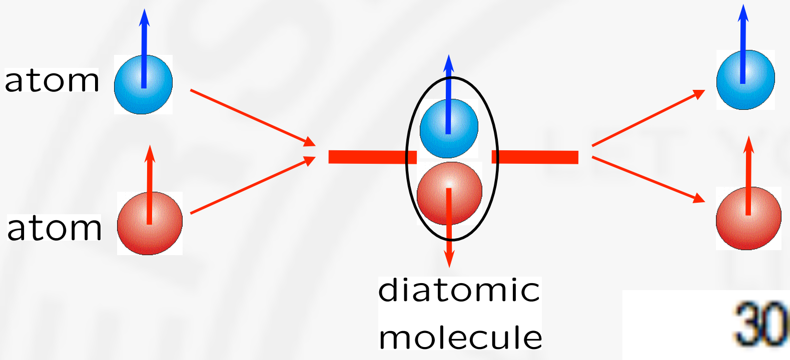

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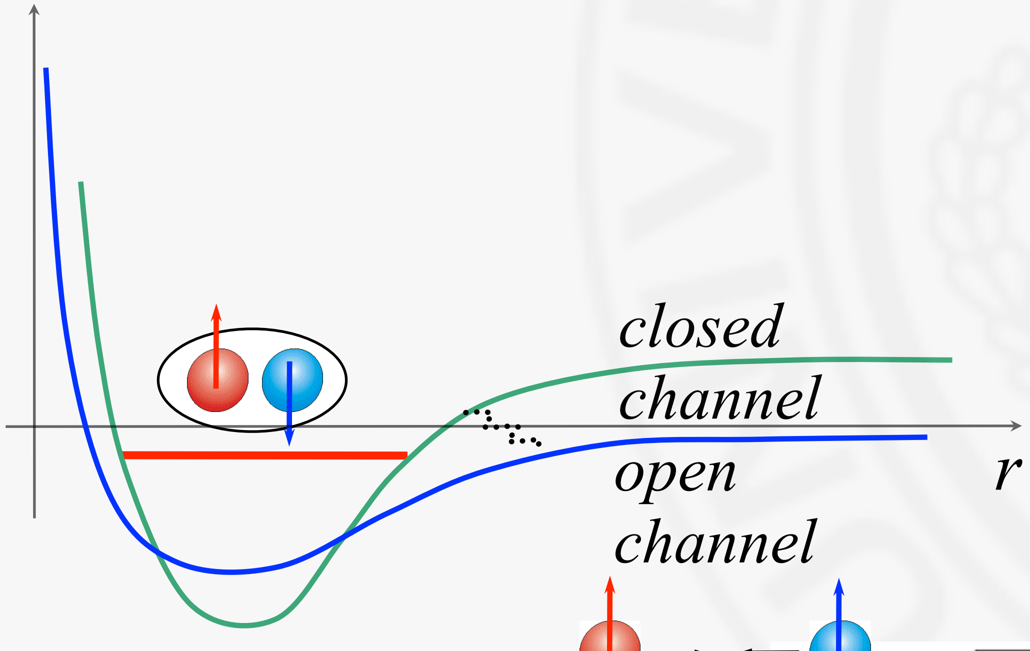
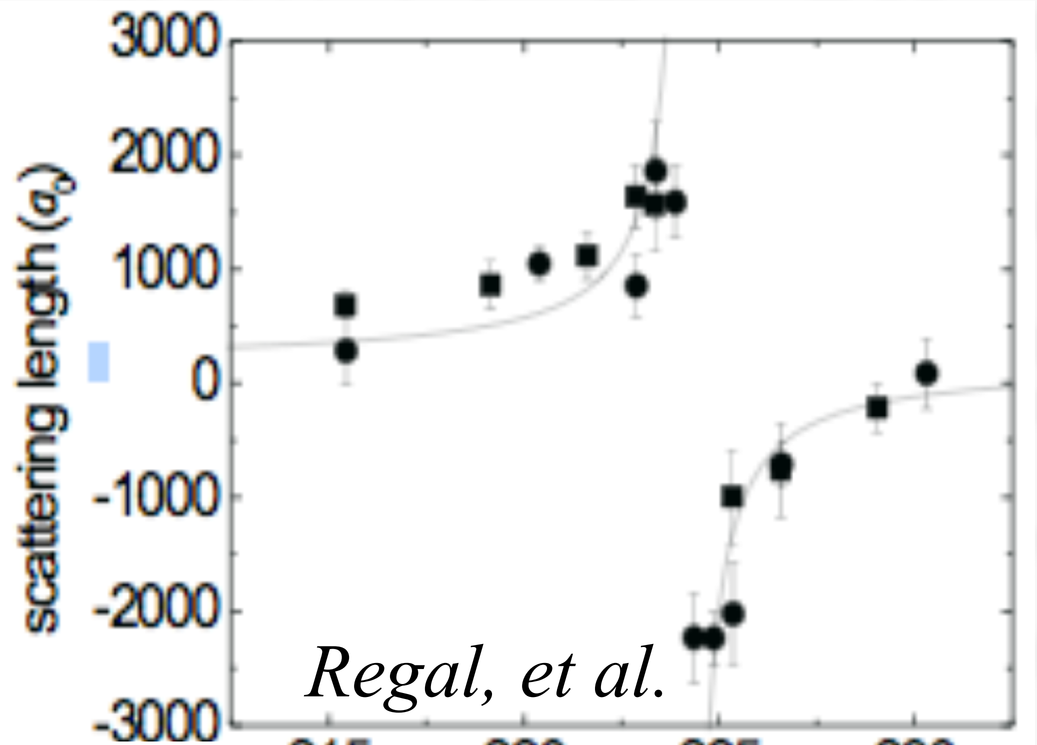
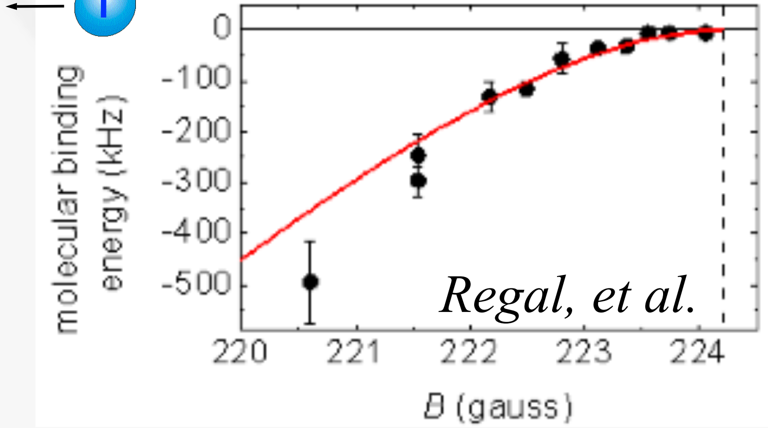




Regal, et al.



Regal, et al.

Outline

- Condensed matter and atomic physics
- Early days: BEC (mid 90s)
- Big breakthrough: modeling condensed matter physics with cold atoms (1998-2001)
- Modern developments (2003 on)

Modern developments

- Spinor condensates
- Confining atoms to 1D and creating Luttinger liquids
- Fermions on the lattice (modeling high Tc superconductors) - major project funded by DARPA
- Modeling strongly paired superconductors
- Modeling quantum magnetism

Attractively interacting Fermi gases

BCS-BEC crossover
(Eagles ’69, Leggett ’80)

Fermi gases with attractive interactions:

superconductors

Attractively interacting Fermi gases

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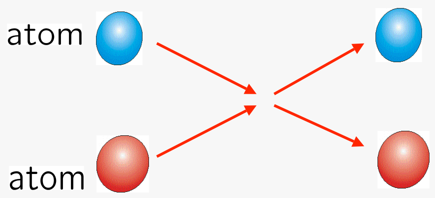
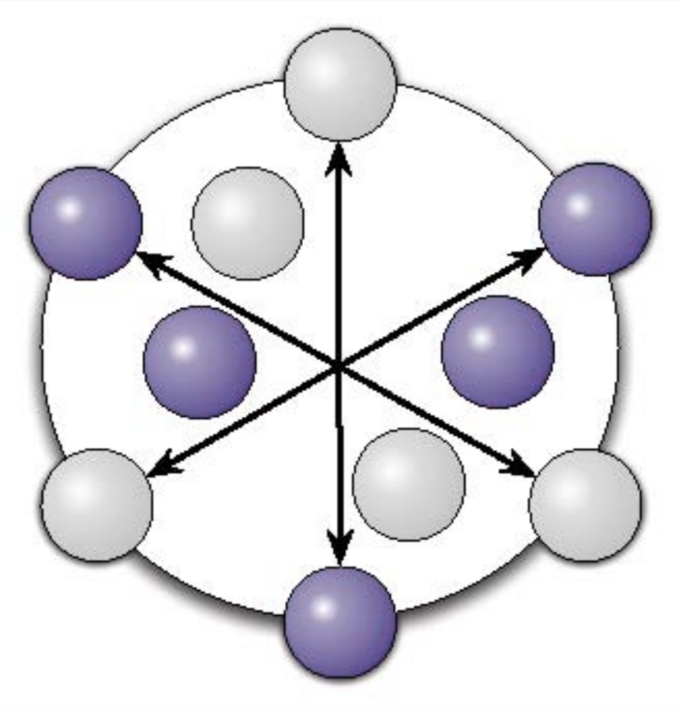
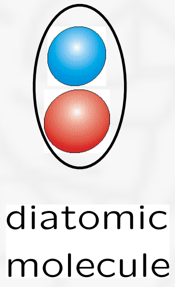
BCS superconductor

attraction strength







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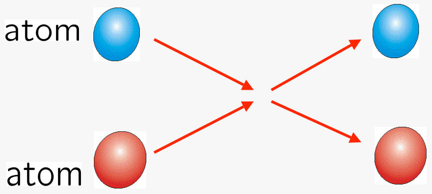

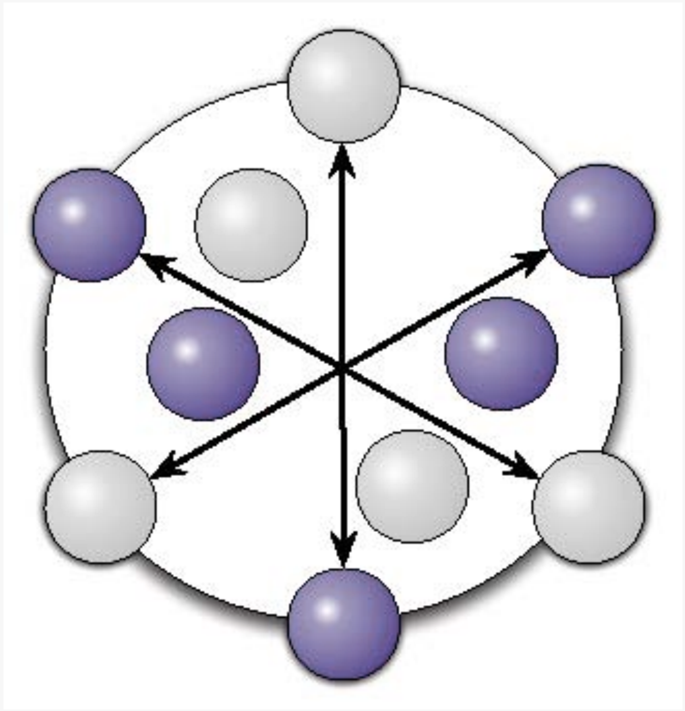

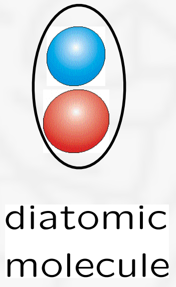

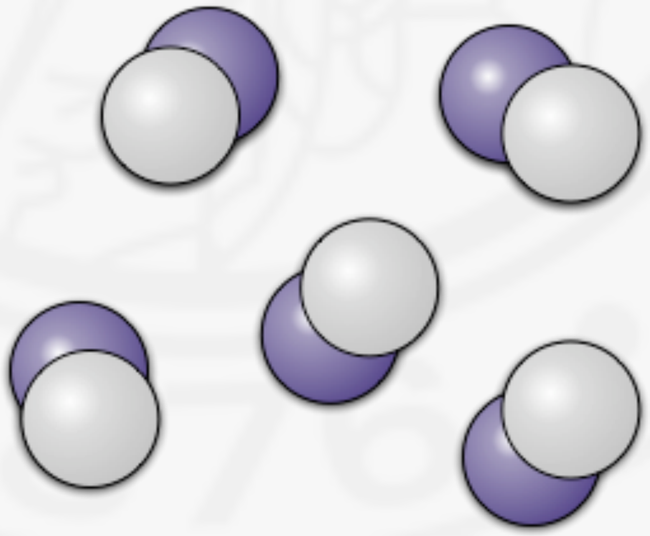

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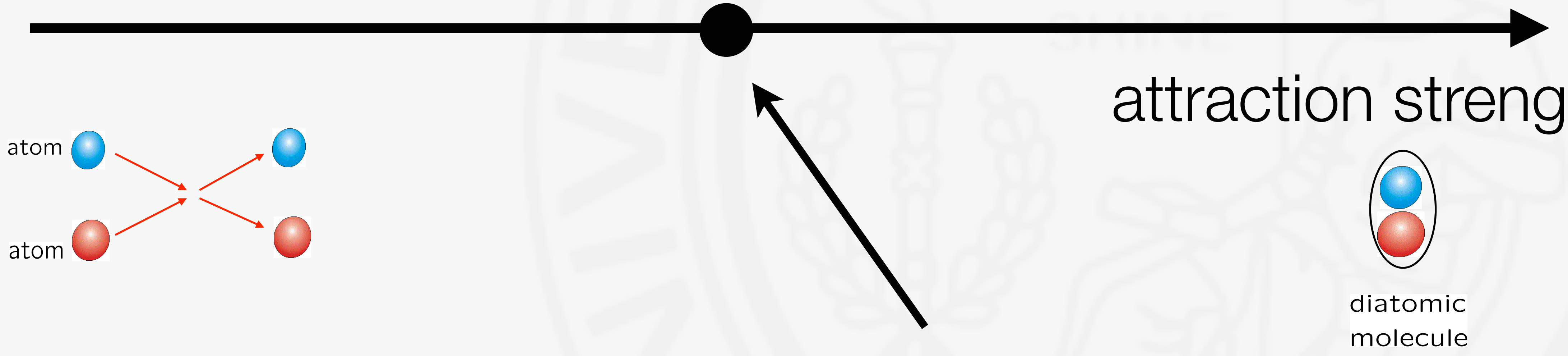


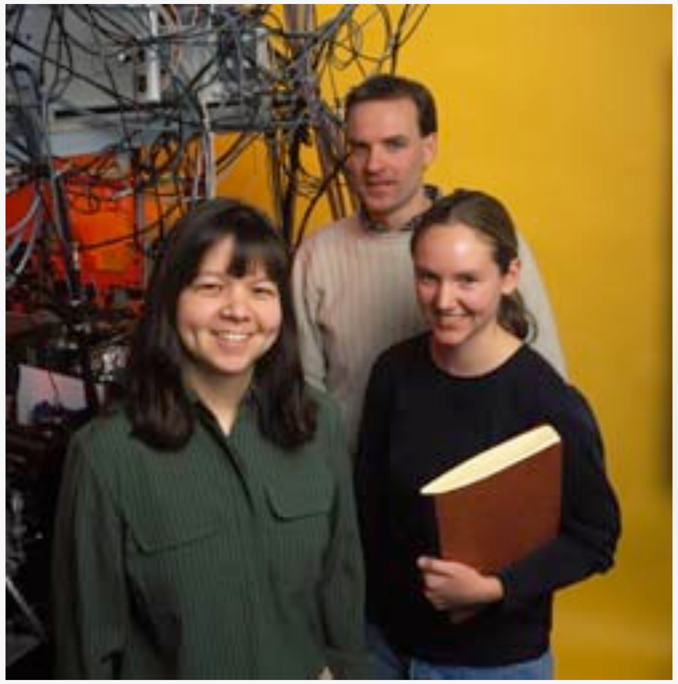
attraction strength

Unitary point

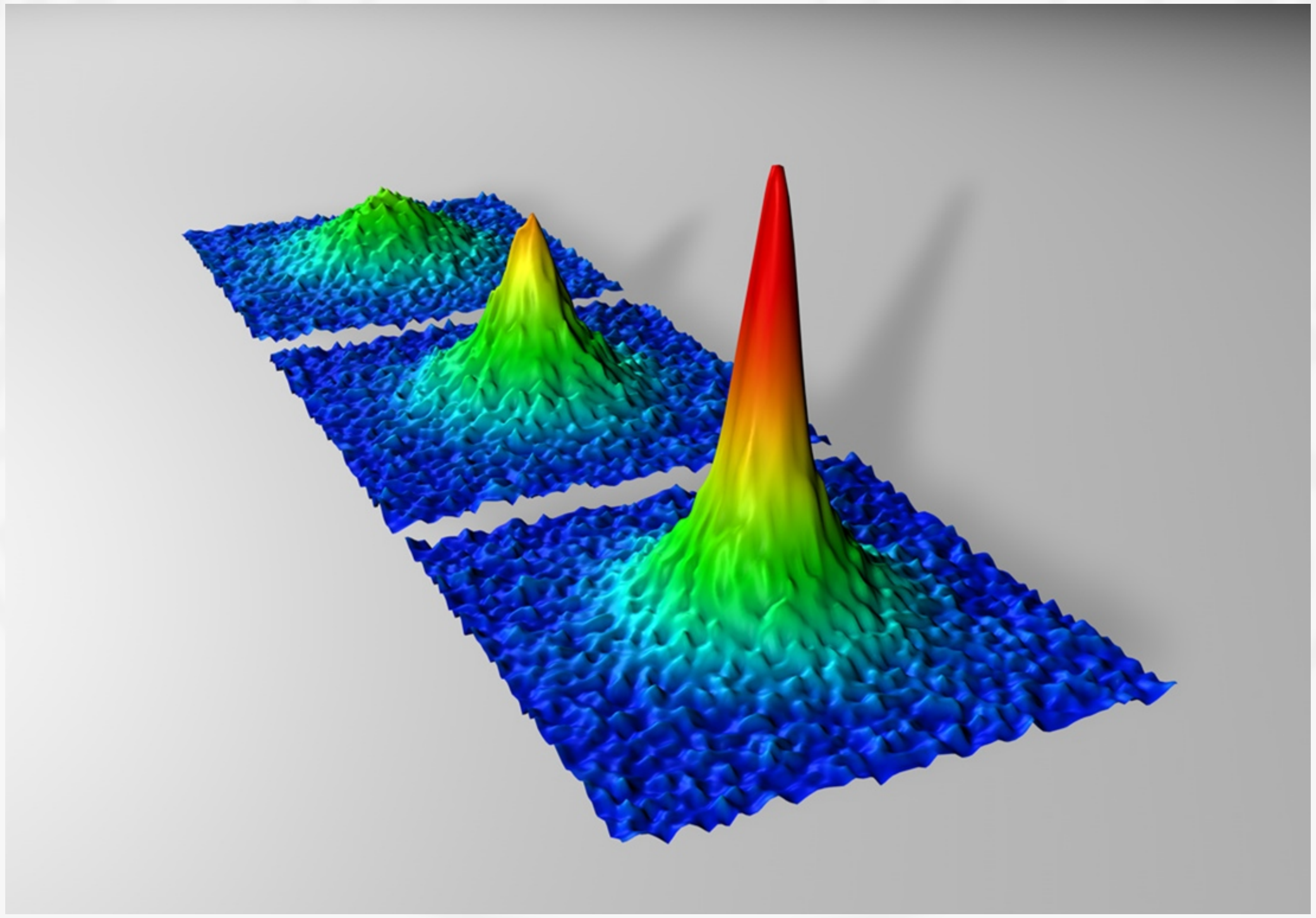
Unitary point:
interactions are limited
by unitarity $\delta_{\mathrm{phaseshift}} = \frac{\pi}{2}$

Unitary point is universal:
interactions drop out from
any physical quantity

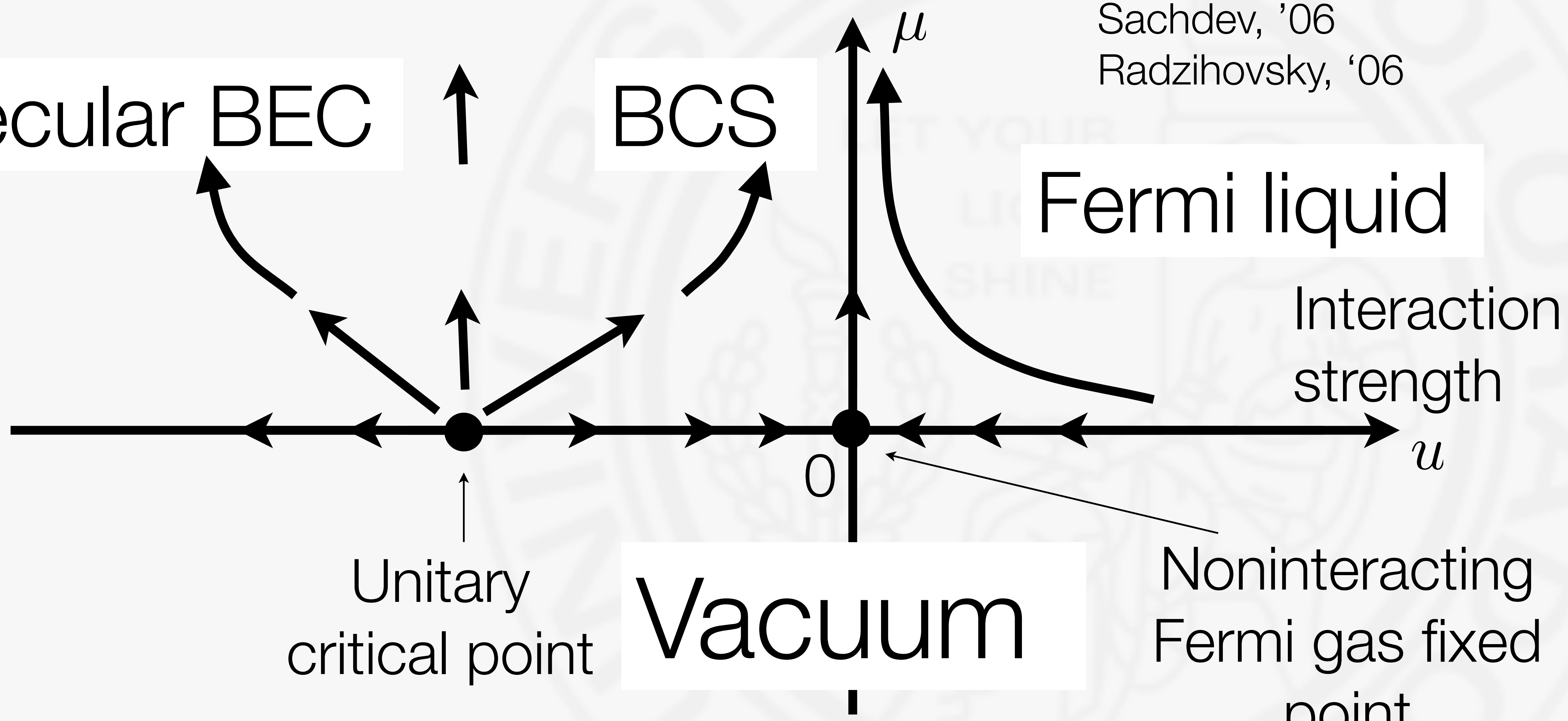
Experimental observation of the crossover



D. Jin, M. Greiner, C. Regal, ‘03-04



RG picture of the BCS-BEC crossover



Sachdev, '06
Radzihovsky, '06

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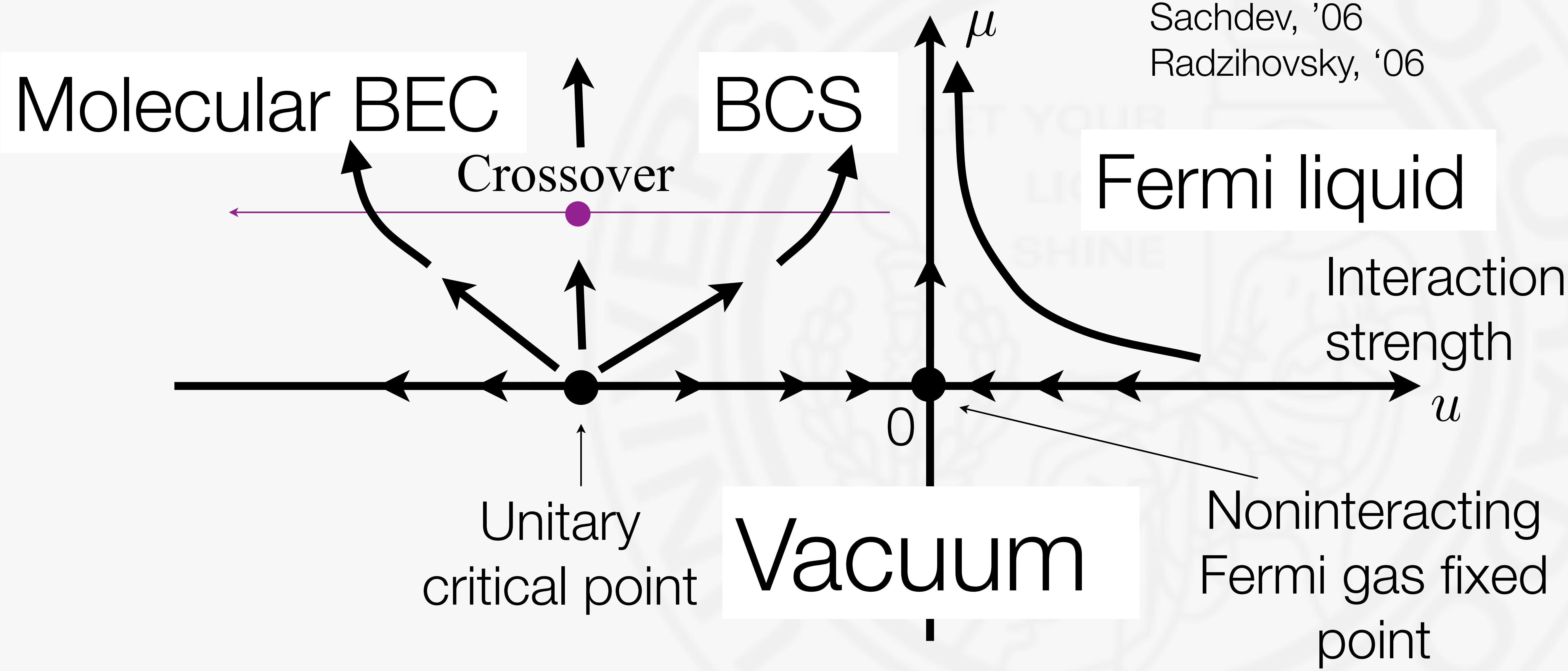

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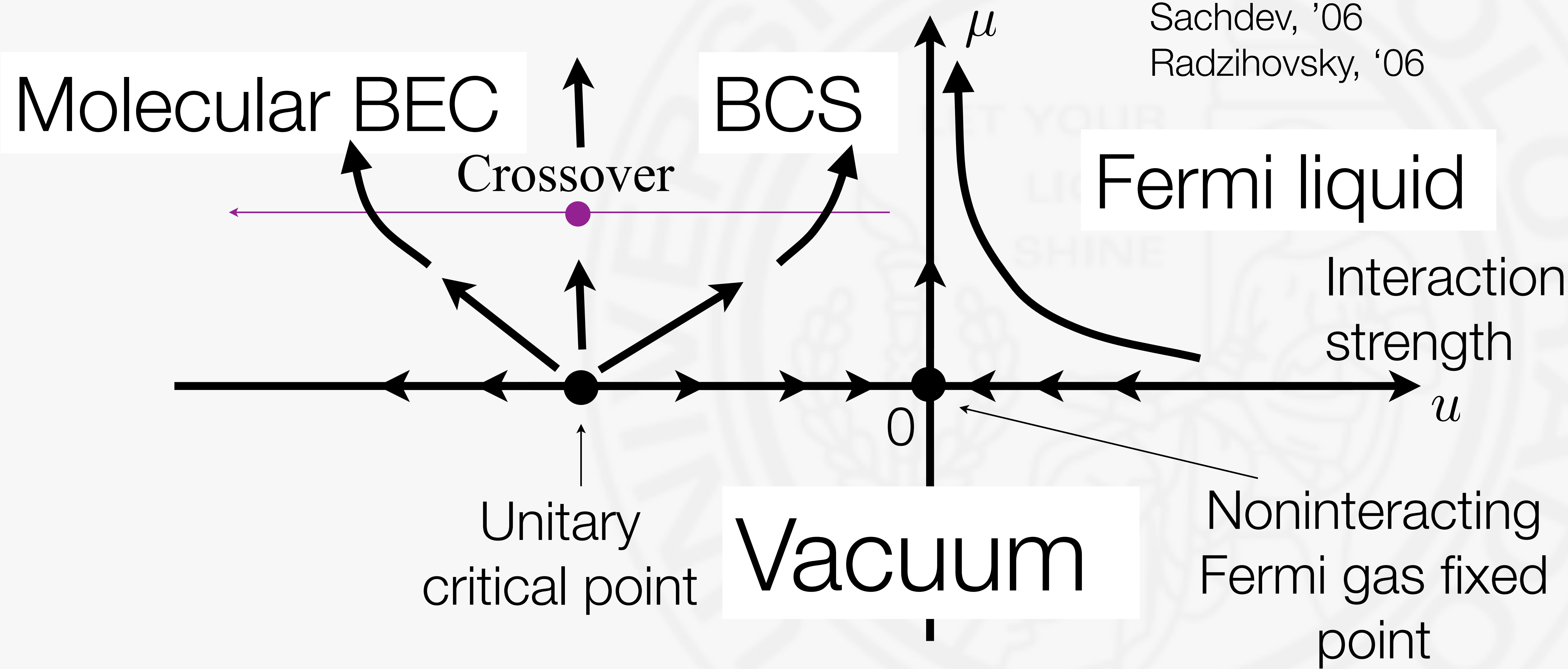

Molecular BEC

BCS

Crossover

Fermi liquid

Interaction strength

Unitary critical point

Vacuum

Noninteracting Fermi gas fixed point

At unitarity $\mu = \xi \frac{(3\pi^2 n)^{\frac{2}{3}}}{2m}$

Universal critical amplitude

$\xi \approx 0.3 - 0.45$

Nicolić, Sachdev, ’07
Veillette, Sheehy, Radzihovsky, ‘07

Exotic superconductors

Common superconductors:
atoms in two different
internal states form pairs. Pairs
do not spin.
“s-wave” superconductor

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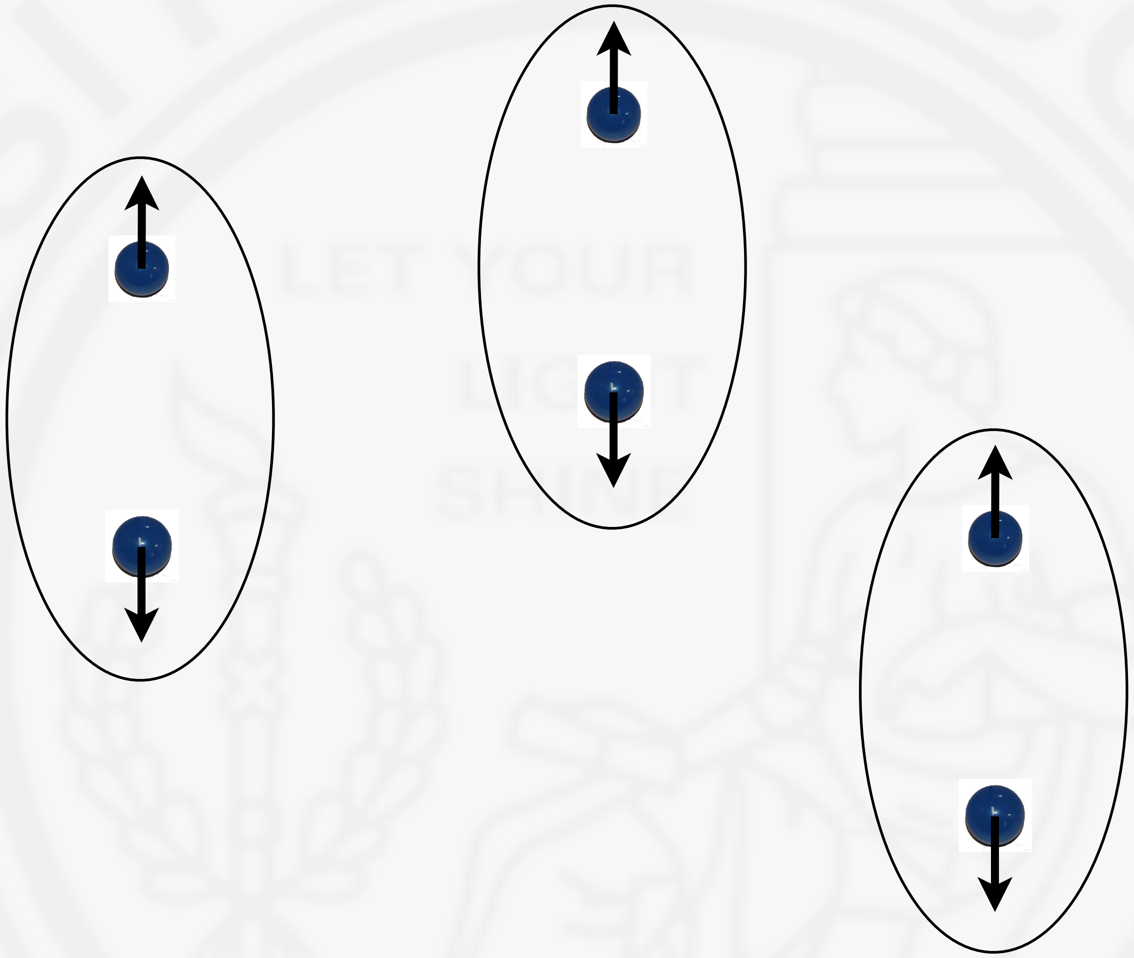

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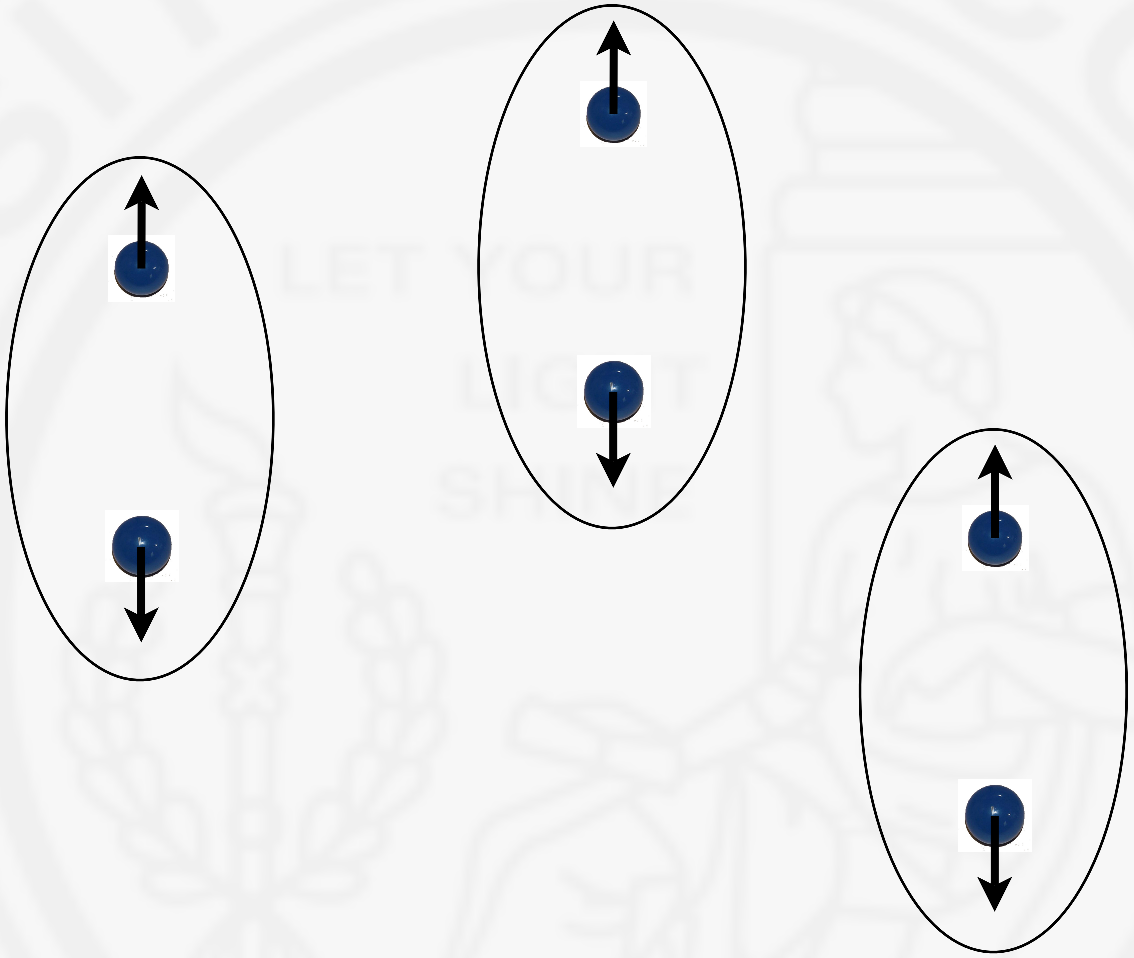

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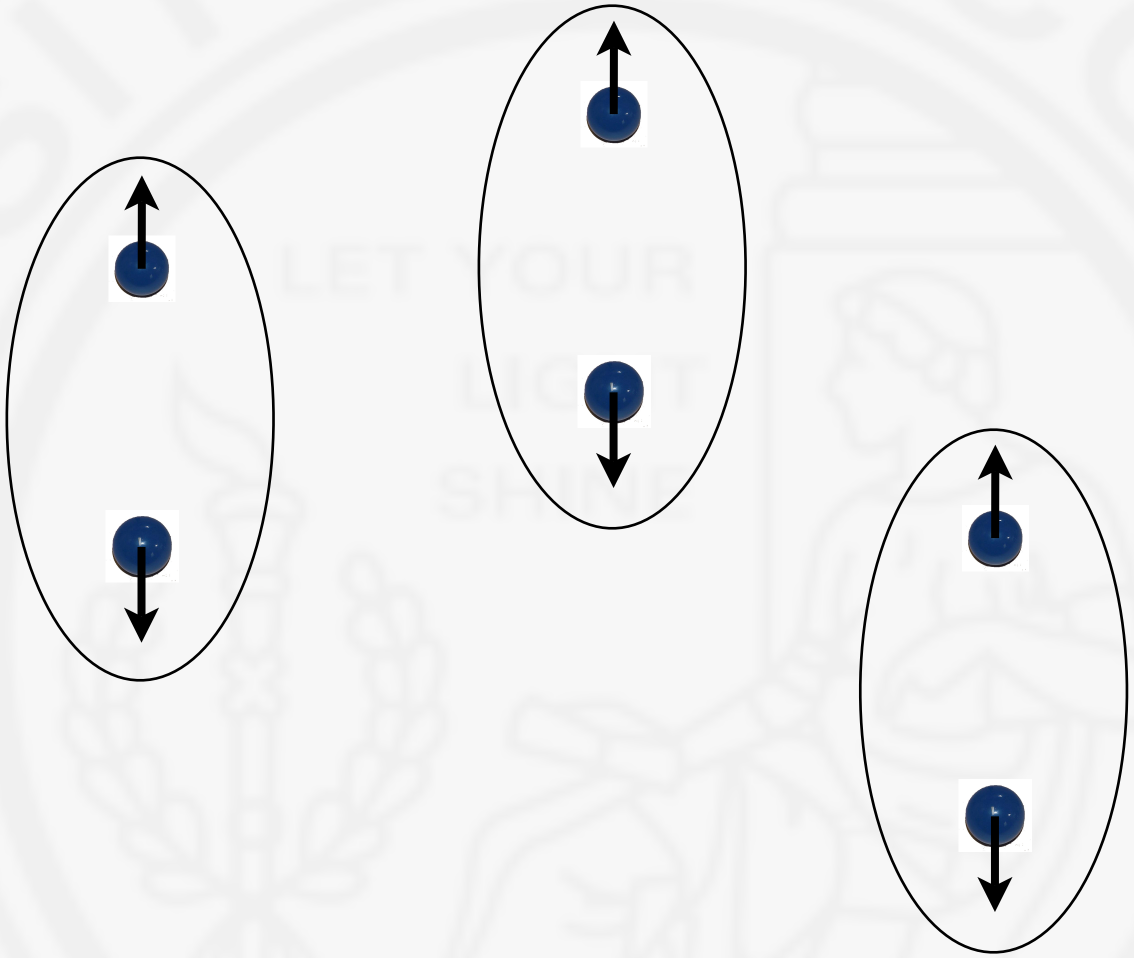

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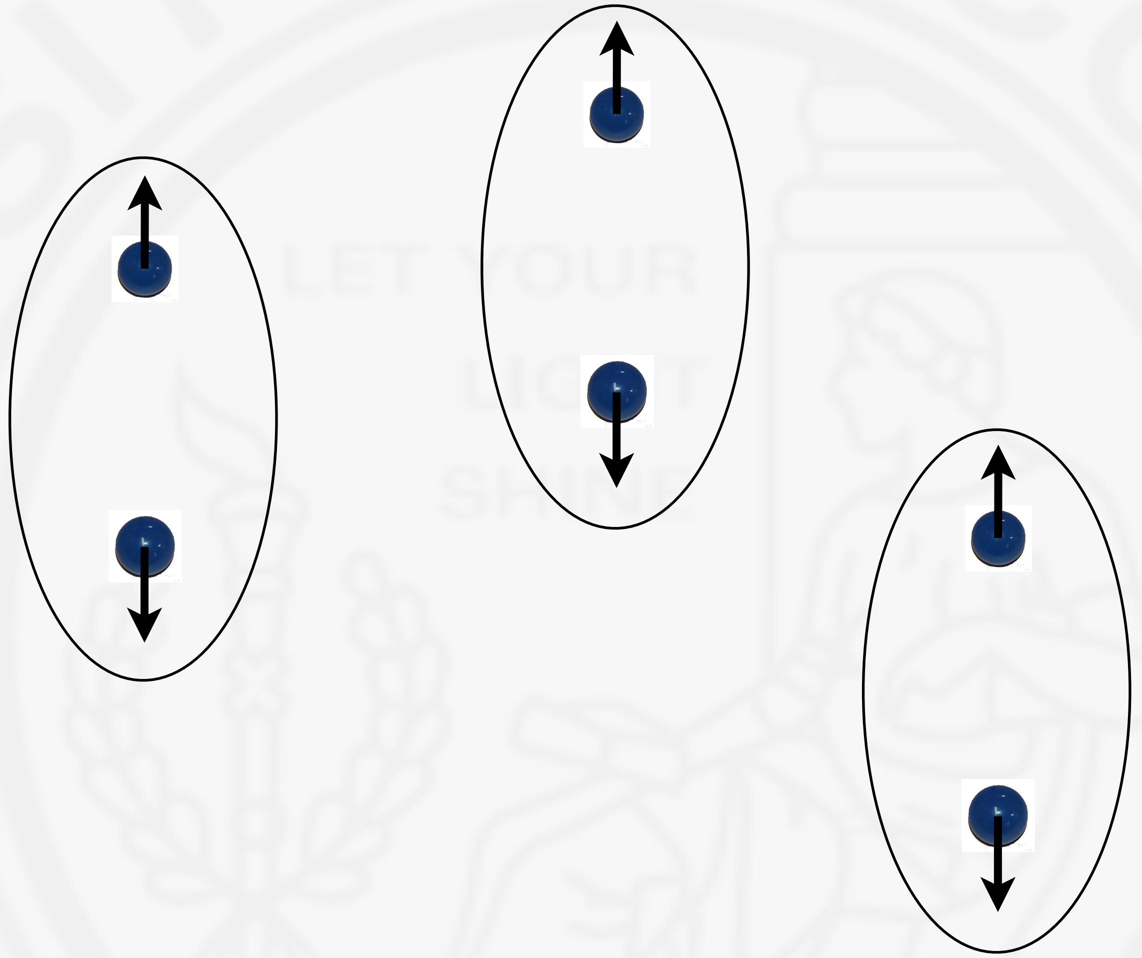

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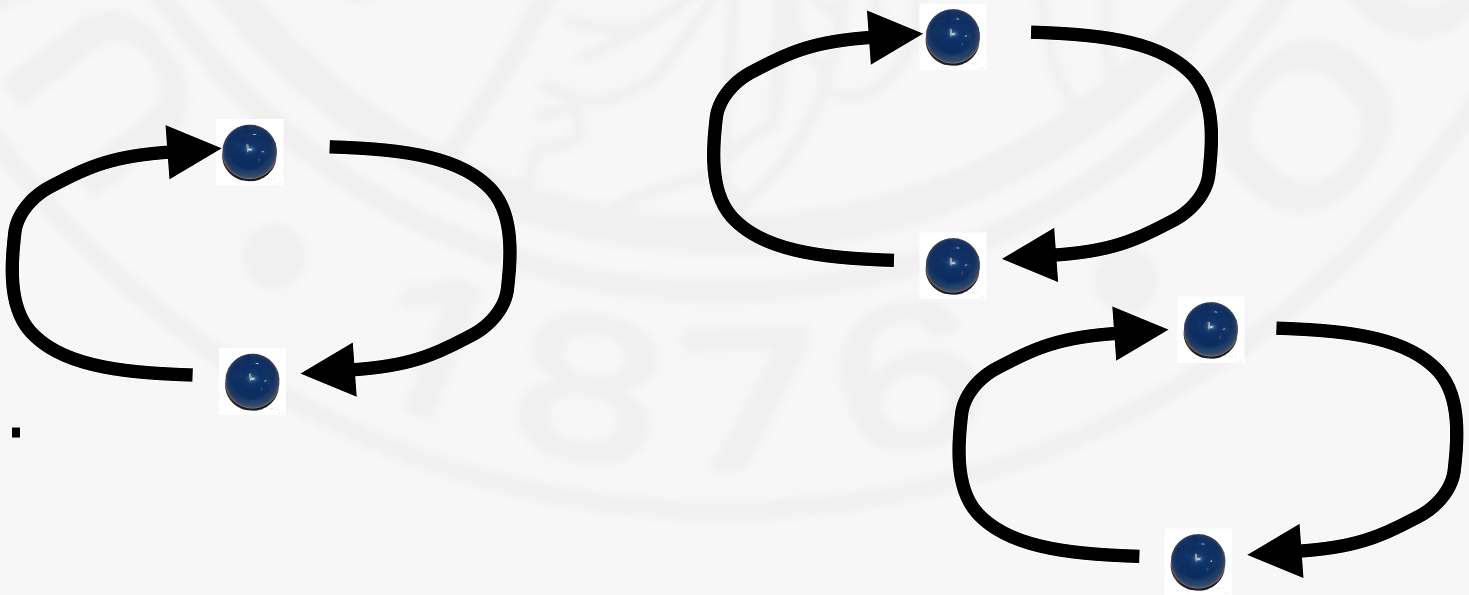


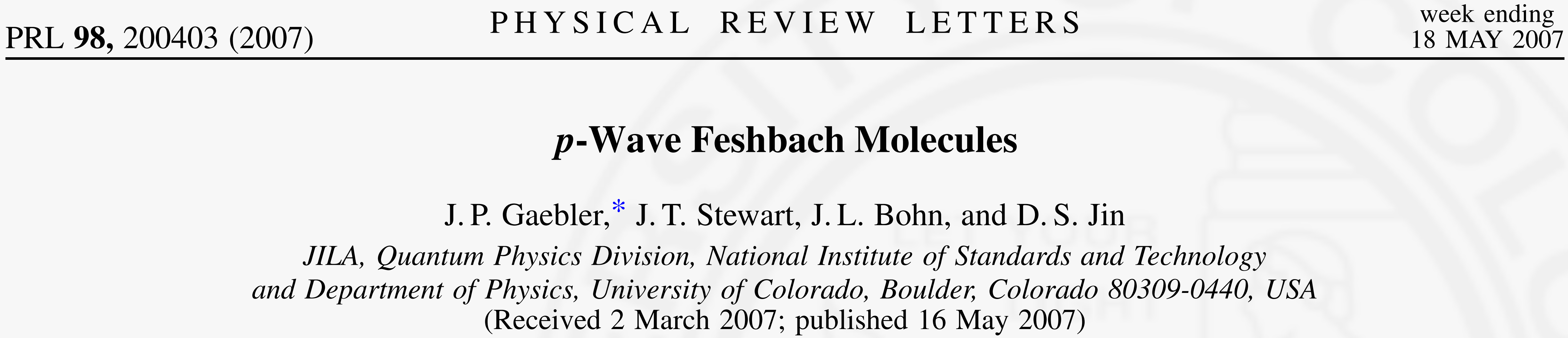
Exotic superconductors: atoms in identical internal states: pairs must spin.
"p-wave" superconductor

p-wave superconductors in cold gases

- Take advantage of p-wave (angular momentum 1) Feshbach resonances
- Have a number of distinct phases, phase diagram has been worked out.
- One of the more common phases has topological order and particles with non-Abelian statistics.

VG, A. Andreev, L. Radzihovsky, 2005

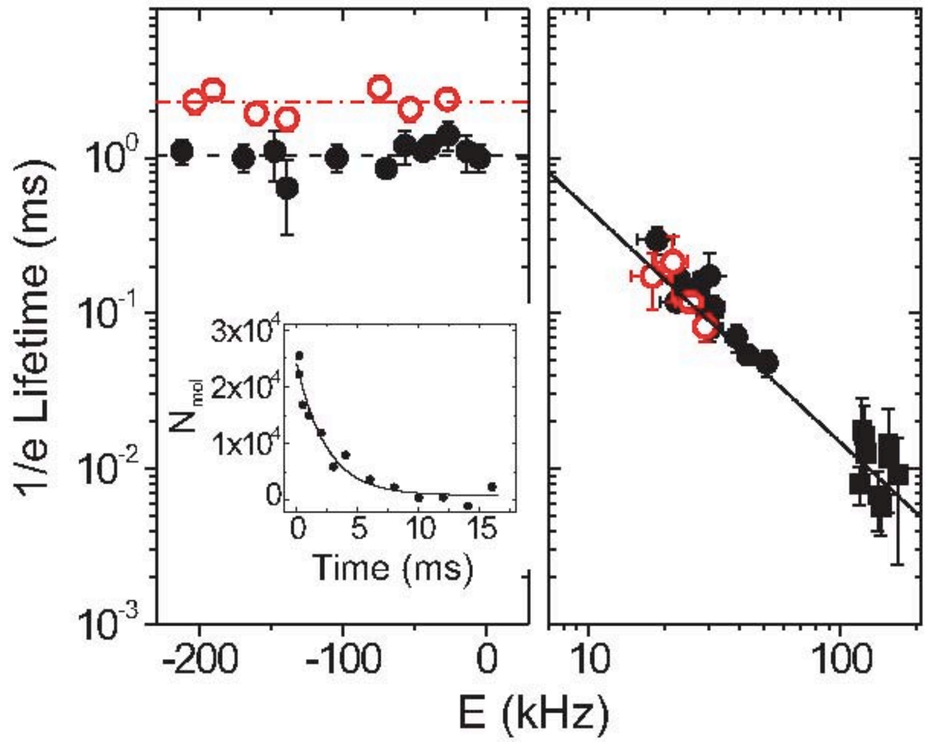
Experiments



PRL **98,** 200403 (2007) PHYSICAL REVIEW LETTERS week ending 18 MAY 2007

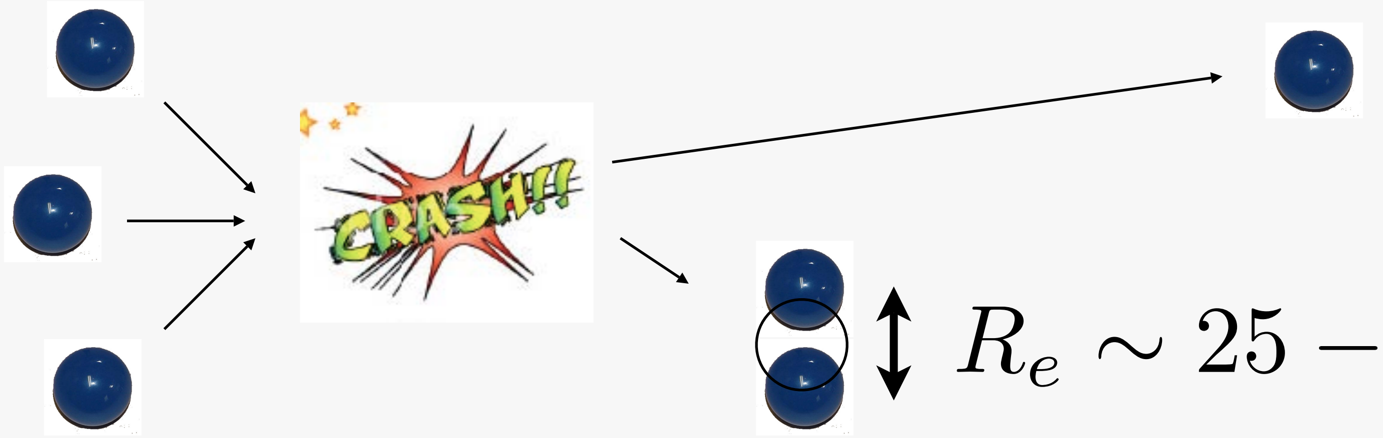
p-Wave Feshbach Molecules

J. P. Gaebler,* J. T. Stewart, J. L. Bohn, and D. S. Jin
JILA, Quantum Physics Division, National Institute of Standards and Technology
and Department of Physics, University of Colorado, Boulder, Colorado 80309-0440, USA
(Received 2 March 2007; published 16 May 2007)



Bottom line:
the molecules are unstable,
with $\tau \sim 2ms$

Origin of instability: 3 body recombination



$R_e \sim 25 - 50\, a.u.$

R_e is the so-called van der Waals length (the typical interaction range)

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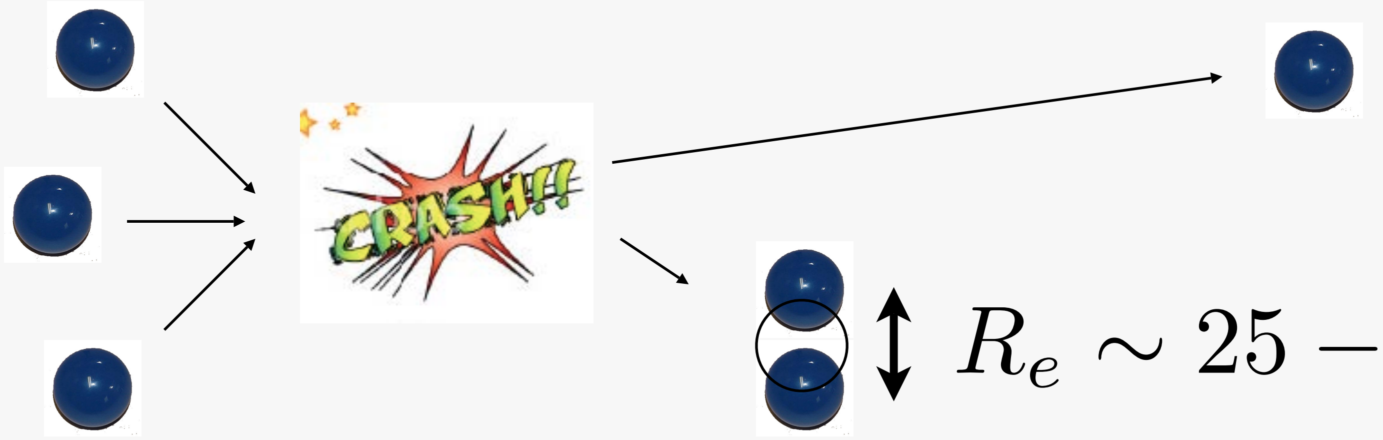

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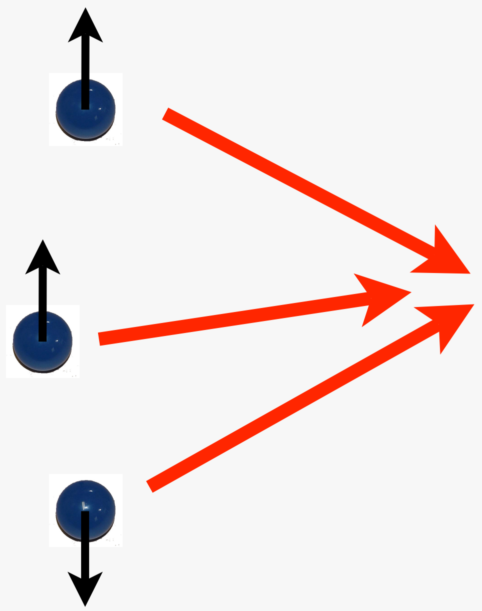
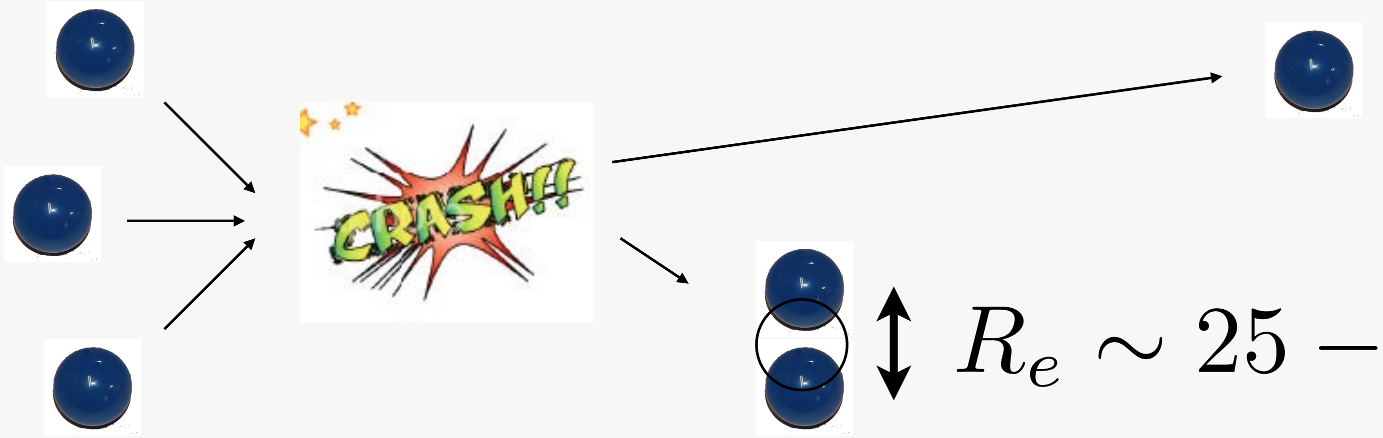
s-wave



Protected by the Pauli principle

Origin of instability: 3 body recombination



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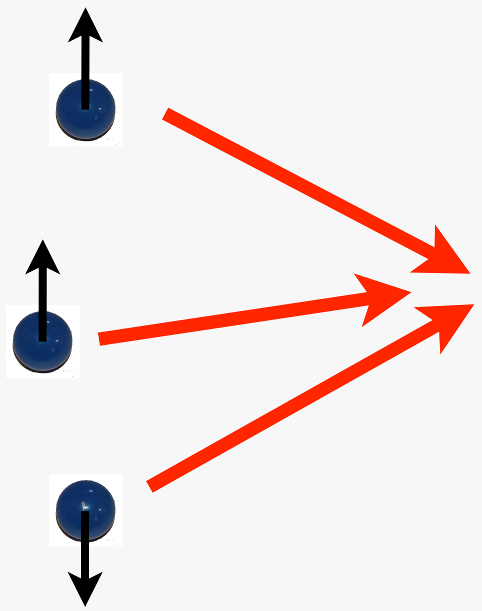

Protected
by the Pauli
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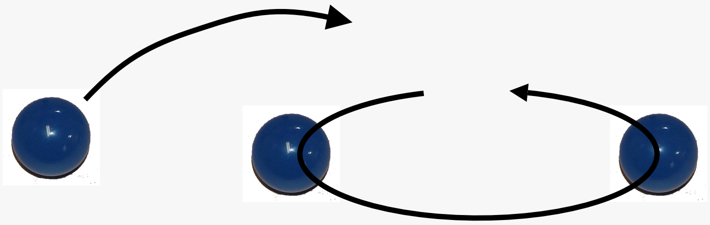
p-wave



By having opposite angular
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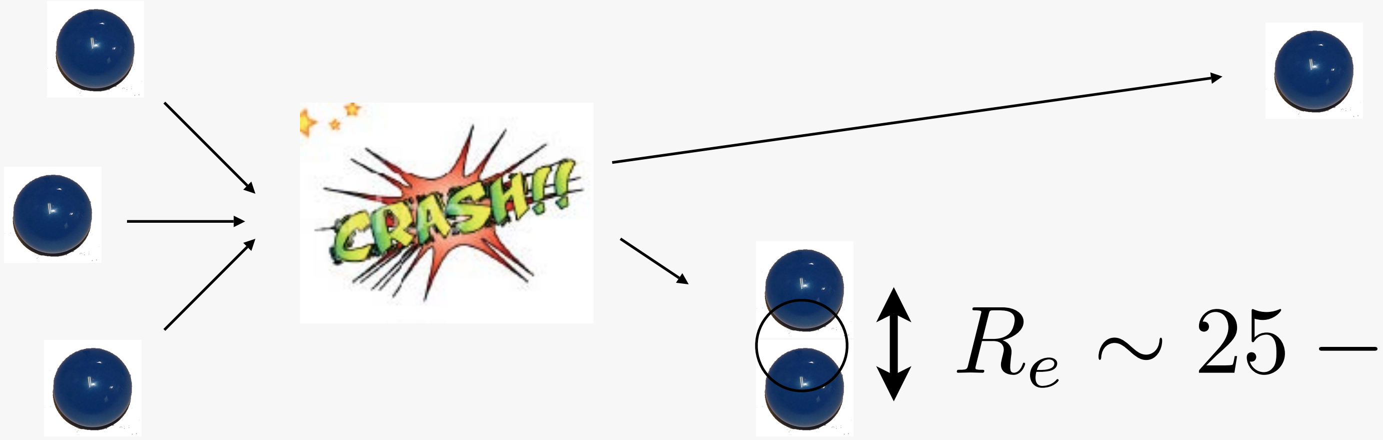

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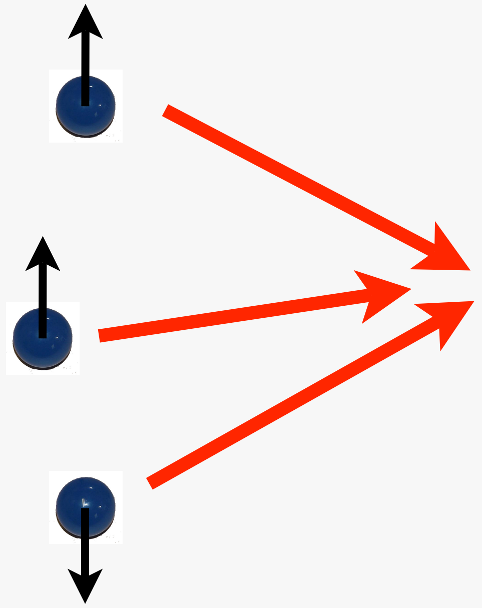

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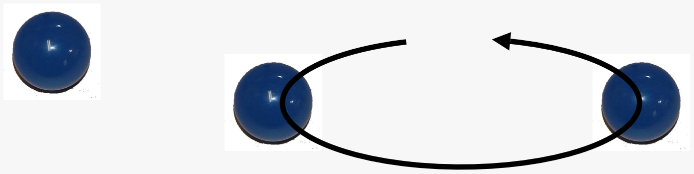

By having opposite angular momenta, *p*-wave fermions beat the Pauli principle

Lifetime calculations

Interatomic distance

atomic mass

$$\text{Lifetime} = \frac{mr^2}{\hbar}\frac{r}{R_e} \sim 20\text{ms}$$

van der Waals length

Probably, their life is too short!

J. Levinsen, N. Cooper, VG, 07-08

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J. Levinsen, N. Cooper, VG, 07-08

Optical lattices may provide a way to overcome short lifetimes...

P. Zoller et al, 09

topological magnets

topological magnets

X.-G. Wen

F. Wilczek

A. Zee

1989

topological magnets

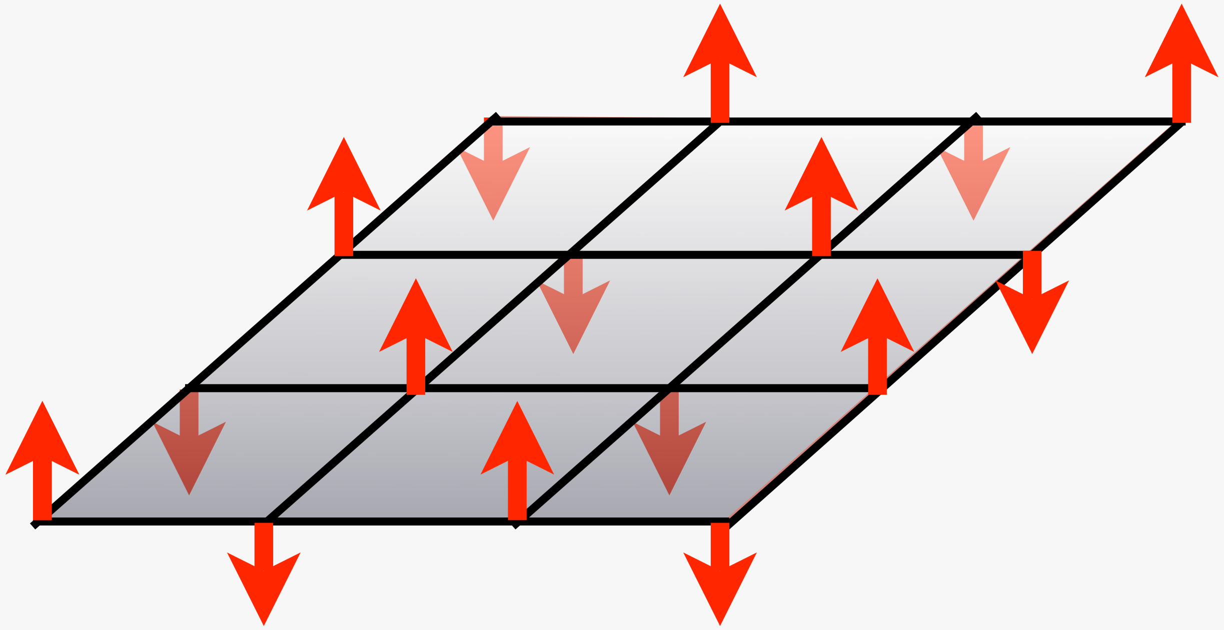

X.-G. Wen F. Wilczek A. Zee

1989

Heisenberg antiferromagnet

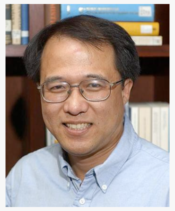
$$H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$

Nearest neighbors

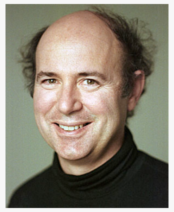


Néel state

topological magnets



X.-G. Wen



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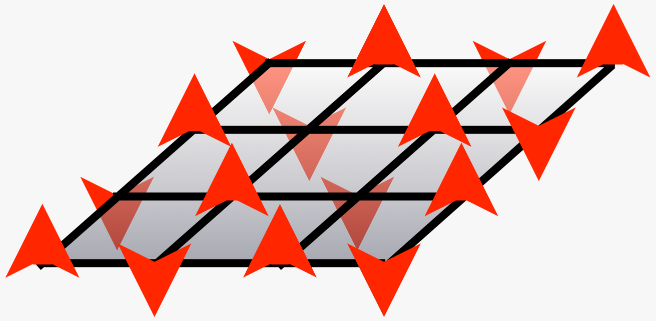
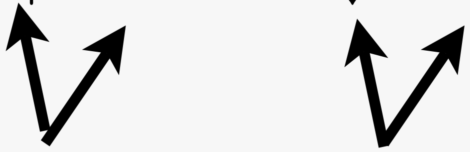


Néel state

Chiral spin liquid (CSL)

Think of spin as attached to particles

$$f^\dagger_{i\uparrow}, f_{i\uparrow}; f^\dagger_{i\downarrow}, f_{i\downarrow}$$

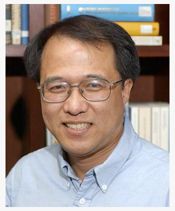


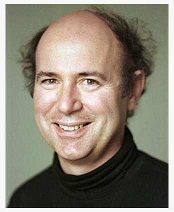
spin-up

spin-down

$$H = J \sum_{<ij>,\alpha,\beta=\uparrow,\downarrow} f^\dagger_{i,\alpha} f_{i,\beta} f^\dagger_{j,\beta} f_{j,\alpha}$$

topological magnets


X.-G. Wen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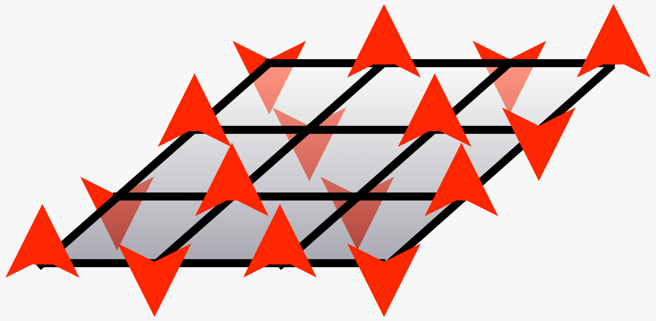

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spin-up spin-down

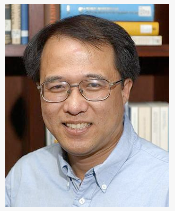
$$H = J \sum_{<ij>,\alpha,\beta=\uparrow,\downarrow} f^\dagger_{i,\alpha} f_{i,\beta} f^\dagger_{j,\beta} f_{j,\alpha}$$

t_{ij}

What if $\sum_{\alpha} \left\langle f^\dagger_{i,\alpha} f_{j,\alpha} \right\rangle = t_{ij}$ $\quad H = J \sum_{<ij>,\beta} t_{ij} f^\dagger_{i,\beta} f_{j,\beta} + \ldots$

“tight-binding Hamiltonian”

topological magnets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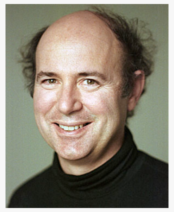
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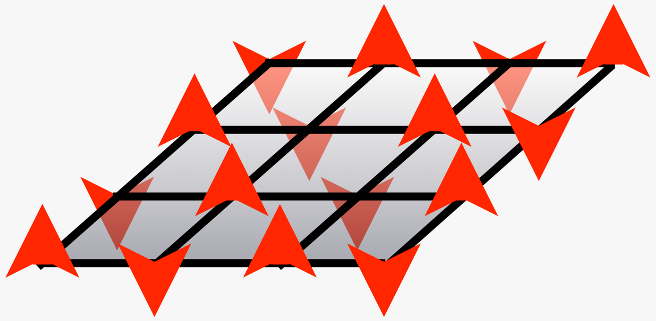

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Think of spin as attached to particles $f^\dagger_{i\uparrow}, f_{i\uparrow}; f^\dagger_{i\downarrow}, f_{i\downarrow}$

spin-up spin-down

$$H = J \sum_{<ij>,\alpha,\beta=\uparrow,\downarrow} \underbrace{f^\dagger_{i,\alpha} \boxed{f_{i,\beta} f^\dagger_{j,\beta}} f_{j,\alpha}}_{t_{ij}}$$

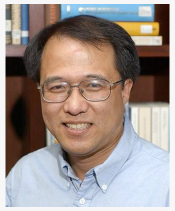
What if $\sum_{\alpha} \left\langle f^\dagger_{i,\alpha} f_{j,\alpha} \right\rangle = t_{ij}$ $\quad H = J \sum_{<ij>,\beta} t_{ij} f^\dagger_{i,\beta} f_{j,\beta} + \ldots$

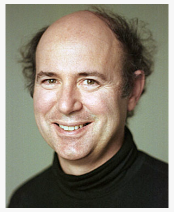
“tight-binding Hamiltonian”

But what if t_{ij} correspond to a constant magnetic field?

This is CSL (or a topological magnet), by analogy with QHE

topological magnets


X.-G. Wen


F. Wilczek


A. Zee

1989

20 years and 552 citations later, nobody could still point out the Hamiltonian for which this scenario would work.

A proposal to generalize spin from SU(2) to to SU(N)

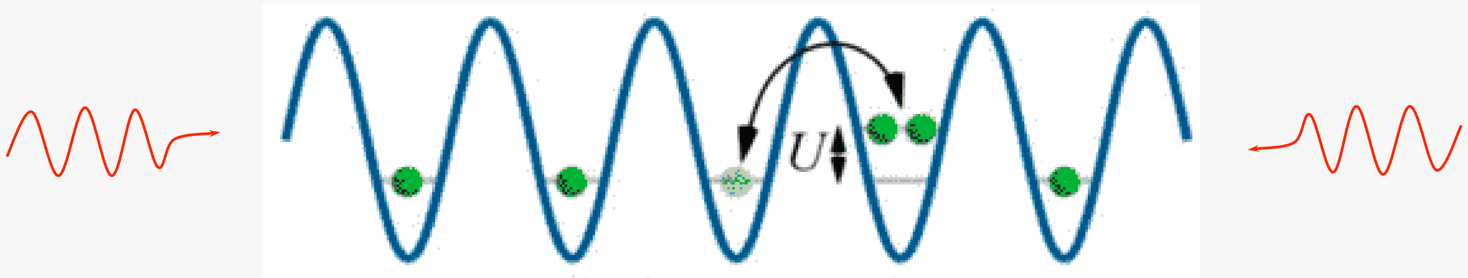
Generalize the usual spin to SU(N) spin by using alkaline-earth atoms. Their nuclear spin does not interact and behaves like an electron spin, only larger.

The spin ***I*** can be as large as *9/2* (for ^{87}Sr).
Then N=***2I+1*** is as large as 10.

A.-M. Rey (2009)

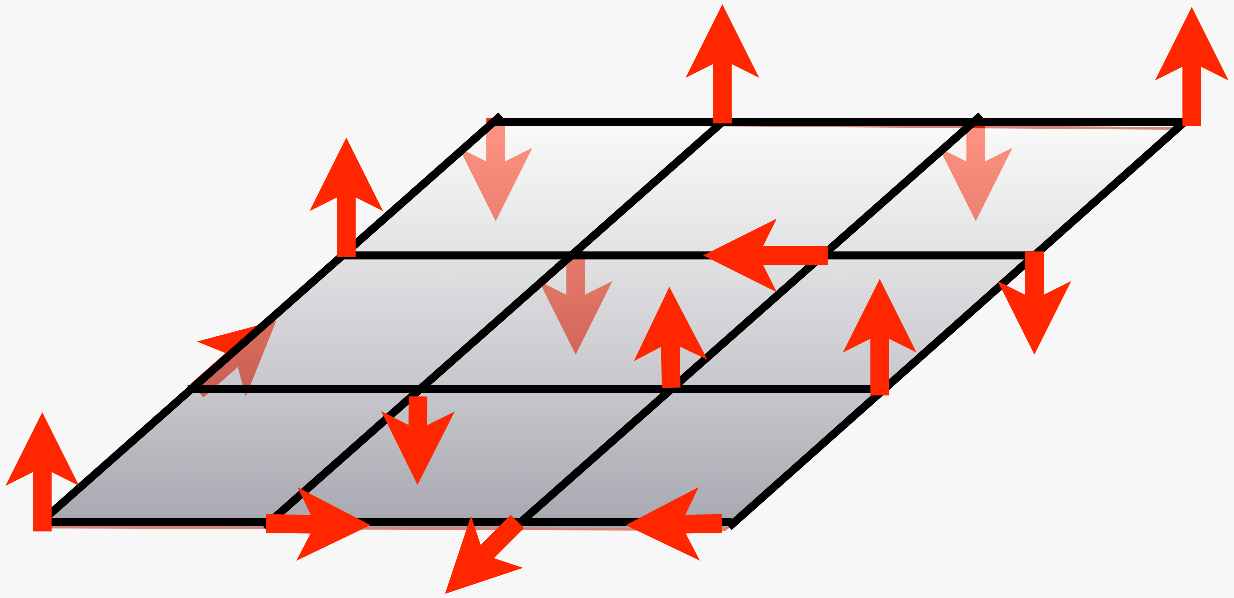
A. Gorshkov, M. Hermele, VG, C. Xu, P. Julienne, J. Ye, P. Zoller, E. Demler, M. Lukin and A.M. Rey (2009)

SU(N) antiferromagnets in optical lattices



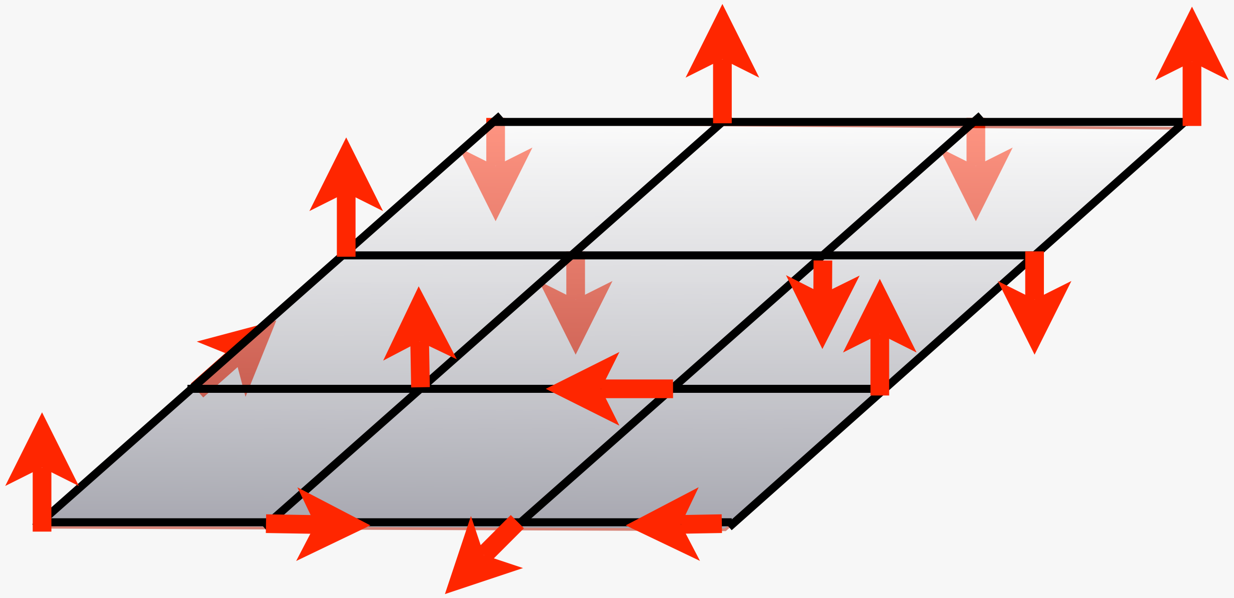
Interfering laser beams

SU(N) antiferromagnets in optical lattices



^{87}Sr atoms

SU(N) antiferromagnets in optical lattices

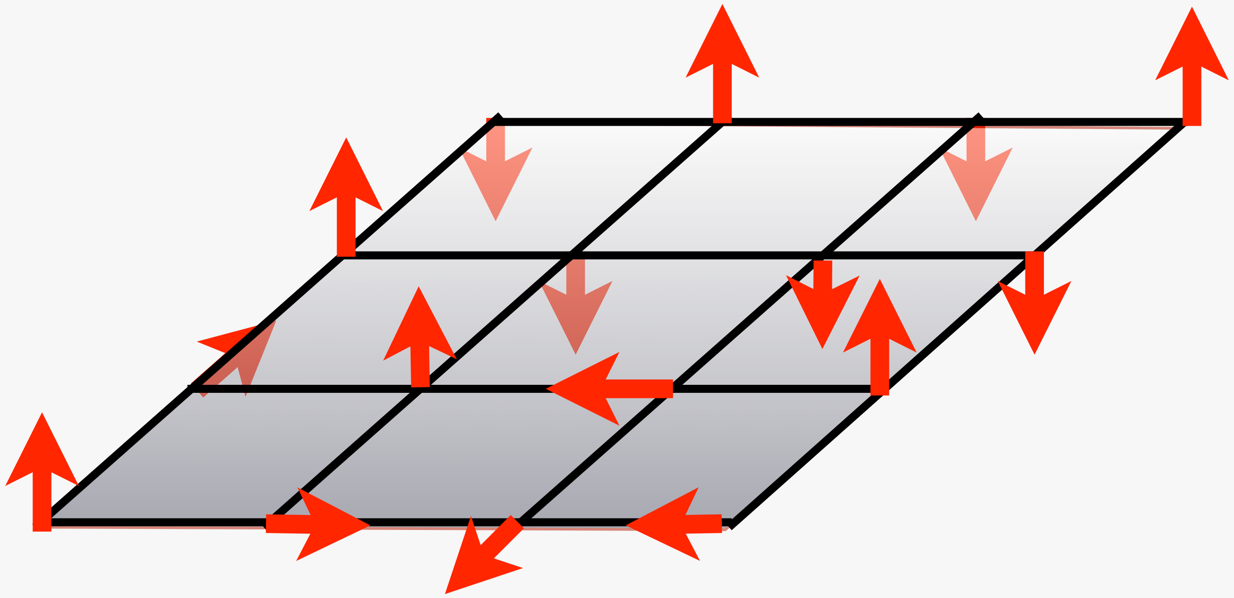


^{87}Sr atoms

$$H = J \sum_{<ij>,\ \alpha,\beta=1,\ldots,N} f^\dagger_{i,\alpha} f_{i,\beta} f^\dagger_{j,\beta} f_{j,\alpha}$$

Atom exchange leads to antiferromagnetic interactions (for nuclear spin).

SU(N) antiferromagnets in optical lattices



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Atom exchange leads to antiferromagnetic interactions (for nuclear spin).

Such SU(N) spins have a hard time ordering: too many directions nearby spins can point to while still being “opposite” to each other (minimize $\vec{S}_i \cdot \vec{S}_j$)

M. Hermele (2009)

Topological SU(N) antiferromagnet

It turns out, for N≥5, the ground state is a chiral spin liquid (that is, a topological magnet), exactly of the type proposed by Wen, Wilczek and Zee.

M. Hermele, VG, A.-M. Rey, (2009)

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M. Hermele, VG, A.-M. Rey, (2009)

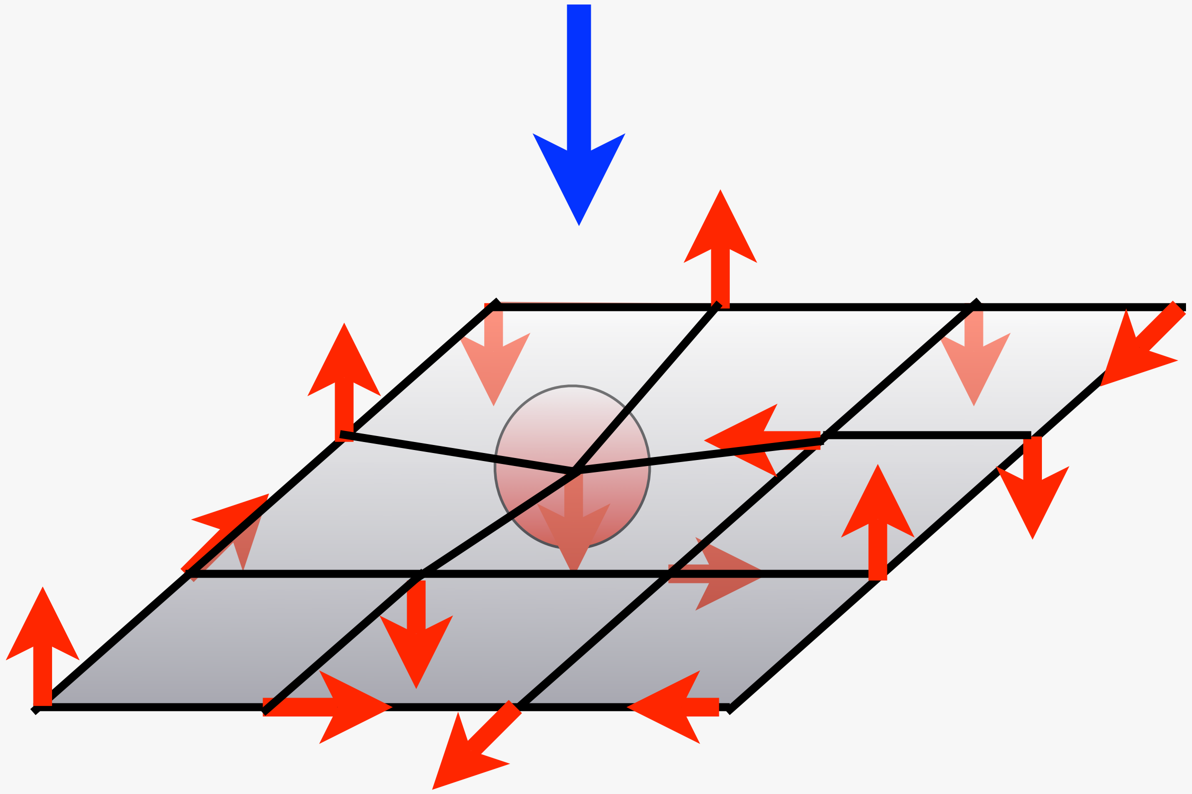
To show that, we employed the large N techniques:

$$H = J \sum_{i,\alpha} t_{ij} \left(f^{\dagger}_{i,\alpha} f_{j,\alpha} + hc \right) + \frac{N}{J} \sum_{<ij>} \left| t_{ij} \right|^2$$

$$S = N \mathrm{Tr} \log \left[\mathcal{S}_{ij} \right] + \frac{N}{J} \sum_{<ij>} \left| t_{ij} \right|^2$$

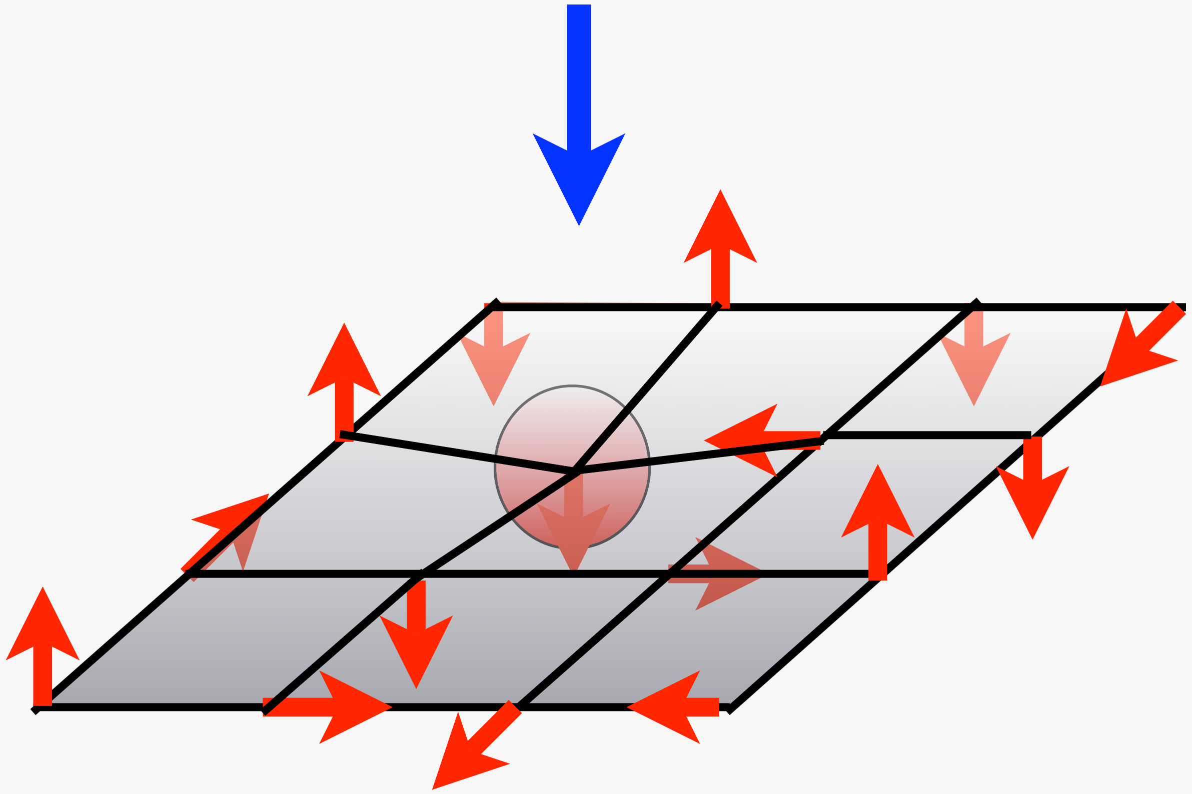
\+ saddle point in *t*

Anyons and non-Abelions



Lowering the potential at one site localizes a fractional or non-Abelian particle at that site.

Anyons and non-Abelions



Lowering the potential at one site localizes a fractional or non-Abelian particle at that site.

Experimental detection? Too soon to tell...

This is but the beginning...

We will see new remarkable experiments which will to build artificial “materials” with novel properties out of cold atoms...