The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

SMR 1666 - 30

SCHOOL ON QUANTUM PHASE TRANSITIONS
AND
NON-EQUILIBRIUM PHENOMENA IN COLD ATOMIC GASES

11 - 22 July 2005

Fermi condensates

Presented by:

Markus Greiner

University of Colorado at Boulder, USA

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

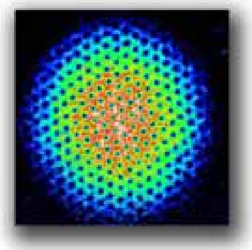
ICTP SCHOOL ON QUANTUM PHASE TRANSITIONS AND NON-EQUILIBRIUM PHENOMENA IN COLD ATOMIC GASES 2005

Fermi condensates

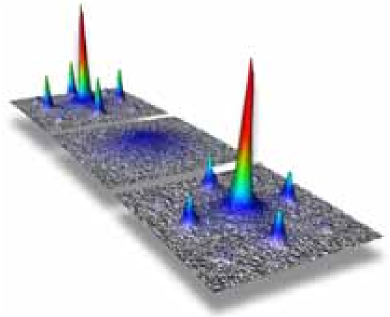
Markus Greiner

JILA, Group of D. Jin;
Coworkers: C. Regal and J. Stewart
NIST and the University of Colorado, Boulder

Highly controlled many-body quantum systems

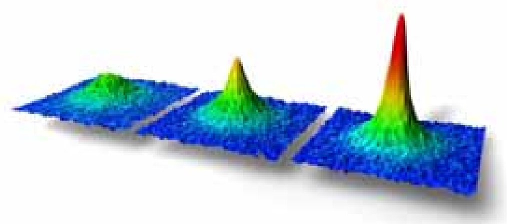


Weakly interacting Bose gases:
Coherence, superfluid flow, vortices …



Strongly correlated Bose systems:
Superfluid to Mott insulator transition

Fermionic superfluidity:
BCS-BEC crossover physics



- *Condensed matter physics studied with an atomic physics system*

Outline:

- Fermionic superfluidity;
  The tools: trapping, cooling, probing;

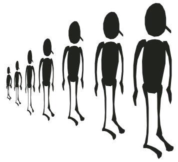
- Controlling interactions;
  Molecular Bose-Einstein condensate;
  Fermi condensate: Generalized Cooper pairs in the BCS-BEC crossover;

- Probing the fermion momentum distribution

- Detecting atom-atom correlations via atom shot noise;

Bosons ⟷ Fermions

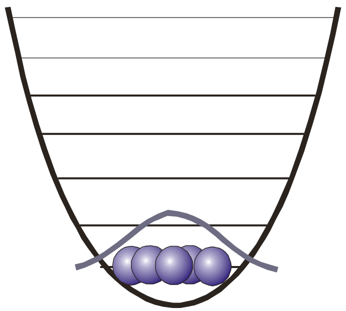
Bosons



integer spin

$\Psi_{1,2} = \Psi_{2,1}$

→ Bosonic enhancement

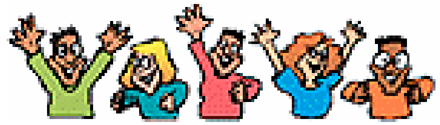


1995: Bose-Einstein condensation

e.g. ^{87}Rb, ^{23}Na, H, ^{39}K …

photons, liquid ^{4}He

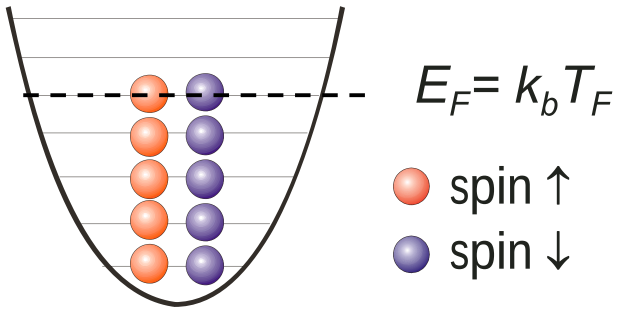
Fermions



half-integer spin

$\Psi_{1,2} = -\Psi_{2,1}$

→ Pauli exclusion principle



1999: Fermi sea of atoms

^{40}K, ^{6}Li

electrons, protons, neutrons

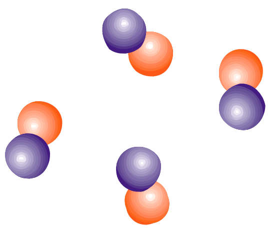
Pairing and Superfluidity

→ Spin is additive: Fermions can pair up and form effective bosons:

$$\Psi(1,\ldots,N) = \hat{A}\,[\,\phi(1,2)\,\phi(3,4)\,\ldots\,\phi(N\text{-}1,N)\,]$$

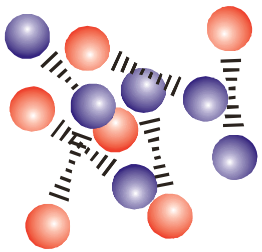
spin ↑
spin ↓

Molecules of fermionic atoms



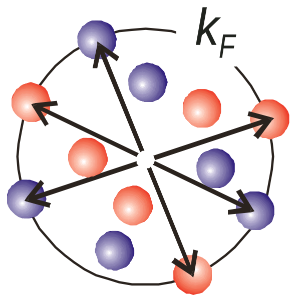
BEC of weakly bound molecules

Generalized Cooper pairs of fermionic atoms



BCS - BEC crossover

Cooper pairs

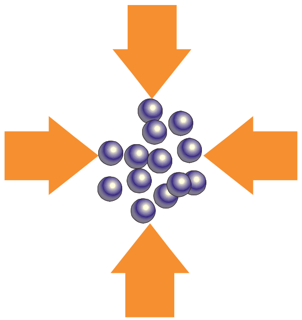


BCS superconductivity
Cooper pairs: correlated momentum-space pairing

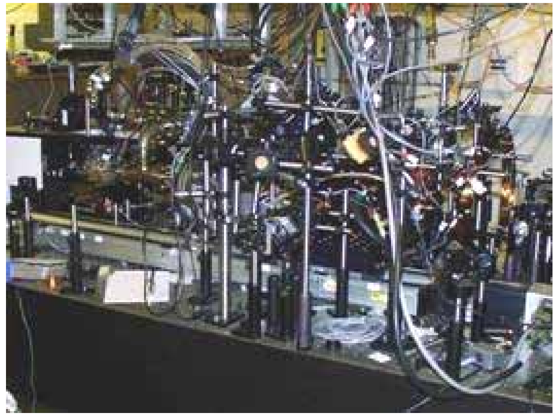
BCS-BEC crossover for example:
Eagles, Leggett, Nozieres and Schmitt-Rink, Randeria, Strinati, Zwerger, Holland, Timmermans, Griffin, Levin …

Cooling a gas of fermionic ^{40}K atoms

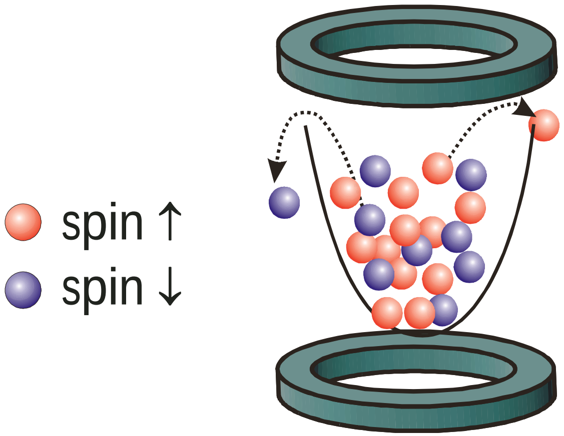
1. Laser cooling and trapping of ^{40}K



300 K to 1 mK
~10^9 atoms



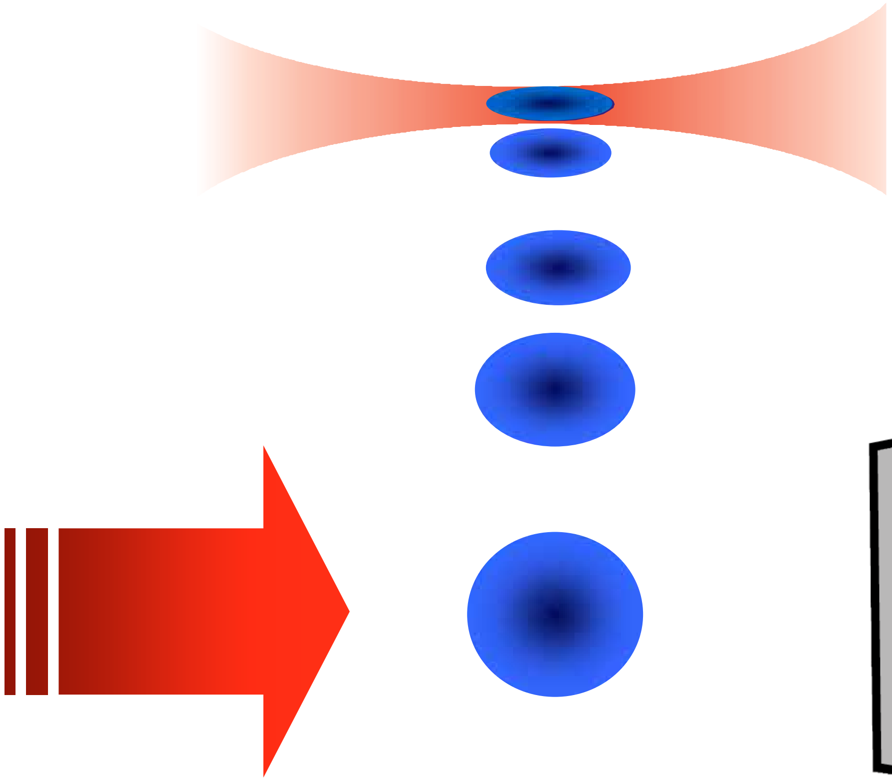
2. Magnetic trapping and evaporative cooling



1 mK to 10 μK
~$10^9 \rightarrow 10^7$ atoms

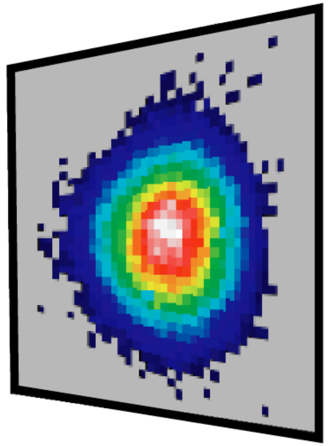
Cooling a gas of fermionic ^{40}K atoms

3. Optical trapping and evaporative cooling

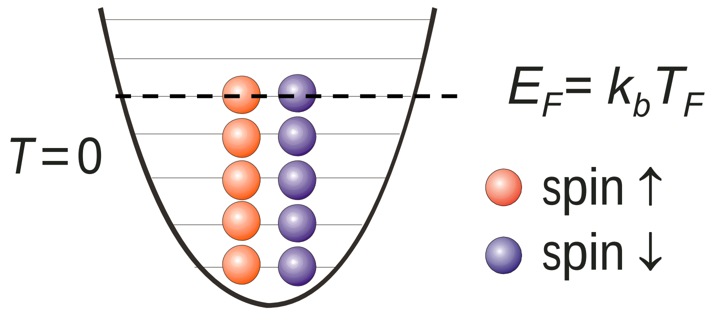


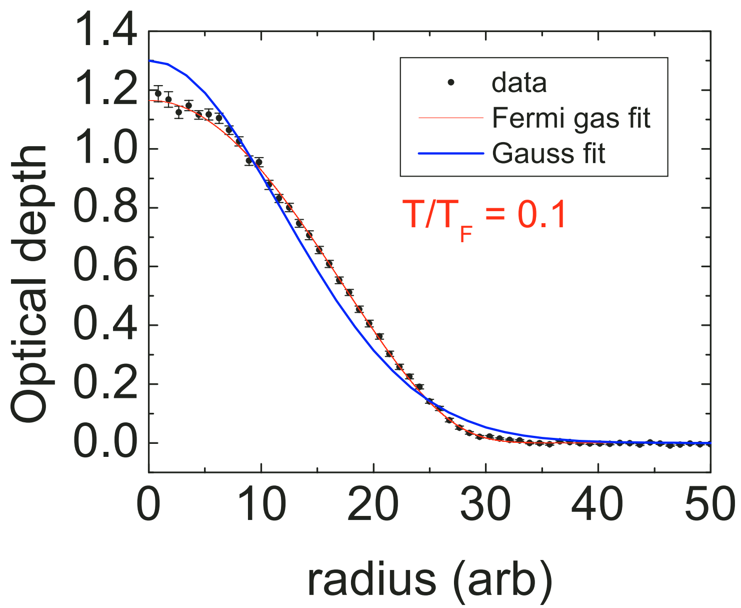
10 µK to 50 nK
$10^7 \rightarrow 10^5$ atoms

- can confine any spin-state
- can apply arbitrary B-field

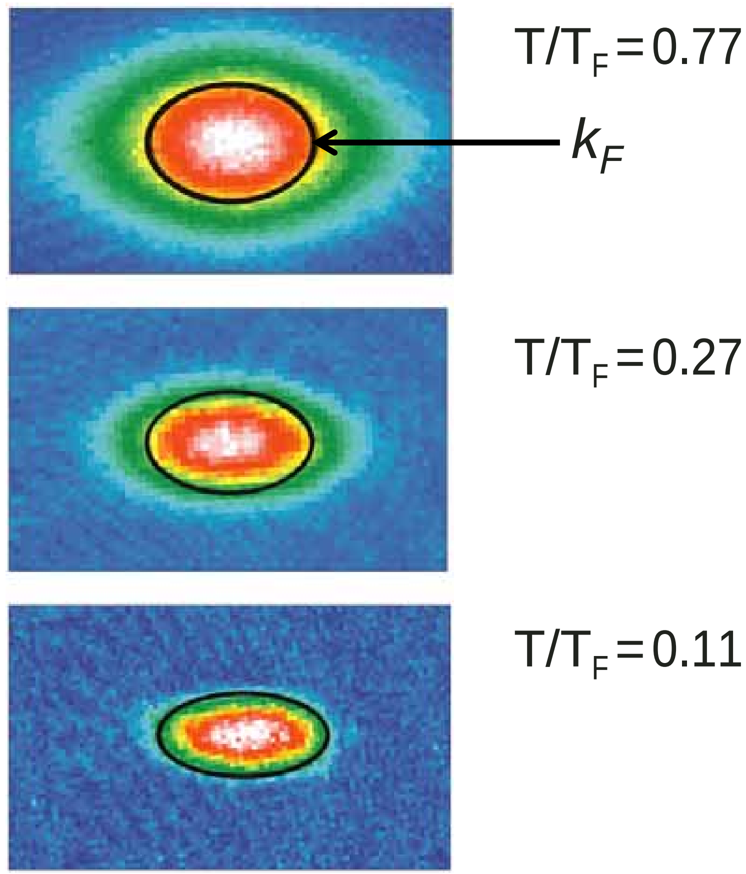


Quantum degeneracy



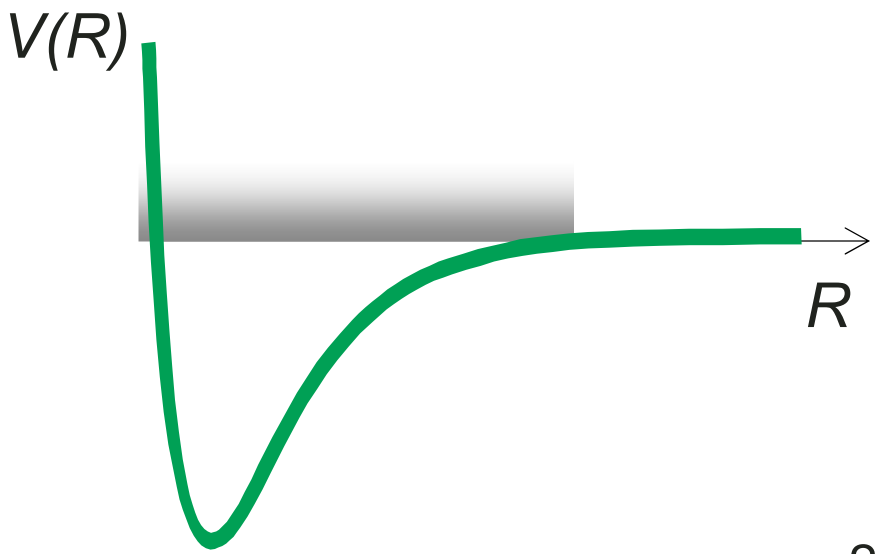


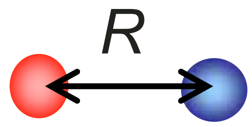
momentum distributions



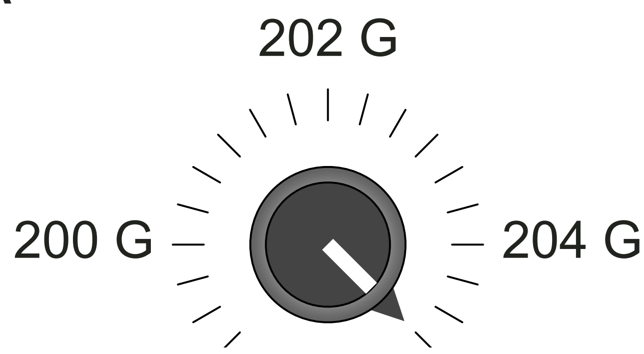
Controlling interaction

Magnetic Feshbach resonance
Turning the knob: a new molecular bound state appears as *B* is varied





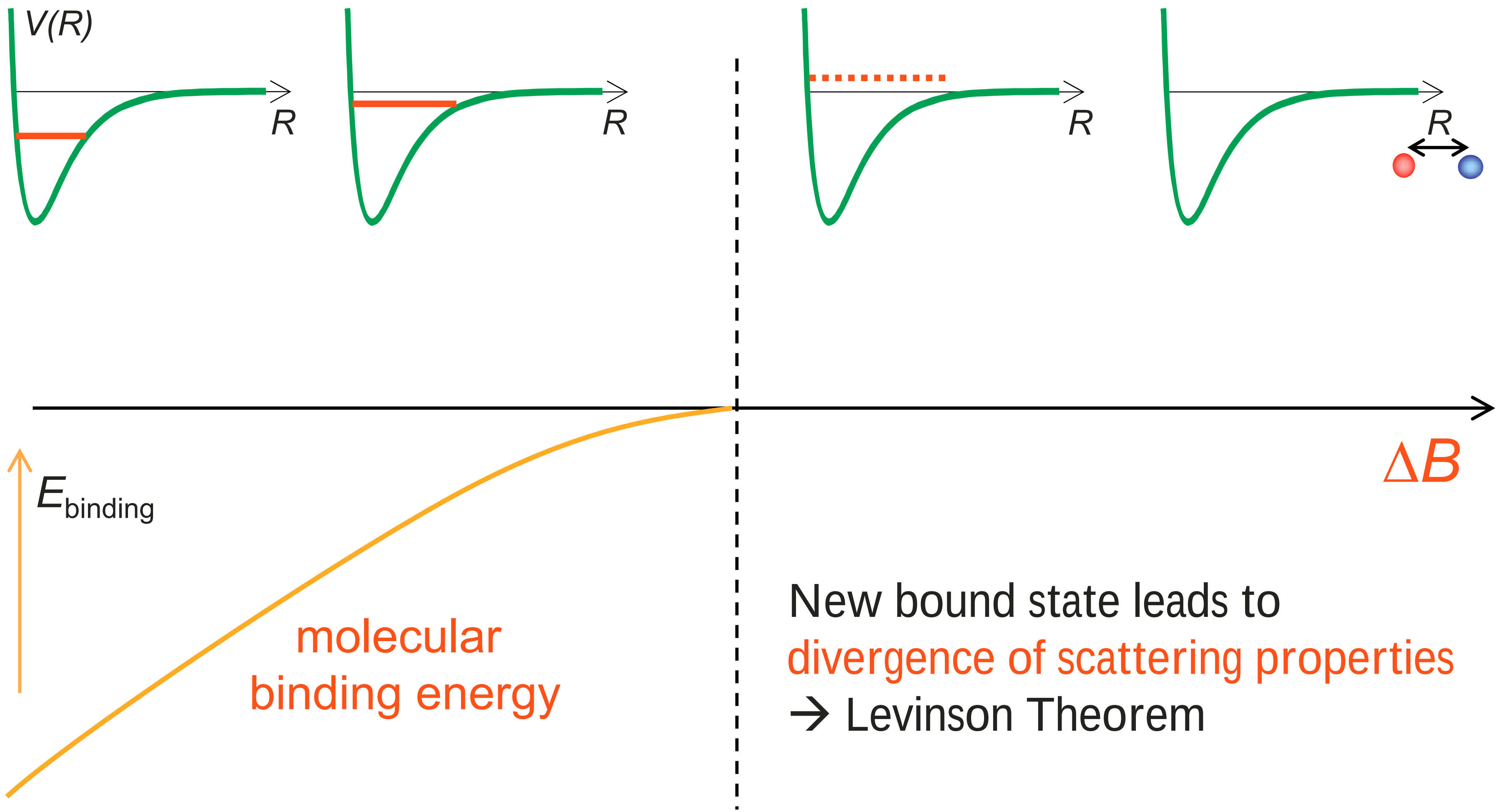
internuclear separation



B-field

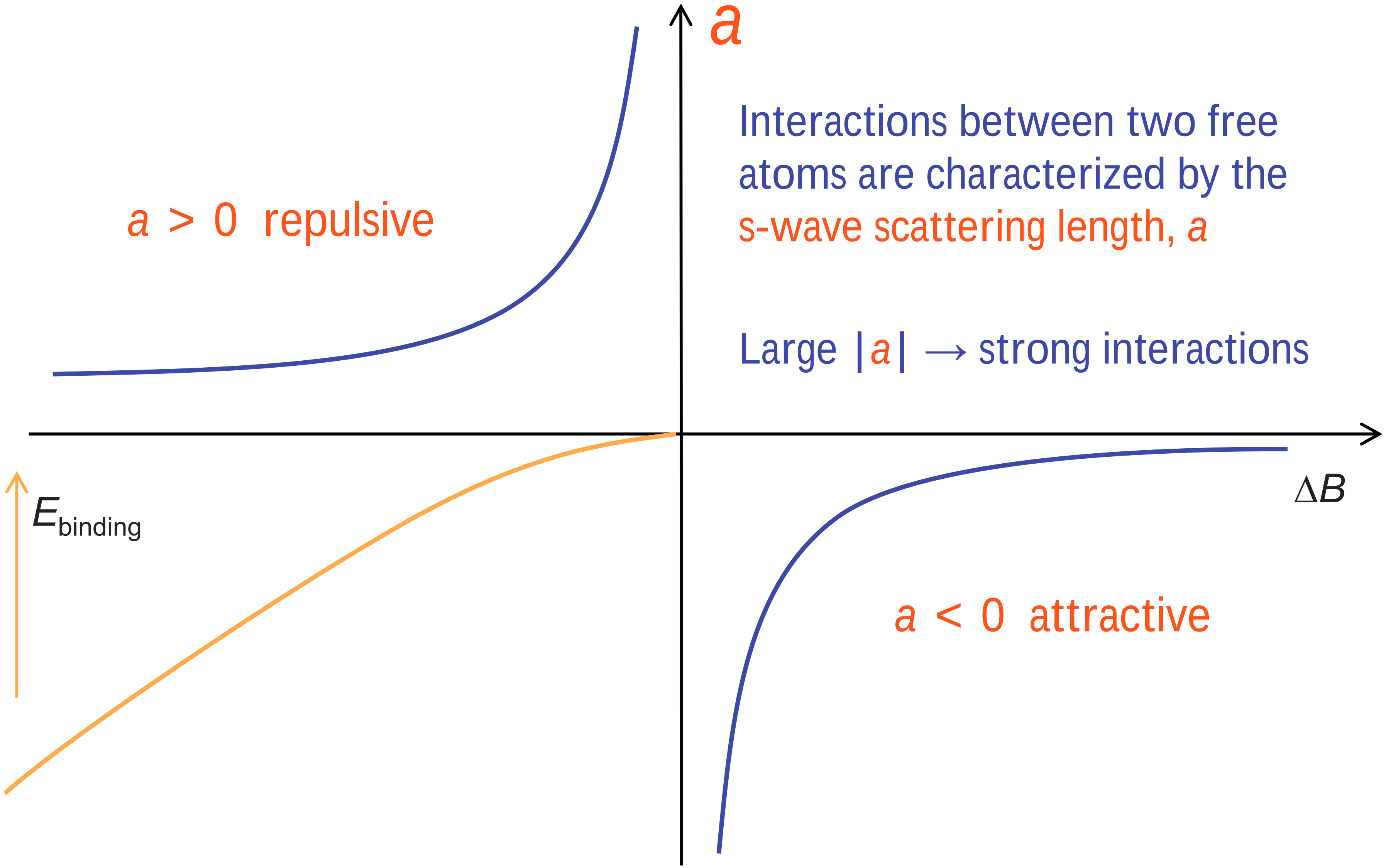
Controlling interaction

Magnetic Feshbach resonance: a new molecular bound state appears as B is varied

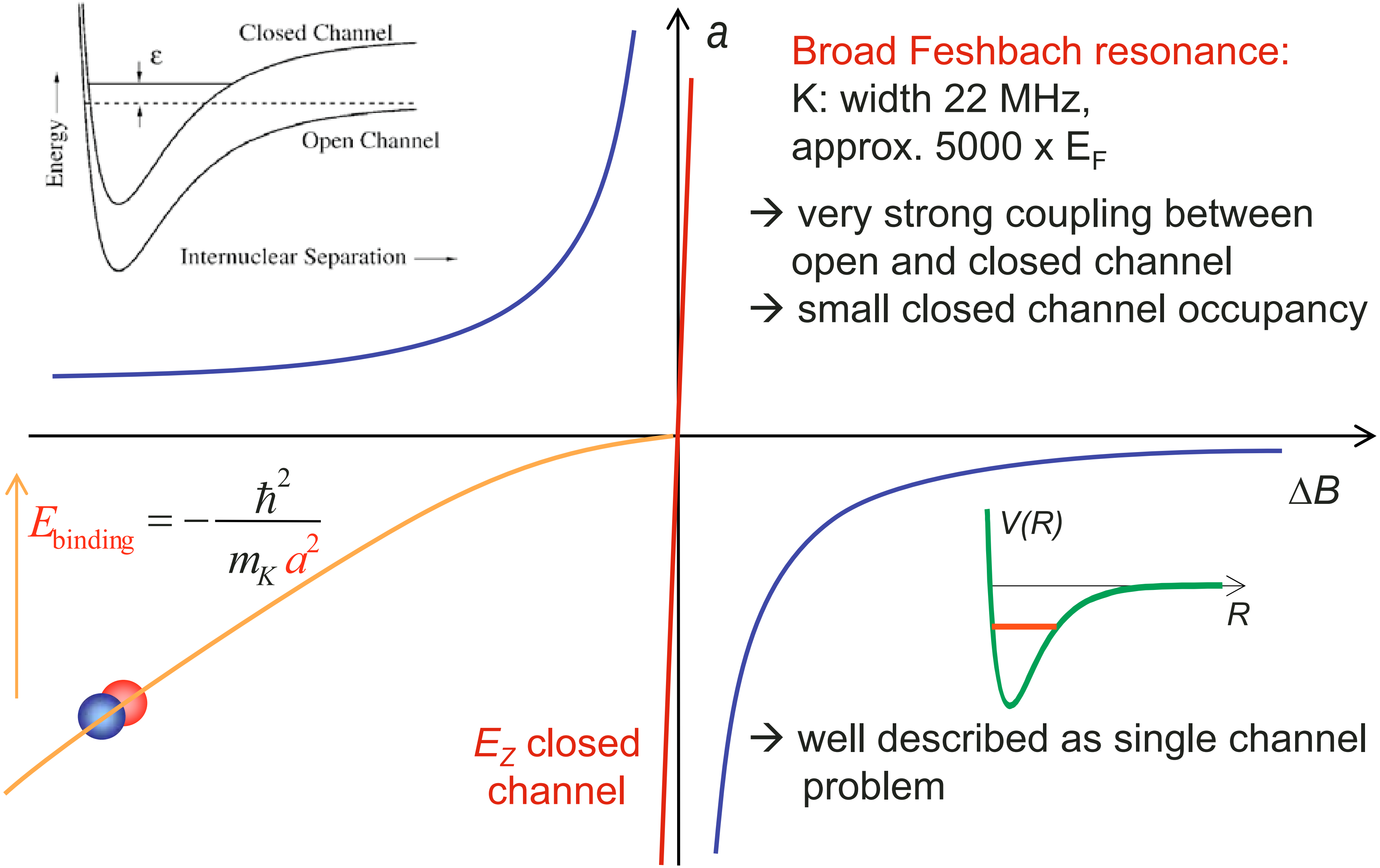


New bound state leads to
divergence of scattering properties
→ Levinson Theorem

Divergence of scattering length



Broad feshbach resonance



$$E_{\text{binding}} = -\frac{\hbar^2}{m_K a^2}$$

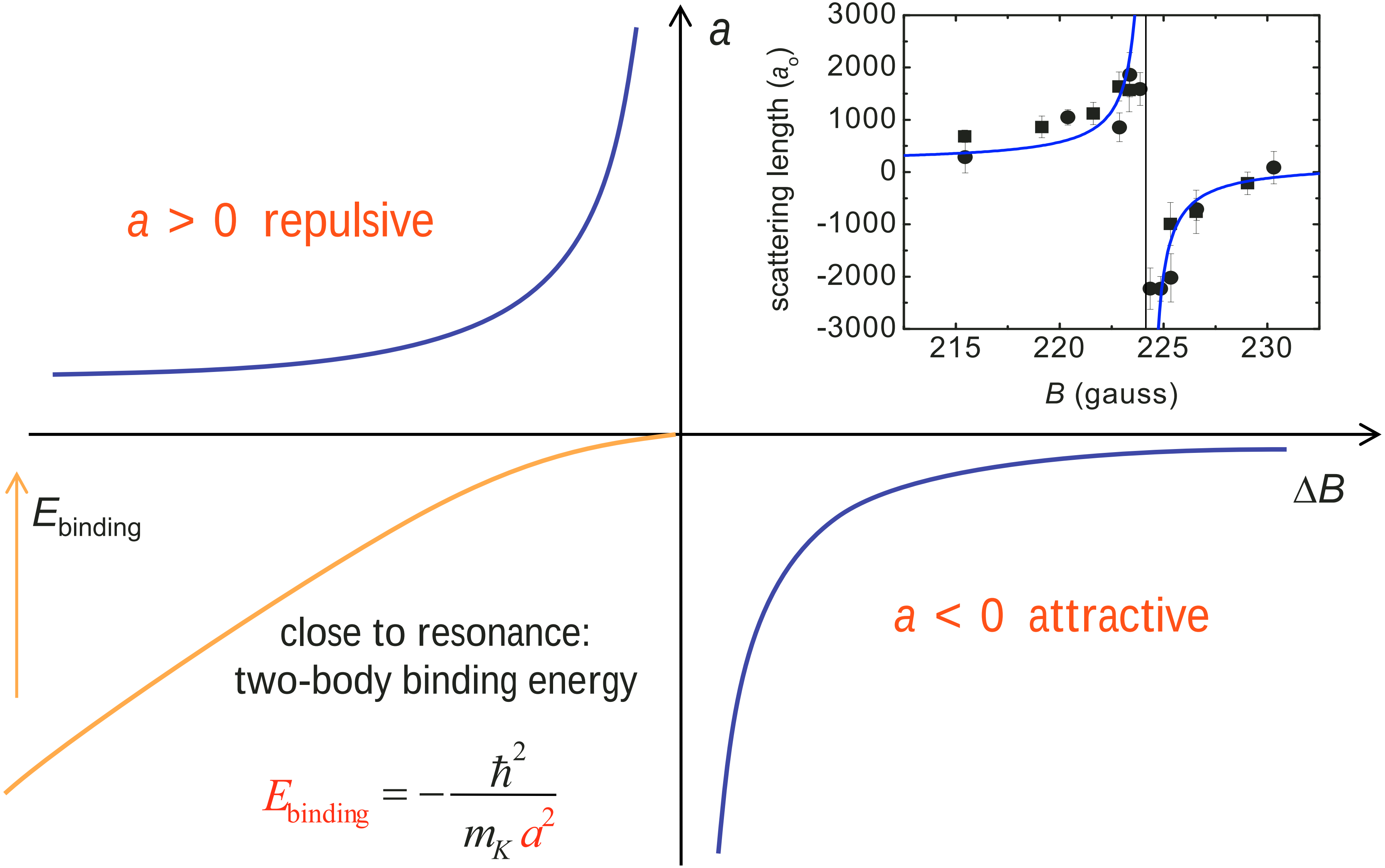
Broad Feshbach resonance:
K: width 22 MHz,
approx. 5000 x E_F

→ very strong coupling between open and closed channel

→ small closed channel occupancy

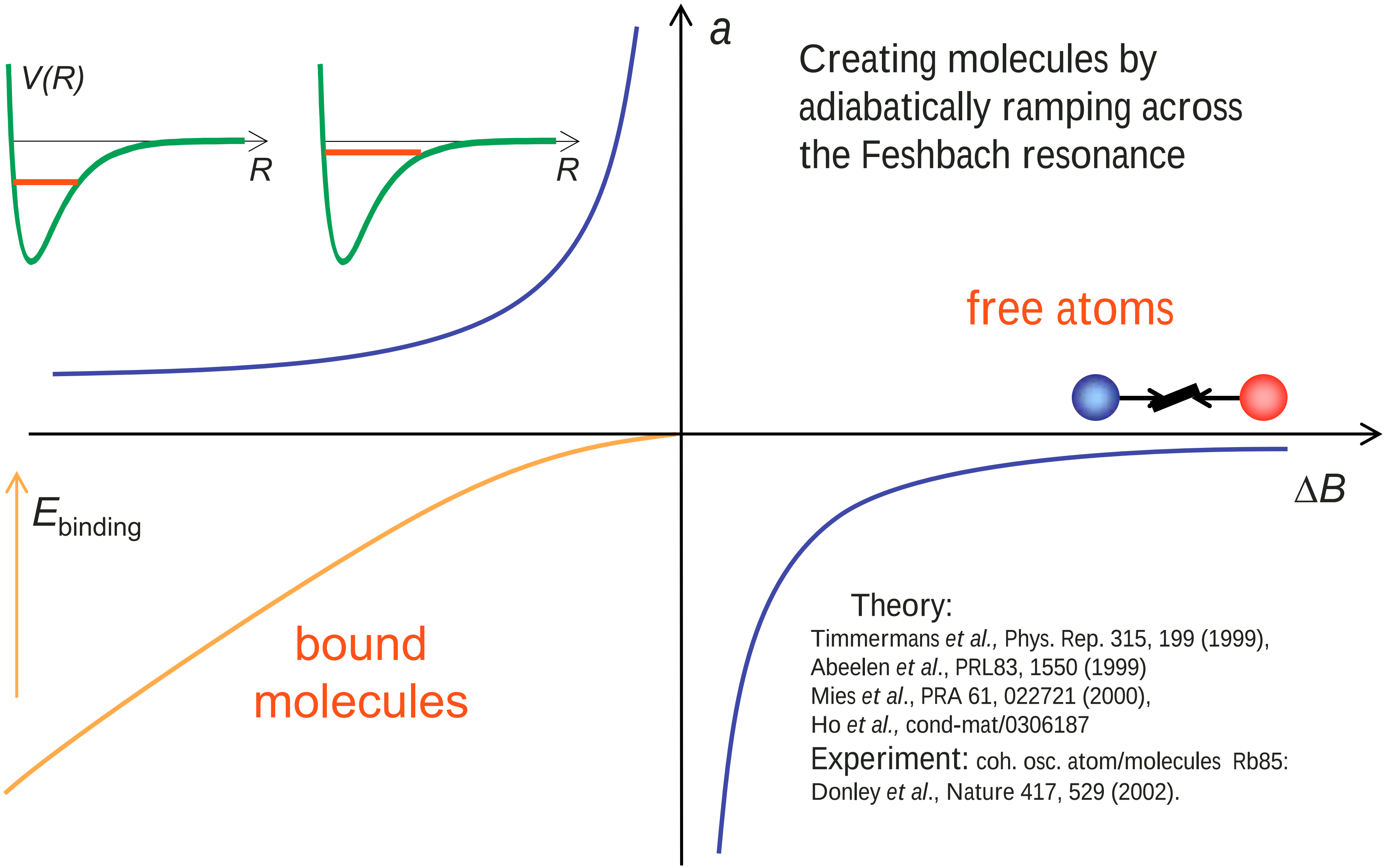
→ well described as single channel problem

Measurement of scattering length



$$E_{\text{binding}} = -\frac{\hbar^2}{m_K a^2}$$

Creating molecules

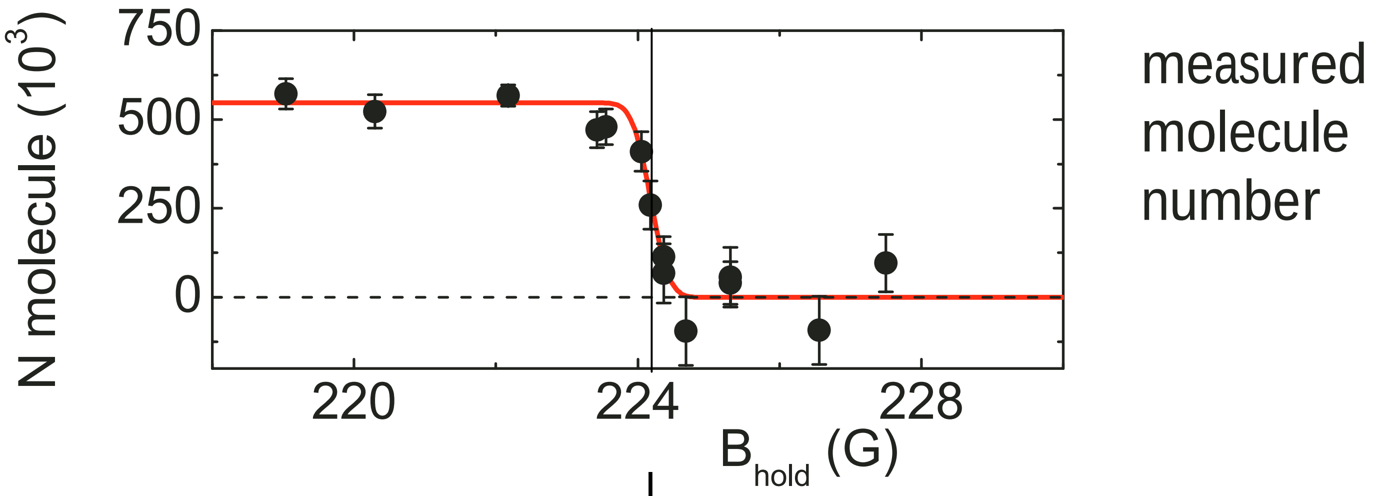


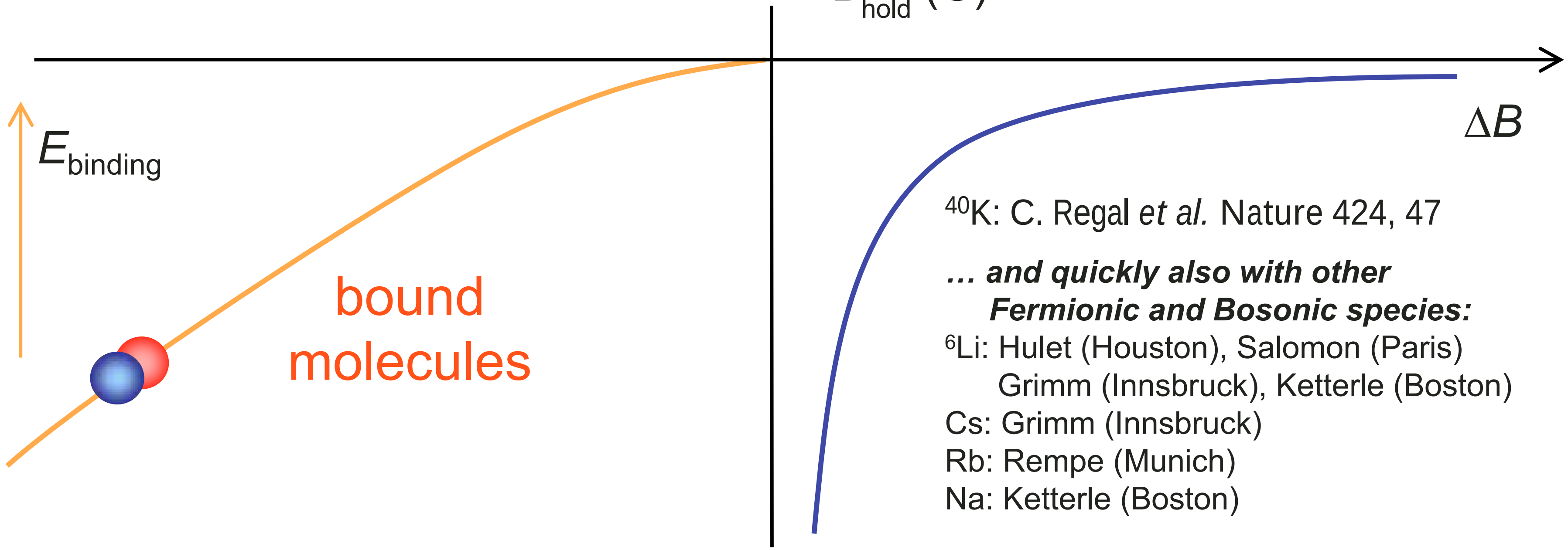
Creating molecules by adiabatically ramping across the Feshbach resonance

Theory:
Timmermans *et al.*, Phys. Rep. 315, 199 (1999),
Abeelen *et al.*, PRL83, 1550 (1999)
Mies *et al.*, PRA 61, 022721 (2000),
Ho *et al.*, cond-mat/0306187

Experiment: coh. osc. atom/molecules Rb85:
Donley *et al.*, Nature 417, 529 (2002).

Creating molecules





[40]K: C. Regal *et al.* Nature 424, 47

… and quickly also with other Fermionic and Bosonic species:

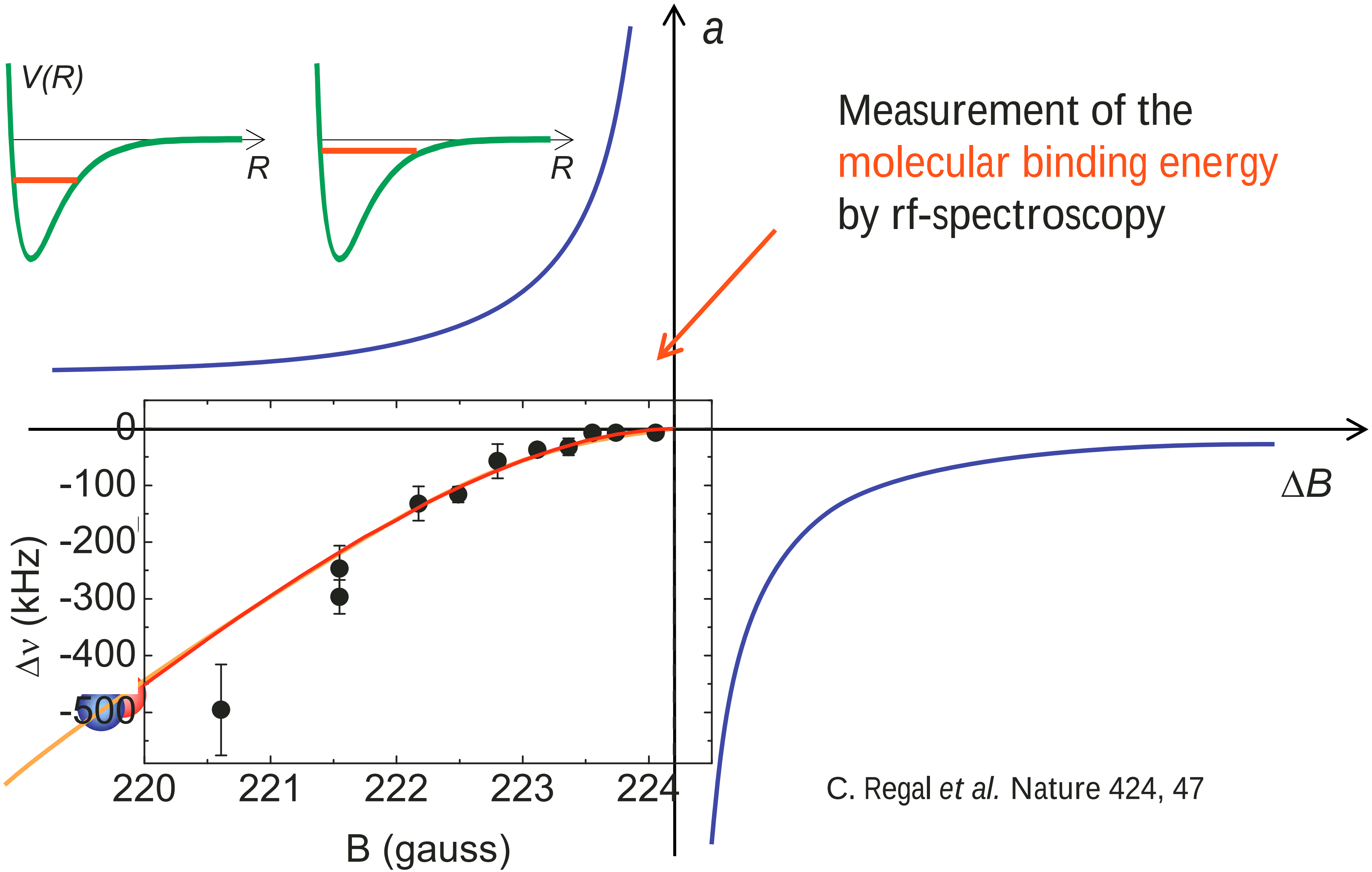
[6]Li: Hulet (Houston), Salomon (Paris) Grimm (Innsbruck), Ketterle (Boston)

Cs: Grimm (Innsbruck)

Rb: Rempe (Munich)

Na: Ketterle (Boston)

Molecule binding energy

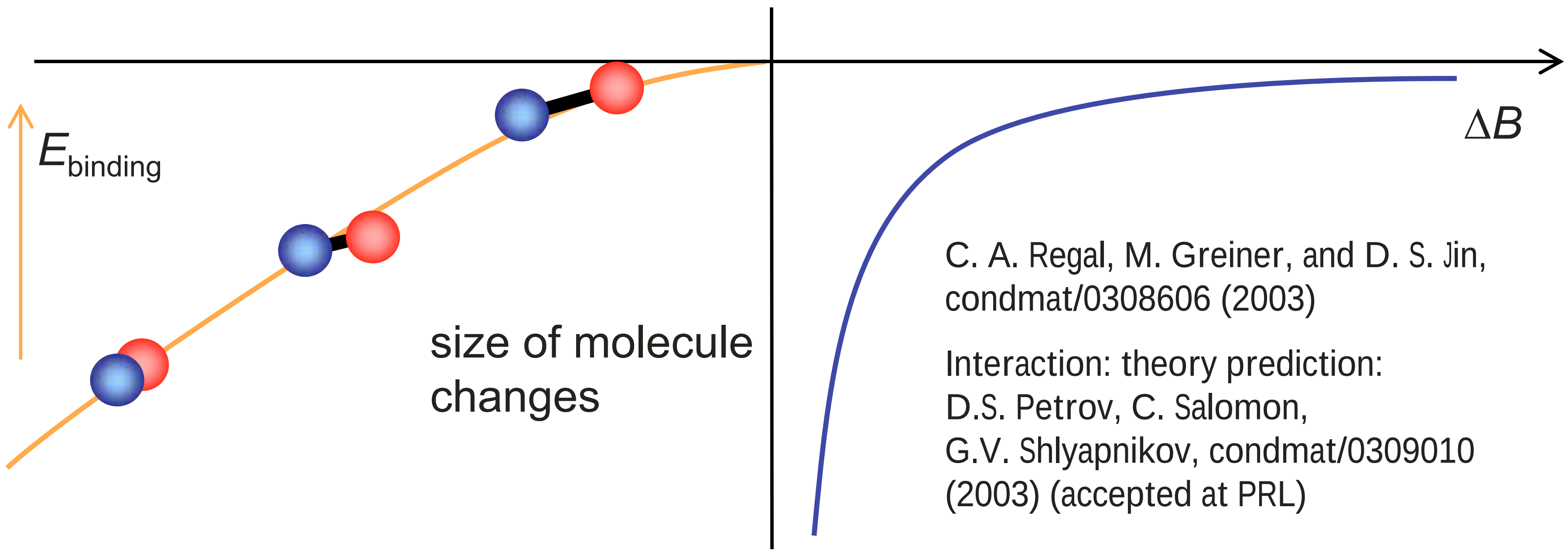


Measurement of the
molecular binding energy
by rf-spectroscopy

C. Regal *et al.* Nature 424, 47

Molecule properties

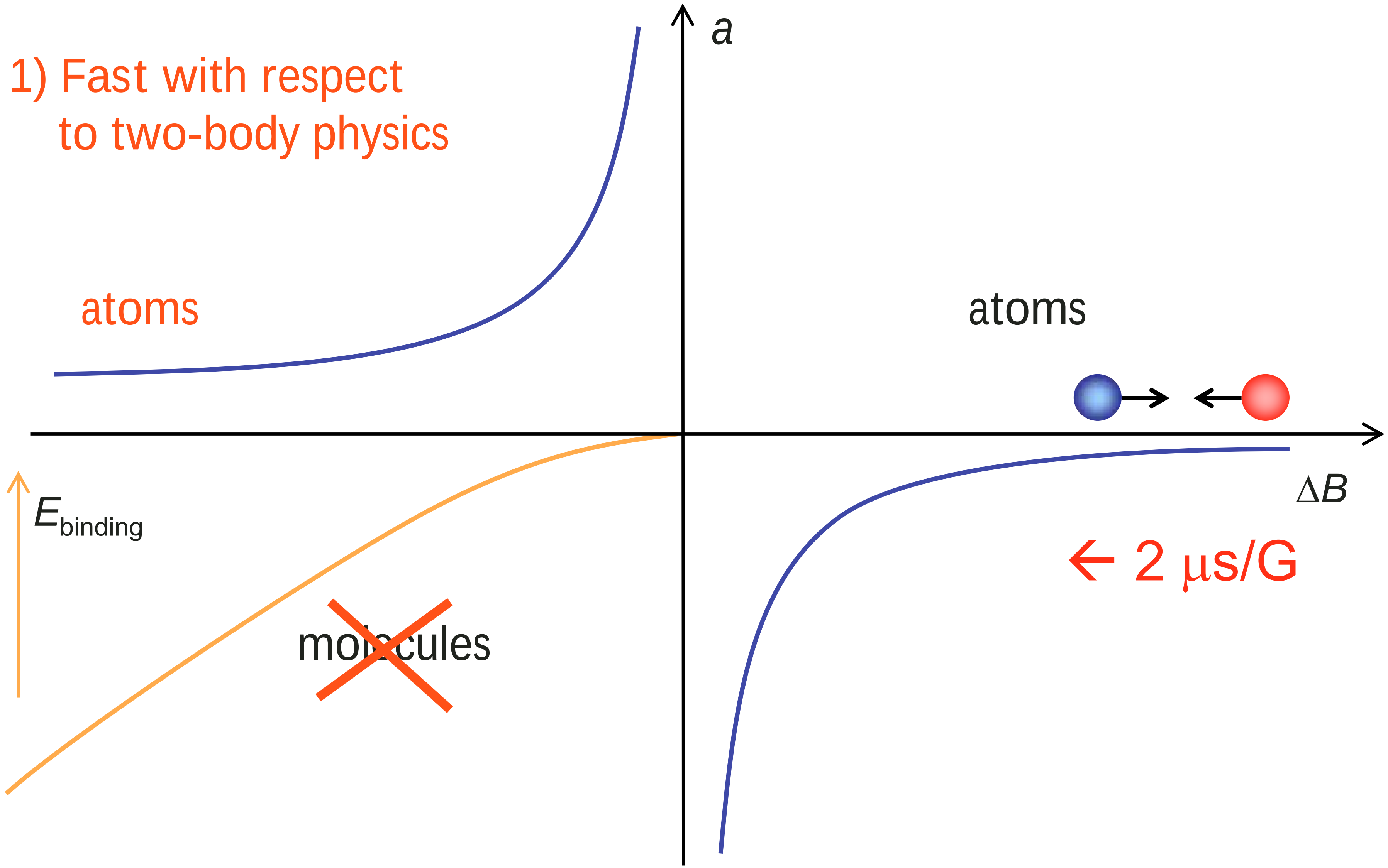
- extremely weakly bound
- large, molecule size ≈ a
- but: ridiculously stable close to Feshbach resonance



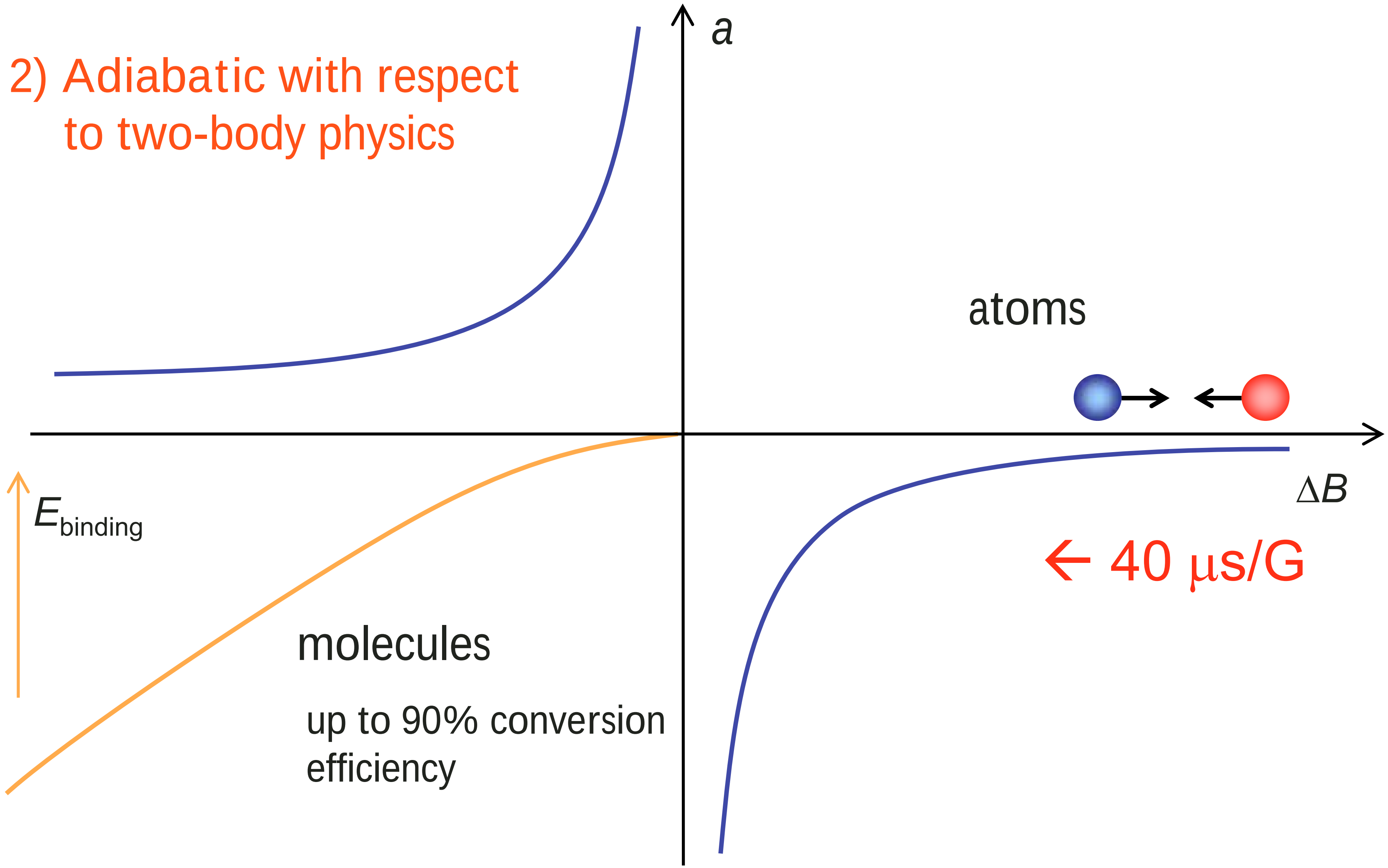
C. A. Regal, M. Greiner, and D. S. Jin, condmat/0308606 (2003)

Interaction: theory prediction: D.S. Petrov, C. Salomon, G.V. Shlyapnikov, condmat/0309010 (2003) (accepted at PRL)

Timescale of *B*-ramp

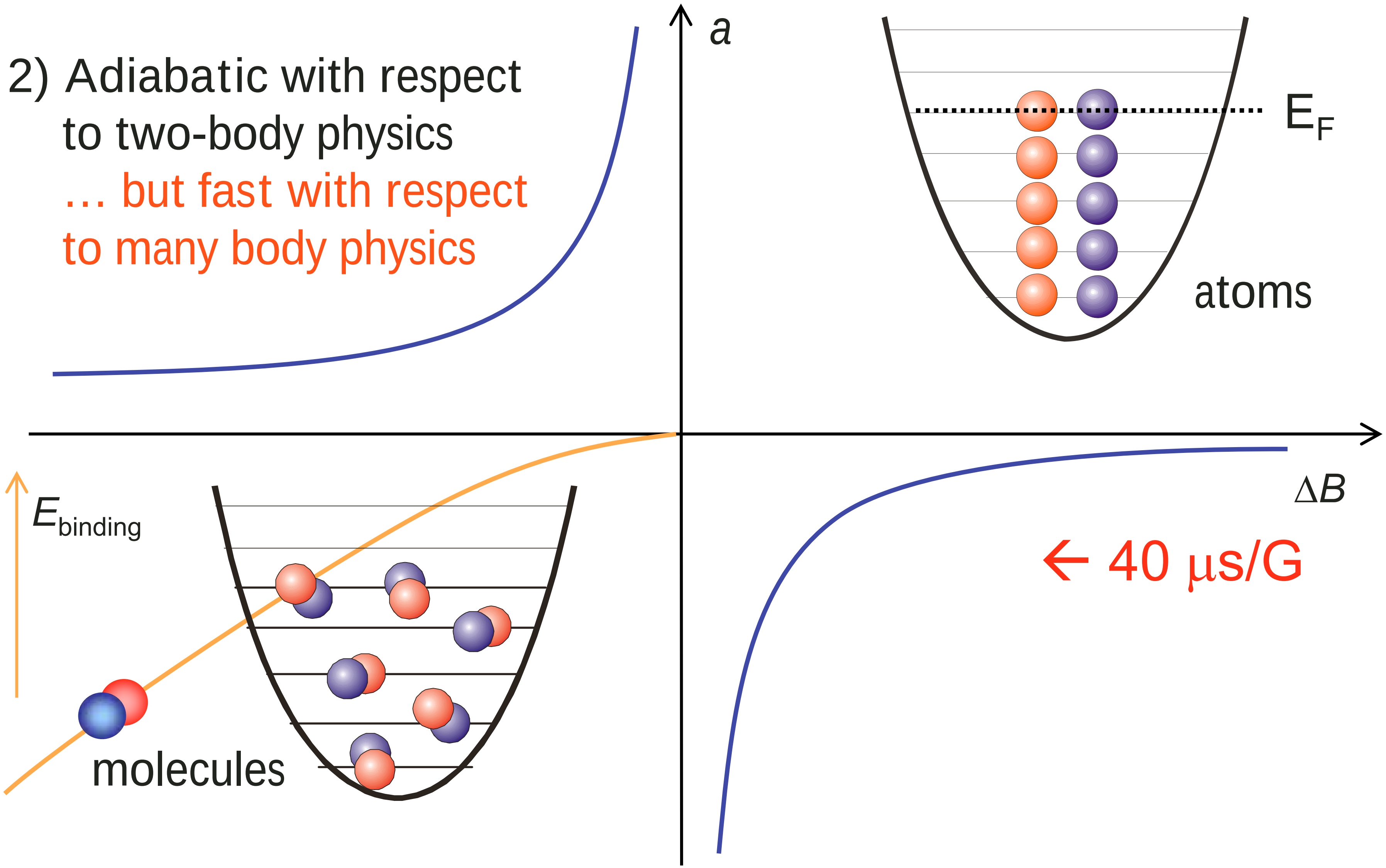


Timescale of *B*-ramp



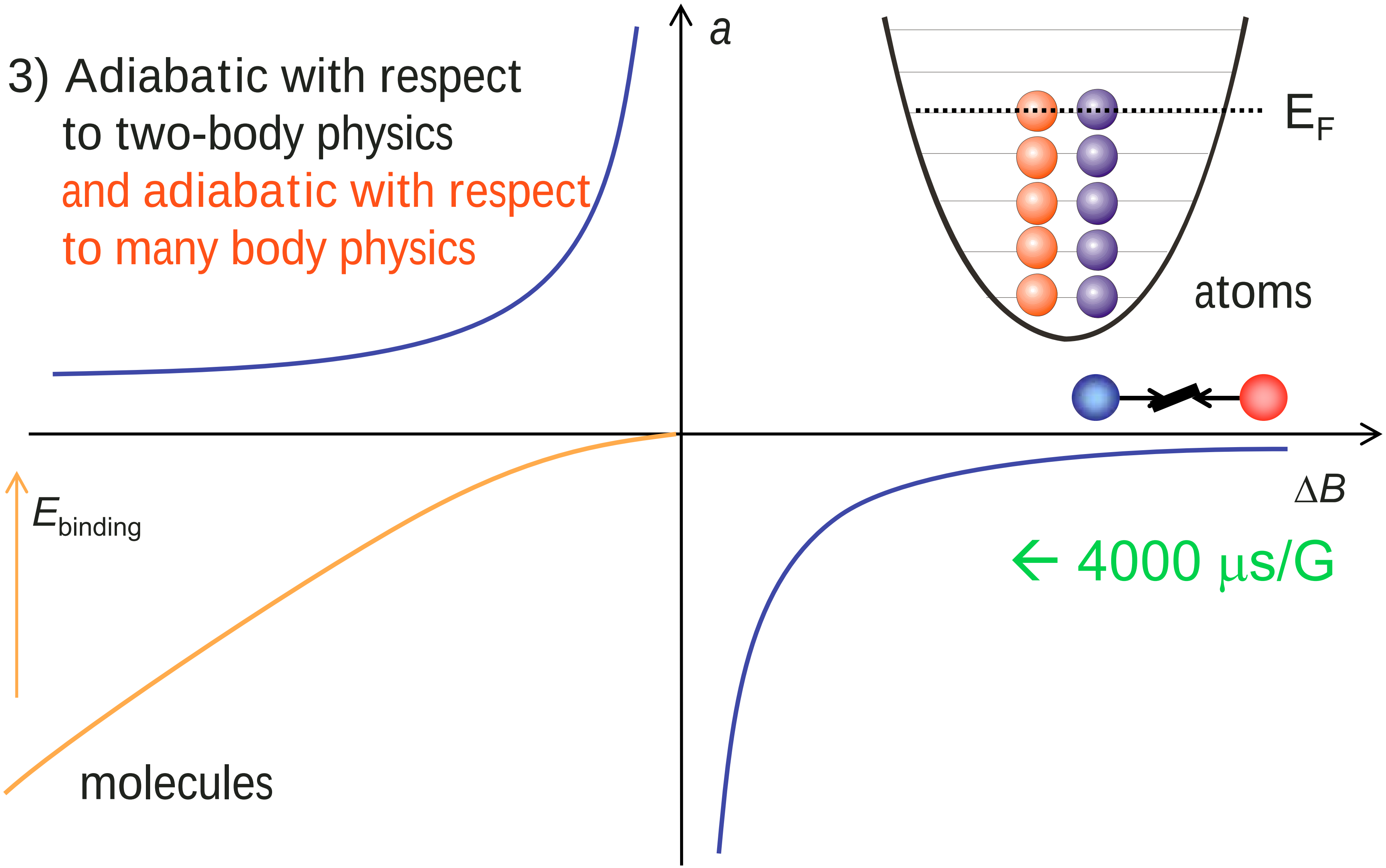
Timescale of *B*-ramp

2) Adiabatic with respect to two-body physics
… but fast with respect to many body physics



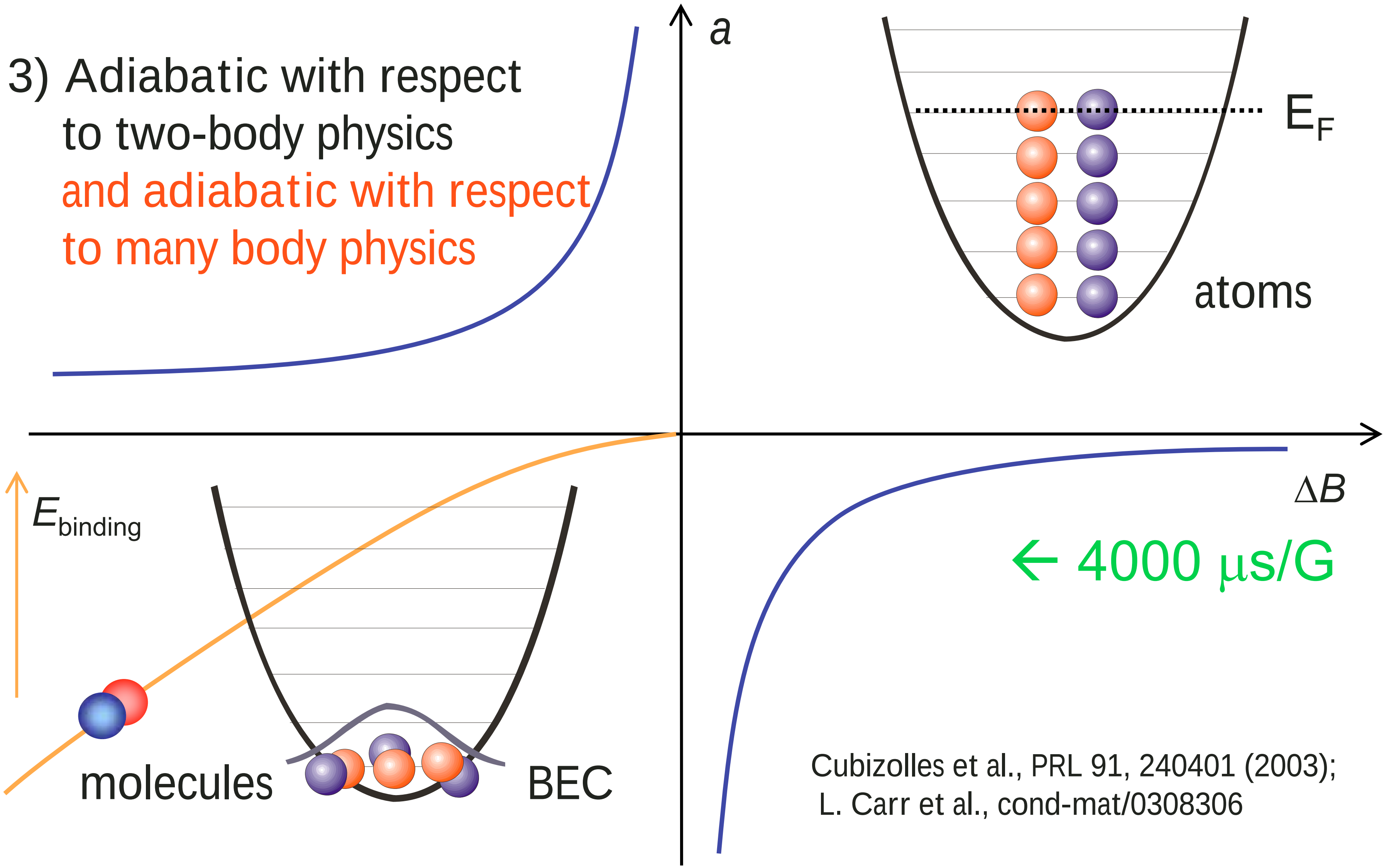
Timescale of *B*-ramp

3) Adiabatic with respect to two-body physics and adiabatic with respect to many body physics



Timescale of *B*-ramp

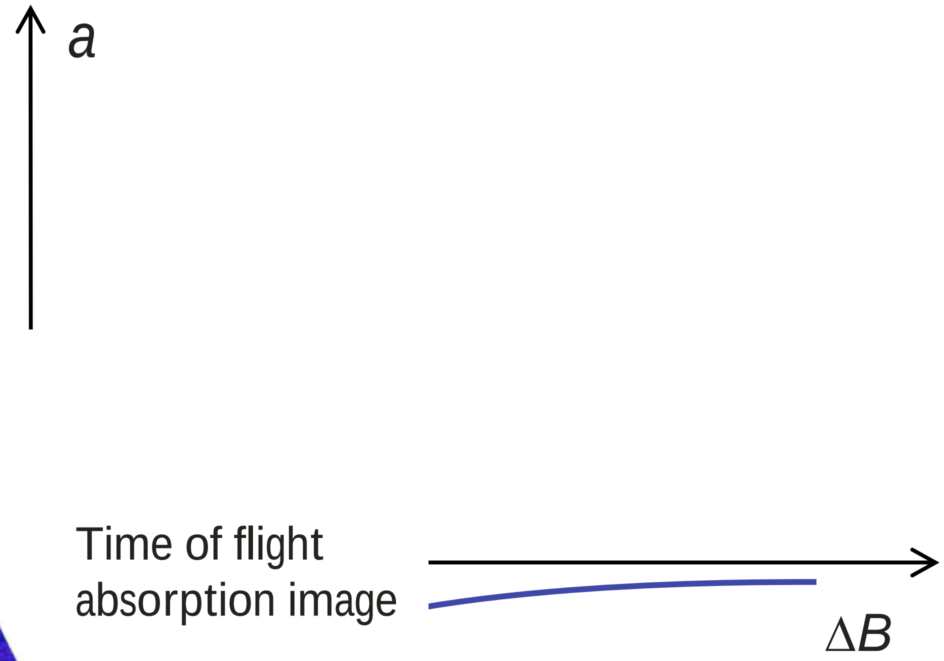
3) Adiabatic with respect
to two-body physics
and adiabatic with respect
to many body physics

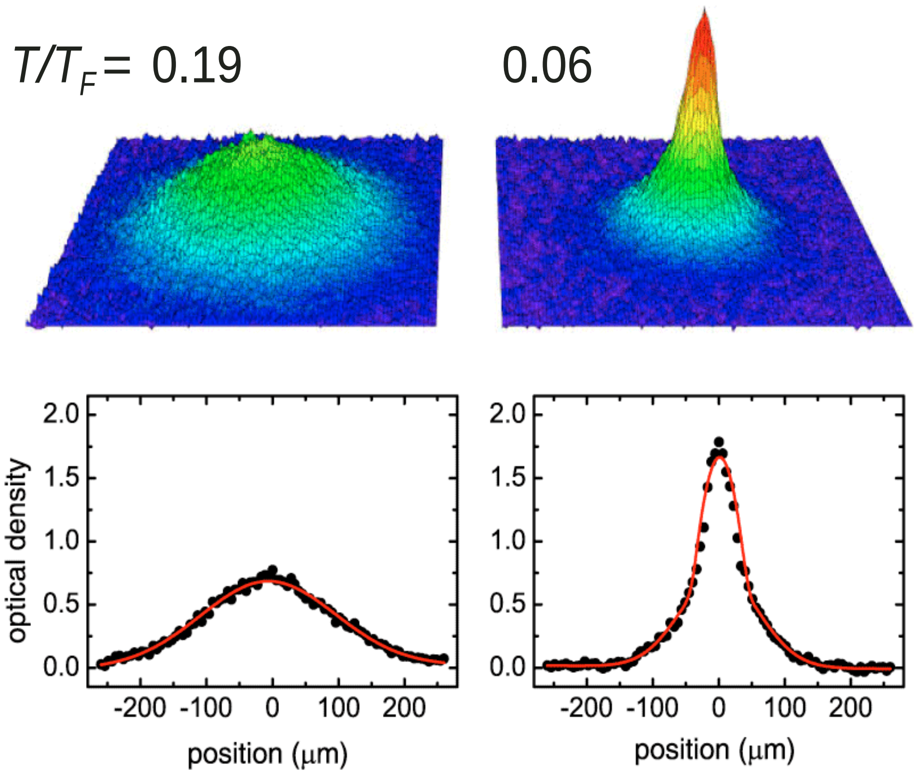


Cubizolles et al., PRL 91, 240401 (2003);
L. Carr et al., cond-mat/0308306

Molecular Bose-Einstein condensate

A molecular BEC
emerges from a
Fermi sea!





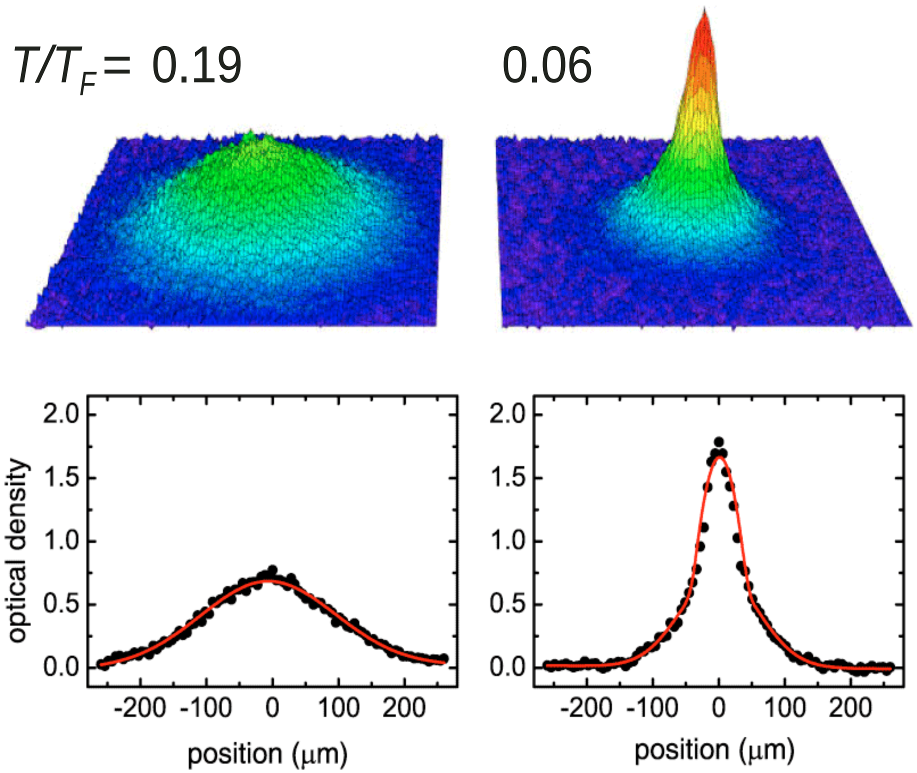
profile

M. Greiner, C. A. Regal, and D. S. Jin,
Nature 426, 537 (2003)

[6]Li:
Jochim *et al*., *Science* 302: 2101(2003),
M. Zwierlein *et al*.,
Phys. Rev. Lett. 91, 250401 (2003).
T. Bourdel *et al.*, cond-mat/0403091

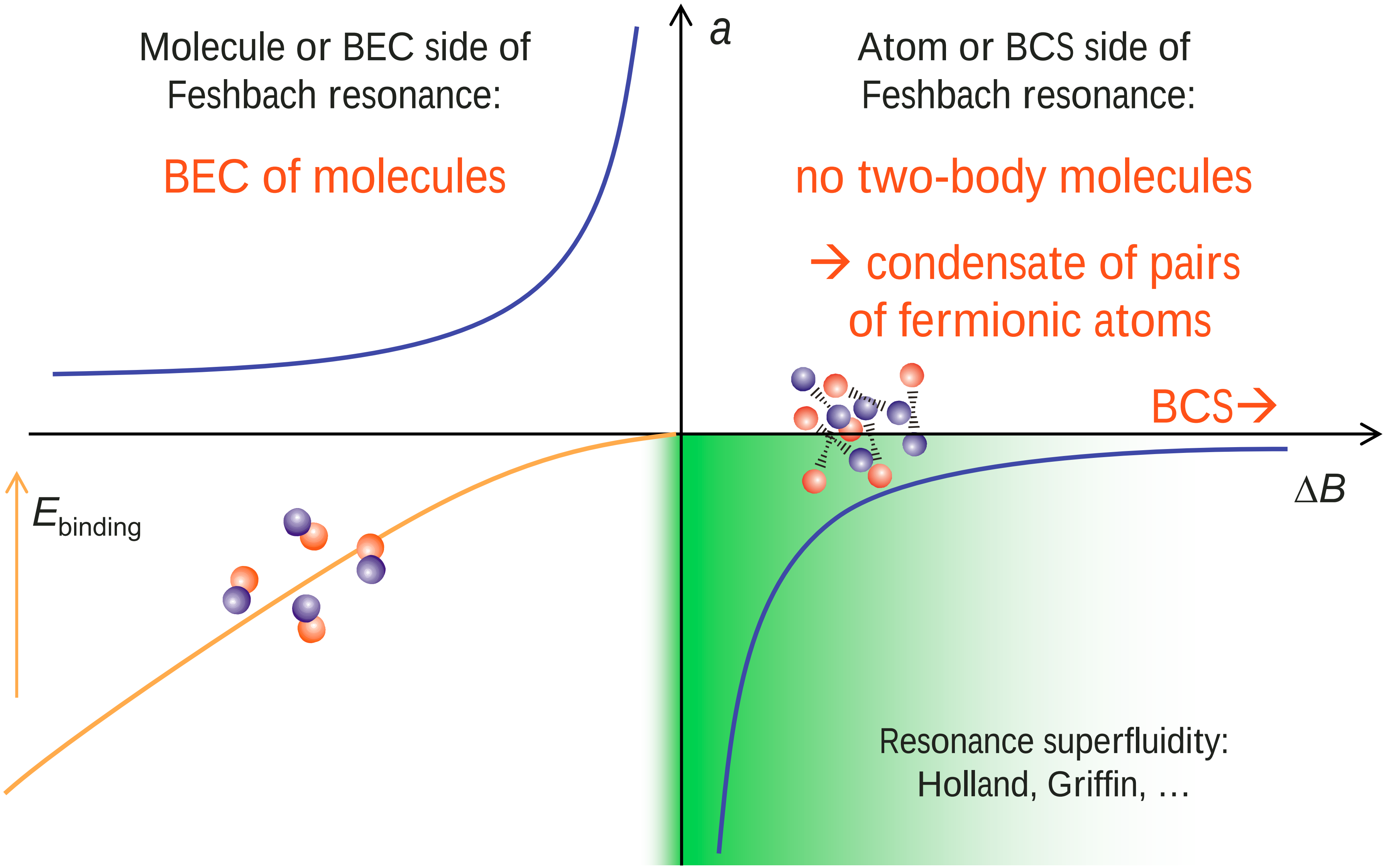
Molecular Bose-Einstein condensate

A molecular BEC
emerges from a
Fermi sea!

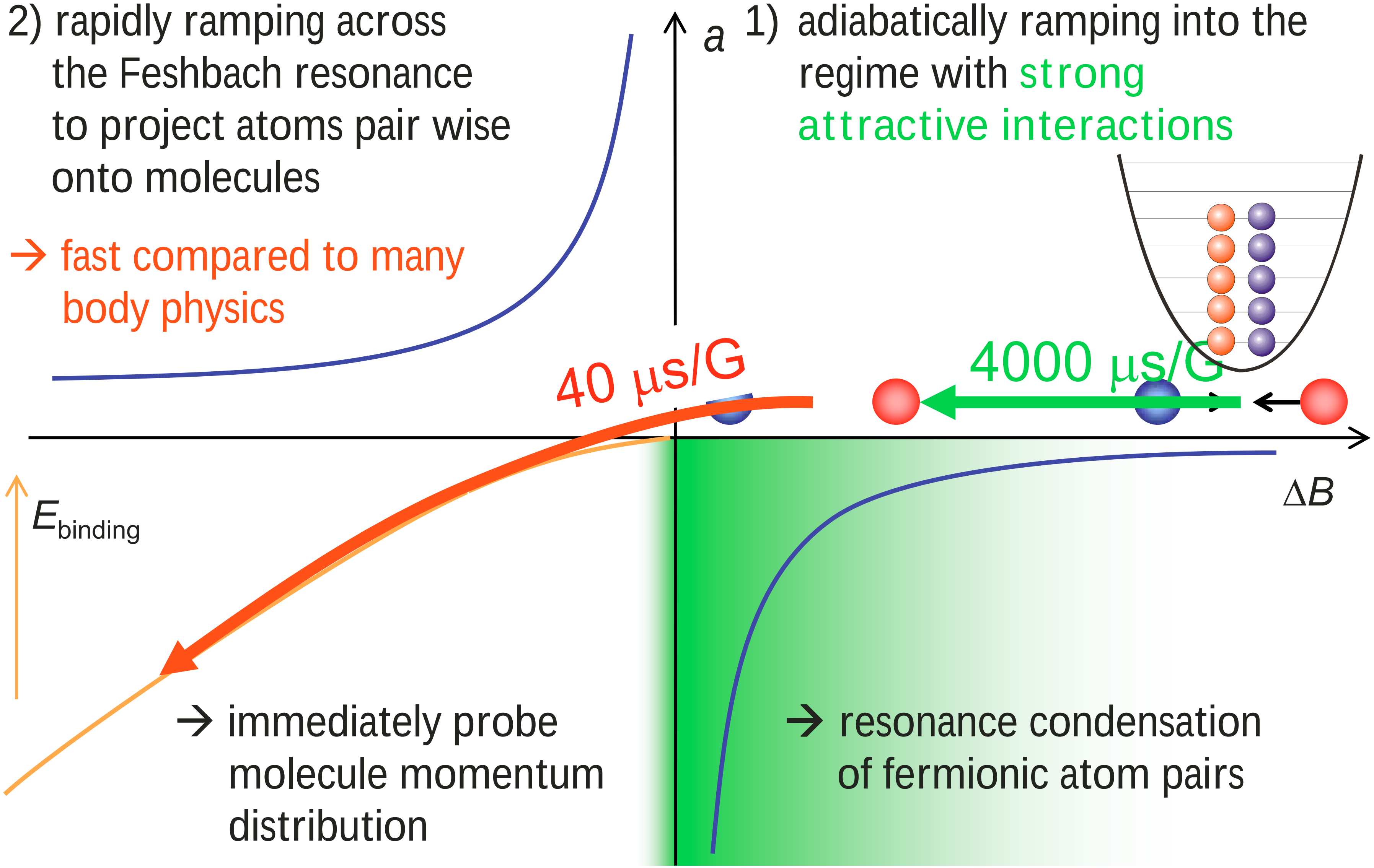


→ timescale for many-body adiabaticity is 100x slower than for two-body adiabaticity

Condensation of pairs of fermionic atoms

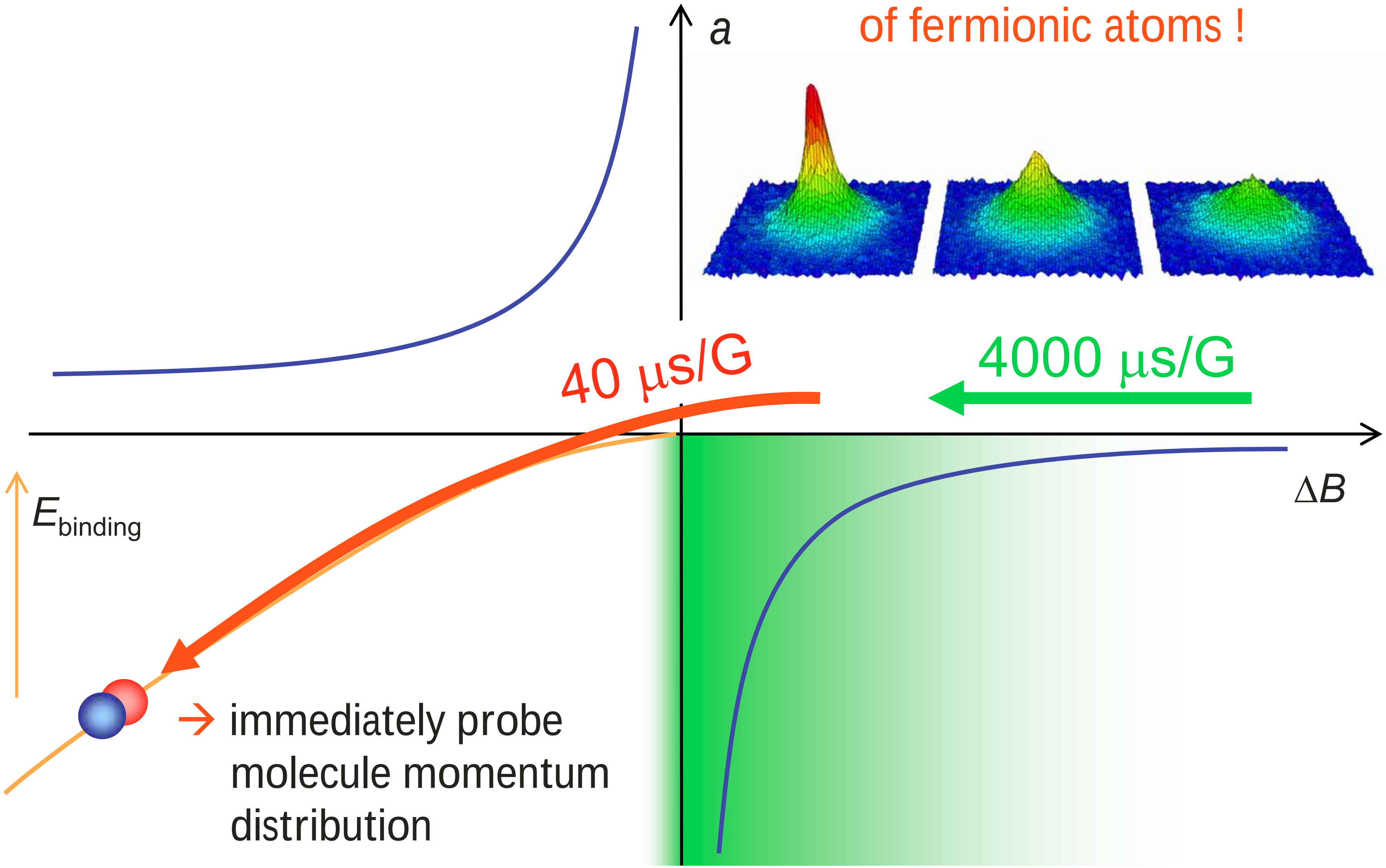


Detecting a Fermi condensate

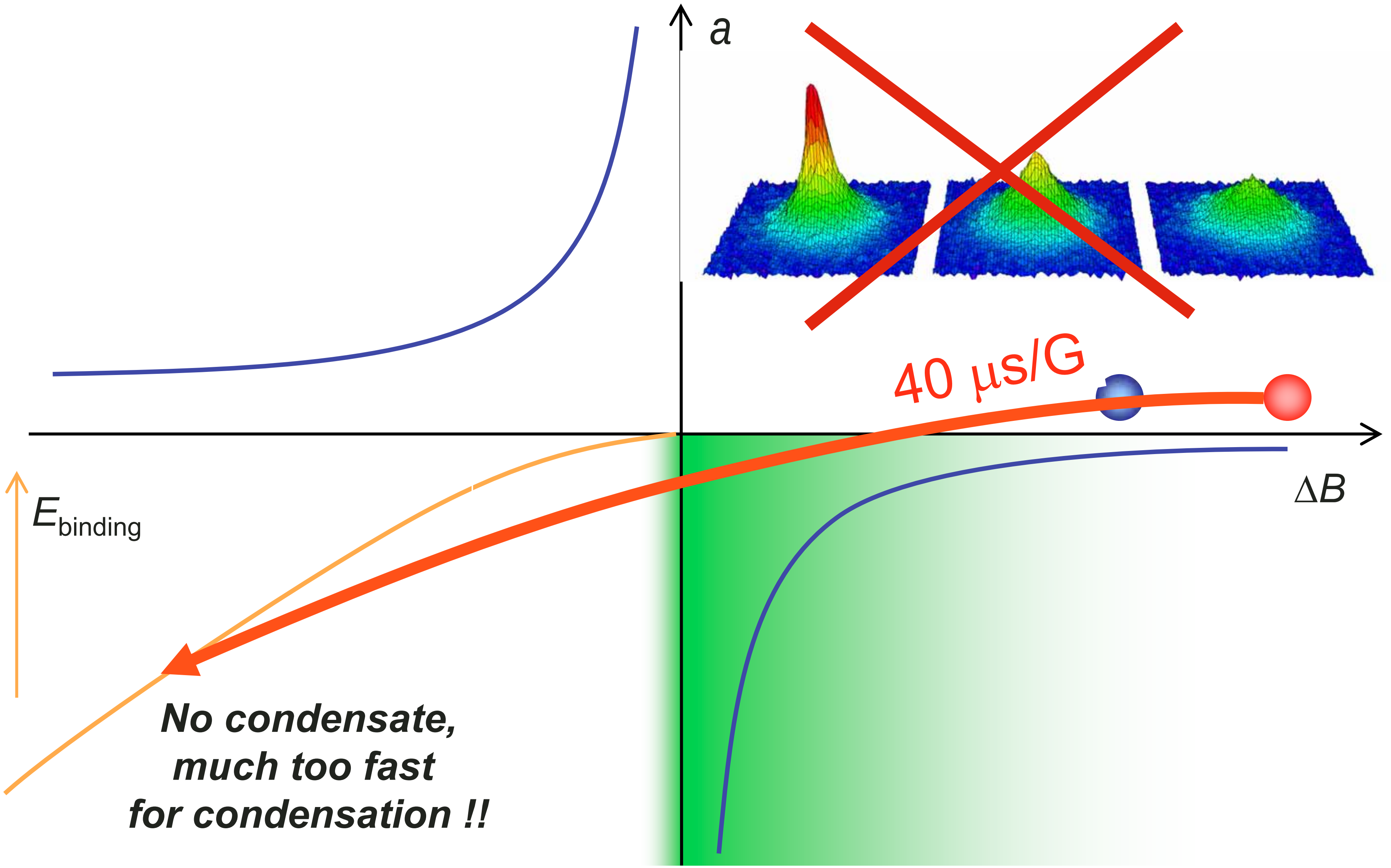


Detecting a Fermi condensate

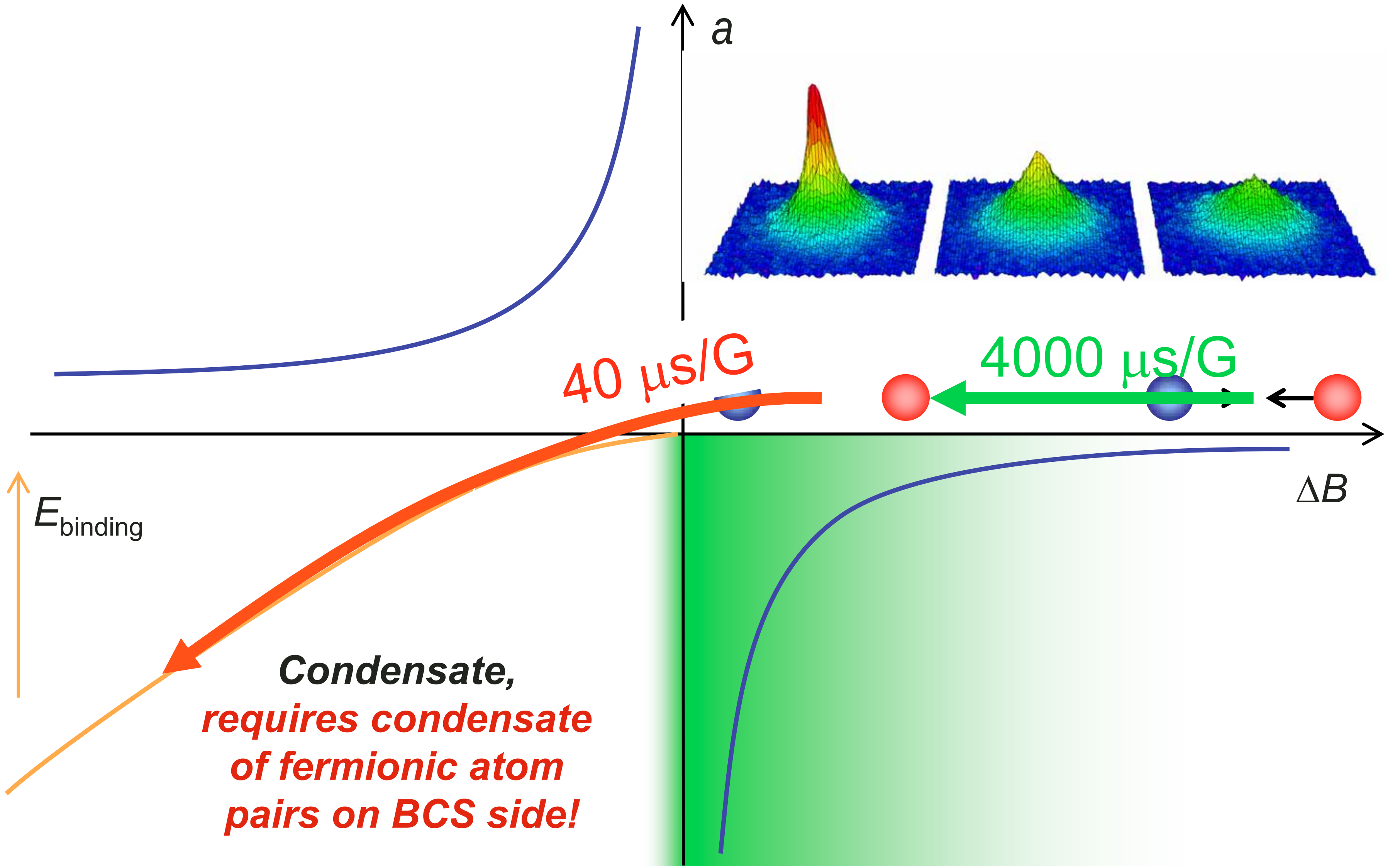
condensate of pairs
of fermionic atoms !



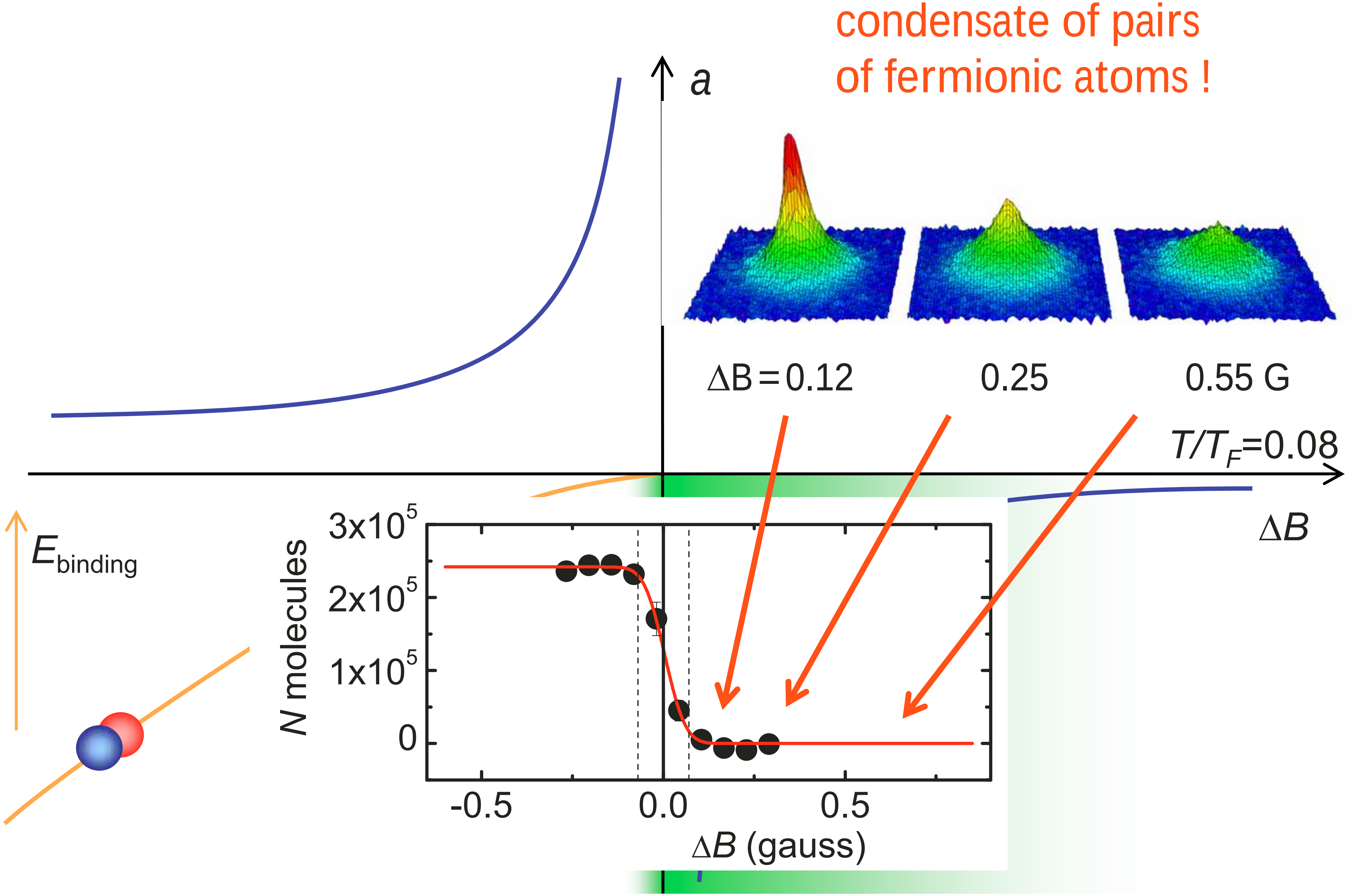
Detecting a Fermi condensate



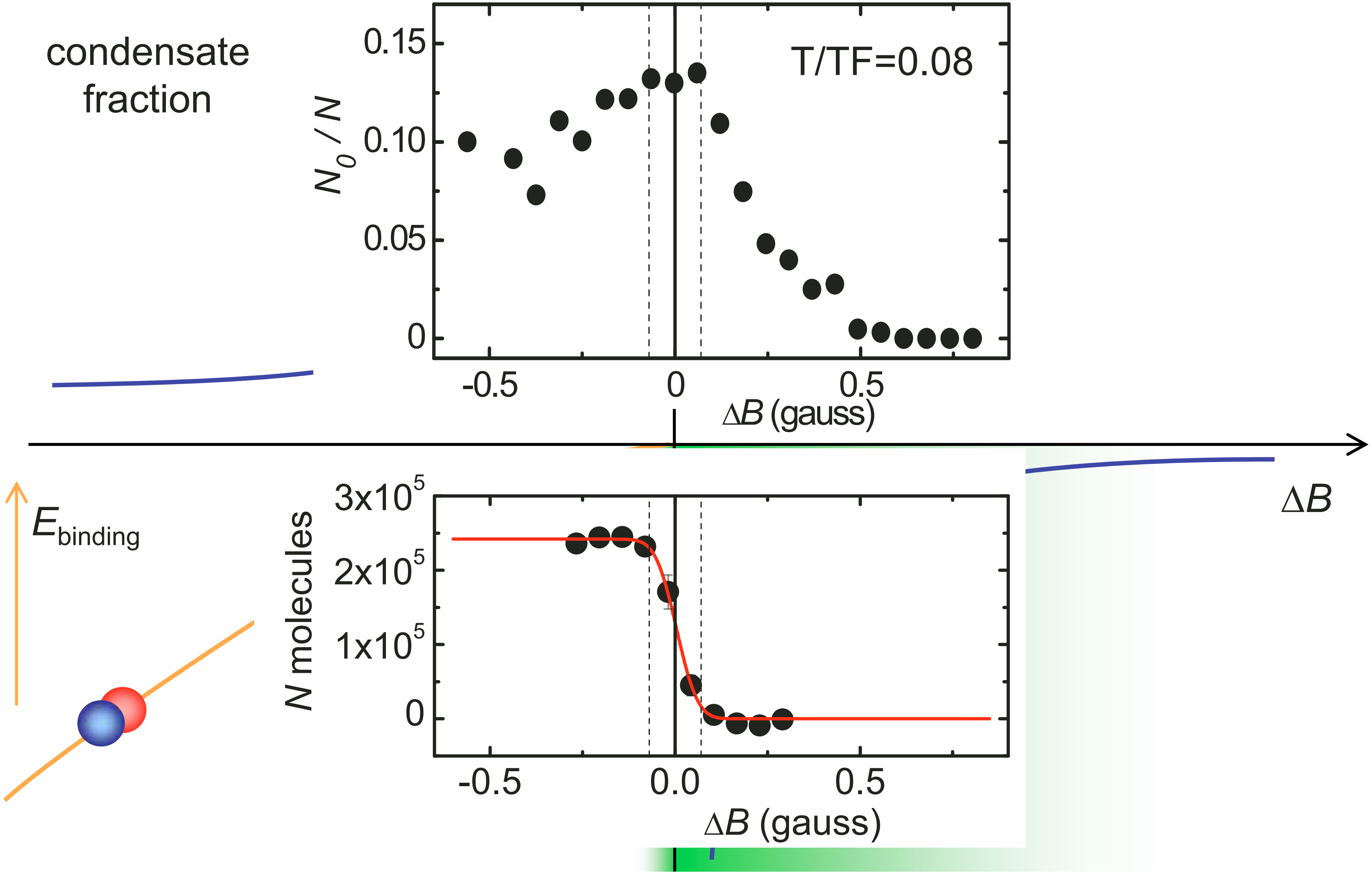
Detecting a Fermi condensate



Fermionic condensate

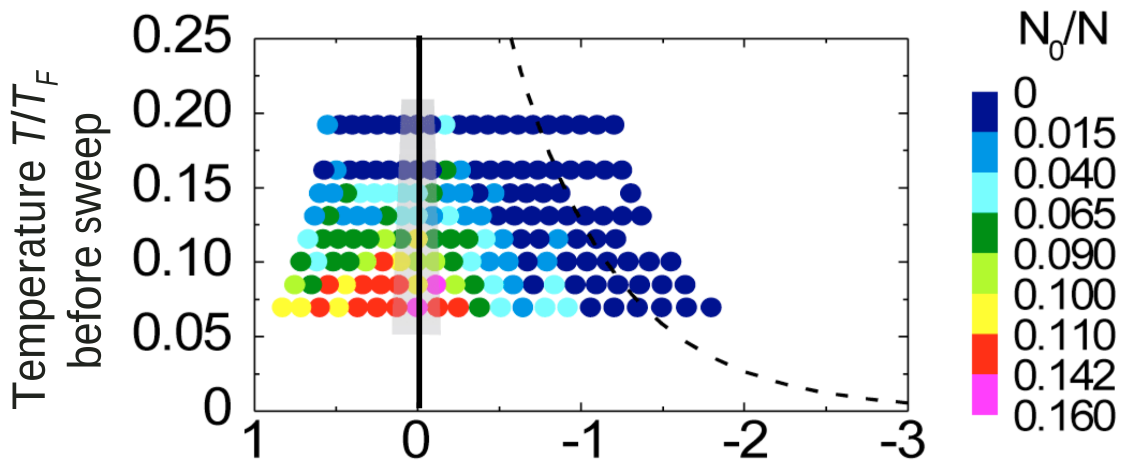


Fermionic condensate



BCS-BEC crossover

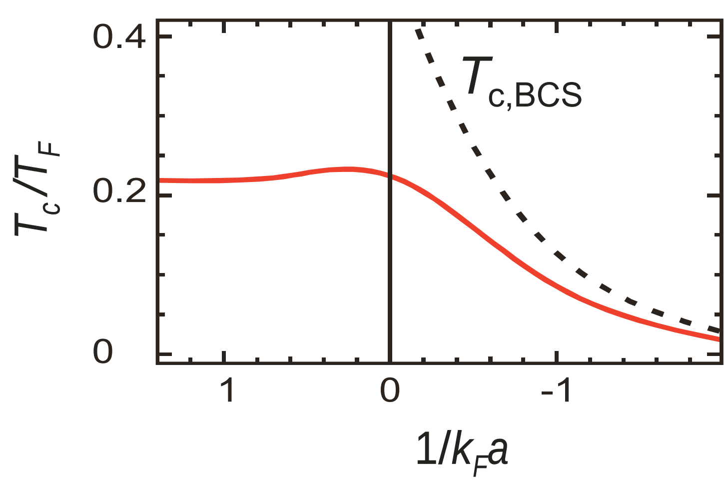
BEC
of
molecules



inverse interaction strength $1/(k_F a)$
→ *universal parameter*

BCS
of
Cooper pairs

Figure:
M. Randeria



$$T_{c,BCS} \approx e^{-\frac{\pi}{2k_F|a|}}$$

BEC-BCS crossover theory for example:
Eagles, Leggett, Nozieres *et al.*, Randeria, Holland *et al.*, Timmermans *et al.*, Ohashi *et al.*, Stajic *et al.* …

BCS-BEC crossover

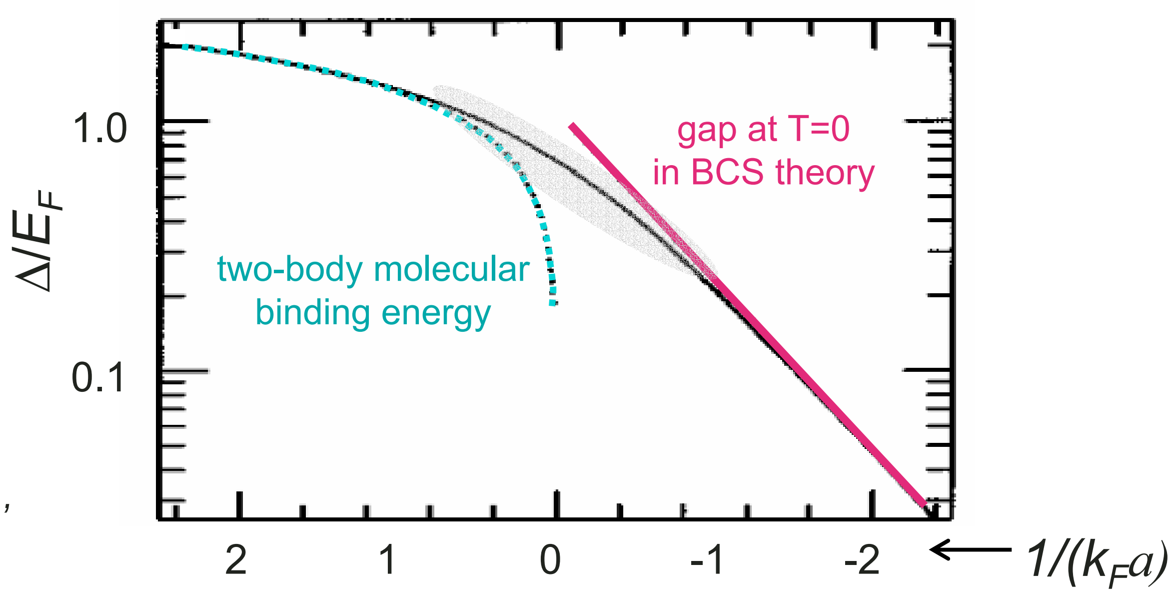
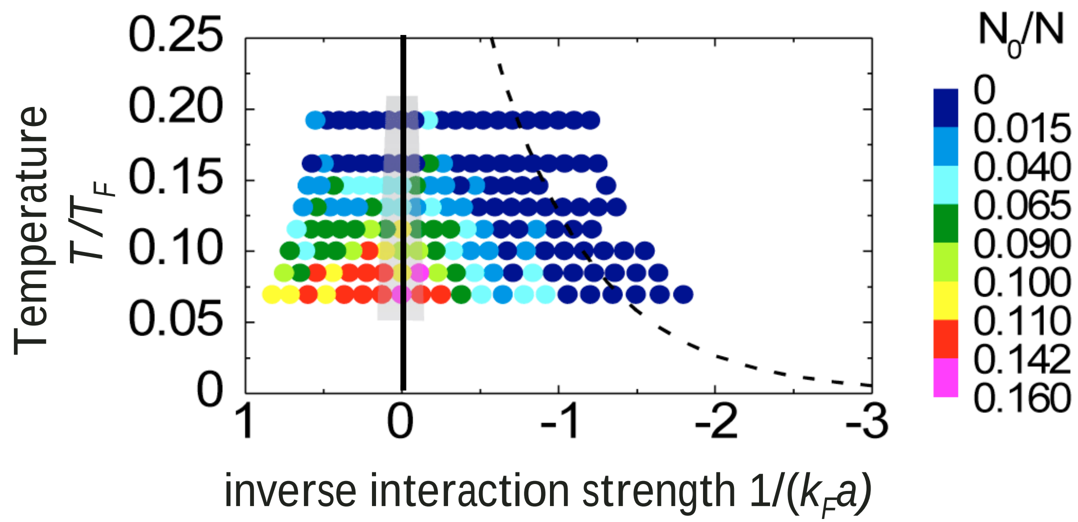
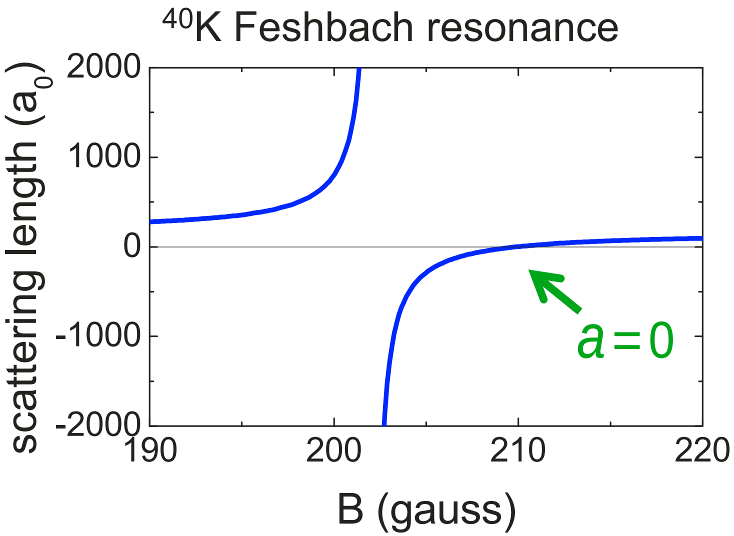


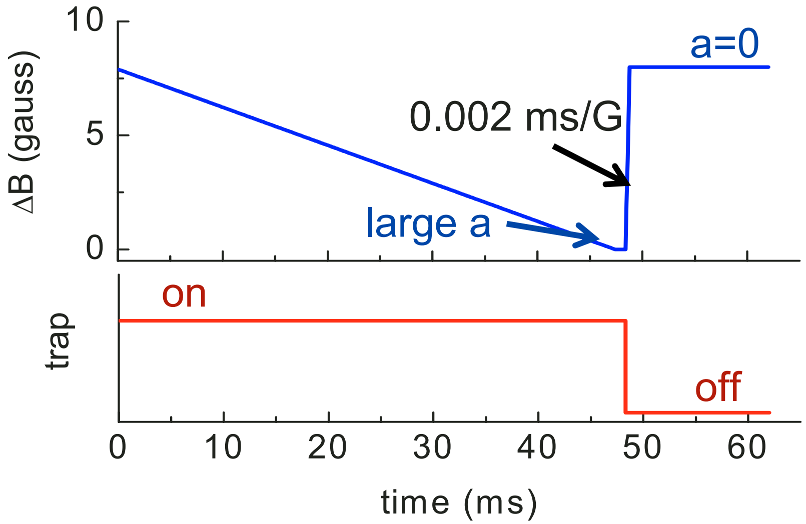
Figure: J. R. Engelbrecht *et al.*, PRB 55, 15153 (1997)



Probing atom momentum distribution

rapidly switching off interactions before TOF expansion:
→ pairs dissociate, momentum distribution of fermions is measured

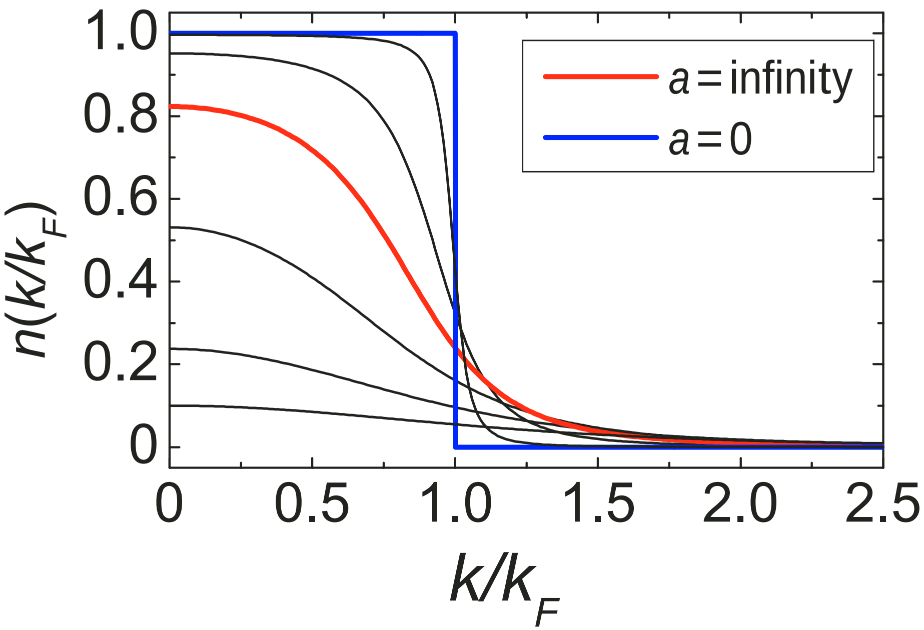




BCS-BEC crossover theory

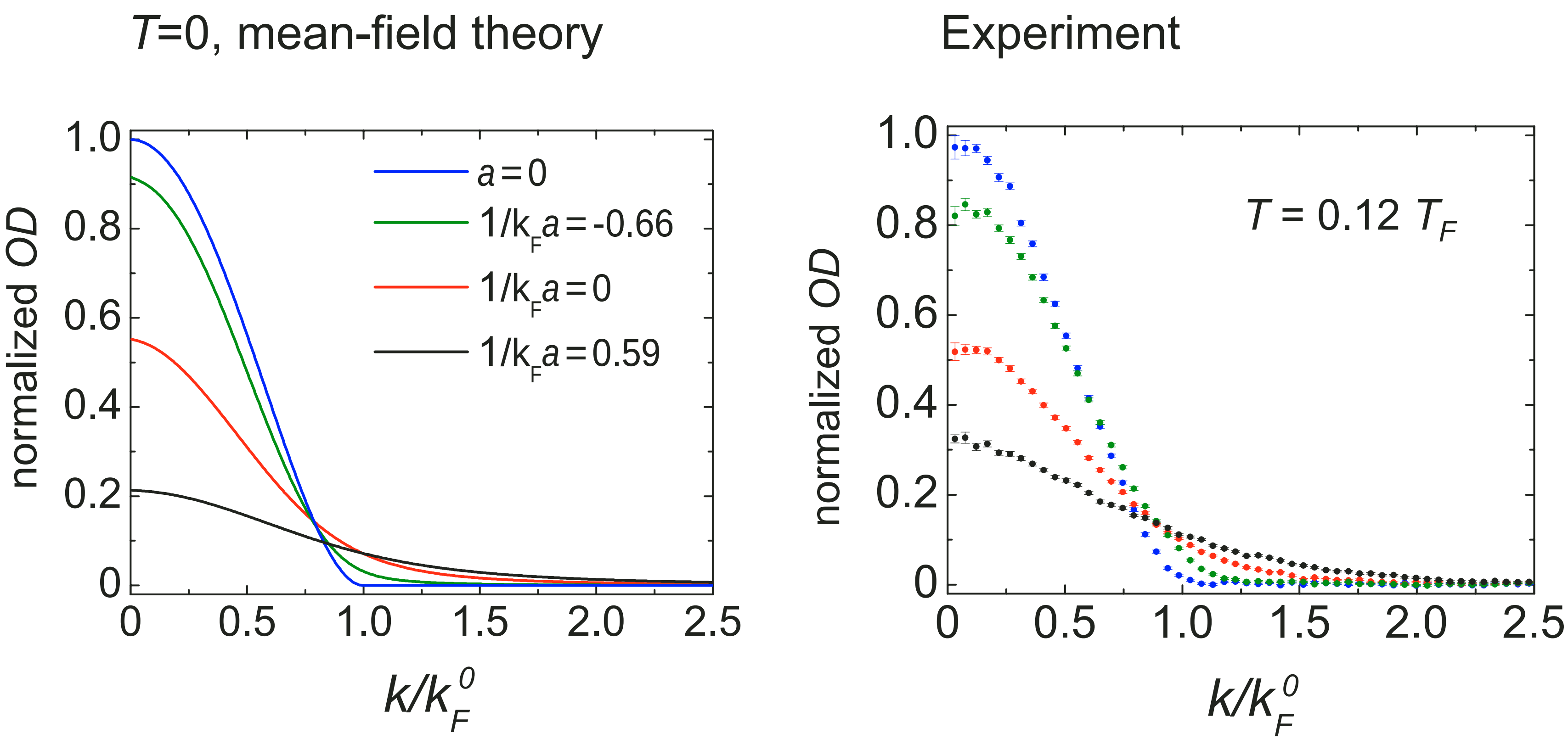
Homogeneous gas, T=0:

Momentum distribution broadens because of pairing



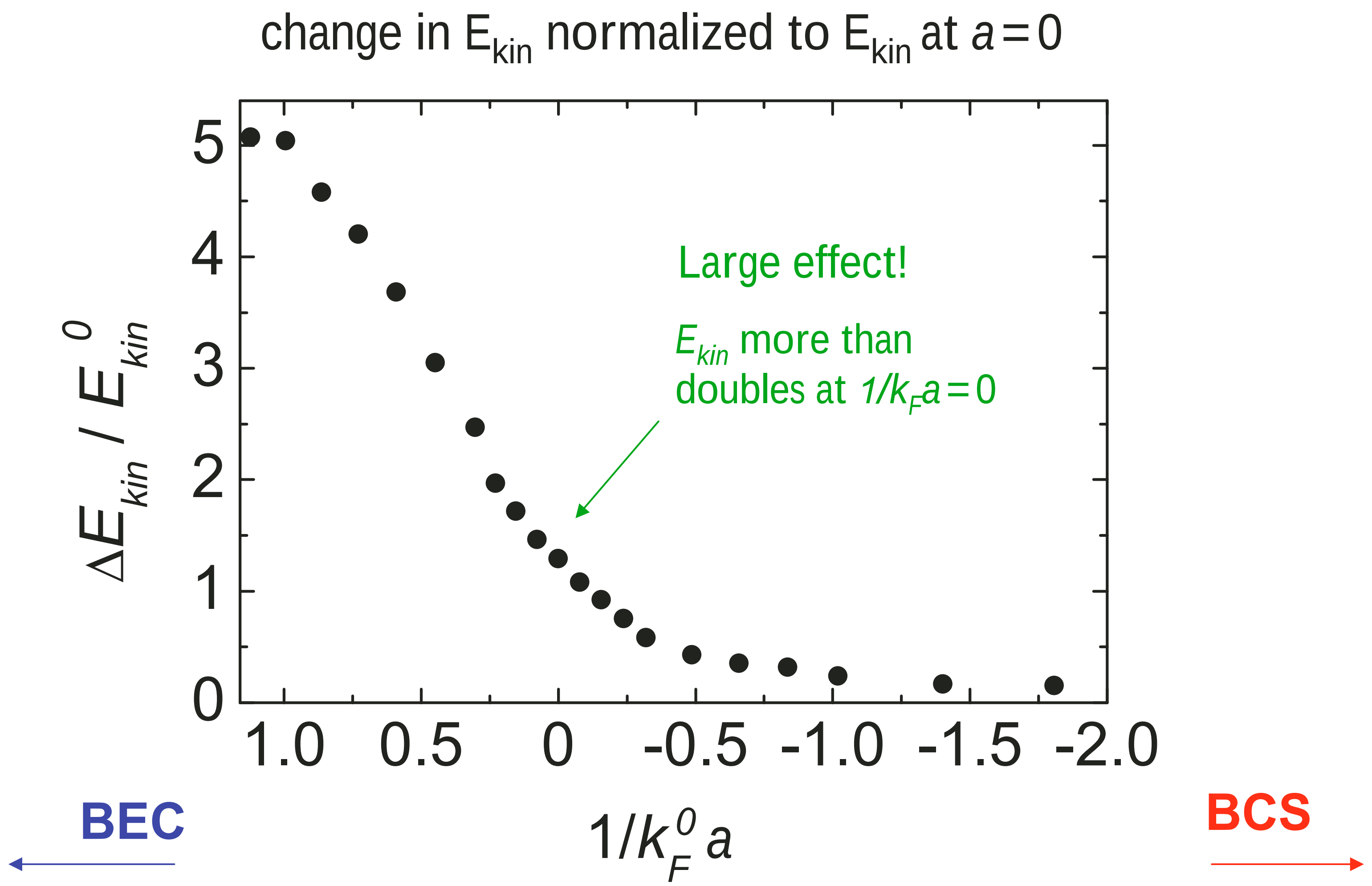
M. Marini, F. Pistolesi, G. C. Strinati, Euro. Phys. J. B 1, 151 (1998)

Momentum distributions of trapped gas

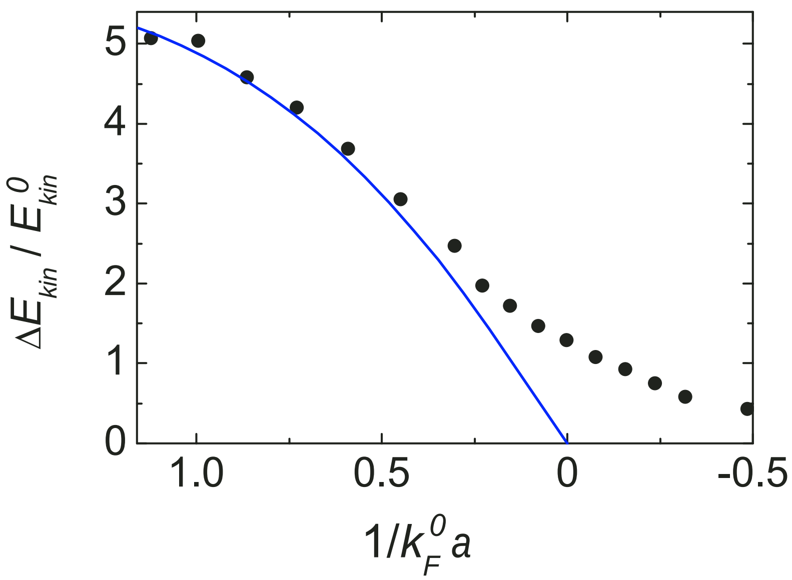


L. Viverit, S. Giorgini, L.P. Pitaevskii and S. Stringari, PRA 69, 013607 (2004)

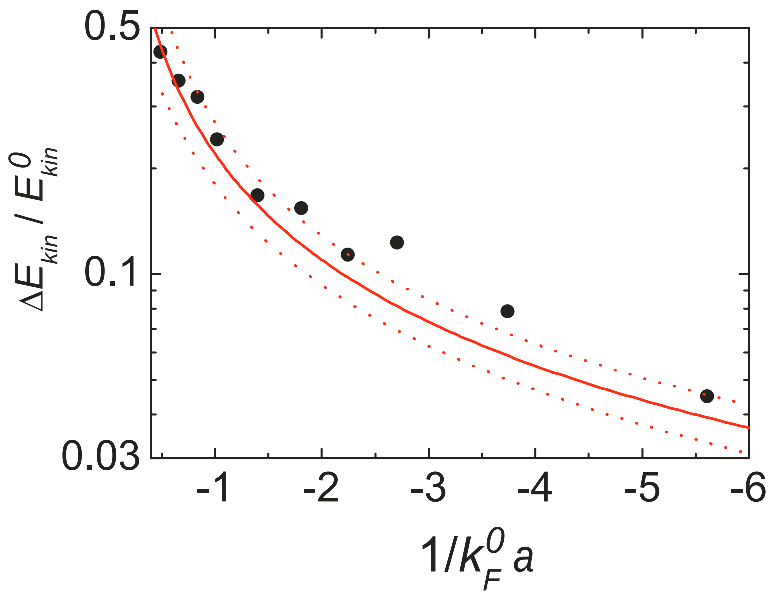
Kinetic energy



Two limits: exact theories



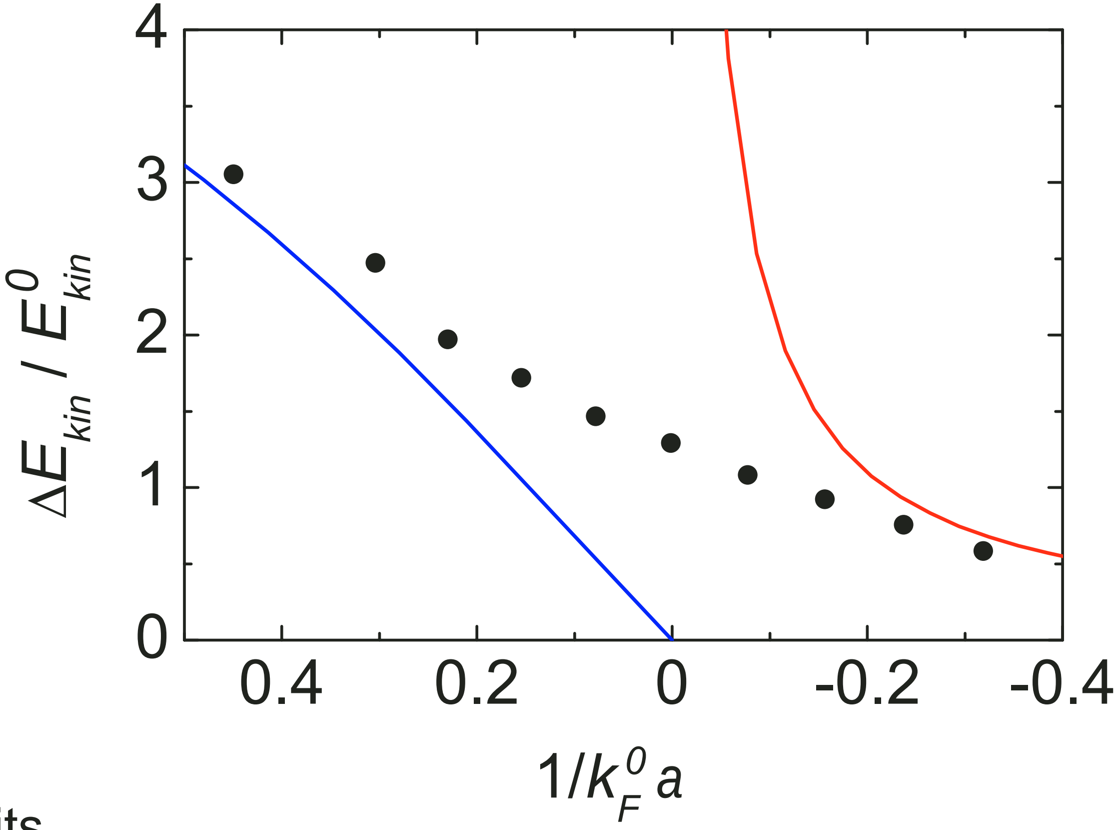
Time-evolve wavefunction
of isolated molecule



Calculate change due to
weak attractive interactions
in the normal state

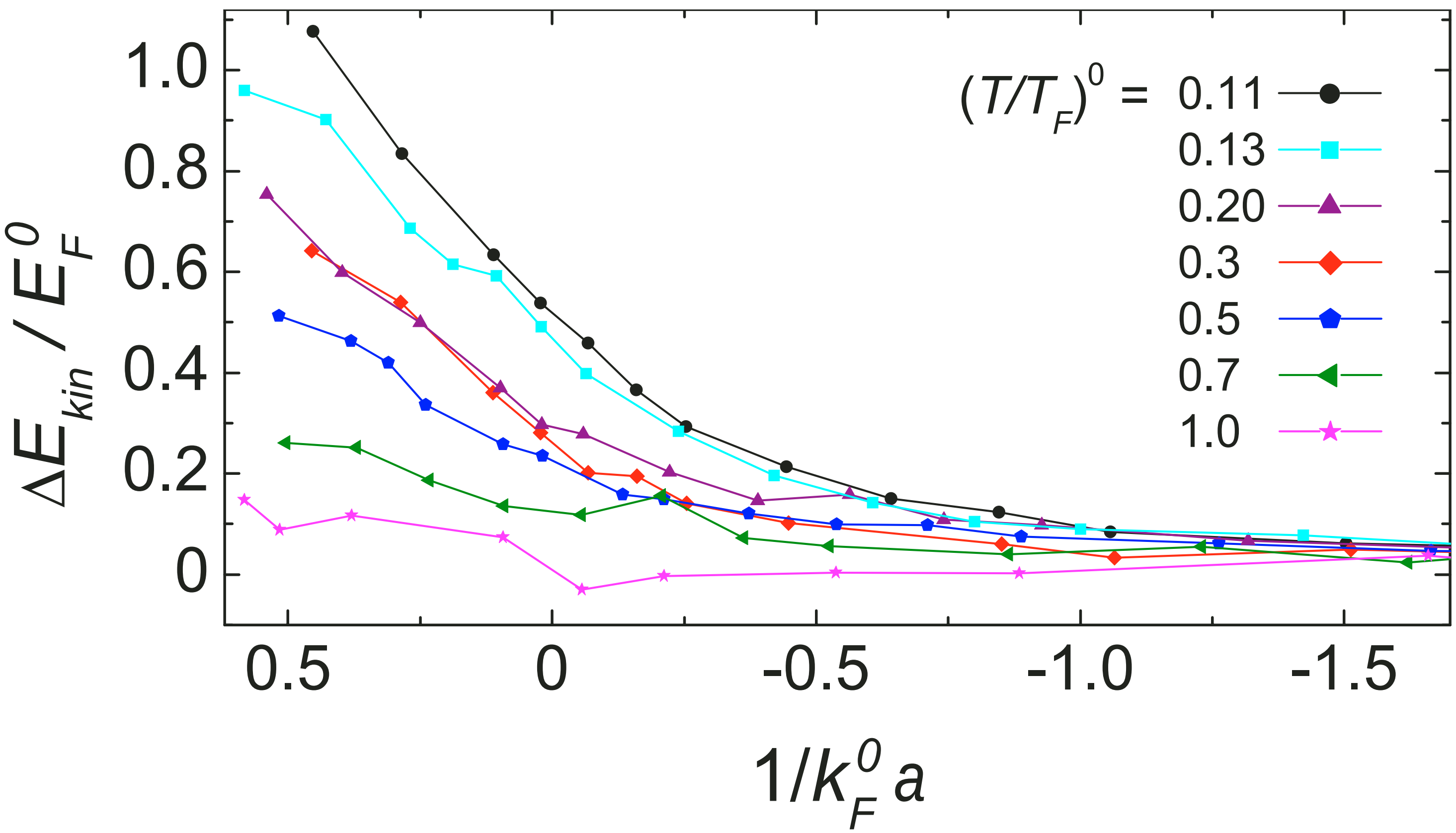
Theory: Murray Holland and Stefano Giorgini

In between



- Neither theory fits
- probe of pairing in crossover
- future goal: compare to full crossover theory

Varying T/T_F



- T_F is roughly constant but n changes

Thanks:

Deborah Jin
Cindy Regal

Jayson Stewart

… I am starting a research group this summer,

***PhD students** and **postdocs** welcome …*

Markus Greiner
Deborah Jin Cindy Regal

ICTP School on Quantum Phase Transitions and
Non-Equilibrium Phenomena in Cold Atomic Gases 2005

Correlations in atom shot noise

Markus Greiner

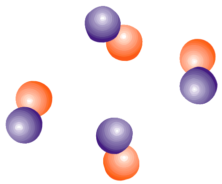
JILA, Group of D. Jin;
Coworkers: C. Regal and J. Stewart
NIST and the University of Colorado, Boulder

Detecting atom-atom correlations

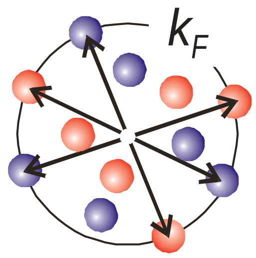
New experimental systems show interesting atom-atom correlations:

- atom pair correlations:

spatial:
molecules

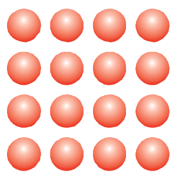


in momentum space:
Cooper pairs

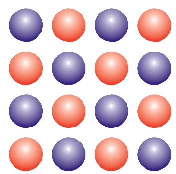


- in lattices:

Mott insulator:



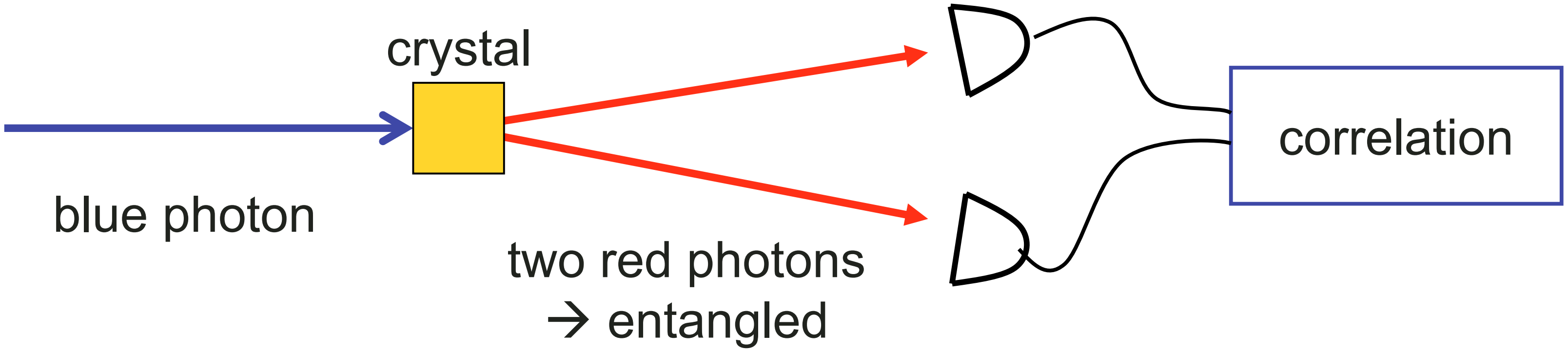
Anti-ferromagnetic
phases:



- presently only the overall density distribution is measured
  in time-of-flight absorption imaging
  → no information about atom-atom correlations

Photon pair detection in quantum optics

Parametric down conversion:



practically all experiments detecting non-classical states of light are based on the detection of photon-photon correlations

… papers too good to be published … ;-)

Proposal on the detection of correlations in atom shot noise
by Ehud Altman *et al.*, PRA 70, 013603

Probing many-body states of ultra-cold atoms via noise correlations

Ehud Altman, Eugene Demler, and Mikhail D.Lukin
Physics Department, Harvard University, Cambridge, MA 02138
(Dated: June 9, 2003)

We propose to utilize density-density correlations in the image of an expanding gas cloud to probe complex many body states of trapped ultra-cold atoms. In particular we show how this technique can be used to detect superfluidity of fermionic gases and reveal broken spin symmetries in Mott-states of atoms in optical lattices. The feasibility of the method is investigated by analysis of the relevant signal to noise ratio including experimental imperfections.

Much of the excitement in the field of Bose-Einstein condensation owes to the clear demonstration it provides of the wave character of matter. The condensed state of bosons involves macroscopic occupation of a delocalized single particle state. Consequently, it is characterized by sharp density peaks in the freely expanding gas cloud after it is released from the trap[1]. Patterns that appear when two or more superfluid clouds interfere[2], are a direct probe of the single particle coherence, amplified by macroscopic occupation.

Recent experiments open intriguing directions for studying many body phenomena beyond single particle coherence. For example, observation of the superfluid to Mott insulator transition [3], as well as experiments in-…

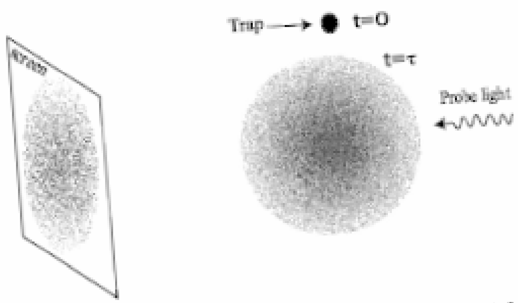
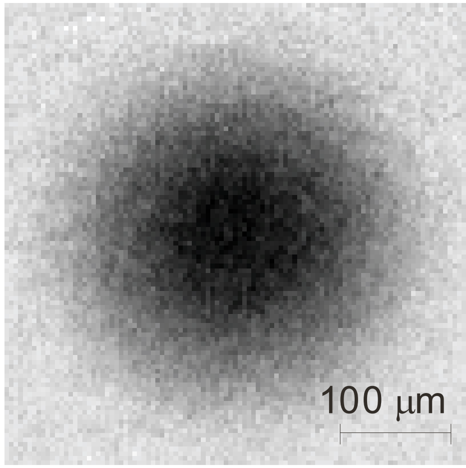


FIG. 1: Time of flight imaging. The atoms are released from the confining potential at time $t = 0$ and the density of the expanding cloud is imaged at a later time. Spatial noise correlations in this image can be used to probe the quantum state at $t = 0$.

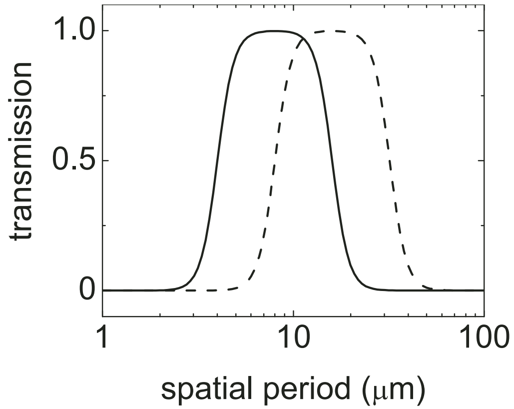
Atom shot-noise limited imaging

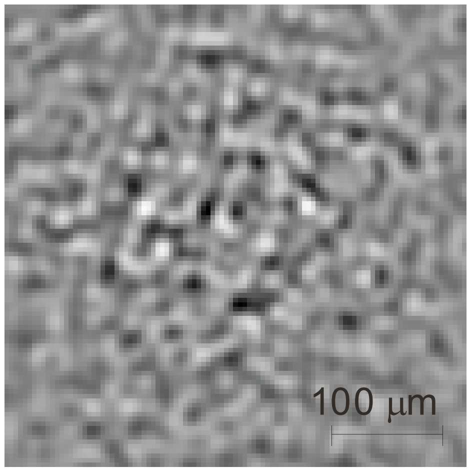
→ proposed by E. Altman, E. Demler, and M.D.Lukin, PRA 70, 013603 (2004)

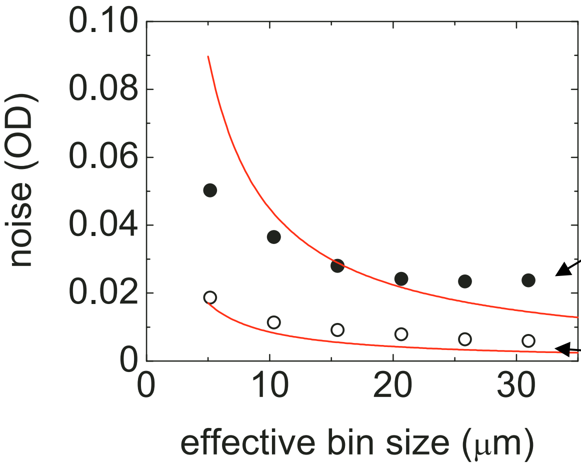


- TOF absorption image

- take fit residual
- spatial filter to "bin" picture on variable length scale







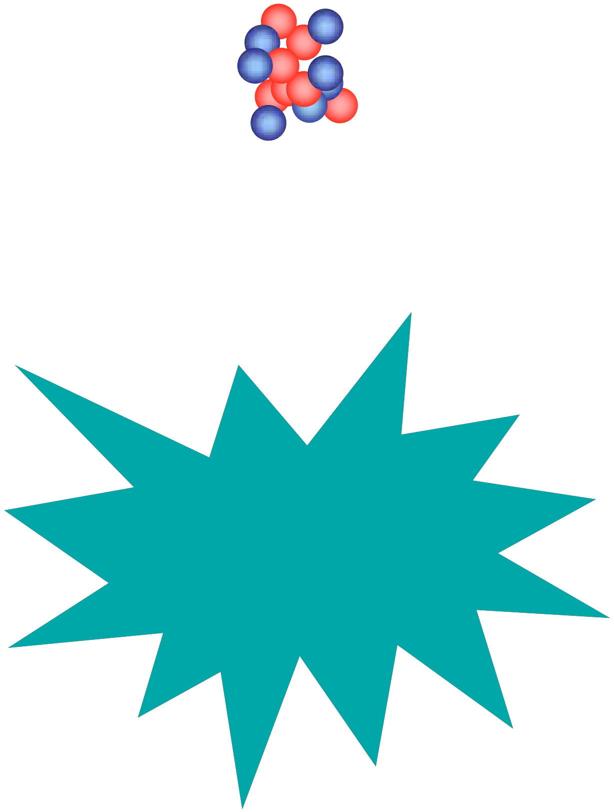
Atom shot-noise limited image:

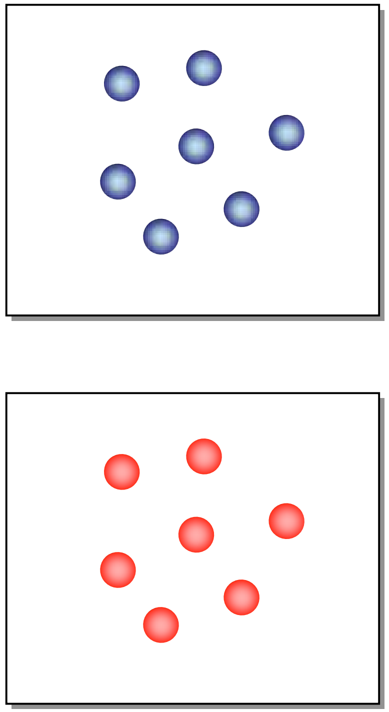
measured noise at OD=1, Poisson noise

background noise, expected photon SN

Spatial shot-noise correlations

- TOF absorption image in two spin states after molecule dissociation

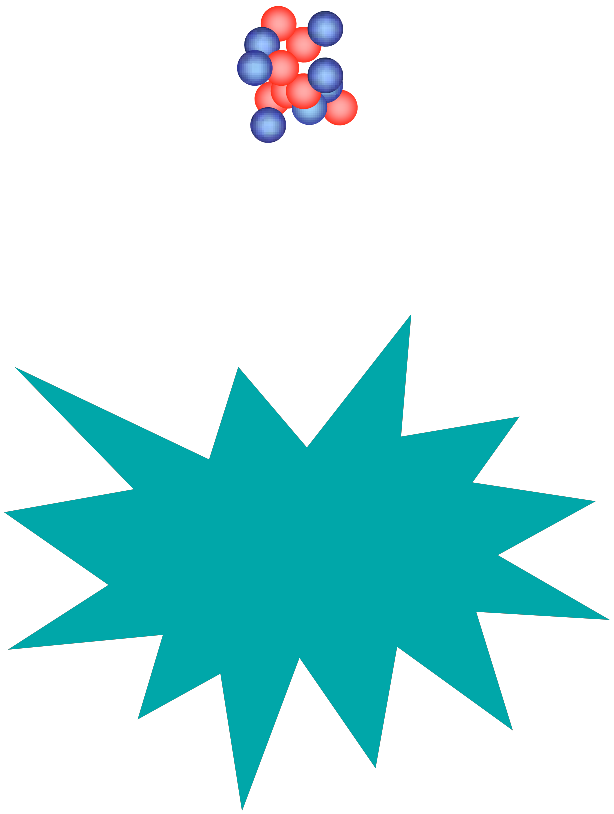




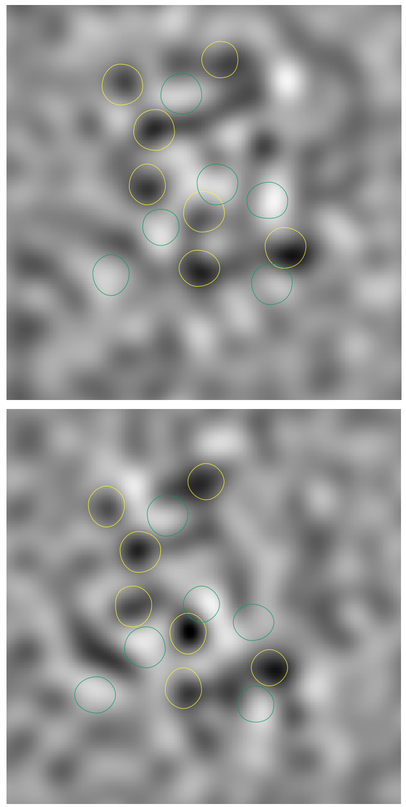
$m_f = -9/2$

$m_f = -7/2$

Spatial shot-noise correlations



- TOF absorption image in two spin states after molecule dissociation

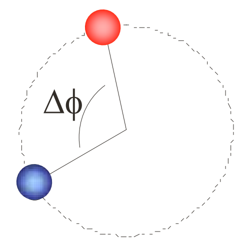


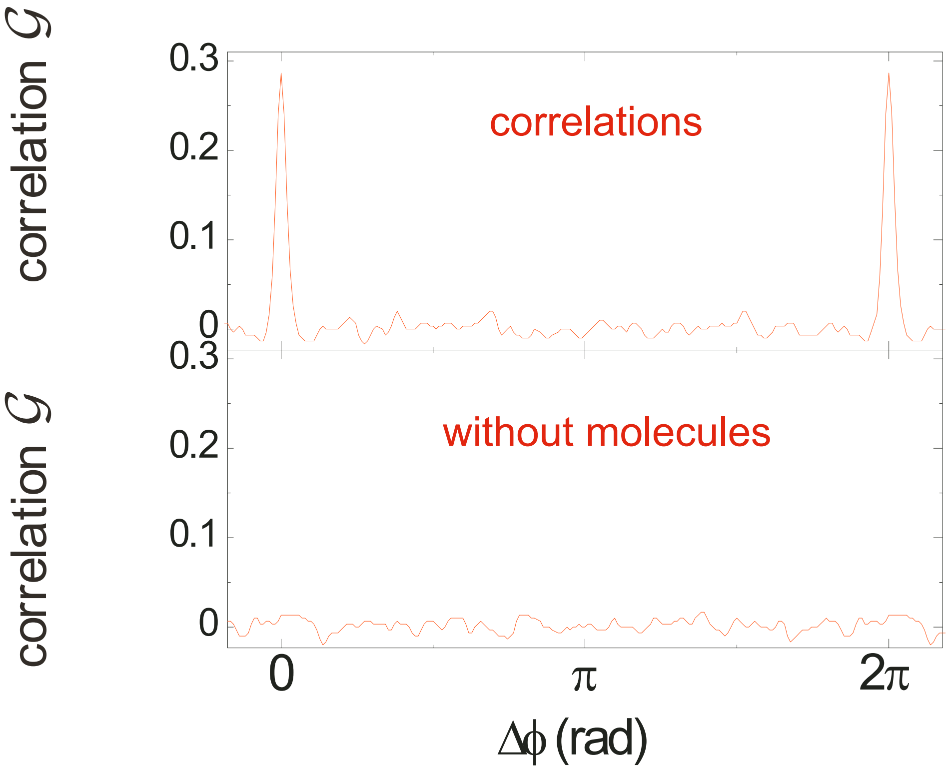
$m_f = -9/2$

$m_f = -7/2$

Finding shot-noise correlations

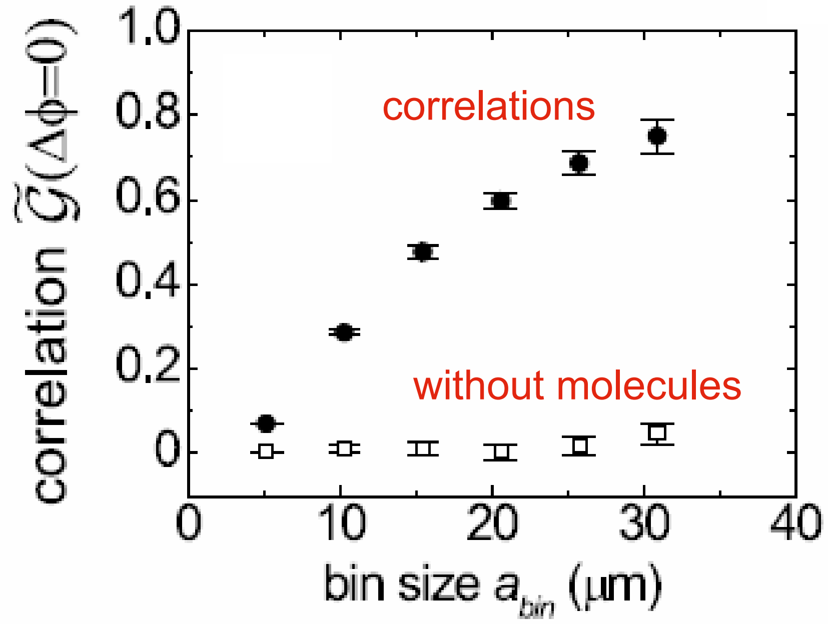
$$\tilde{\mathcal{G}}_{(-7/2,-9/2)}(\Delta\phi) = \left\langle \frac{\left\langle \delta N_{-7/2}(r,\phi)\cdot \delta N_{-9/2}(r,\phi+\Delta\phi)\right\rangle_{\phi}}{\sqrt{\overline{N}_{-7/2}(r)\overline{N}_{-9/2}(r)}} \right\rangle_{r}$$

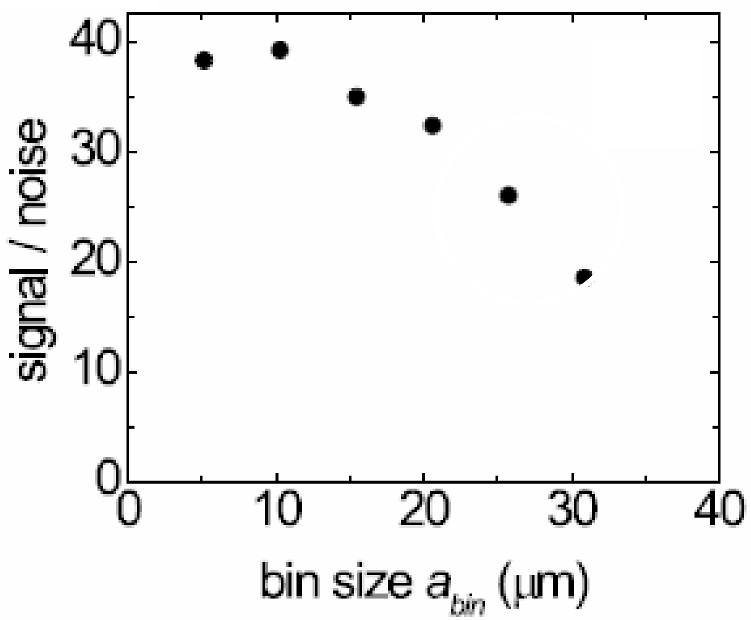




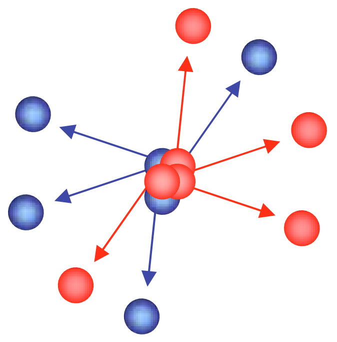
Finding shot-noise correlations

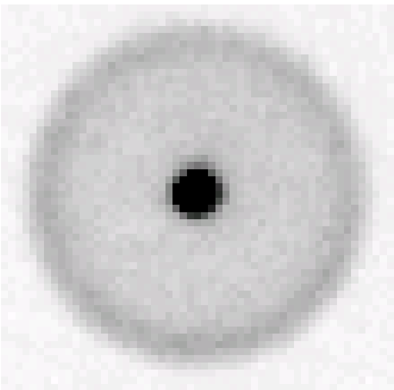
$$\widetilde{\mathcal{G}}_{(-7/2,-9/2)}(\Delta\phi) = \left\langle \frac{\left\langle \delta N_{-7/2}(r,\phi)\cdot\delta N_{-9/2}(r,\phi+\Delta\phi)\right\rangle_\phi}{\sqrt{\overline{N}_{-7/2}(r)\overline{N}_{-9/2}(r)}} \right\rangle_r$$



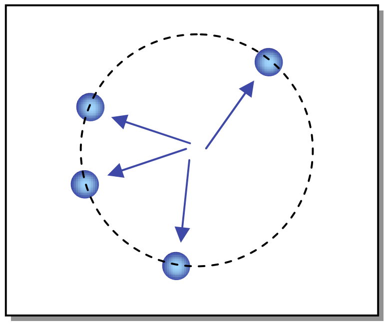


Shot-noise correlations in momentum space

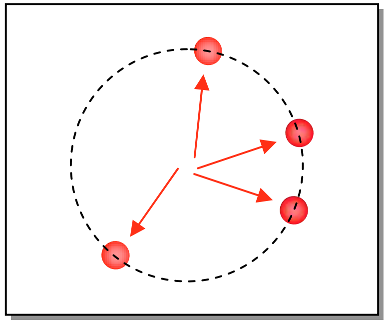




- Correlations of atoms with equal momentum in opposite directions:

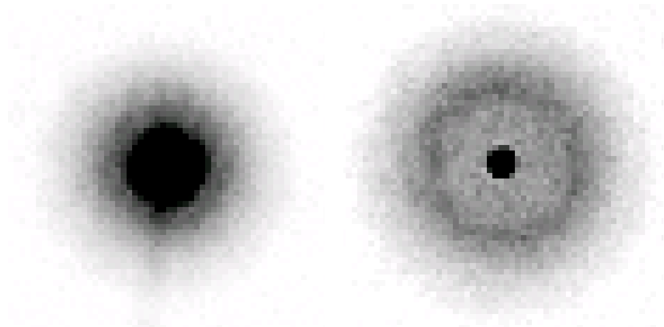


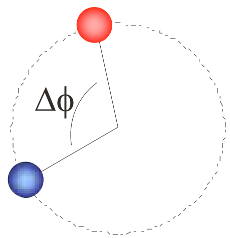
$m_f = -9/2$



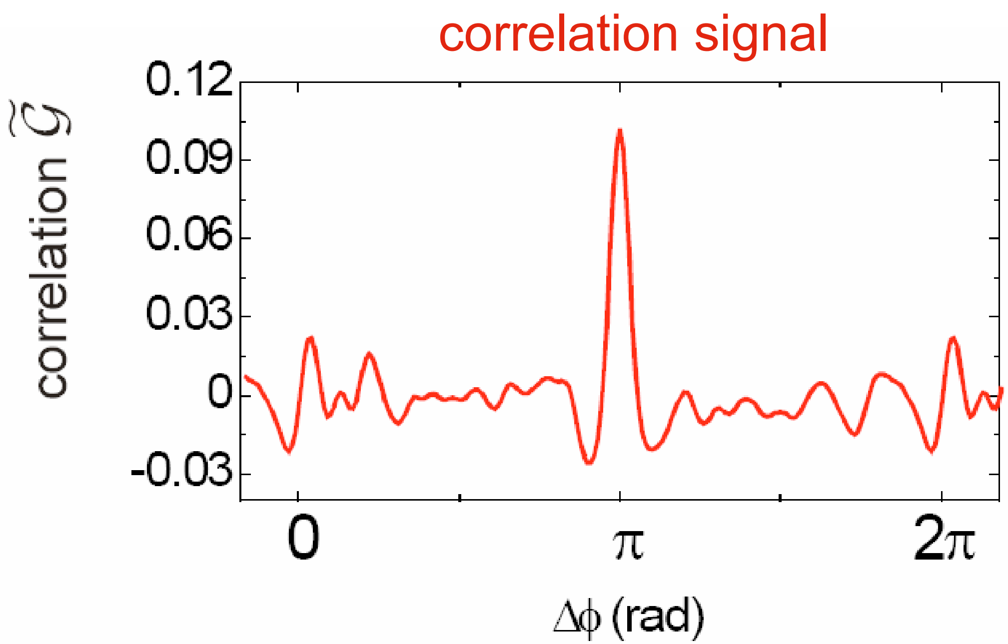
$m_f = -5/2$

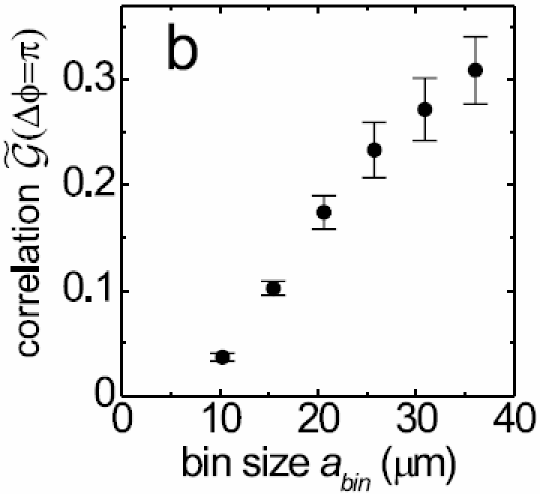
Noise correlations of nonlocal singlet pairs



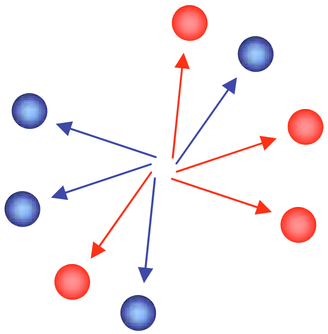


M. Greiner *et al.*,
PRL (2005)





Future applications:

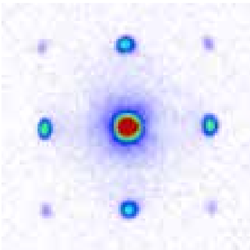


- Detect condensed pairs, should work in the BCS limit;
  Things to optimize:
    - switch off interaction
    - optimize ratio between relative and center of mass motion
    - optimize condensate fraction

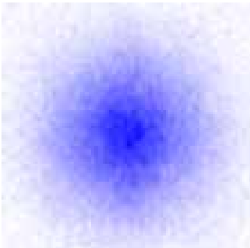
- Pairs are entangled (singlet molecules)
  → EPR pairs
  → study Bell inequalities and entanglement

Noise correlations in optical lattices

→ ***Work by Simon Fölling, Fabrice Gerbier, Artur Widera, Olaf Mandel, Tatjana Gericke and Immanuel Bloch in Mainz***
Proposed by Ehud Altman et al.

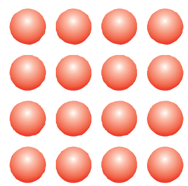


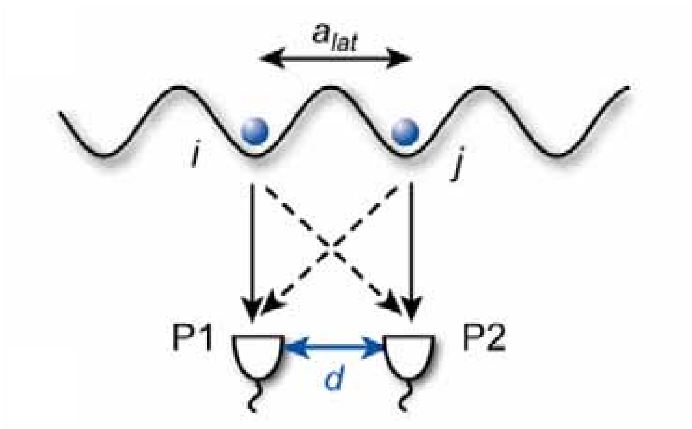
Superfluid phase:
long range phase coherence



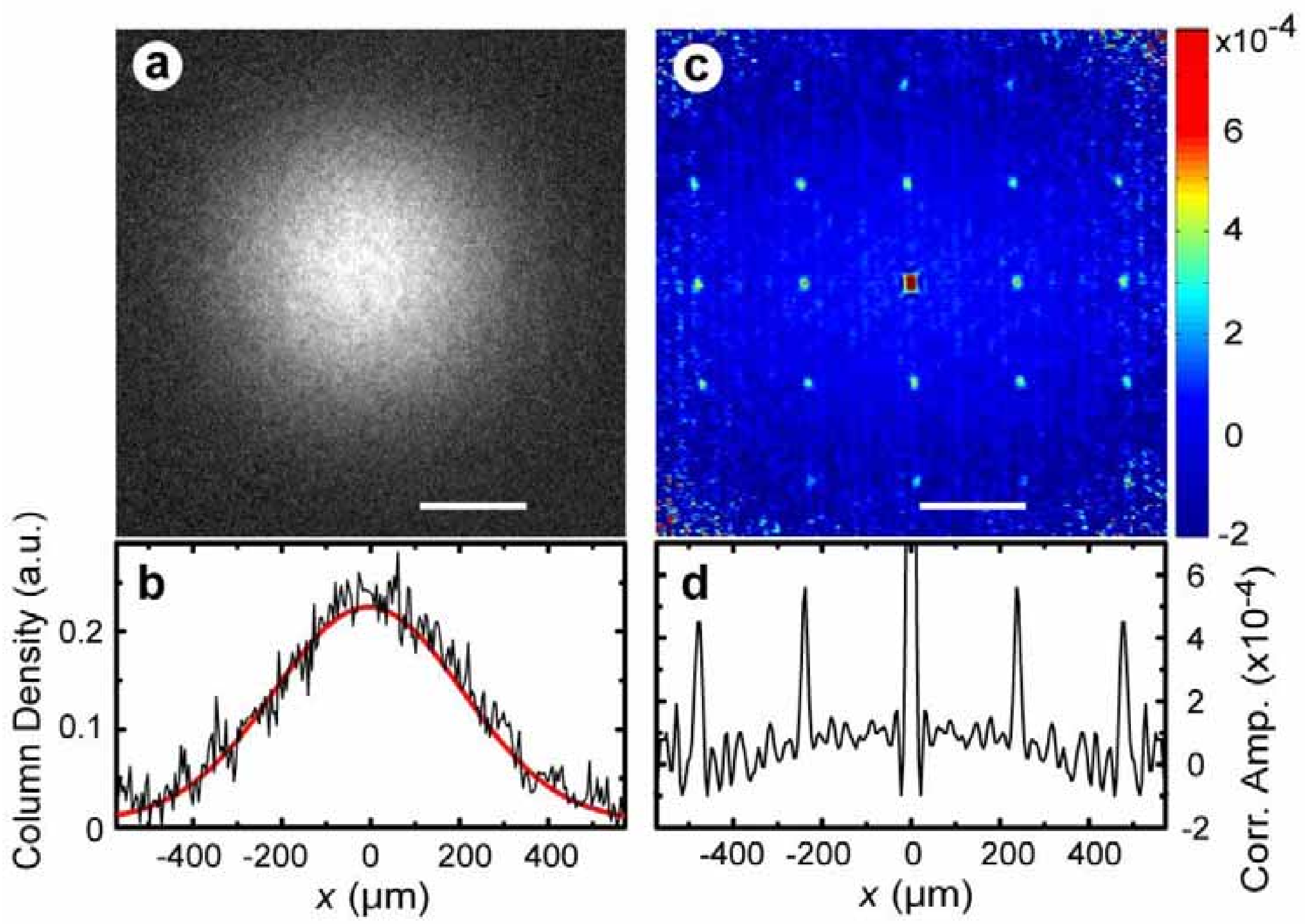
Mott insulator:
no first order phase coherence
→ no interference pattern

Hanbury Brown Twiss (HBT) experiment:
Measure correlations of fluctuations



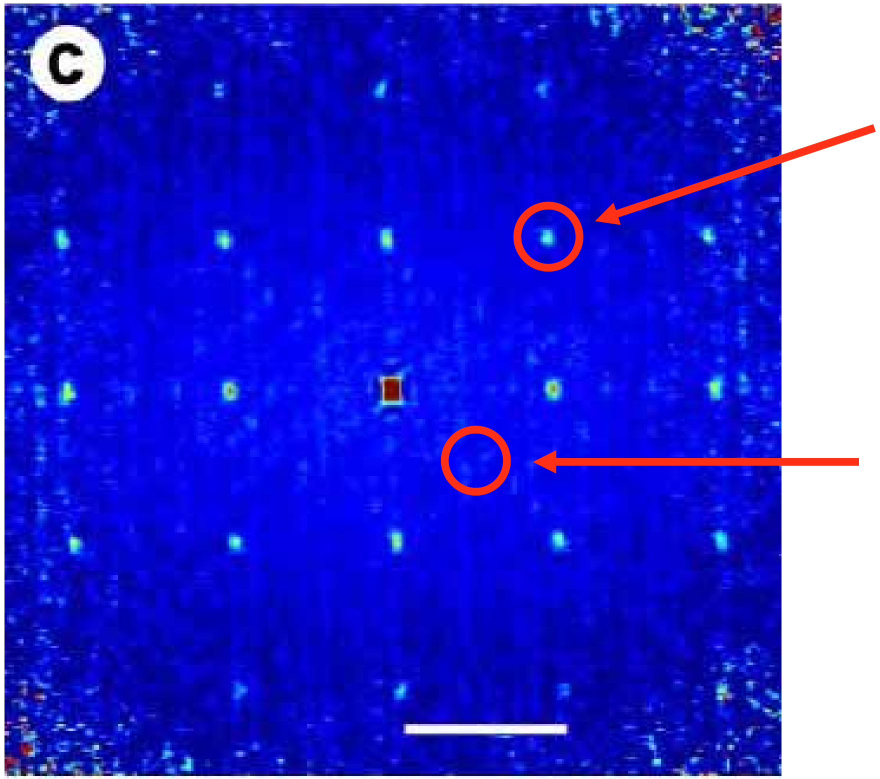


Noise correlations in optical lattices (Mainz)



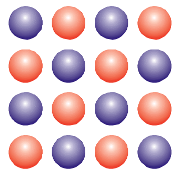
Foelling et al., Nature (2005)

Noise correlations in optical lattices (Mainz)



Fermions:
anti correlations
→ peaks should be negative

Anti-ferromagnetic state:
additional correlations peaks



Spin waves etc. …

Thanks:

Deborah Jin
Cindy Regal

Jayson Stewart

… I am starting a research group this summer,

***PhD students** and **postdocs** welcome …*

Markus Greiner
Deborah Jin Cindy Regal