"Bose-Einstein condensation of lithium molecules and studies of a strongly interacting Fermi gas"

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Massachusetts Institute of Technology
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3/4/04

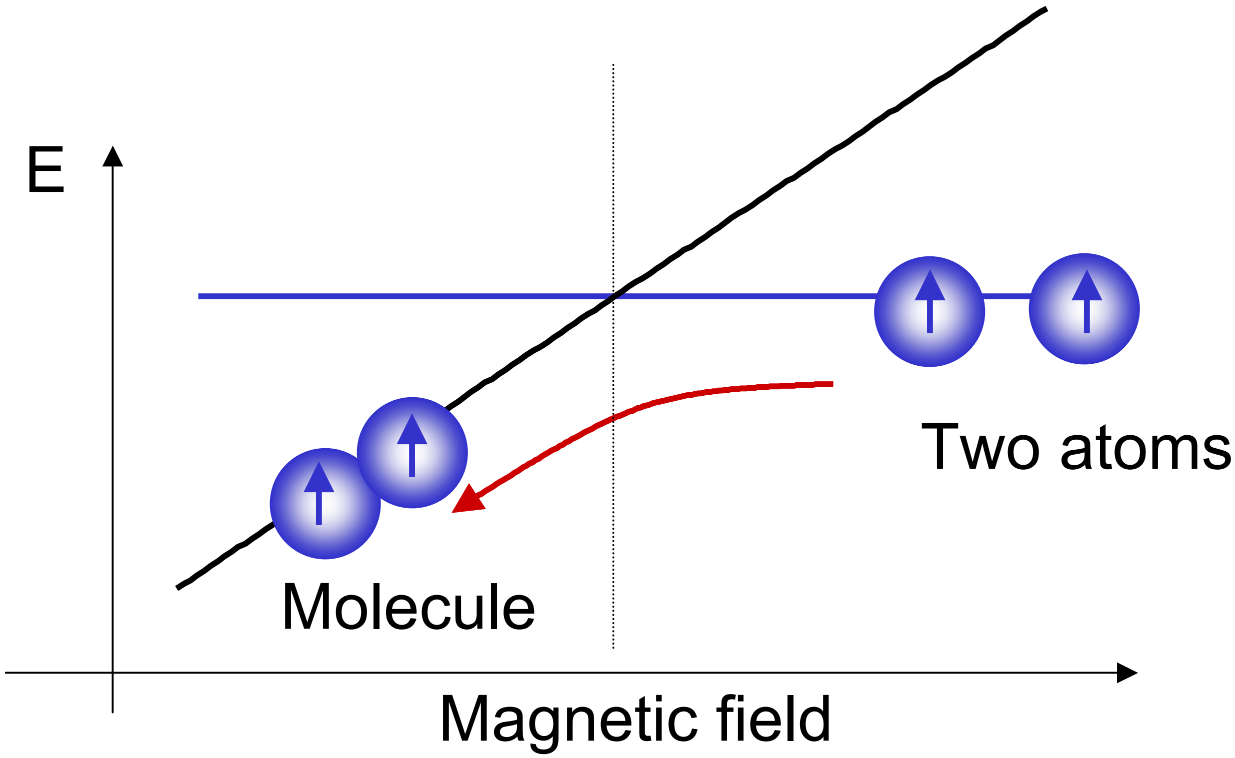
Workshop on Ultracold Fermi Gases, Levico

Quantum degenerate Na_2 molecules

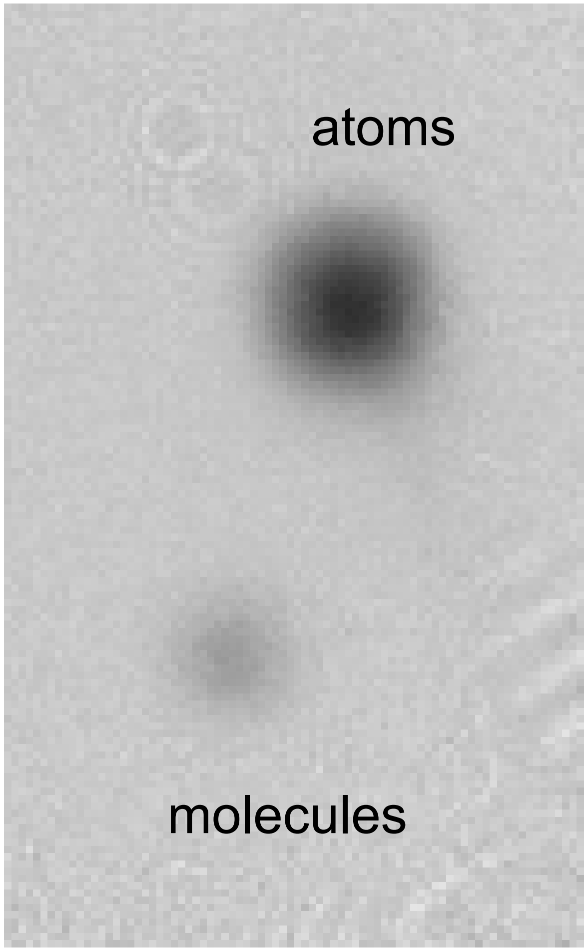
Takashi Mukaiyama, Kaiwen Xu, Jamil Abo-Shaeer, Jit Kee Chin, Daniel Miller, W.K.

Phys. Rev. Lett. **91**, 210402 (2003); Phys. Rev. Lett., in print;
cond-mat/0311558.

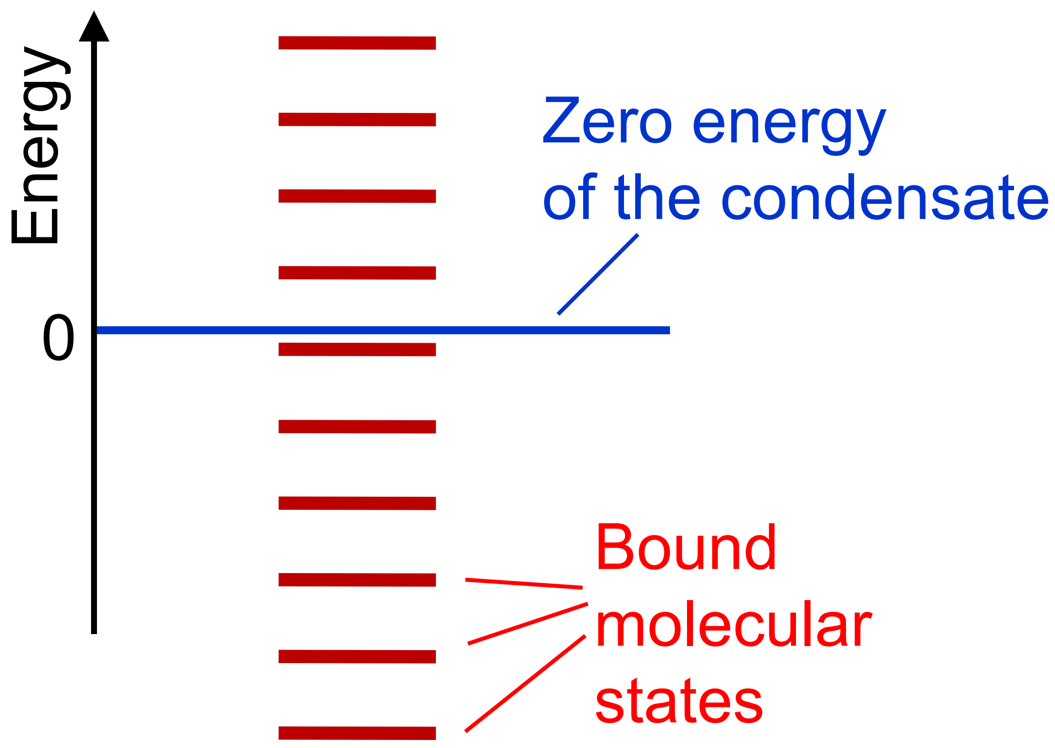
The new cold frontier: molecules



Feshbach resonance



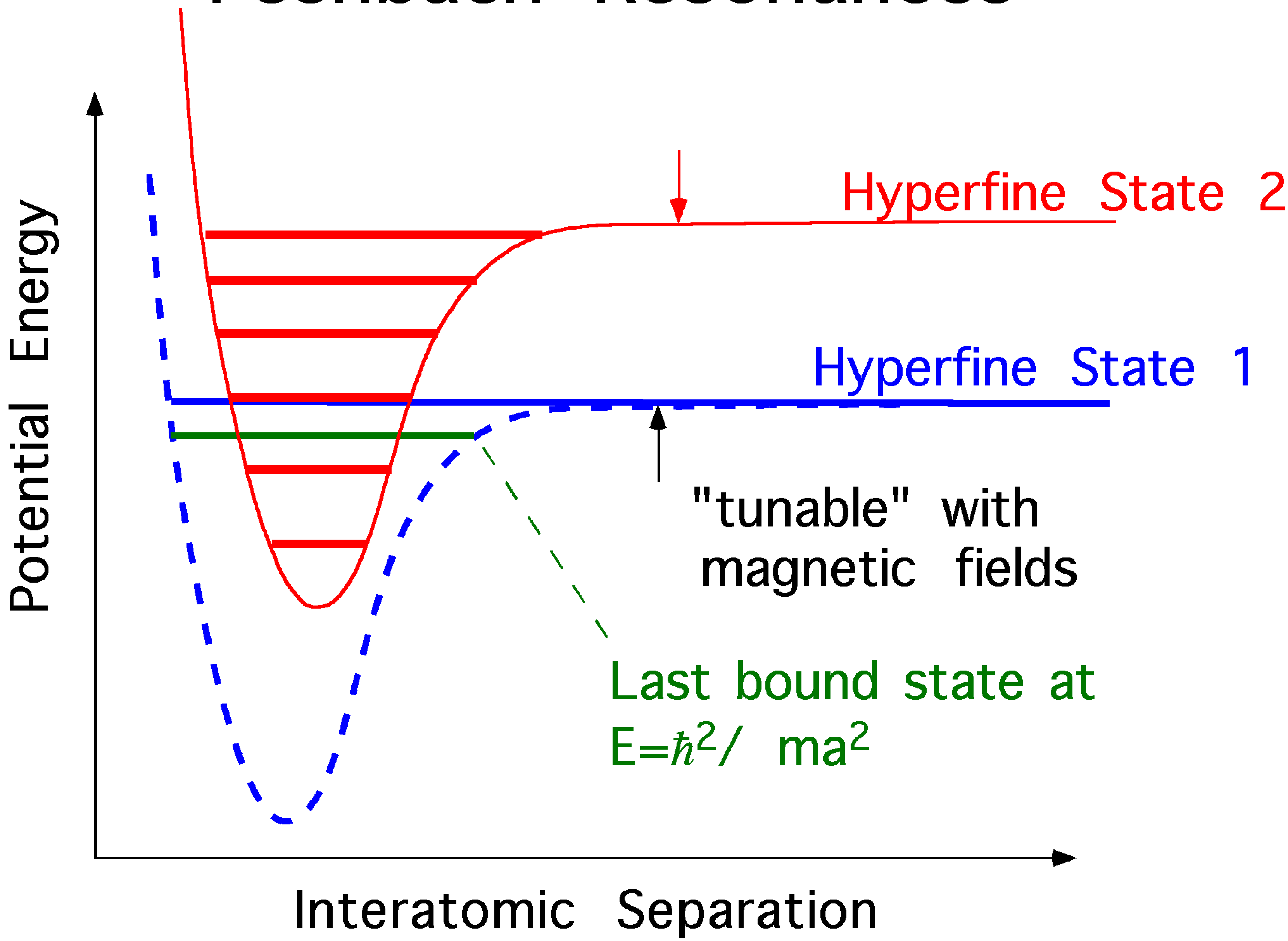
Feshbach resonance

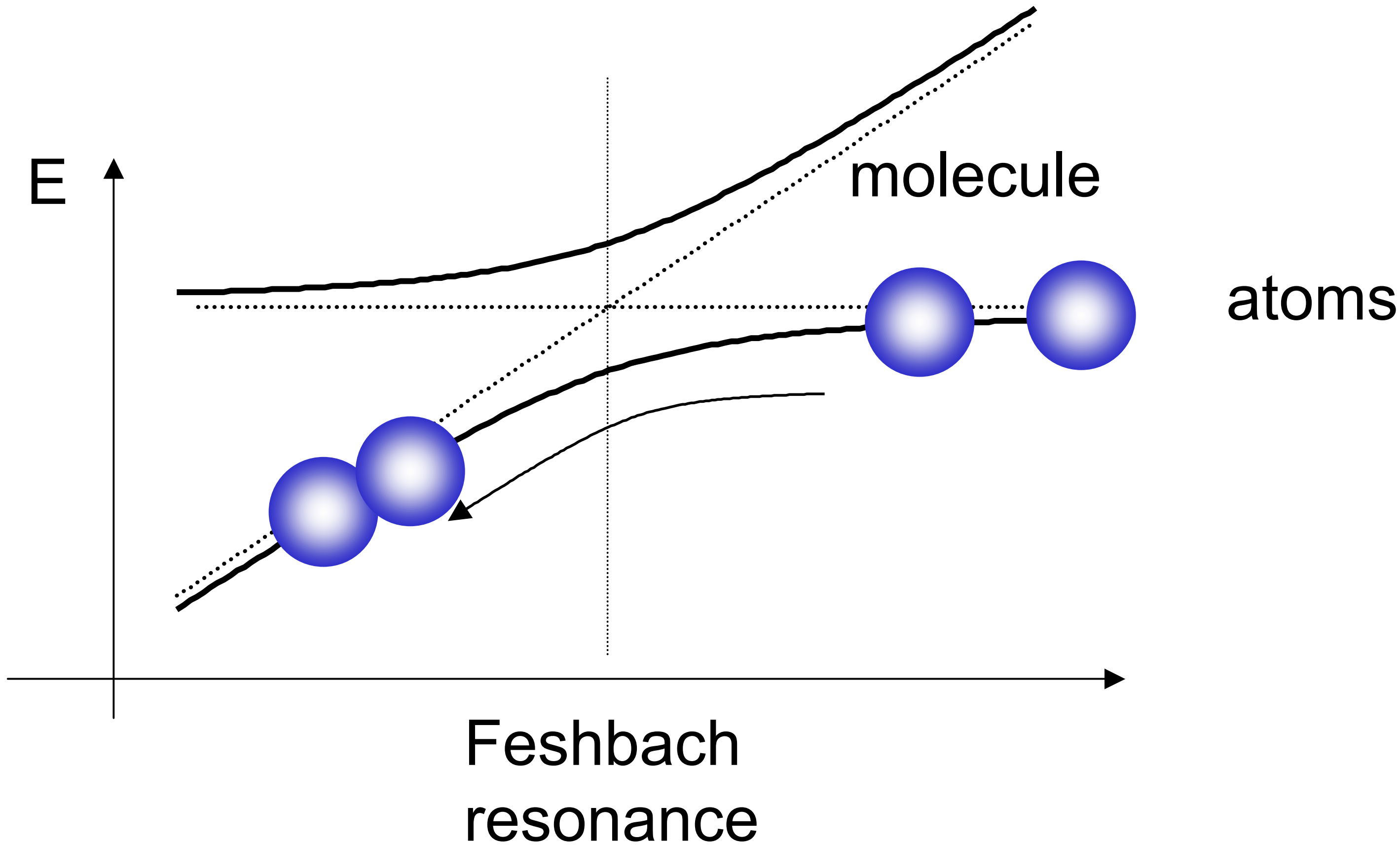


Zeeman tuning a bound molecular state to zero energy!

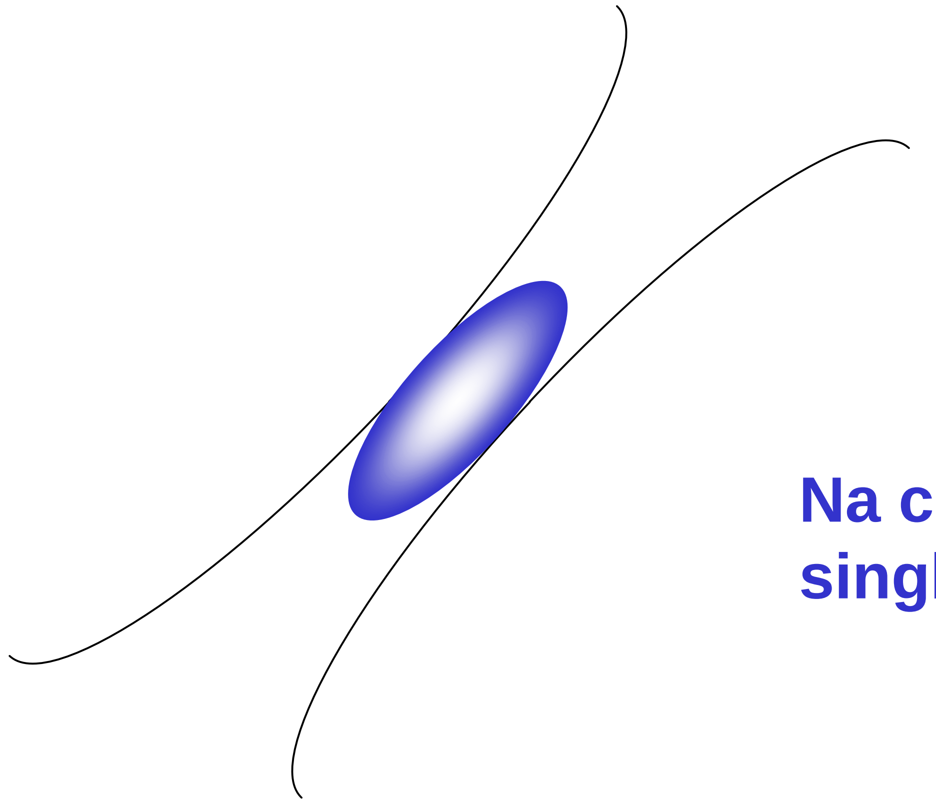
Theory:
Stwalley 1976
Verhaar 1993
Exp:
MIT, Texas 1998

Feshbach Resonances





Bosons: Boulder, Garching, Innsbruck, MIT
Fermions: Boulder, Rice, Paris, Innsbruck, MIT



Na condensate in a single beam optical dipole trap

|F=1, m=1>

$N \sim 3 \times 10^6$

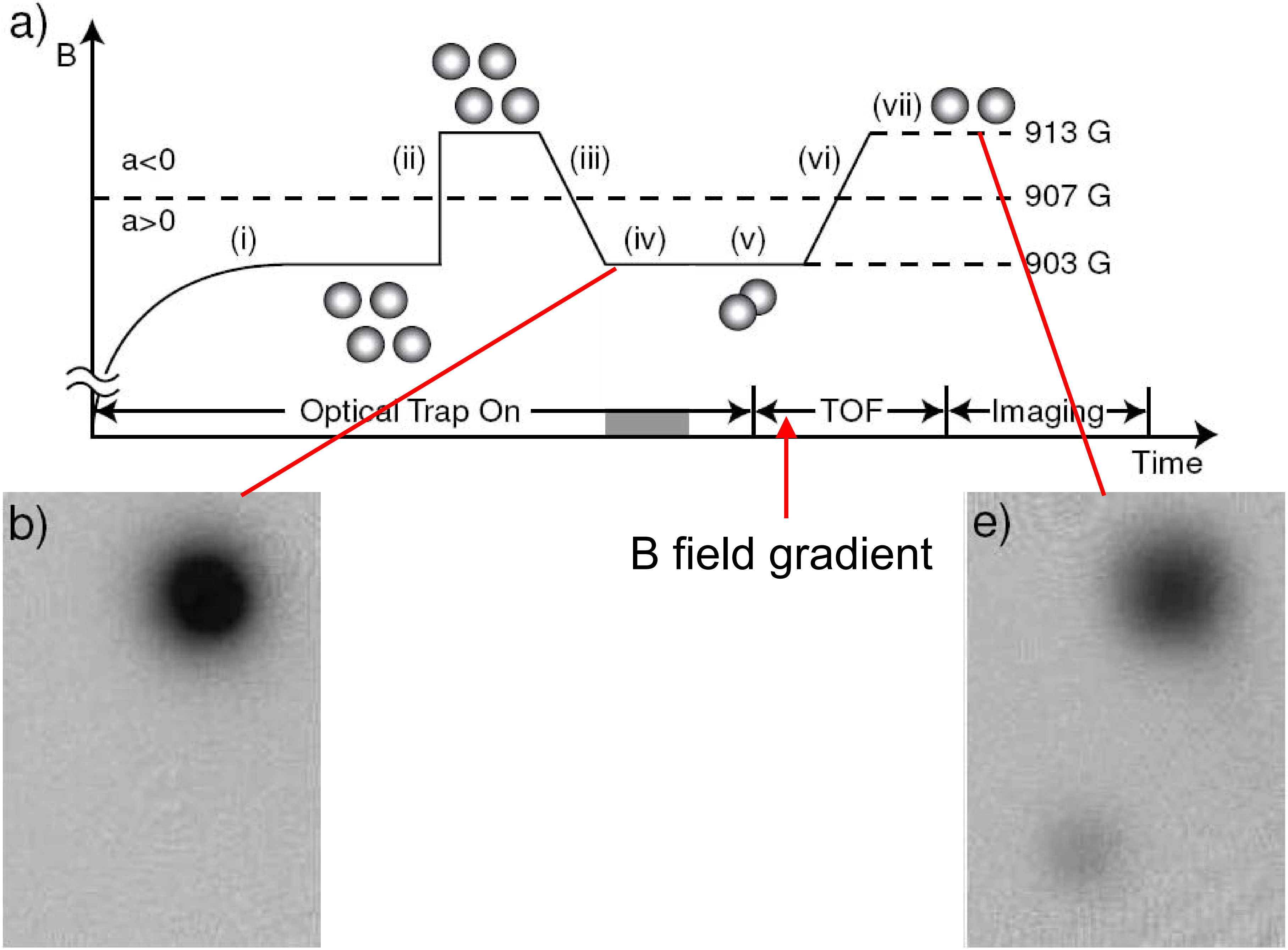
$n \sim 4 \times 10^{14}$ cm^{-3}

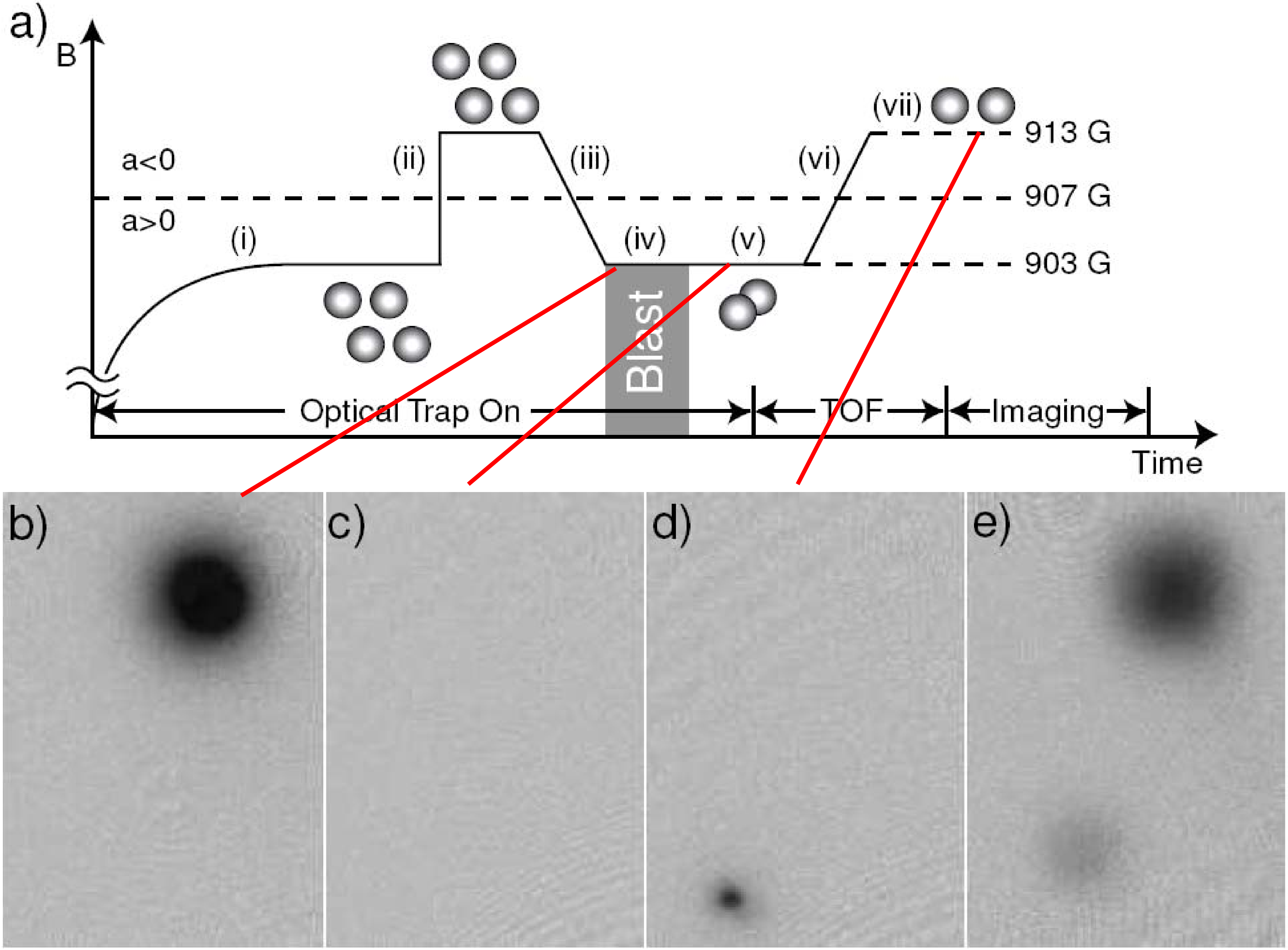
$\omega_{trap} \sim 2\pi \times$ (290 Hz, 290 Hz, 2.5 Hz)

Trap depth ~ 1.4 μK

$B_{FB} \sim$ 907 Gauss

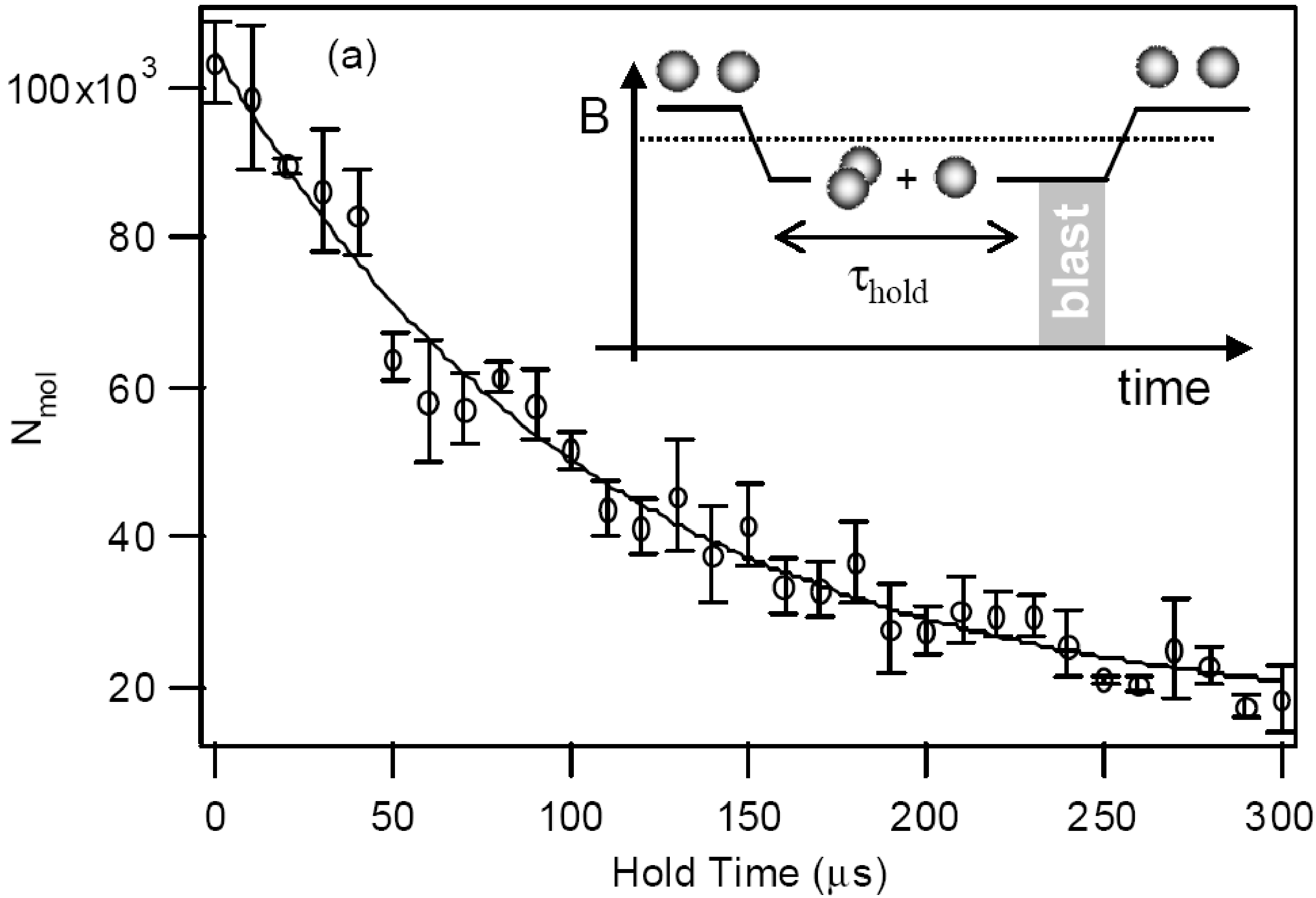
$\Delta B \sim$ 1.0 Gauss


a)
B
a<0
a>0
(i)
(ii)
(iii)
(iv)
(v)
(vi)
(vii)
913 G
907 G
903 G
Optical Trap On
TOF
Imaging
Time
B field gradient
b)
e)



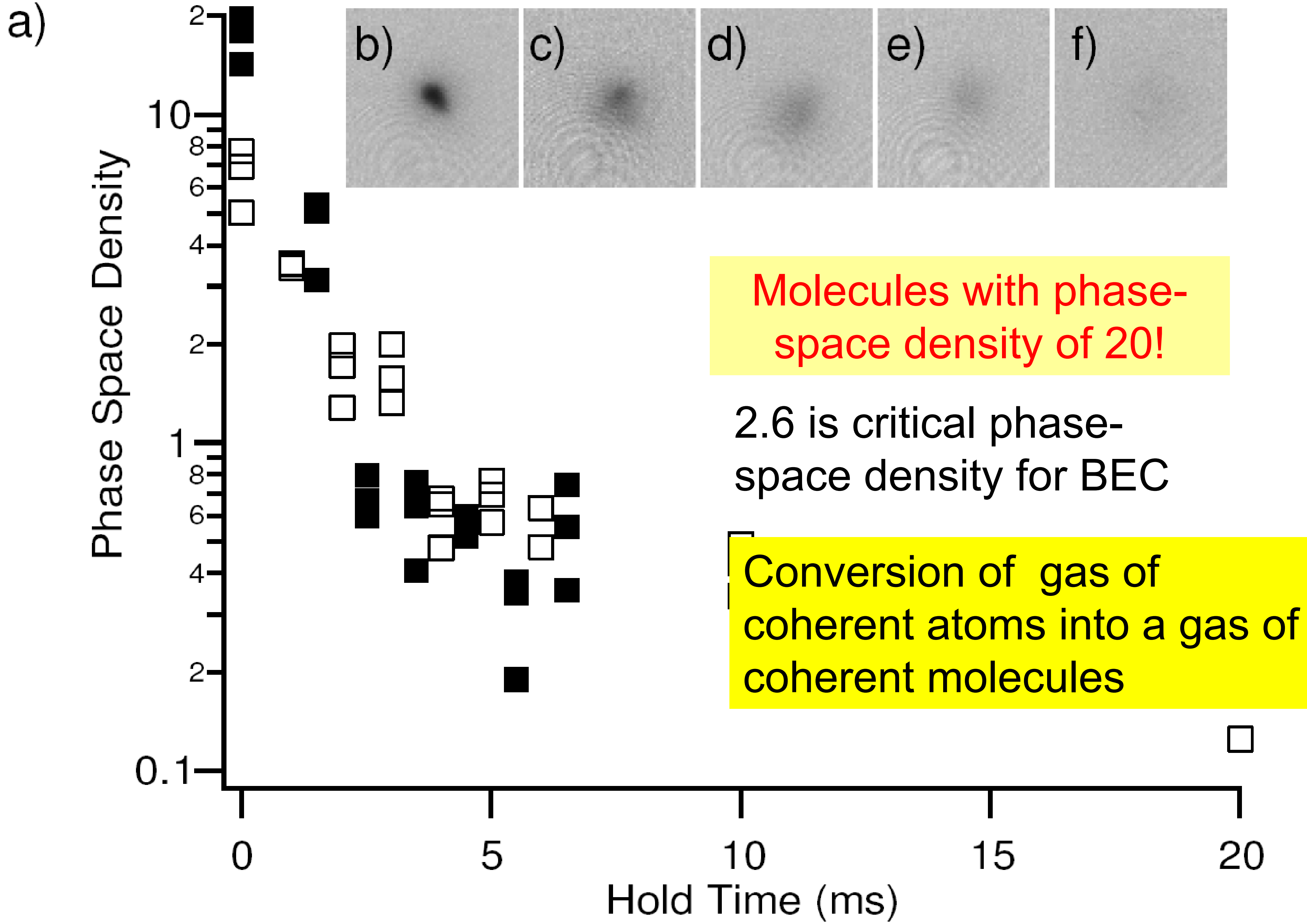
a)
B
a<0
a>0
(i)
(ii)
(iii)
(iv)
(v)
(vi)
(vii)
913 G
907 G
903 G
Blast
Optical Trap On
TOF
Imaging
Time
b)
c)
d)
e)

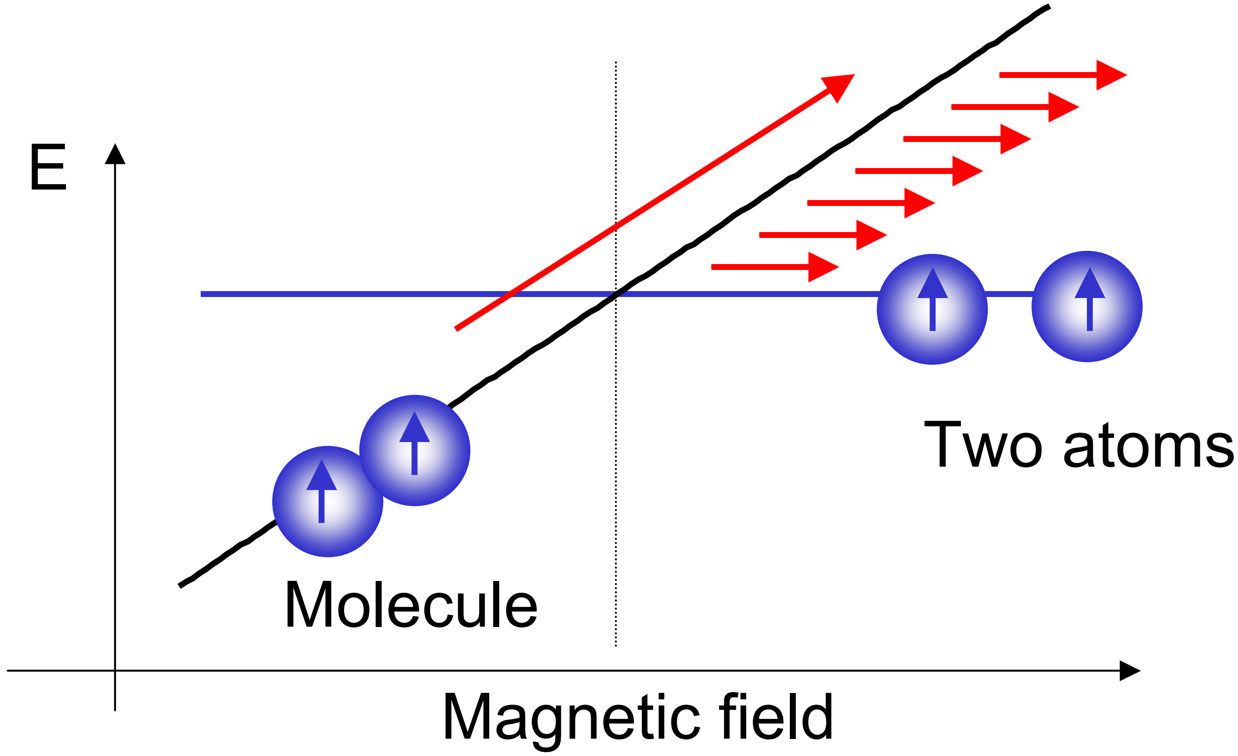
Atom-Molecule Collision



$$\frac{\dot{N}_m}{N_m} = -K_{am} \cdot n_a \quad \Rightarrow \quad K_{am} = 6.4 \times 10^{-11}\ \mathrm{cm}^3/\mathrm{sec}$$

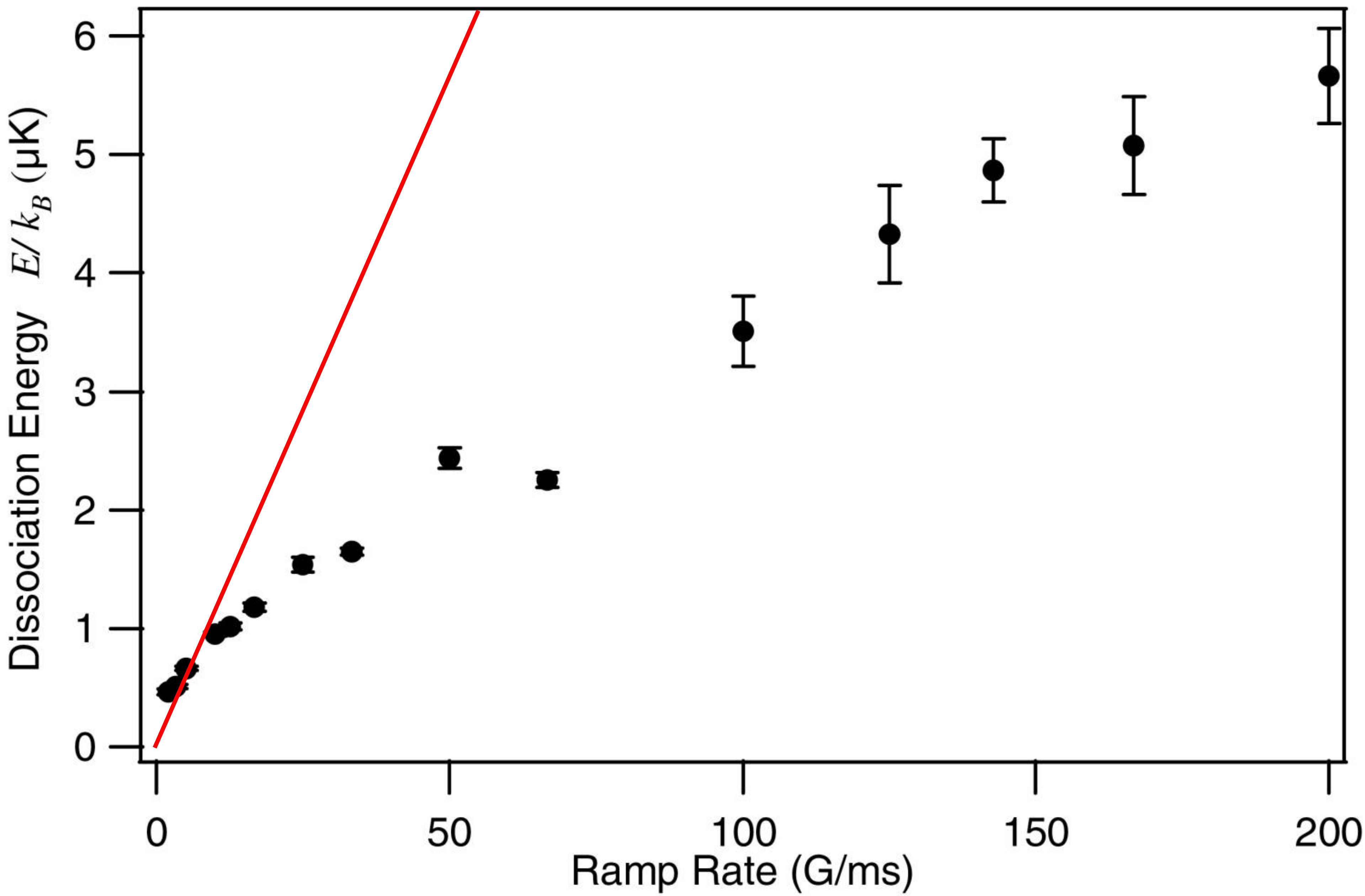
$$\tau \sim 92\ \mu\mathrm{sec}$$


a)
b)
c)
d)
e)
f)
Phase Space Density
Hold Time (ms)
0.1
1
10
2
4
6
8
0
5
10
15
20
Molecules with phase-space density of 20!
2.6 is critical phase-space density for BEC
Conversion of gas of coherent atoms into a gas of coherent molecules

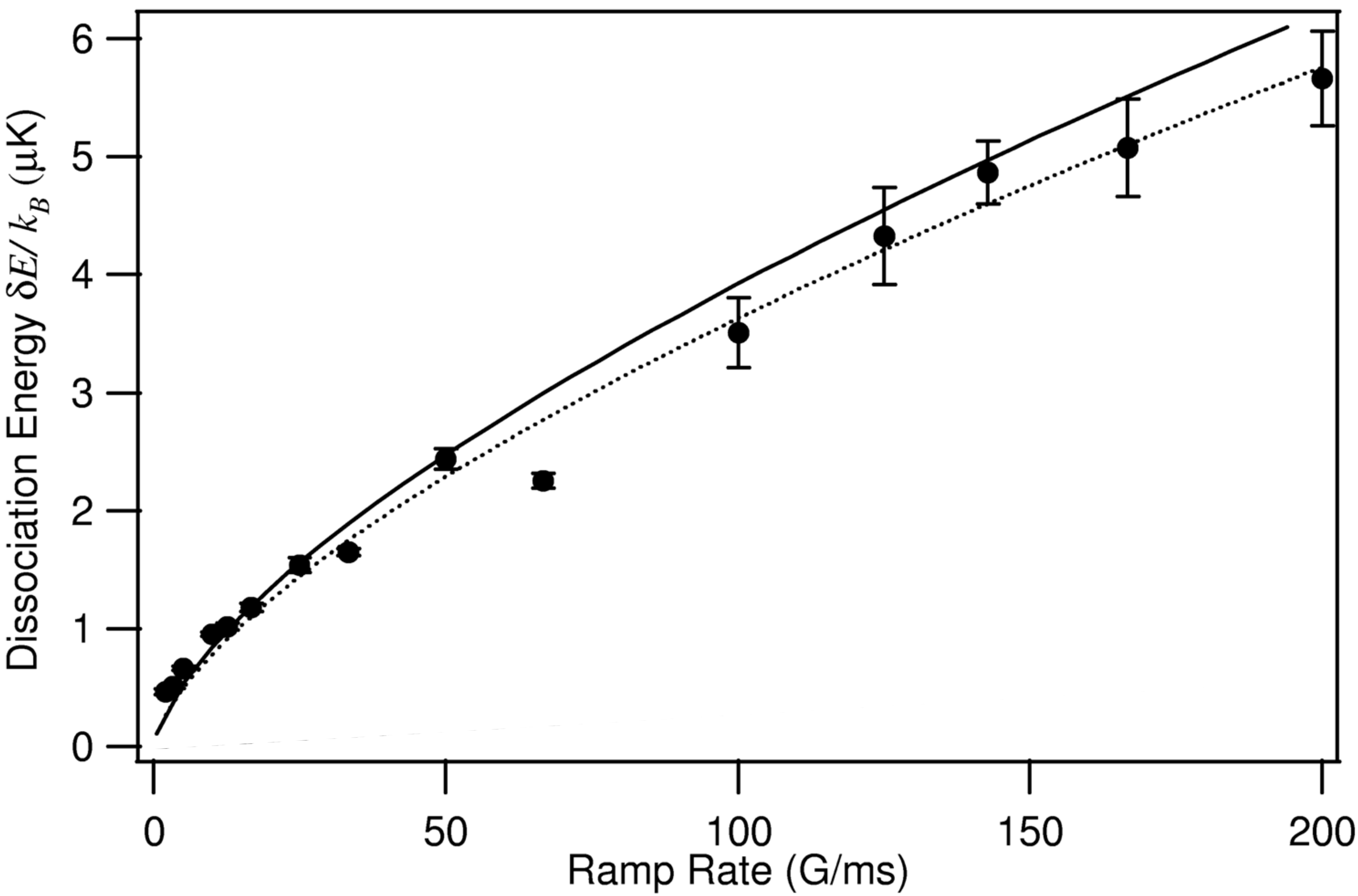


$$\delta E = \tau_p \times \Delta\mu\dot{B}$$

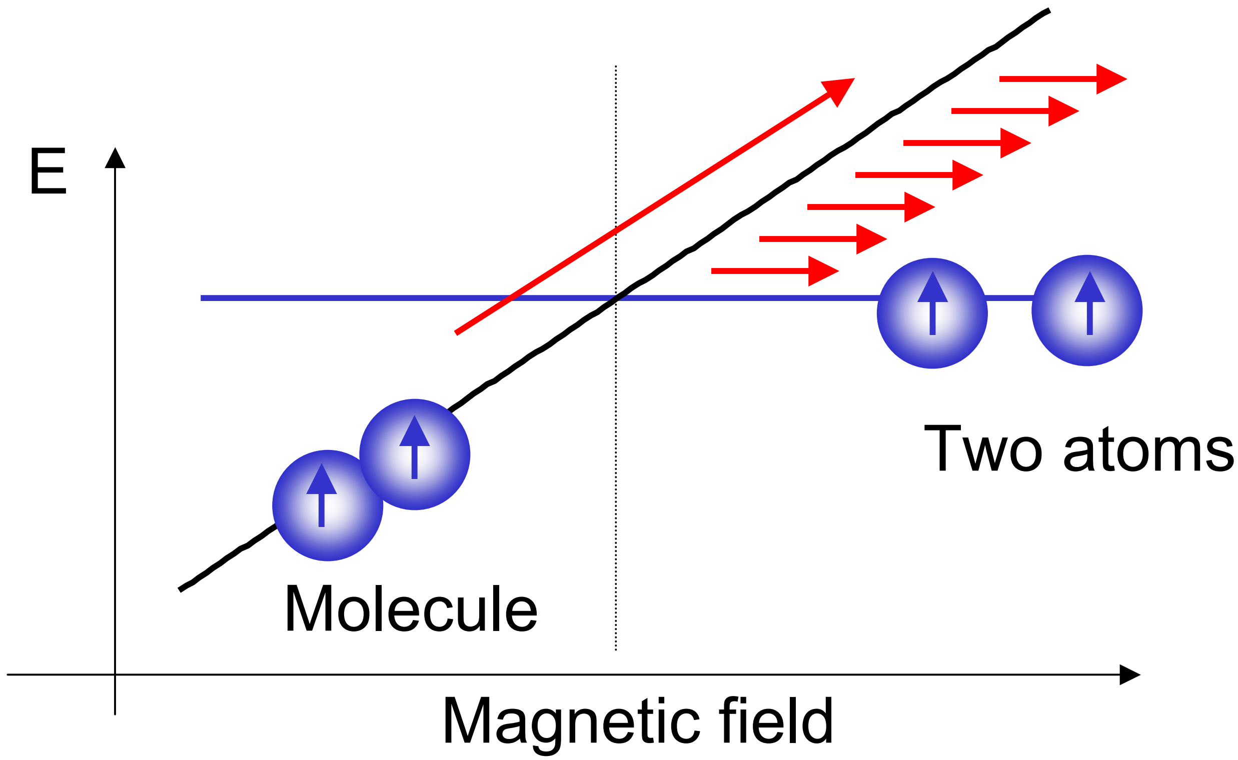
(τ_p : predissociation time)



Dissociation Energy E/k_B (μK)
0
1
2
3
4
5
6
0
50
100
150
200
Ramp Rate (G/ms)



Dissociation Energy $\delta E/k_B$ (μK)
0
1
2
3
4
5
6
0
50
100
150
200
Ramp Rate (G/ms)



$$\delta E = \tau_p \times \Delta\mu\dot{B}$$

(τ_p : predissociation time)

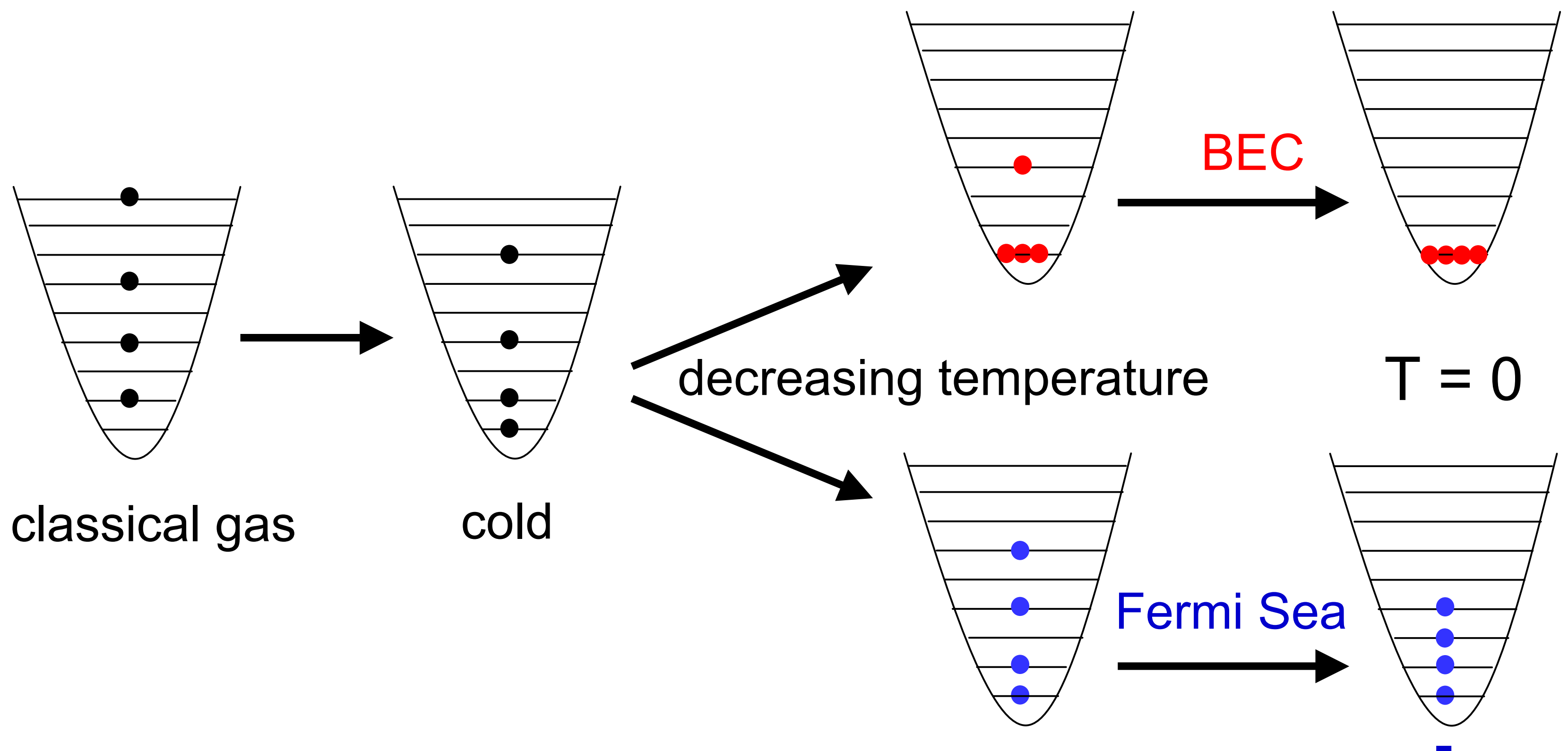
However:

$$\tau_p \propto \sqrt{\delta E}$$

Wigner threshold law

Quantum degeneracy in fermions

Quantum Degenerate Gases

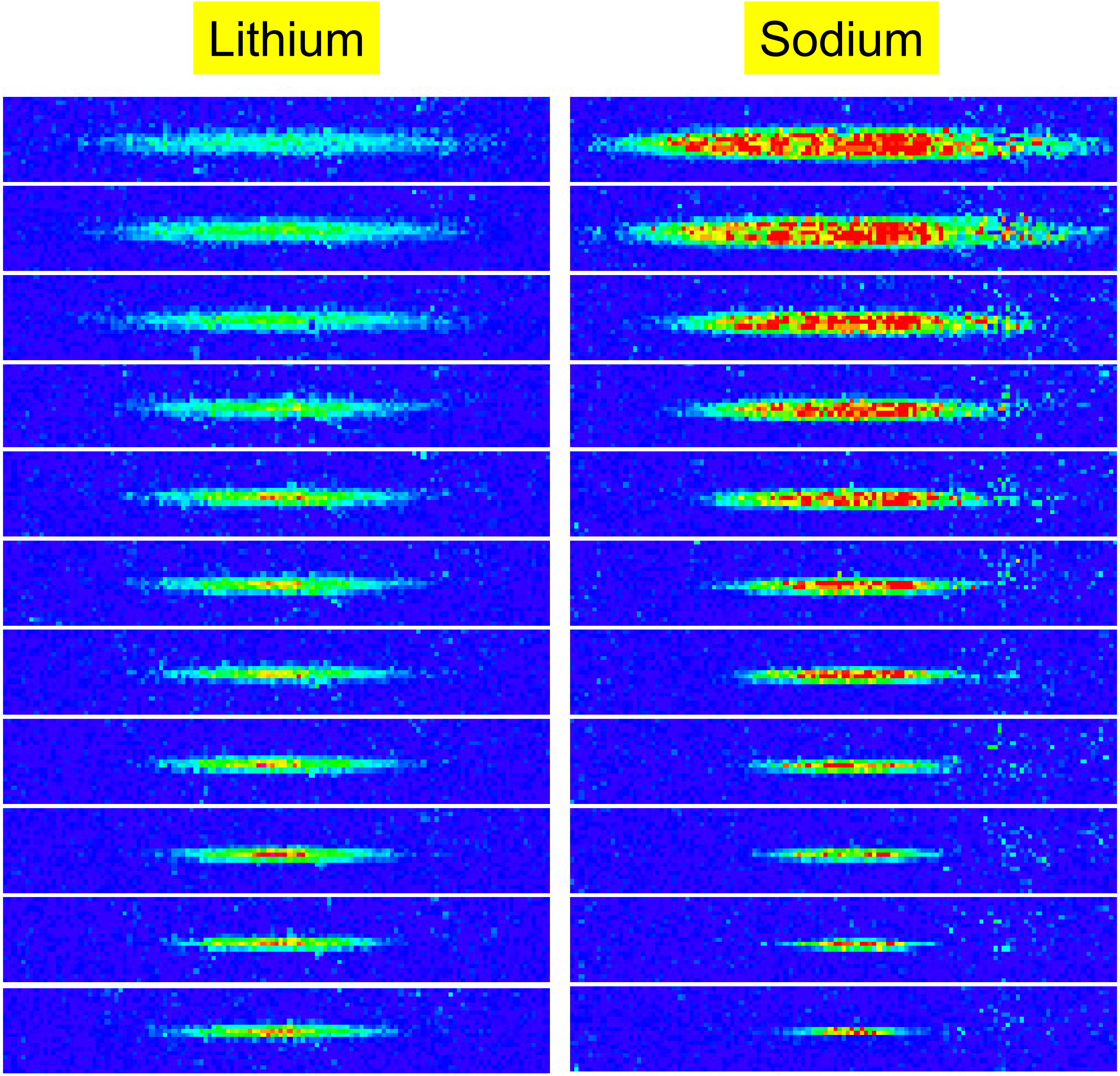


- non-interacting fermions: Pauli blocking
- interacting fermions: BCS-like superfluidity
- mixtures of Bose and Fermi gases

Quantum degenerate fermions

Potassium ^{40}K	Boulder Florence
Lithium ^{6}Li	Rice Paris Duke MIT Innsbruck

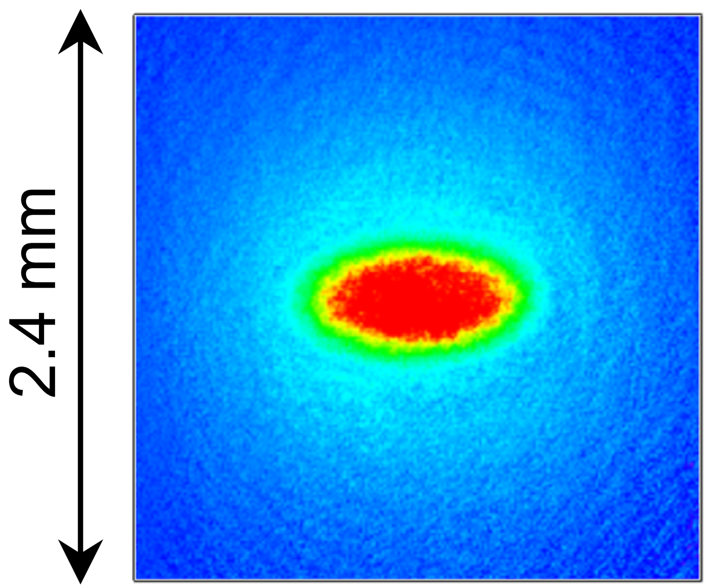
Lots of work in progress: chromium, strontium


Lithium
Sodium

Sodium - Lithium Mixture

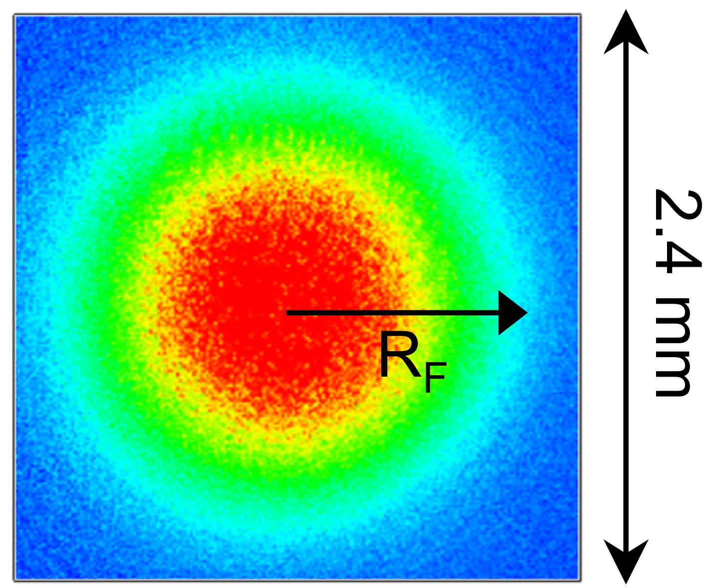
Na F = 2 condensate as refrigerator
cool Li F = 3/2 (state $|6\rangle$) in a magnetic trap -
20s forced evaporation

10^7 atoms in BEC (w/o Li)



50 ms time of flight
$\omega = 2\pi \times (72,72,18)$ Hz

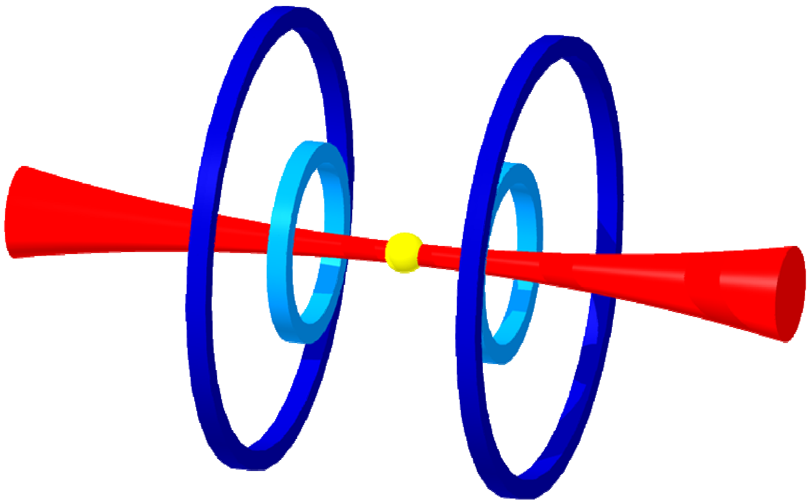
50 10^6 Li atoms at $\frac{T}{T_F} < 0.3$

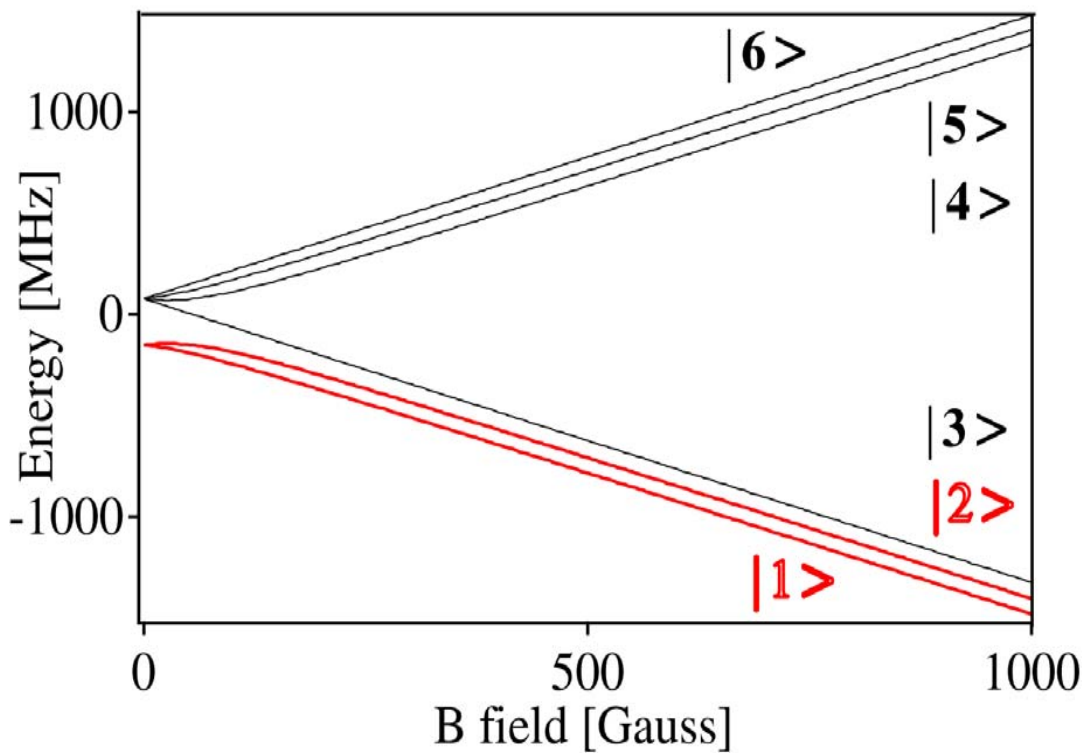


12 ms time of flight
$\omega = 2\pi \times (142,142,36)$ Hz

Z. Hadzibabic, S. Gupta, C. A. Stan, C. H. Schunck, M.W. Zwierlein, K. Dieckmann, and W. Ketterle, Phys. Rev. Lett. **91**, 160401 (2003)

Preparation of an interacting ^{6}Li system





Setup:

Optical trapping:
9 W @ 1064 nm

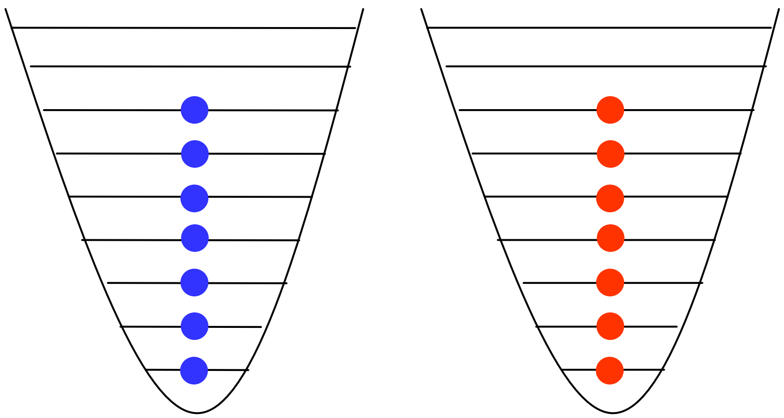
$\omega = 2\pi \times (16, 16, 0.19)$ kHz
$E_{trap} = 800\ \mu K$

Interacting Fermions

Spin-mixture of Spin **Æ** and **∞**

Without interaction:

$a = 0$



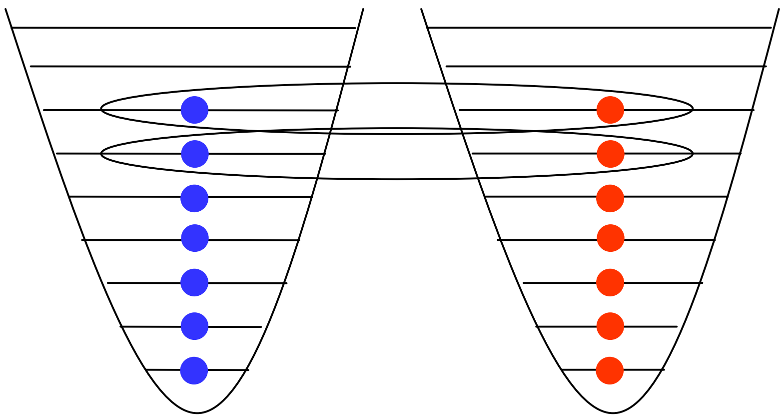
≠ **Ø**

Interacting Fermions

Spin-mixture of Spin Æ and ∞

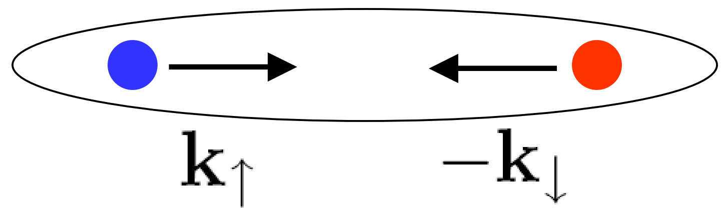
With attractive interaction:

$a < 0$



≠ Ø

BCS-Transition
Condensation of
long-range Cooper pairs



$$T_C \approx 0.5\, T_F e^{-\frac{\pi}{2k_F|a|}}$$

ﬂ We want a large and negative scattering length

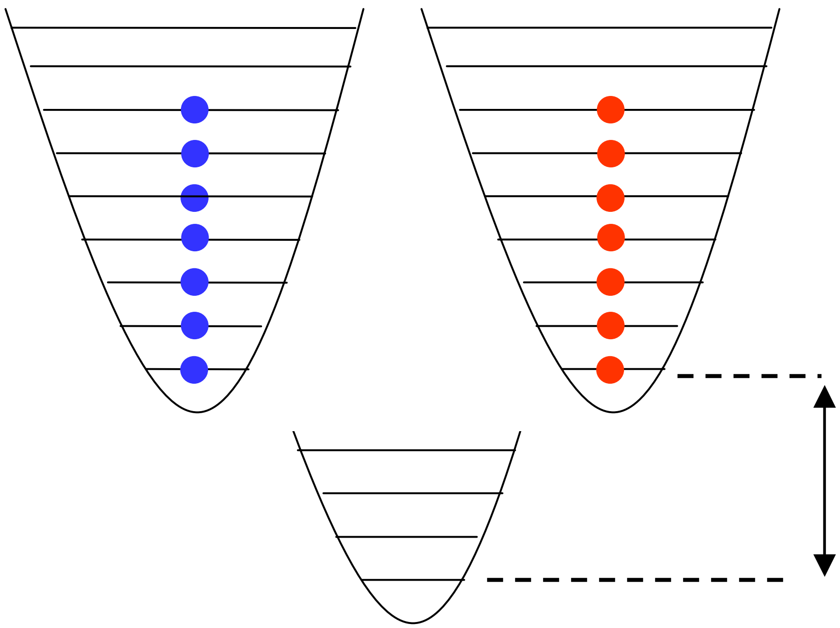
Promising candidate: ^{6}Li, a_T = -2100 a_0

Interacting Fermions

Spin-mixture of Spin **Æ** and **∞**

With repulsive interaction:

$a > 0$



$$E_B = -\frac{\hbar^2}{2ma^2}$$

per atom

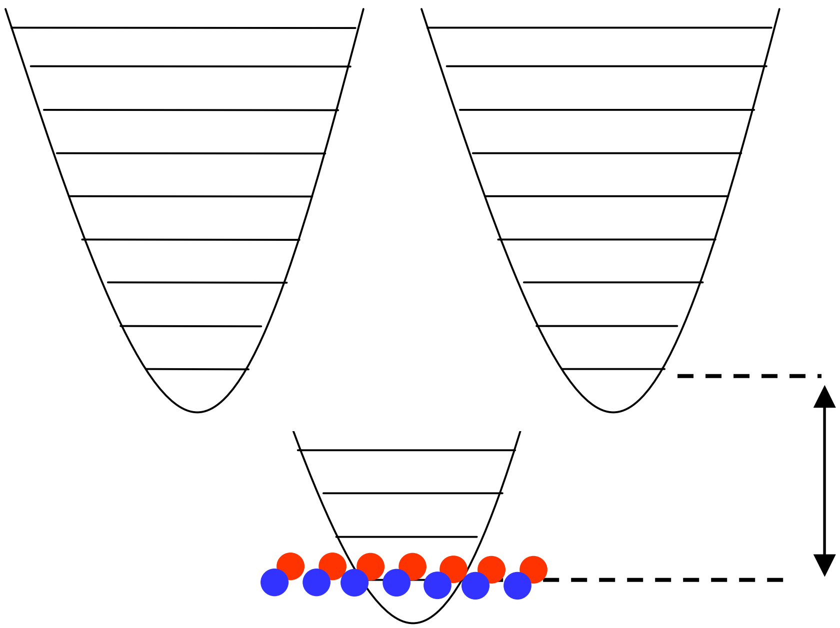
A bound state appears!

Interacting Fermions

Spin-mixture of Spin Æ and ∞

With repulsive interaction:

a > 0



A bound state appears!

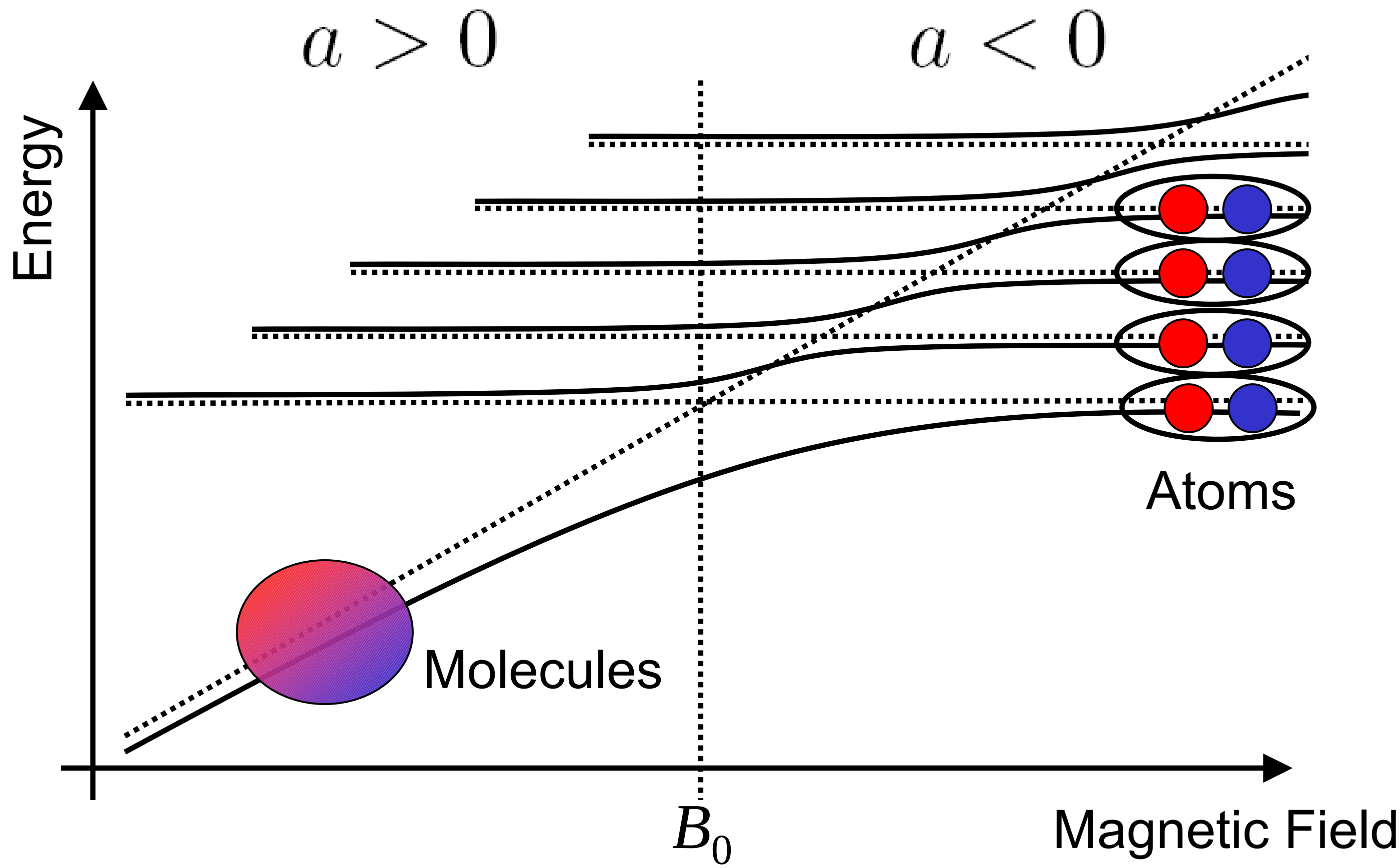
BEC-Transition
Condensation of
tightly bound Fermion pairs

$$\begin{aligned} T_C &= 0.91\,\hbar\bar{\omega}\,N_{\mathrm{mol}}^{1/3} \\ &= 0.5\,T_F \end{aligned}$$

$$E_B = -\frac{\hbar^2}{2ma^2}$$

per atom

The BEC-BCS Crossover



BEC of Molecules:
Condensation of
tightly bound fermion pairs

BCS-limit:
Condensation of
long-range Cooper pairs

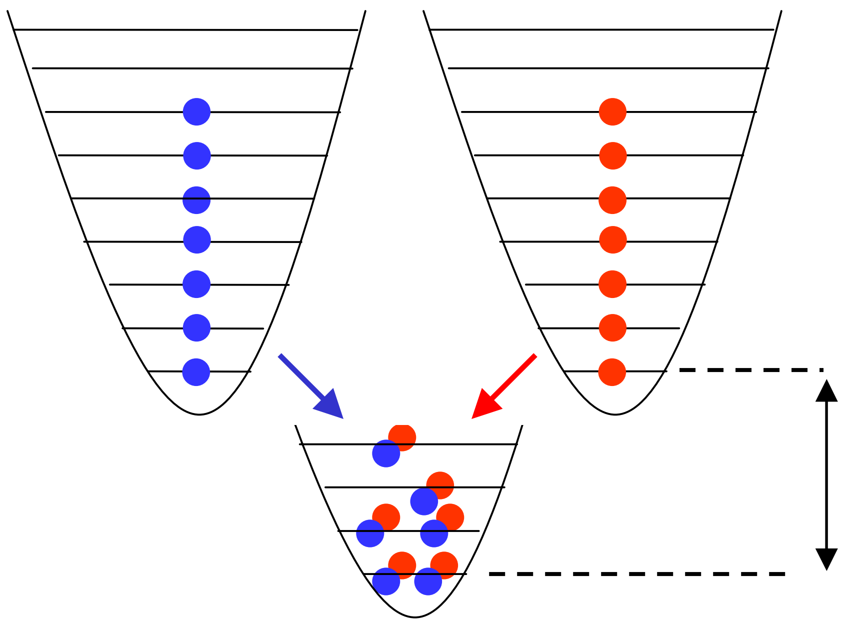
Direct evaporation of ^{6}Li molecules

Long lifetime of Lithium molecules! (ENS, Rice)

fl Directly evaporate at large and positive *a*

fl Form molecules by three-body recombination when kT ***á*** E_B

$a > 0$

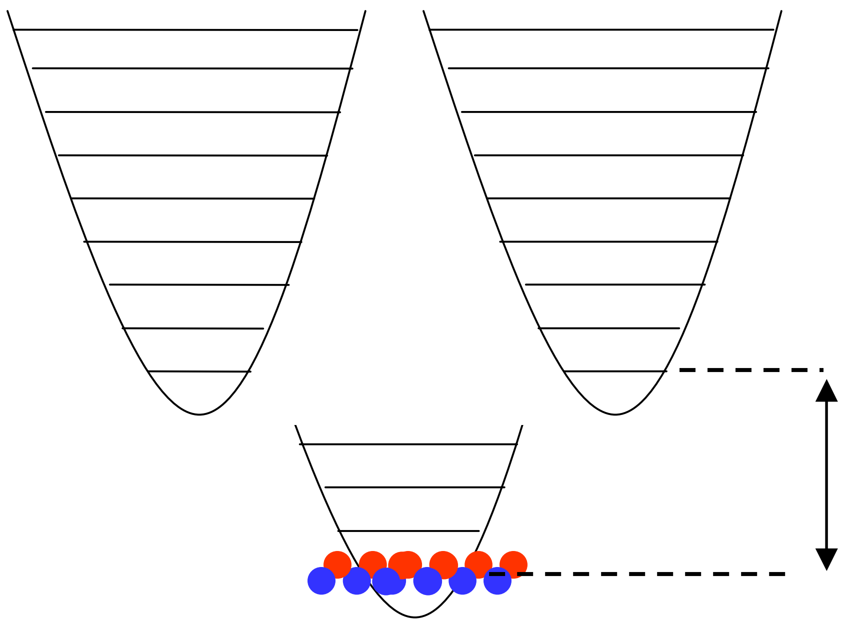


$$E_B = -\frac{\hbar^2}{2ma^2}$$

Direct evaporation of ^{6}Li molecules

Long lifetime of Lithium molecules! (ENS, Rice)
fl Directly evaporate at large and positive *a*
fl Form molecules by three-body recombination when kT á E_B

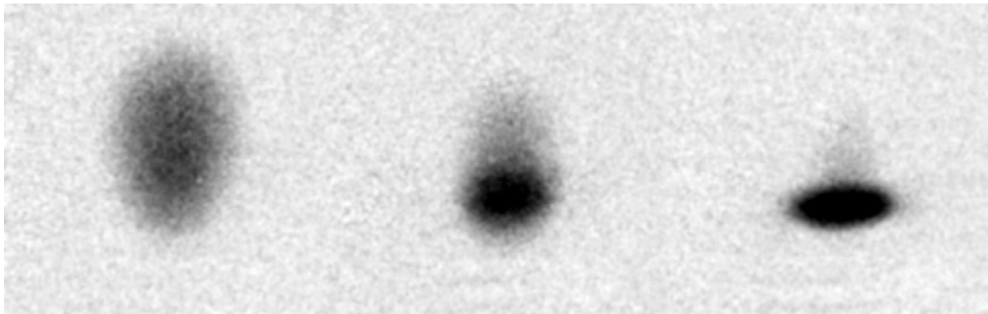
$a > 0$



Cool further
$\Rightarrow$ BEC of molecules!

$$E_B = -\frac{\hbar^2}{2ma^2}$$

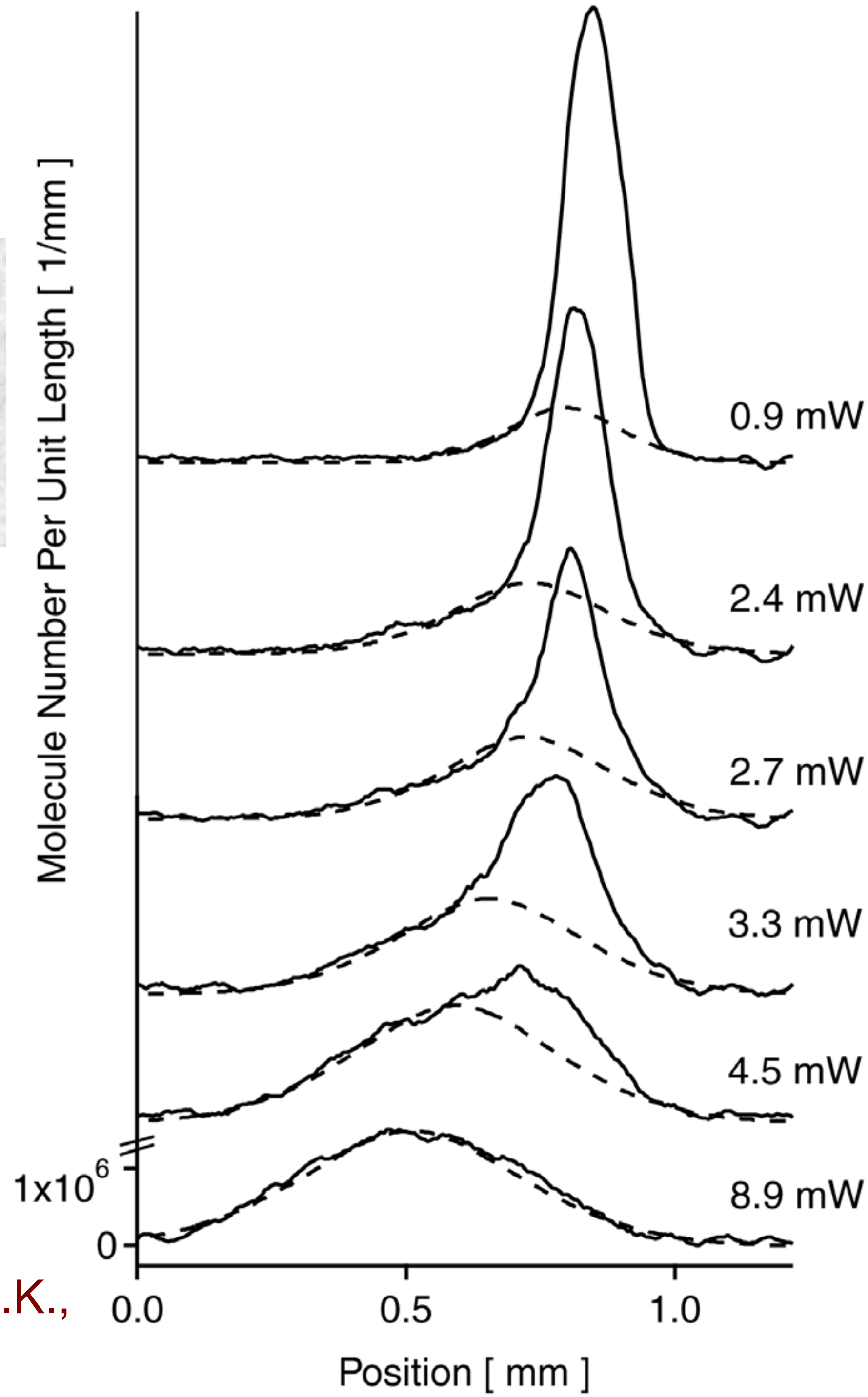
BEC of Molecules

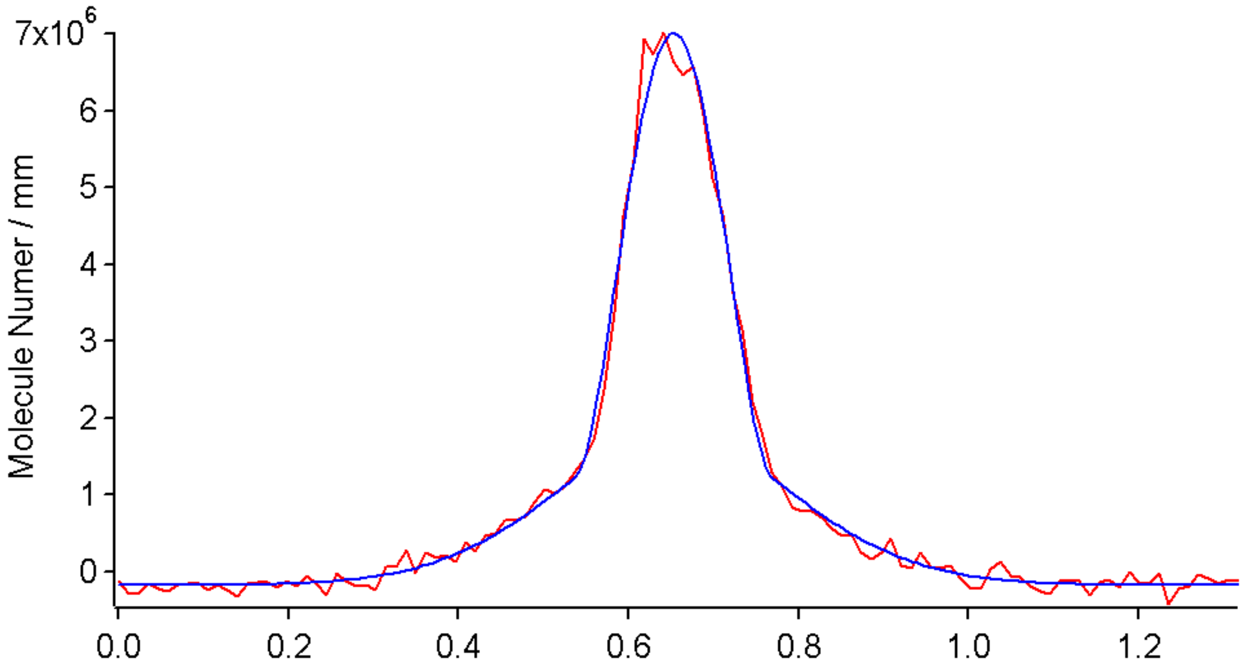


Up to 3 million condensed molecules

Also: Boulder, Innsbruck, Paris

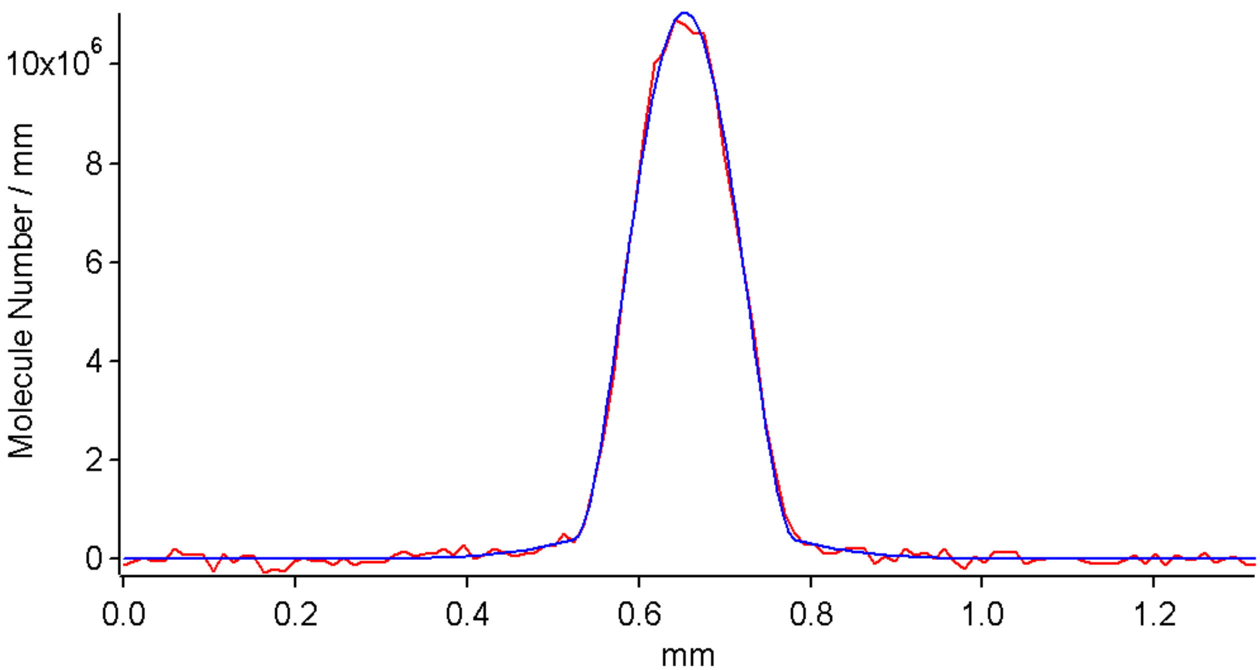
M.W. Zwierlein, C. A. Stan, C. H. Schunck, S.M. F. Raupach, S. Gupta, Z. Hadzibabic, W.K., Phys. Rev. Lett. 91, 250401 (2003)





B = 745G

N_C/N = 45%



B = 797G

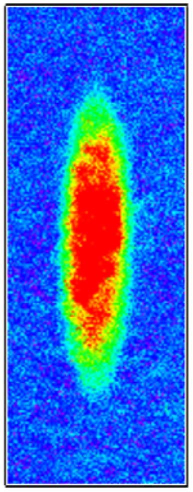
N_C/N = 87%

Direct Imaging of Molecules

Large size R of the molecules:

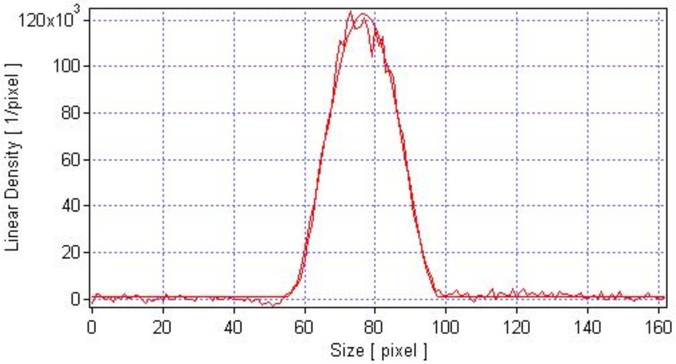
Excited state line-splitting: $\propto \hbar\Gamma(\lambda/R)^3$

For $R > \lambda = 100\,\mathrm{nm}$ absorbs light resonant with the atomic transition:

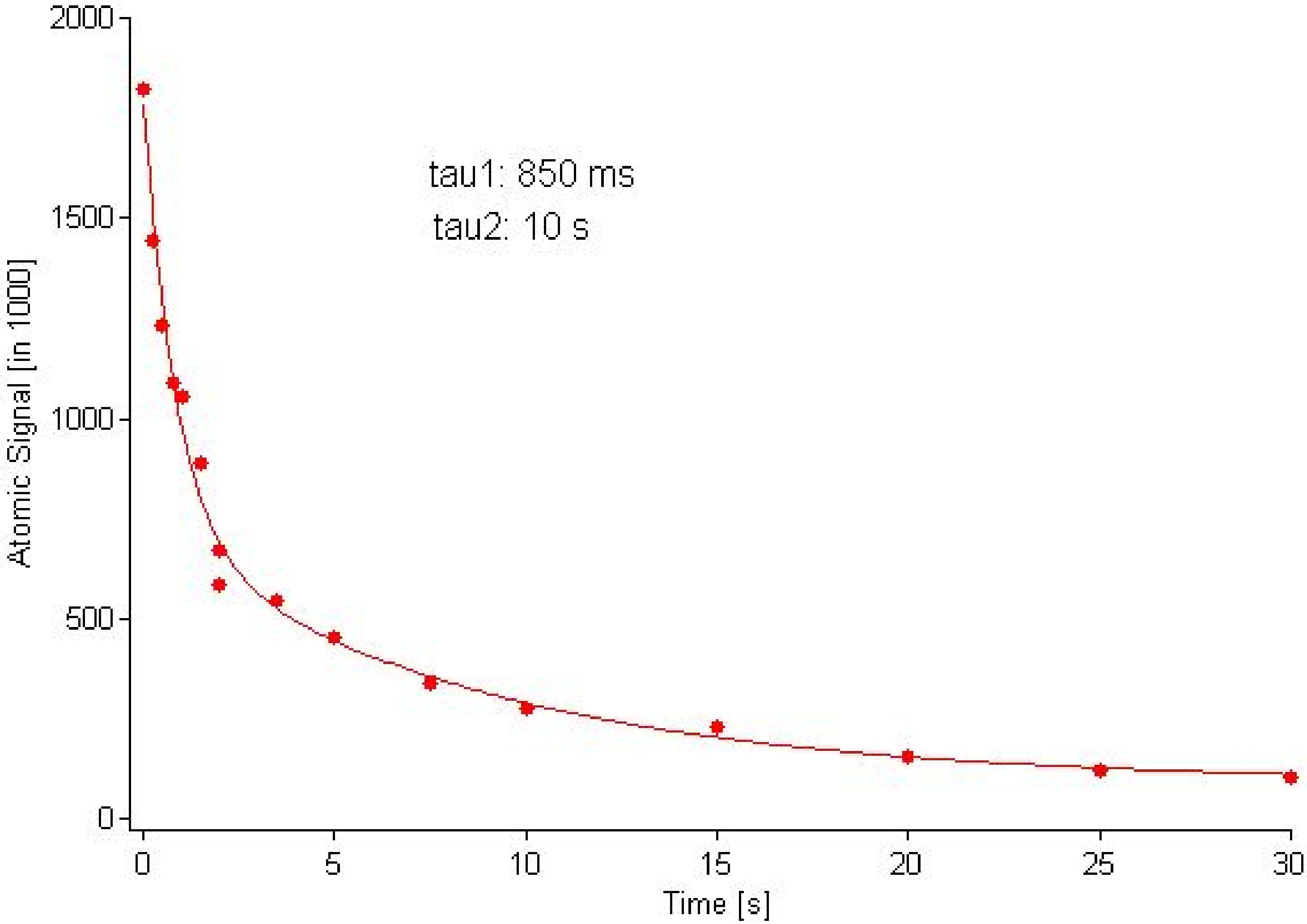


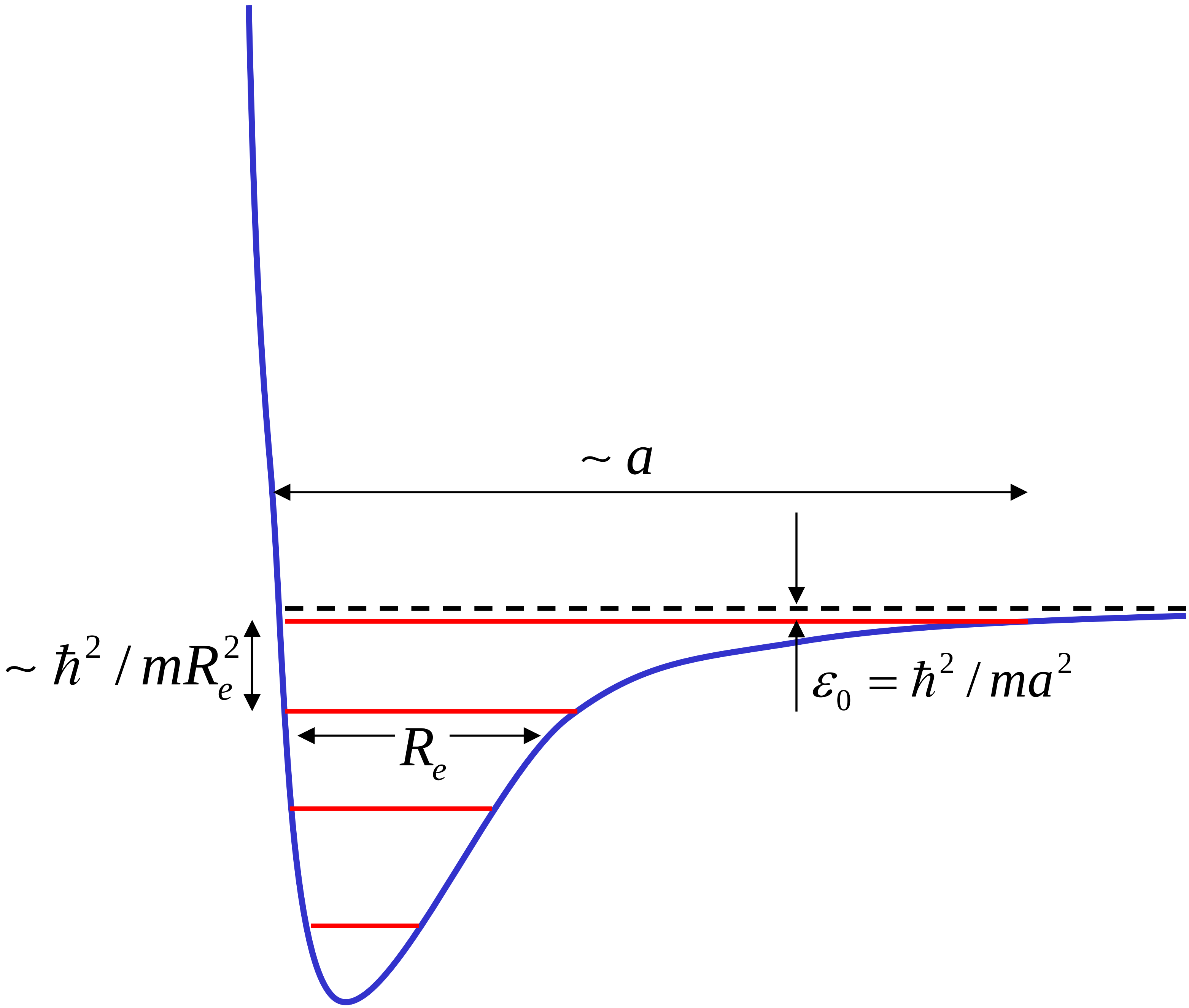
Observations:

Around 770G 100% signal strength
at 650G it is 50%

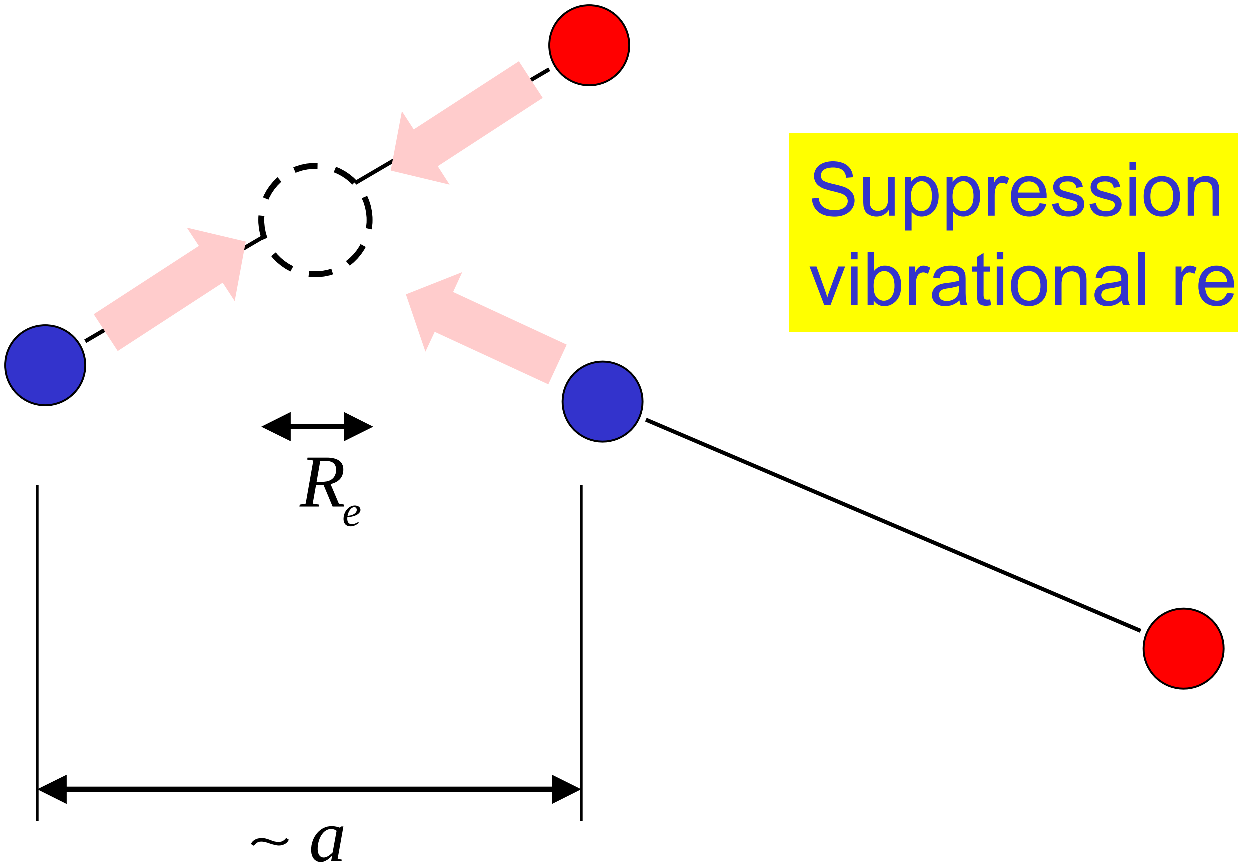


Lifetime of the Molecular BEC





$\sim a$
$\sim \hbar^2 / mR_e^2$
R_e
$\varepsilon_0 = \hbar^2 / ma^2$



Suppression factor for vibrational relaxation $(R_e/a)^2$

Momentum of each atom $\hbar/a$

Relative wave function of the two blue atoms $\psi(r) \approx \sin(kr) \approx \sin(r/a)$

Probability to form molecule with size $R_e \approx |\psi(R_e)|^2 \approx (R_e/a)^2$

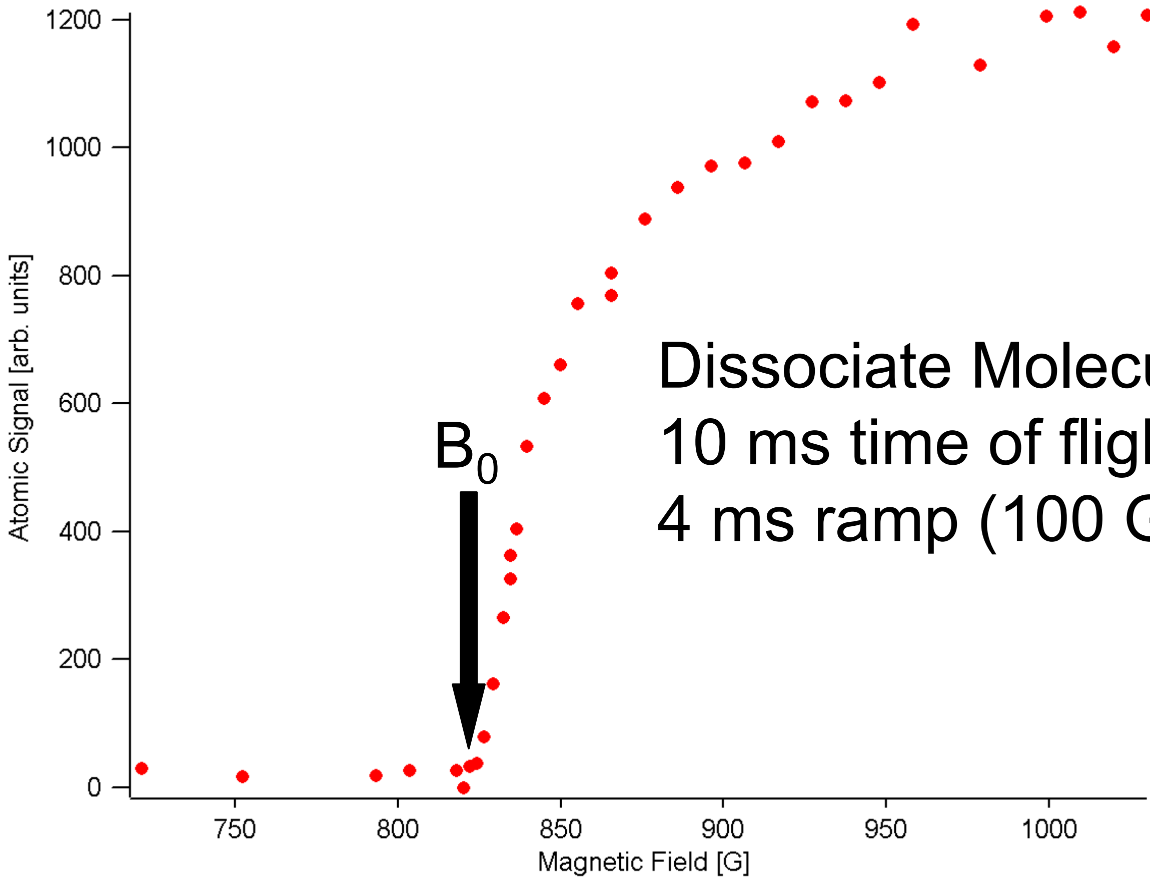
D. S. Petrov, C. Salomon, and G. V. Shlyapnikov, preprint cond-mat/0309010

Crossover from a Degenerate Fermi Gas to a BEC of molecules

Recent results of the last two months:

- Innsbruck
- Boulder
- MIT
- Paris

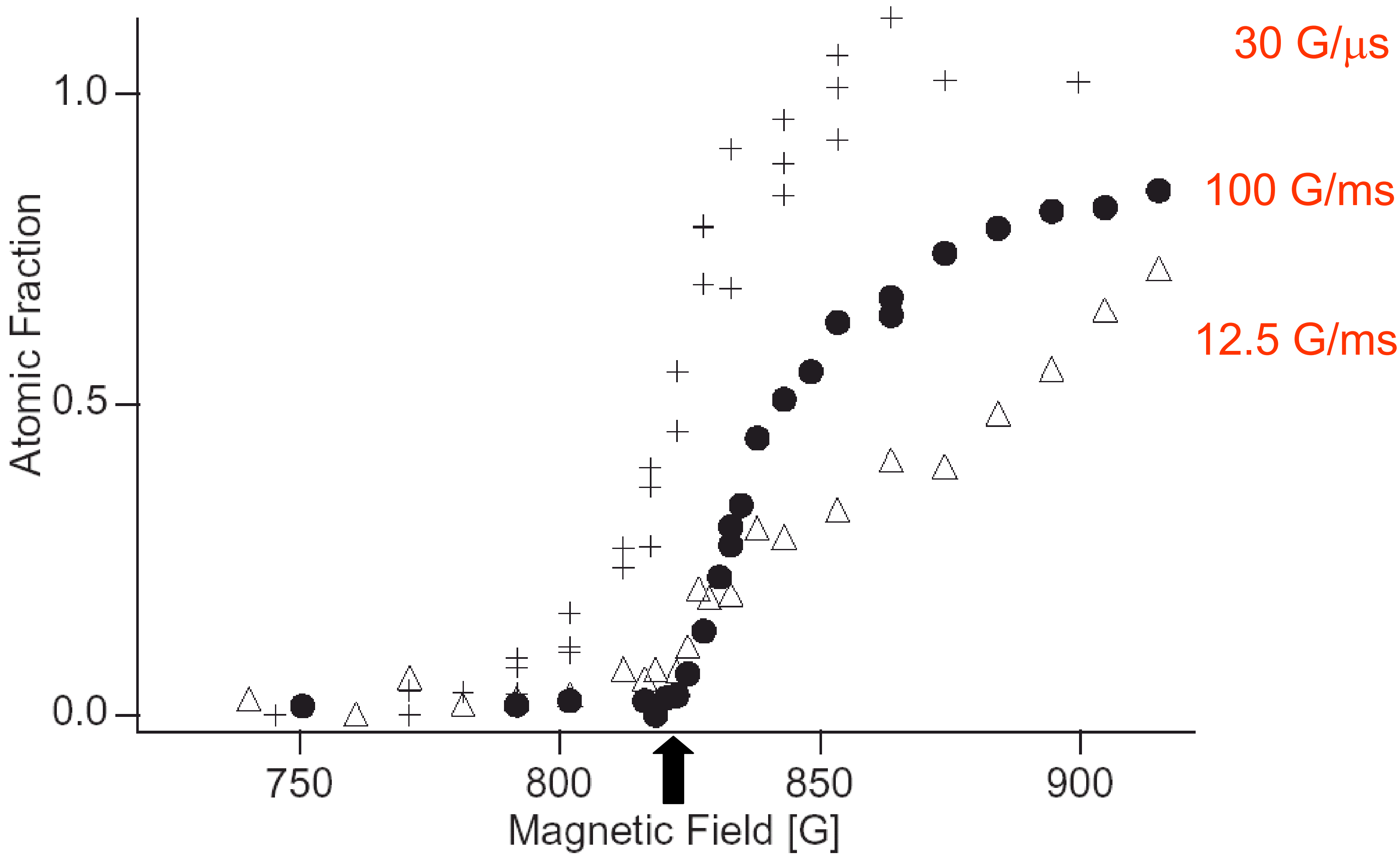
Locating the Feshbach Resonance by Molecule Dissociation



Dissociate Molecules after 10 ms time of flight in a 4 ms ramp (100 G/ms).

B_0 = 822 +/- 3 G

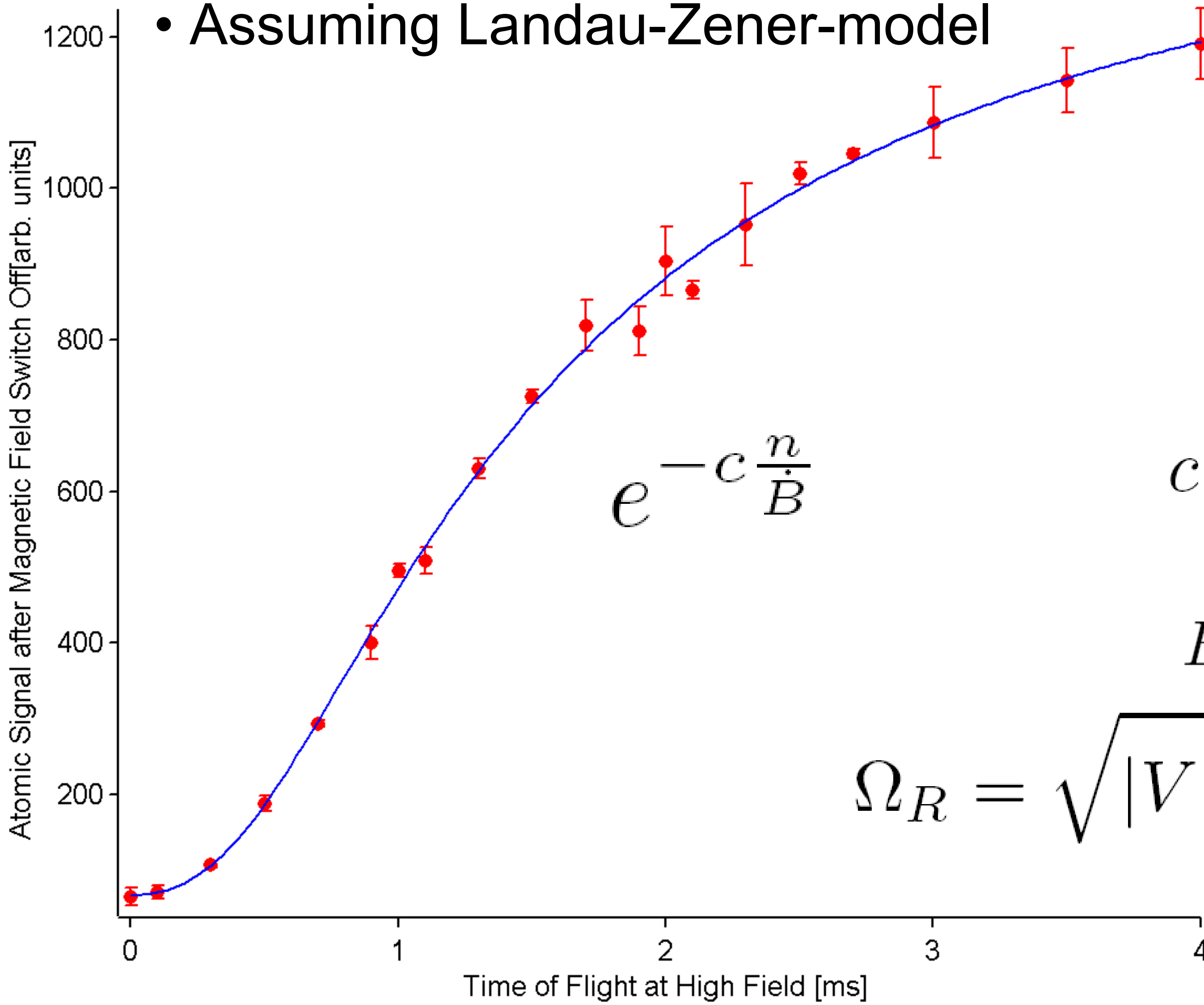
Locating the Feshbach Resonance by Molecule Dissociation



B_0 = 822 +/- 3 G

Strong Coupling Between Atoms and Molecules

- Produce Fermi Sea at 870 G
- Switch off magnetic field after different times of fligh.
- Assuming Landau-Zener-model



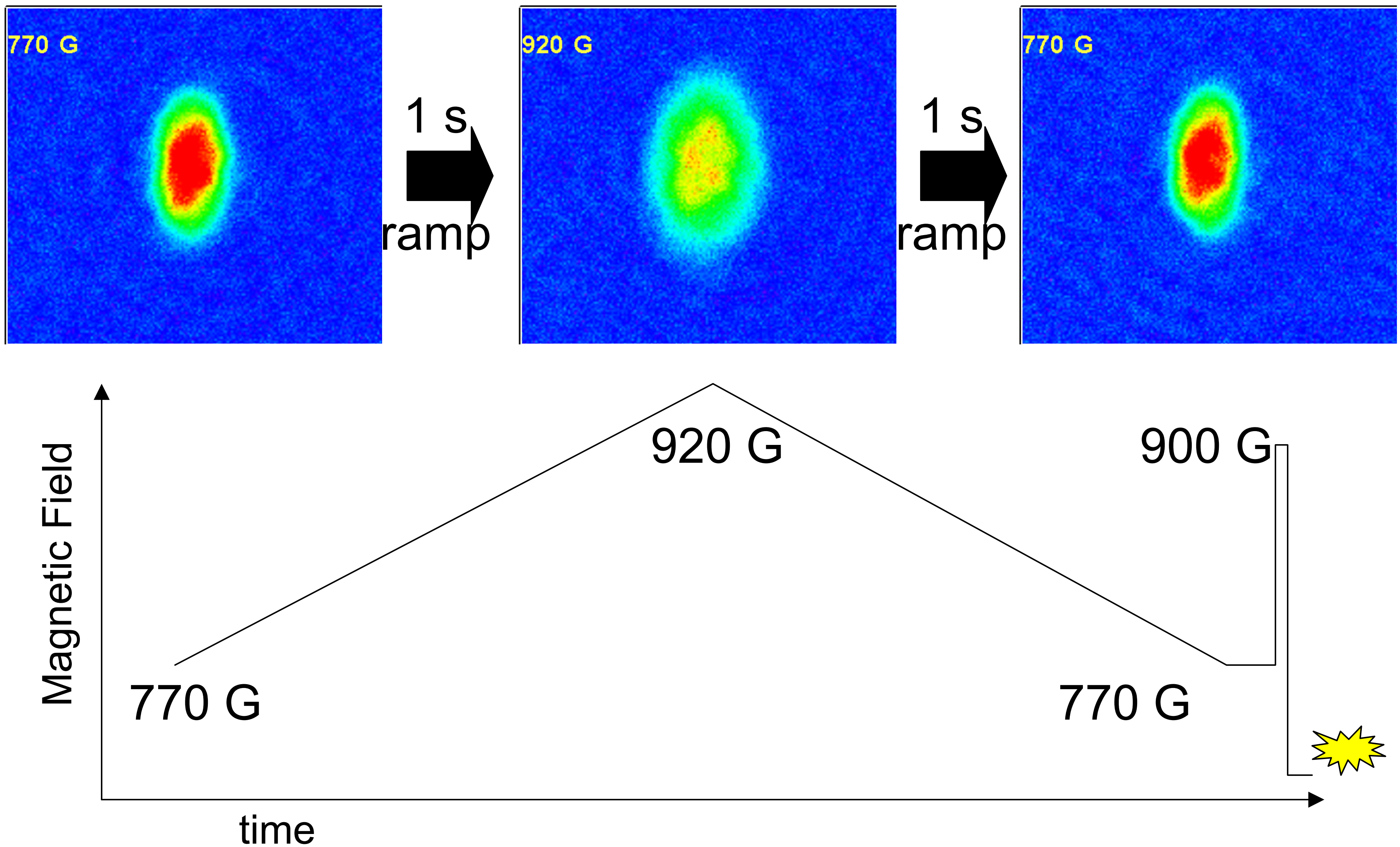
$$e^{-c\frac{n}{\dot{B}}}$$

$$c = \frac{\pi}{2}\frac{\hbar}{\Delta\mu}|V|^2$$

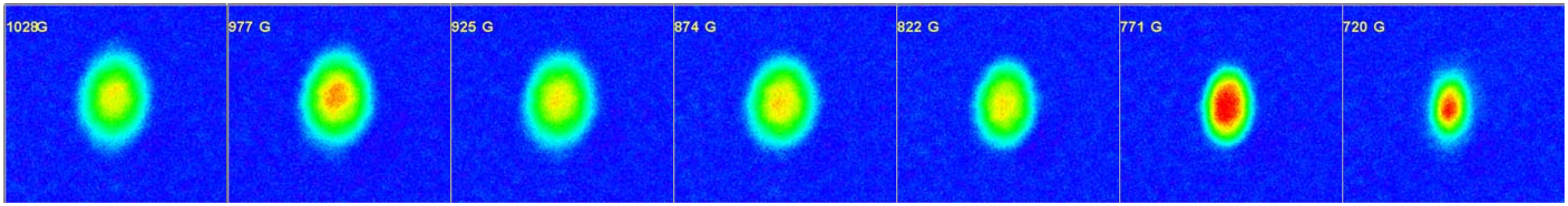
$$\dot{B} = 30\,\mathrm{G}/\mu\mathrm{s}$$

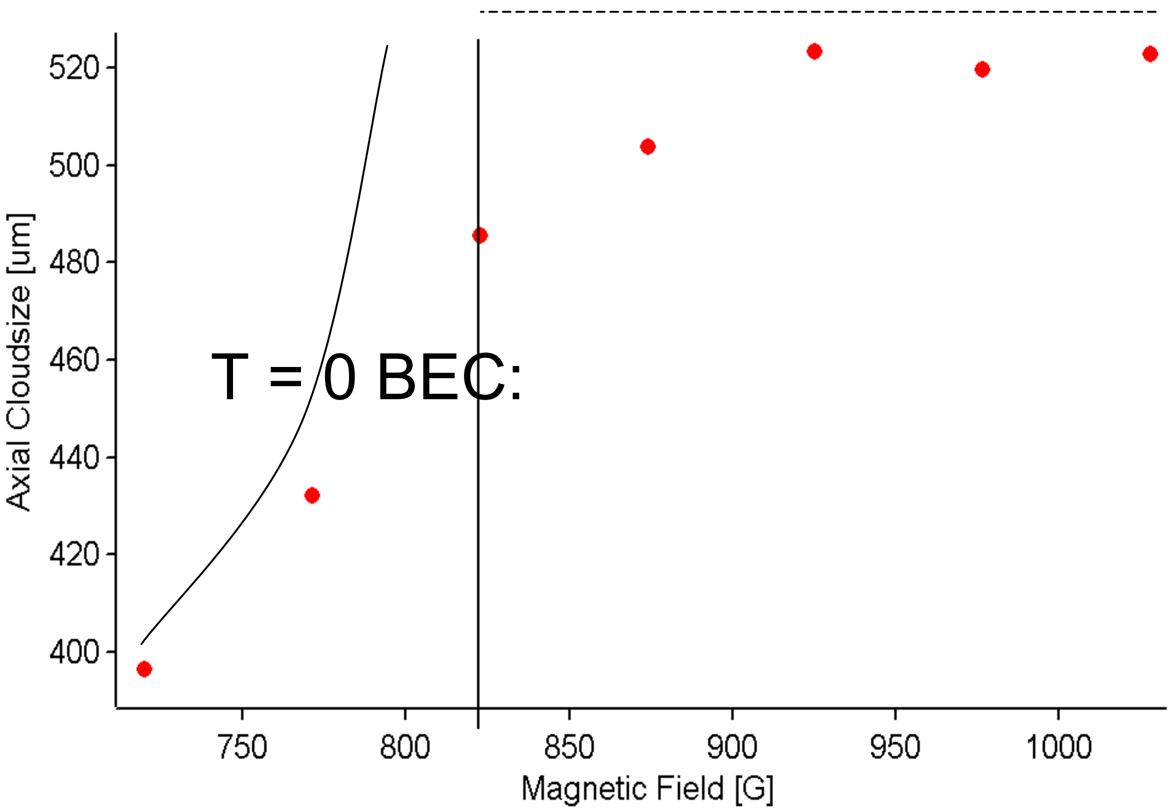
$$\Omega_R = \sqrt{|V|^2\, n} = 6\,\mathrm{MHz}$$

Crossover from a BEC to a DFG …and back



Produce Fermi sea at 920G and ramp in 500ms to final field

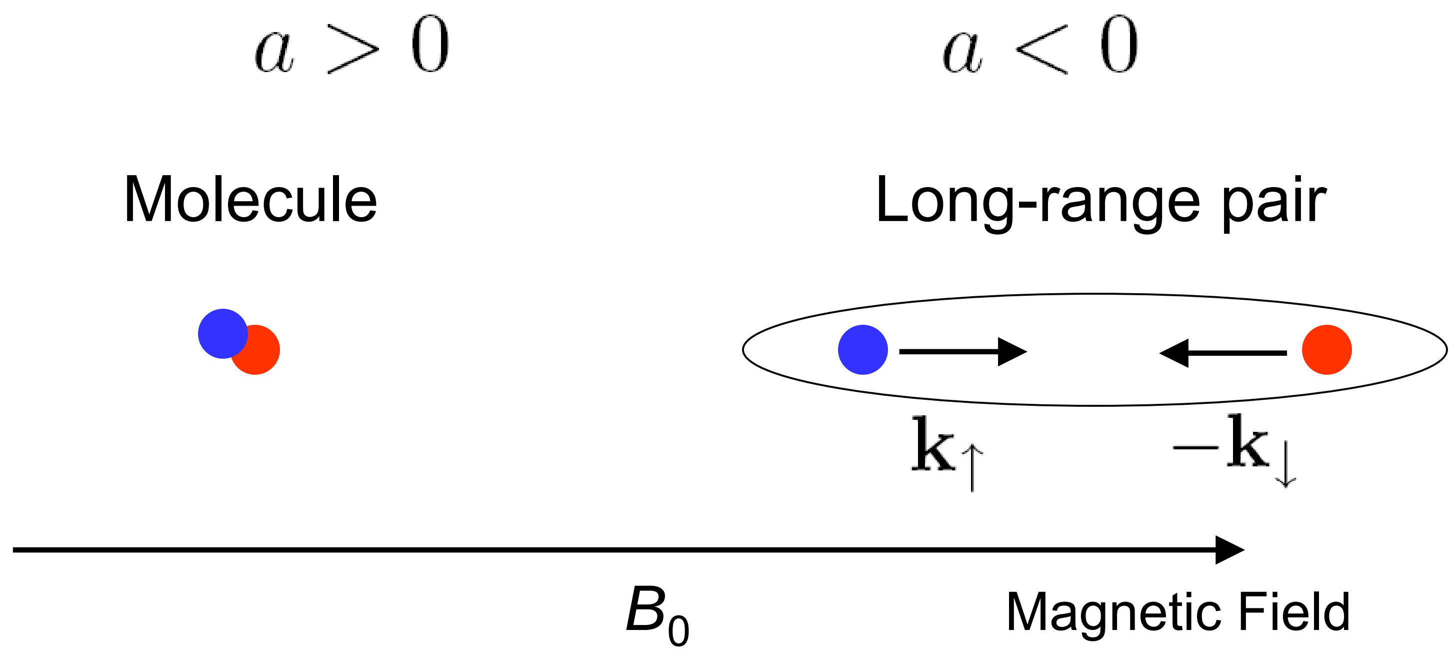




T = 0 Fermi cloud:

Innsbruck
Paris

How to detect
Condensates of Pairs of Fermions?



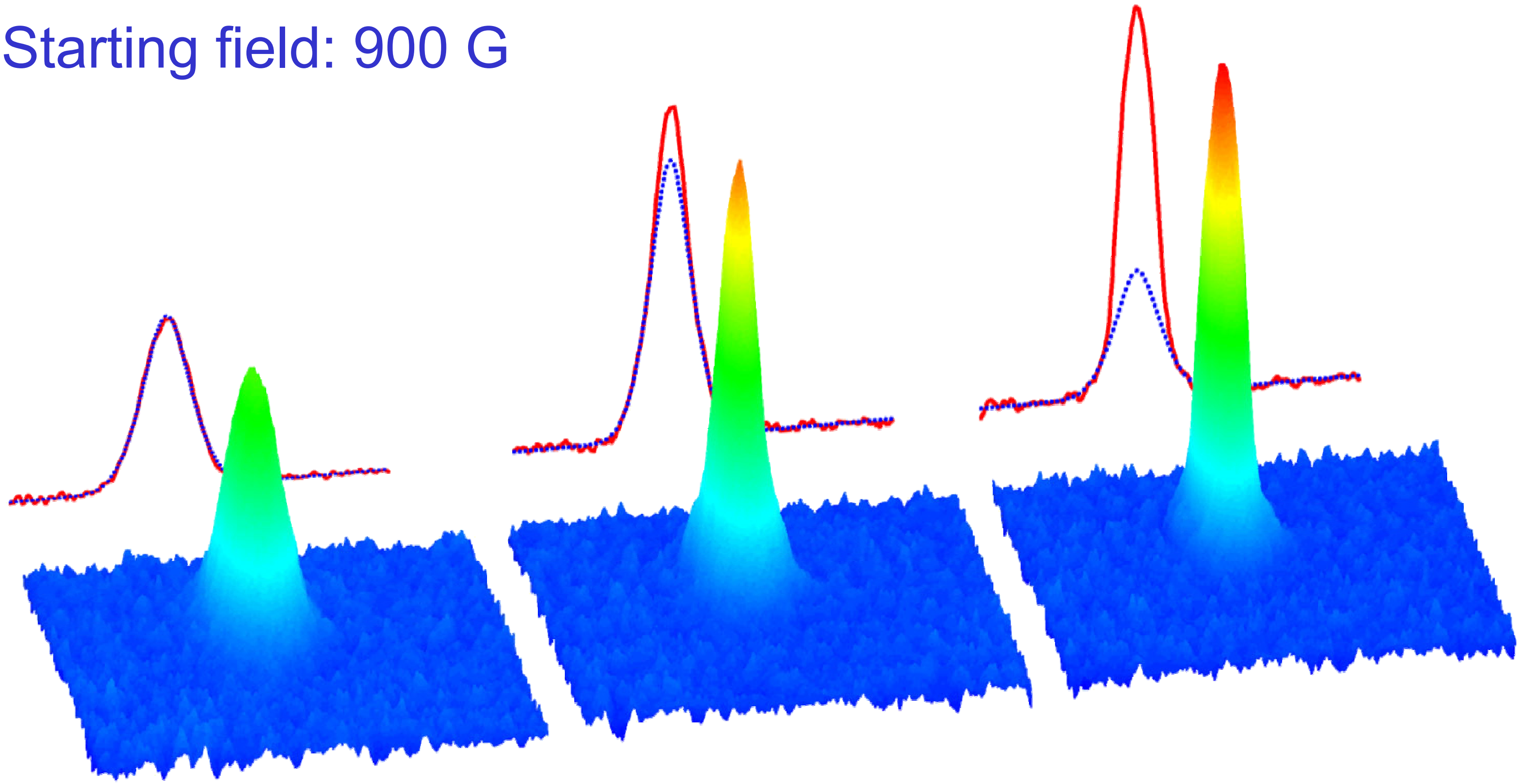
Idea: Quickly ramp over resonance to rapidly transfer fermionic atom pairs into molecules

Is the ramp fast enough to neglect collisions or other dynamics?

Limitation:
Probably works only for next neighbors
Can only detect “molecular” pairs, not long-range Cooper pairs

Observation of Condensates!

Starting field: 900 G

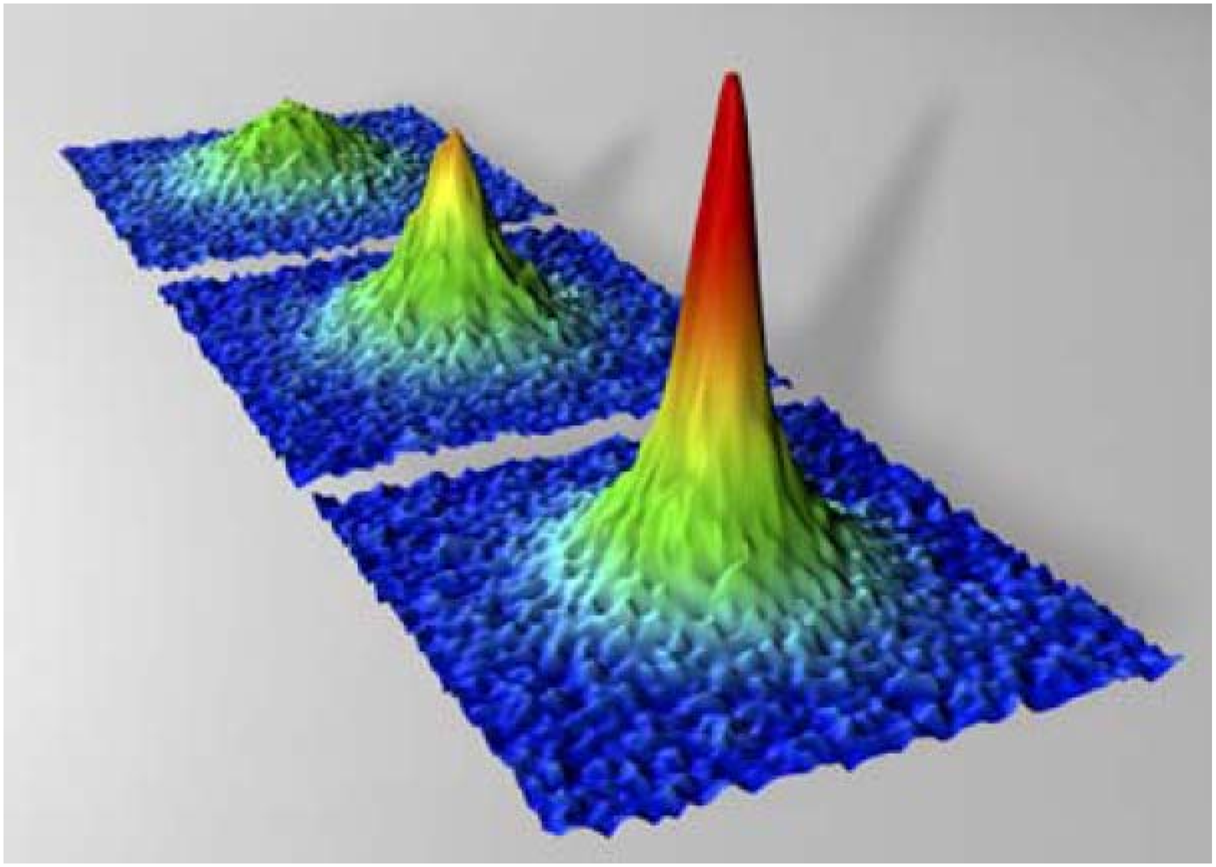


Initial temperature: $T / T_F = 0.2$ $T / T_F = 0.1$ $T / T_F = 0.05$

Also : C. A. Regal et al., Phys. Rev. Lett. **92**, 040403 (2004)

M.W. Zwierlein, C.A. Stan, C.H. Schunck, S.M.F. Raupach, A.J. Kerman, W.K.
preprint, cond-mat//0403049

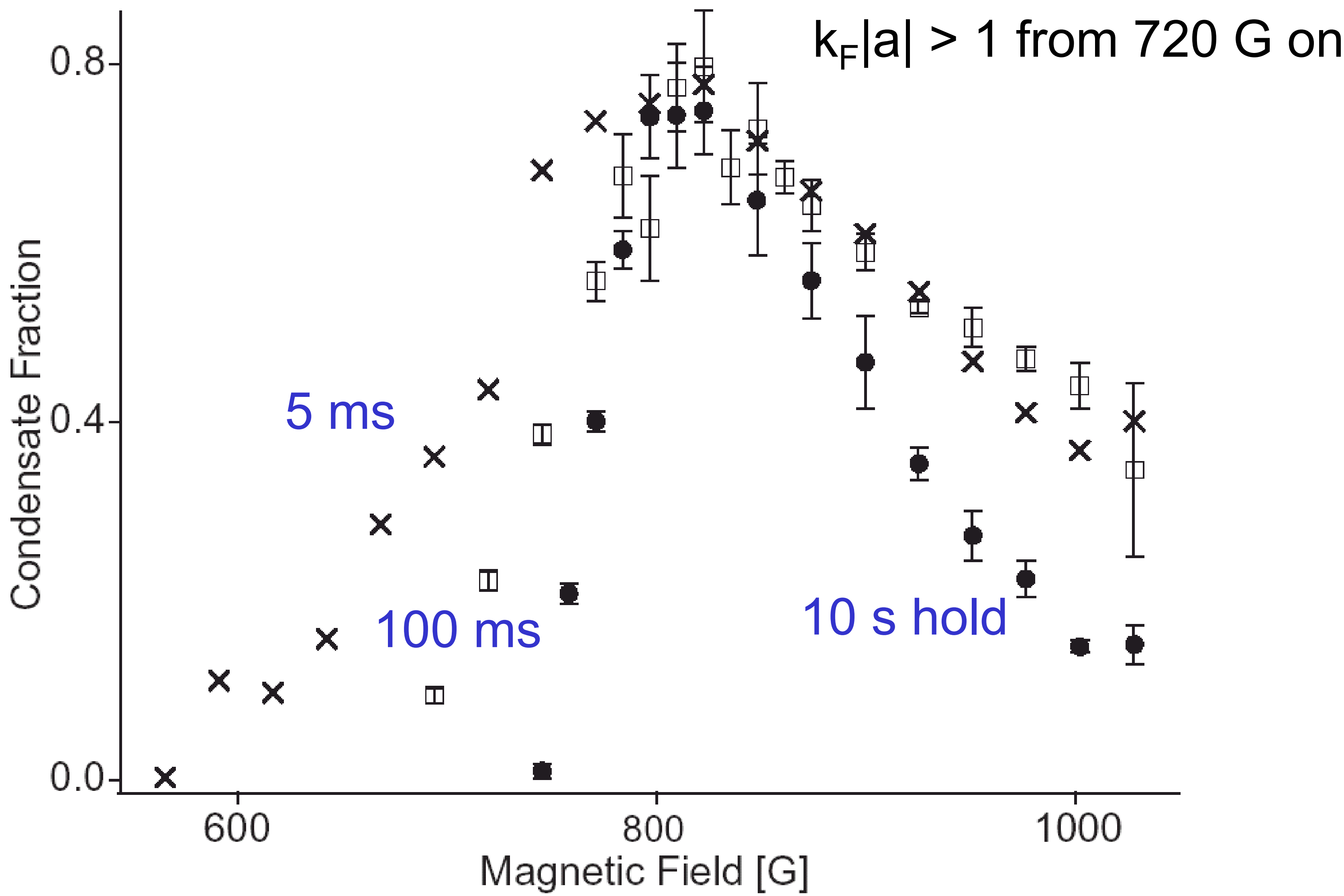
Pair condensation above the Feshbach resonance



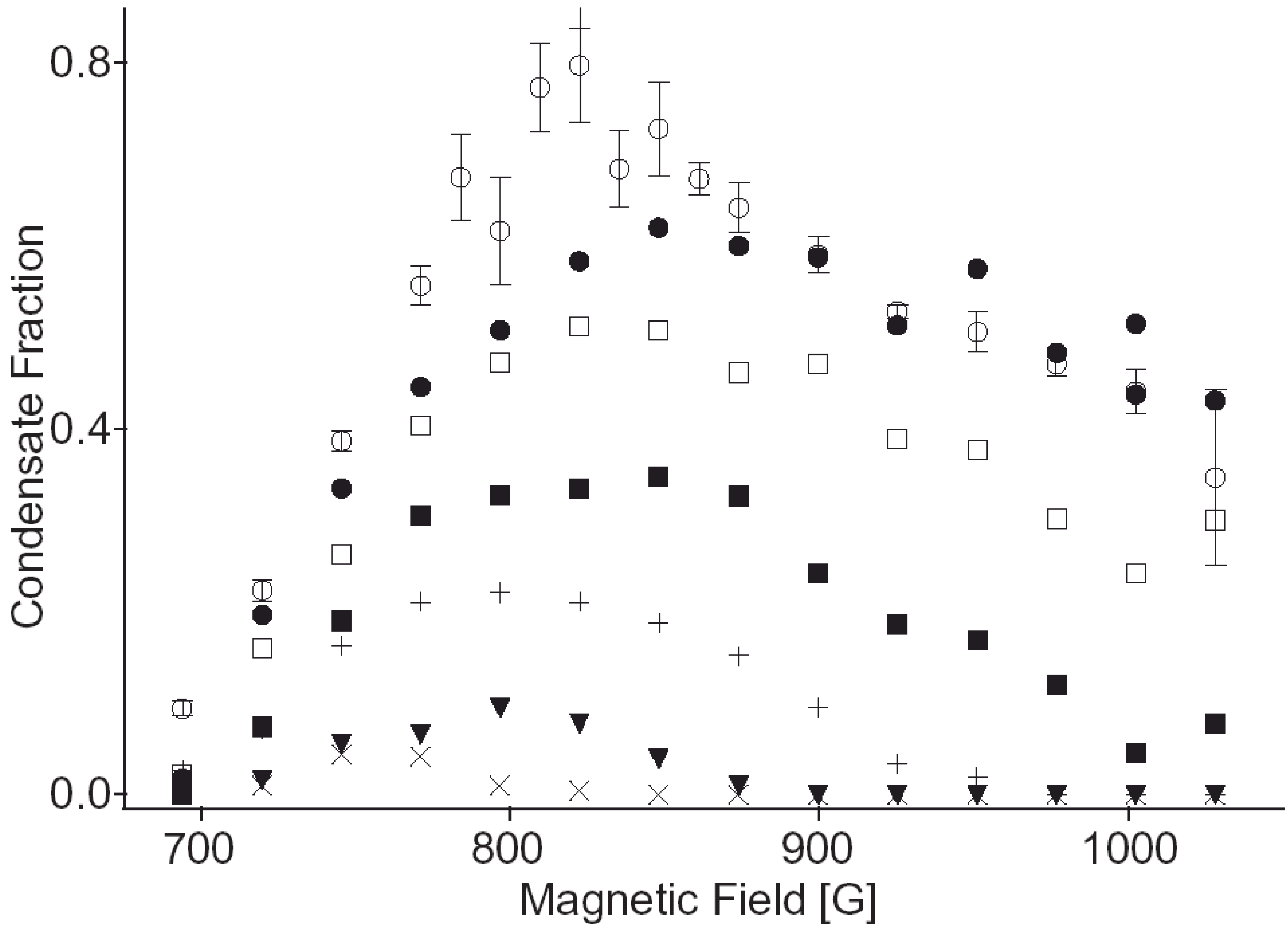
Claim for Cooper pair condensation

C. A. Regal, M. Greiner, and D. S. Jin, Phys. Rev. Lett. 92, 040403 (2004)

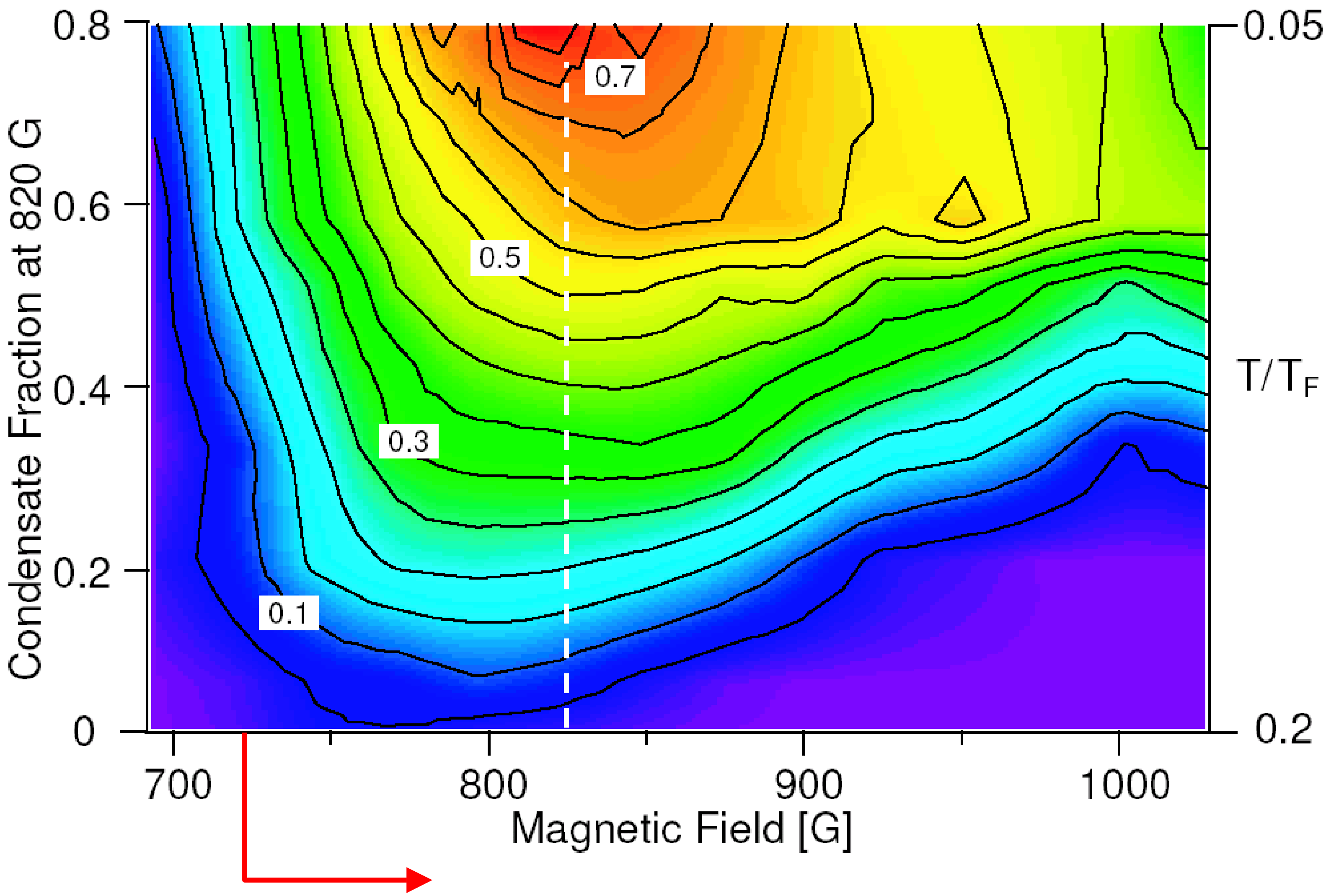
Condensate Fraction vs. hold time



Condensate Fraction vs. temperature



„Phase diagram“ for pair condensation

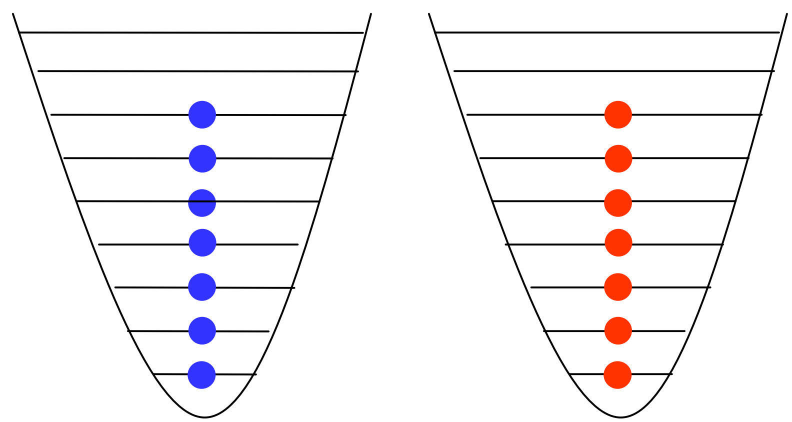


$k_F|a| > 1$

What‘s going on?

Tentative interpretation:
High condensate fraction implies pre-existing molecules above the two-body resonance position – stabilized by the Fermi sea

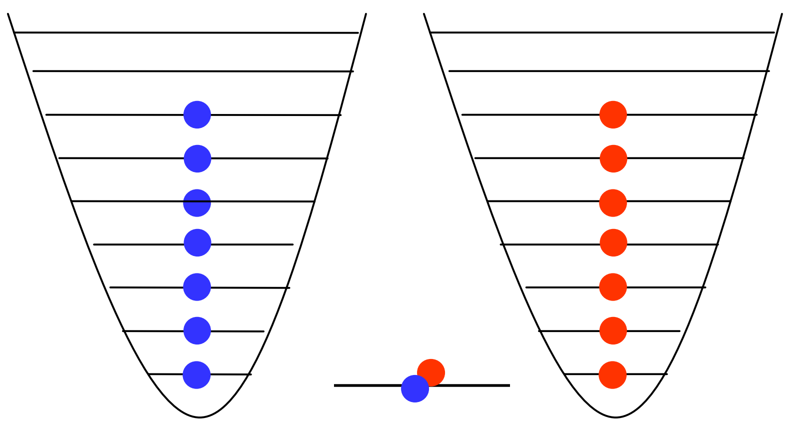
Simple model, neglecting interactions



What‘s going on?

Tentative interpretation:
High condensate fraction implies pre-existing molecules above the two-body resonance position – stabilized by the Fermi sea

Simple model, neglecting interactions



At T/T_F=0.05: Pauli blocking factor 10^{-16}

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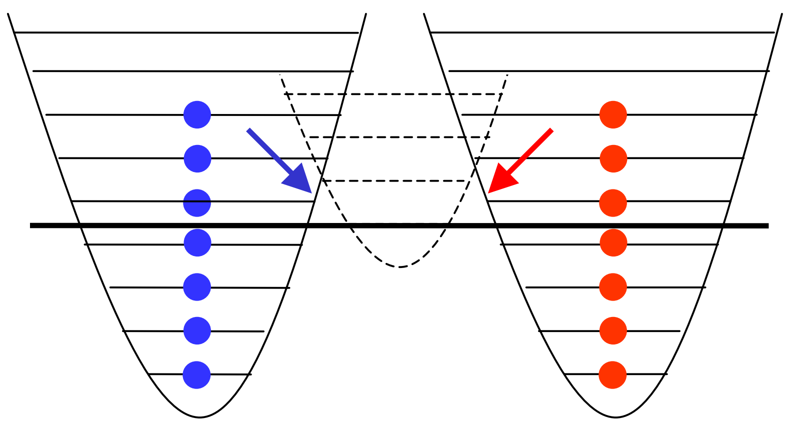

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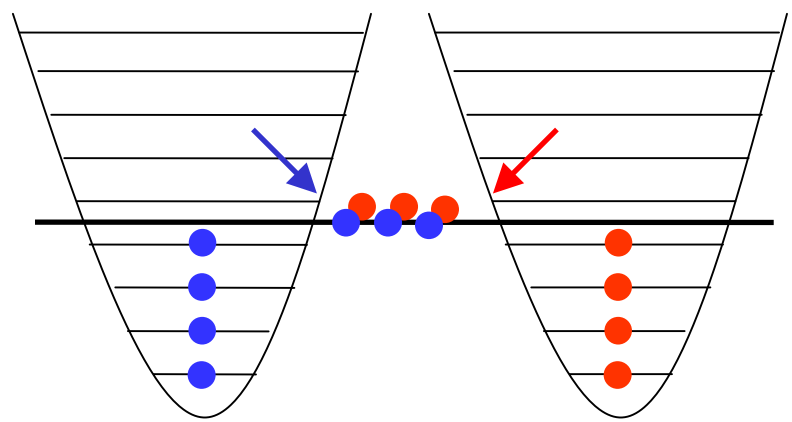

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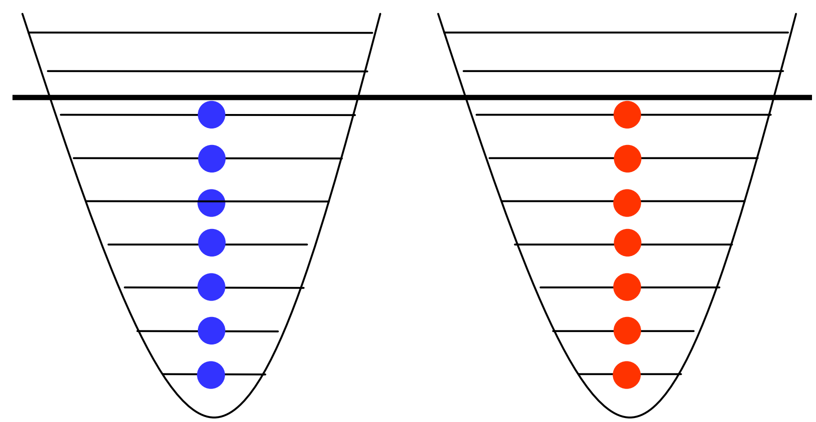
BEC-BCS transition only occurs when
E_{Mol} t 2 E_F or equivalently k_F | a | 1

Simple model, neglecting interactions

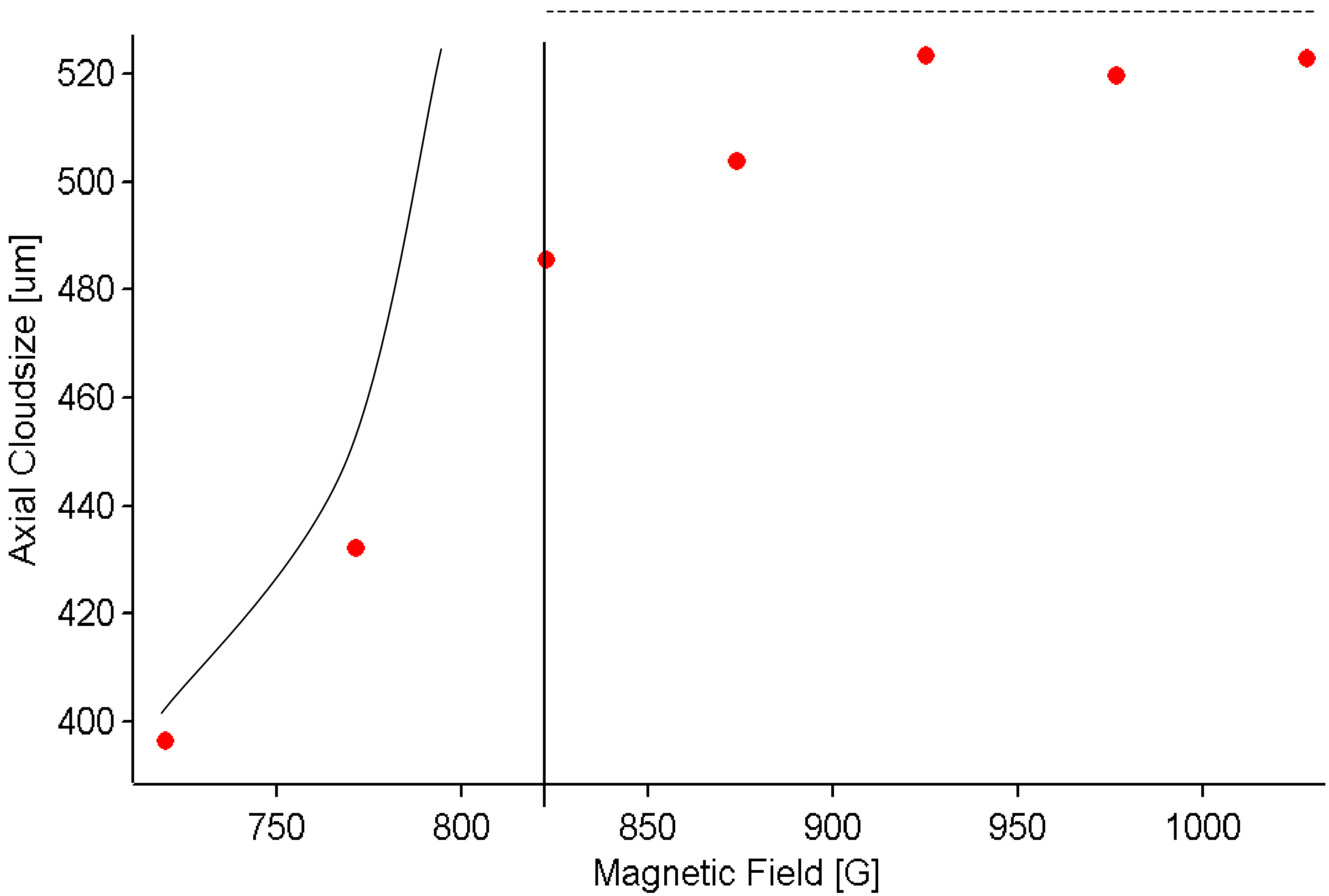


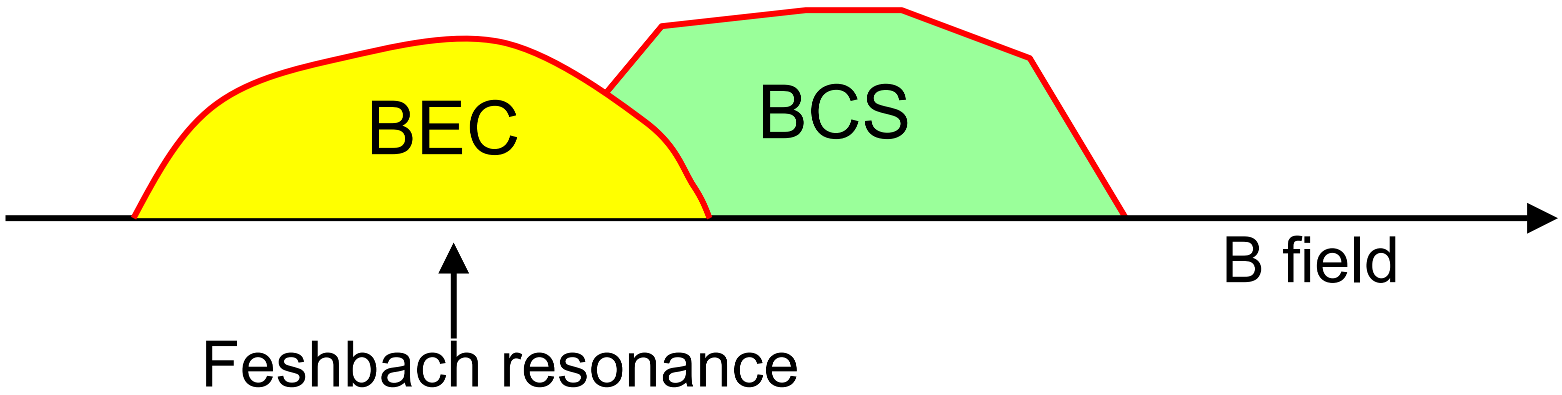
Also: H. T. C. Stoof, preprint cond-mat/0402xxx

Prediction

Fermi sea „leaks“ into molecule BEC:

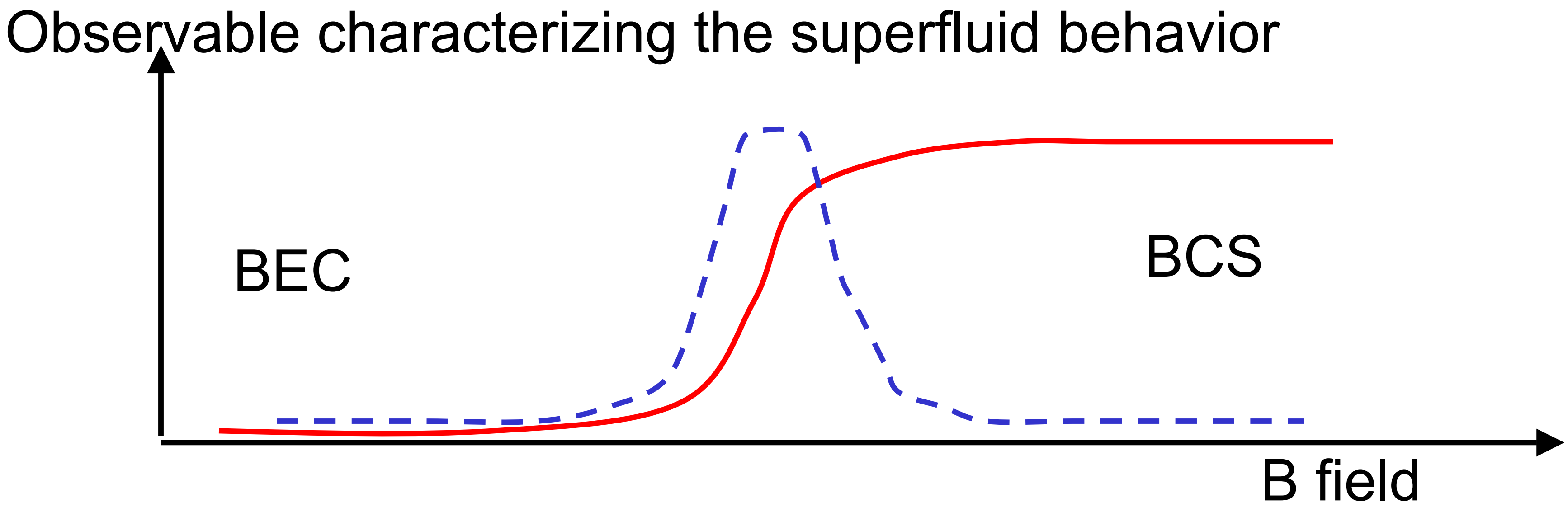
fl k_F is reduced, cloud shrinks!





• None of the experimental results are inconsistent with the existence of a molecular condensate above the Feshbach resonance

• None of the experiments has conclusively identified any feature characteristic for the BCS regime, e.g. delocalization of pairs



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The Lithium Team

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