Ultracold molecules - a new frontier for quantum & chemical physics

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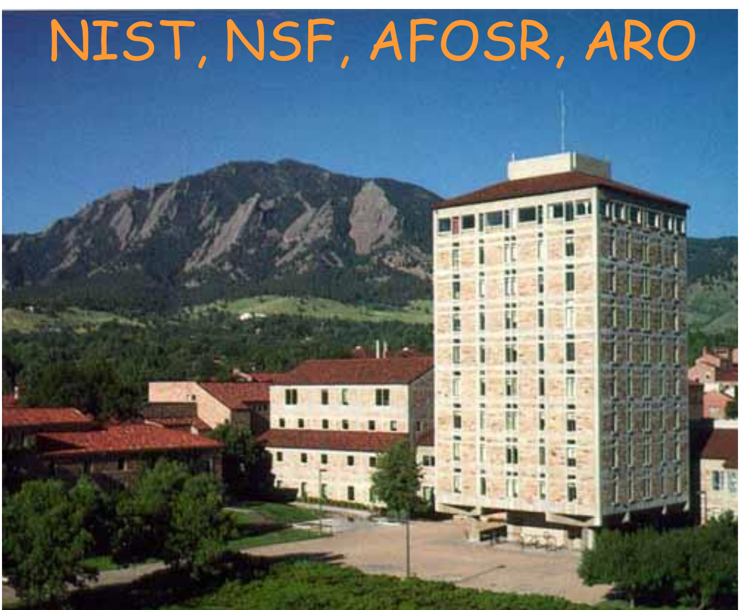
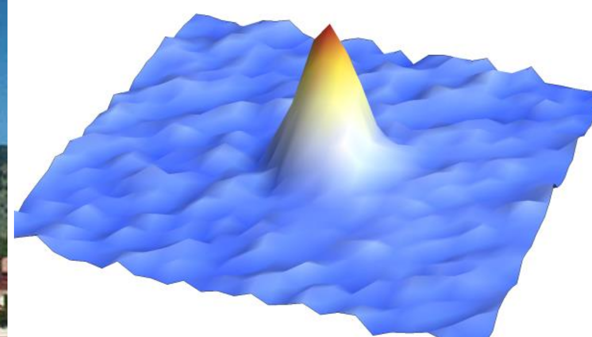
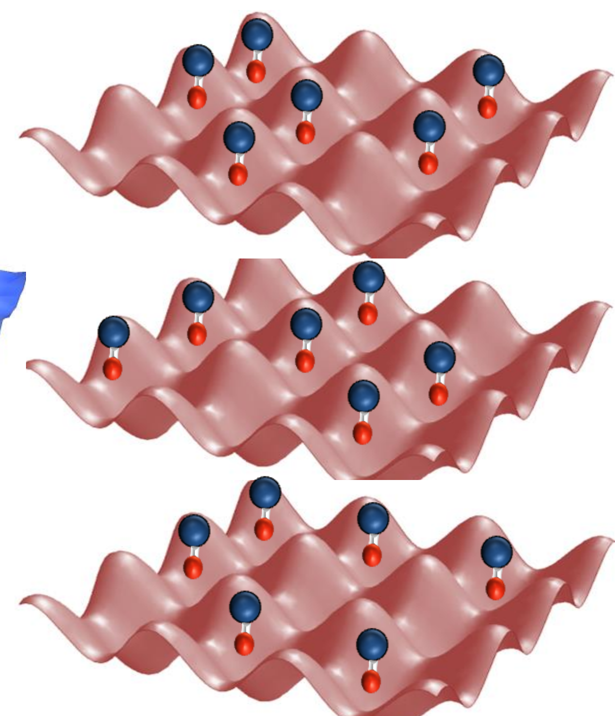
University of Virginia
April 24, 2015







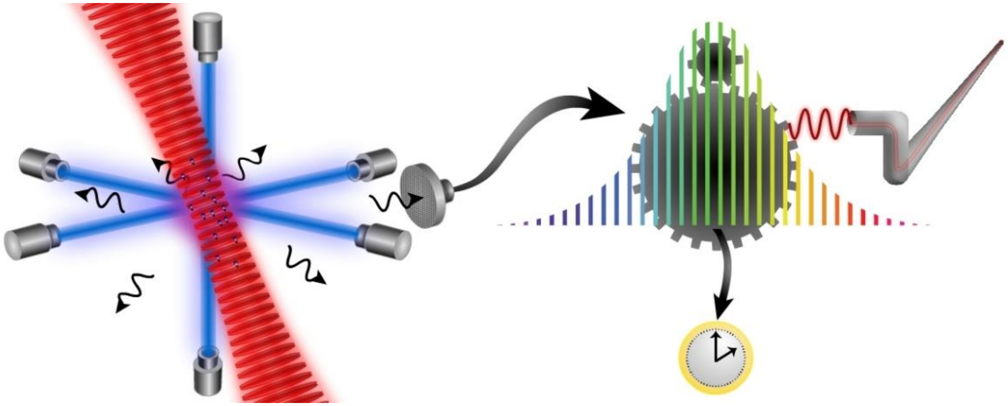
Ultracold atomic matter

Precise control of a quantum system

The most precise measurements, e.g., clock

Quantum information

Quantum sensors



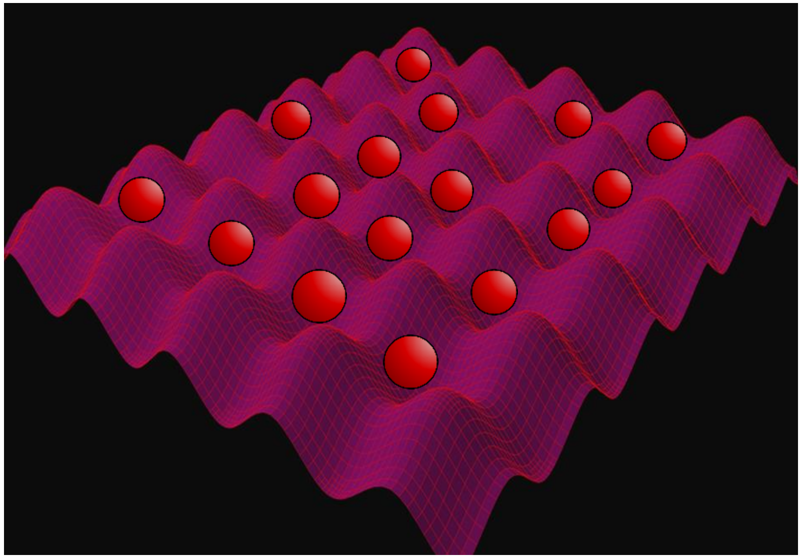
Control: A tool for understanding complexity

Strongly correlated many-body quantum systems

- Superfluidity & Superconductivity

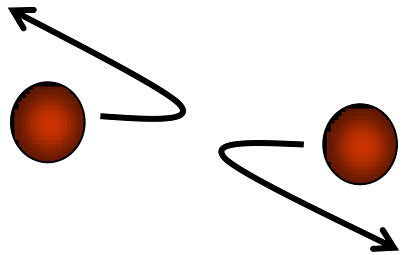
Control atomic interactions

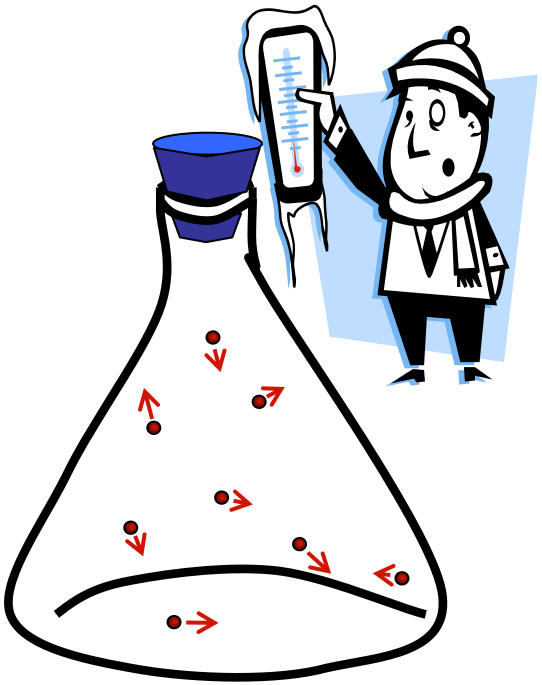
Regulate atomic motions

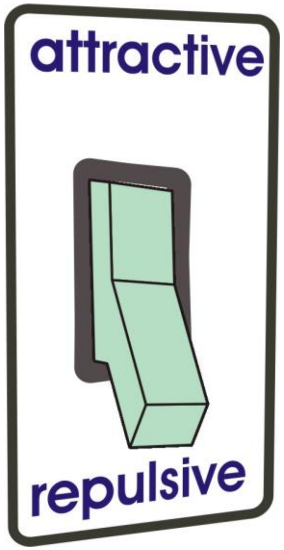


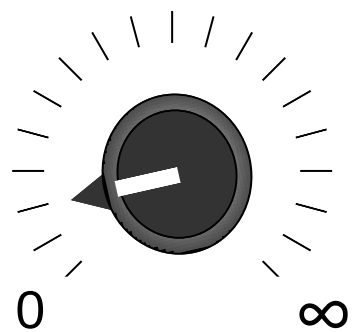
Atomic Interactions

Short-range collisions







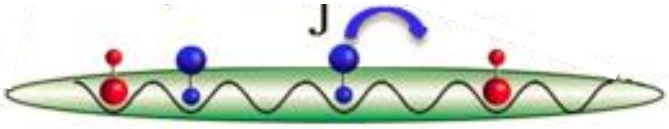


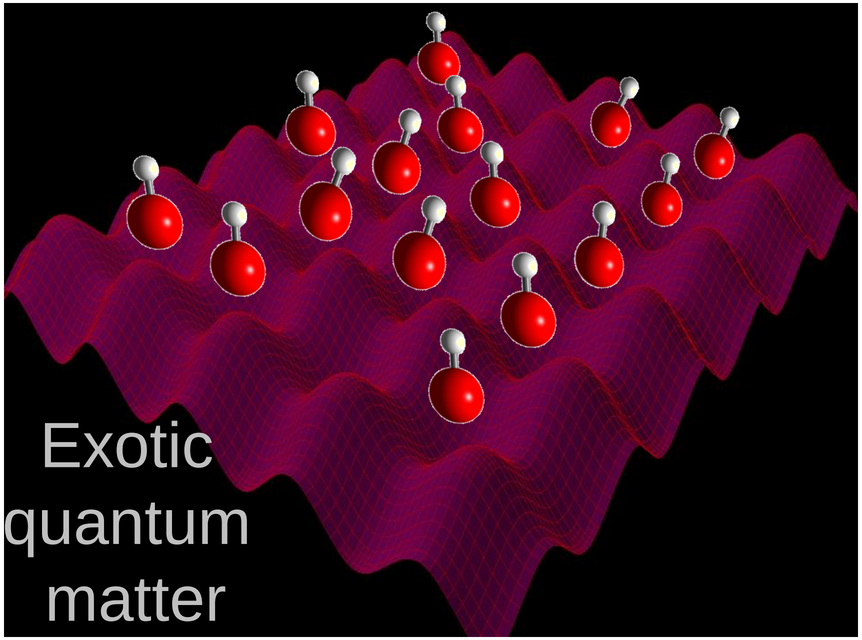
interaction strength

We can understand & control them!

Quantum gas of polar molecules

- Extend capability to control complex quantum systems
- Study frontier problems in strongly correlated quantum material, with
  - well-understood microscopics
  - tunable, long-range interactions
  - non-equilibrium quantum dynamics

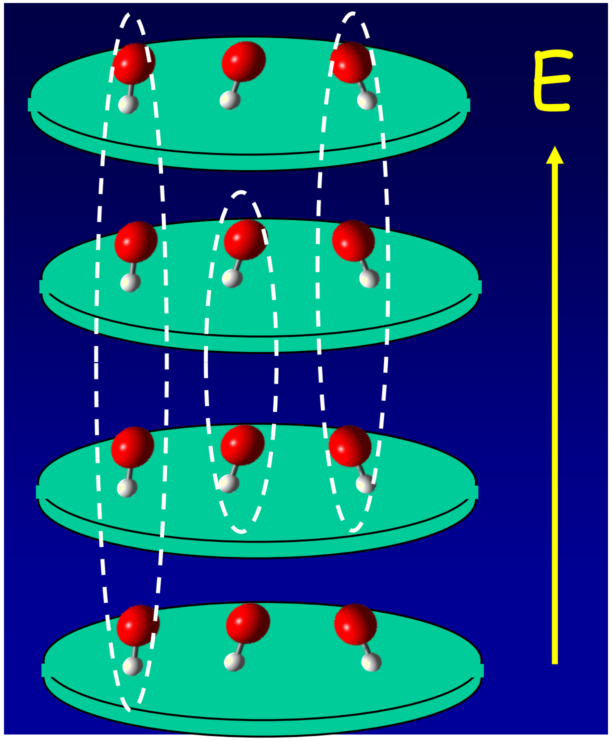




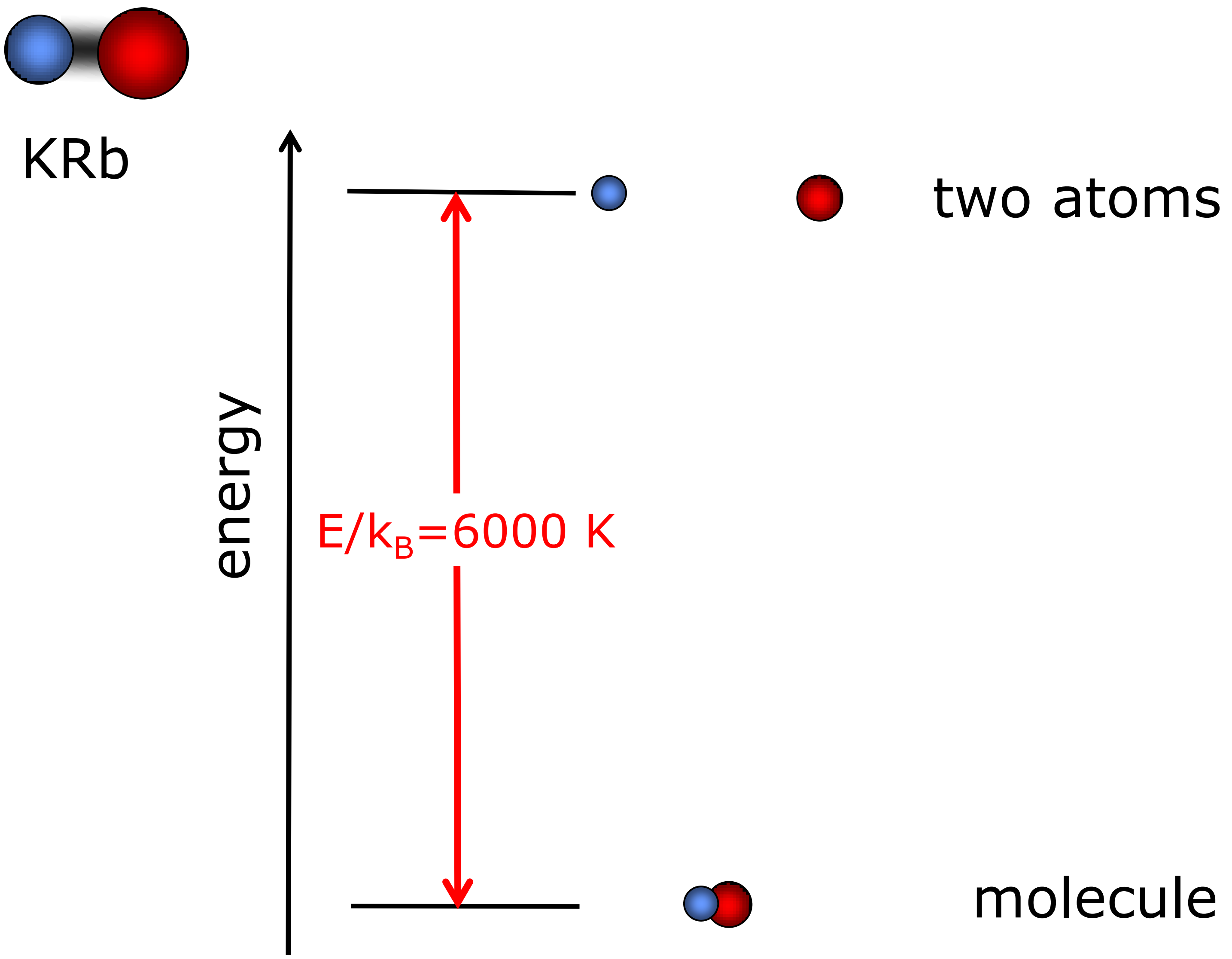
Quantum metrology,

Correlated material,

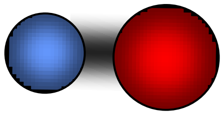
Chemistry



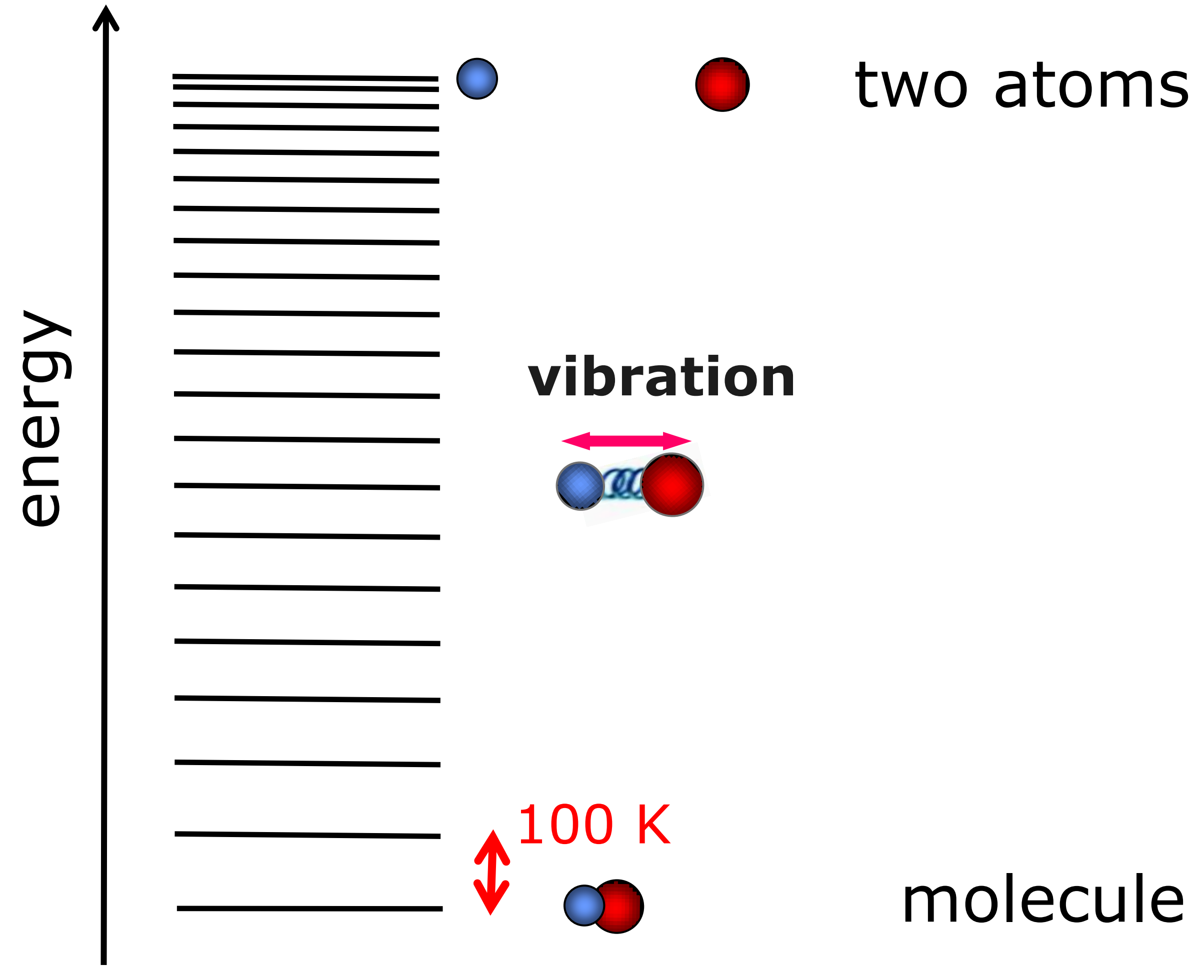
Ultracold molecules: The challenge



Ultracold molecules: The challenge

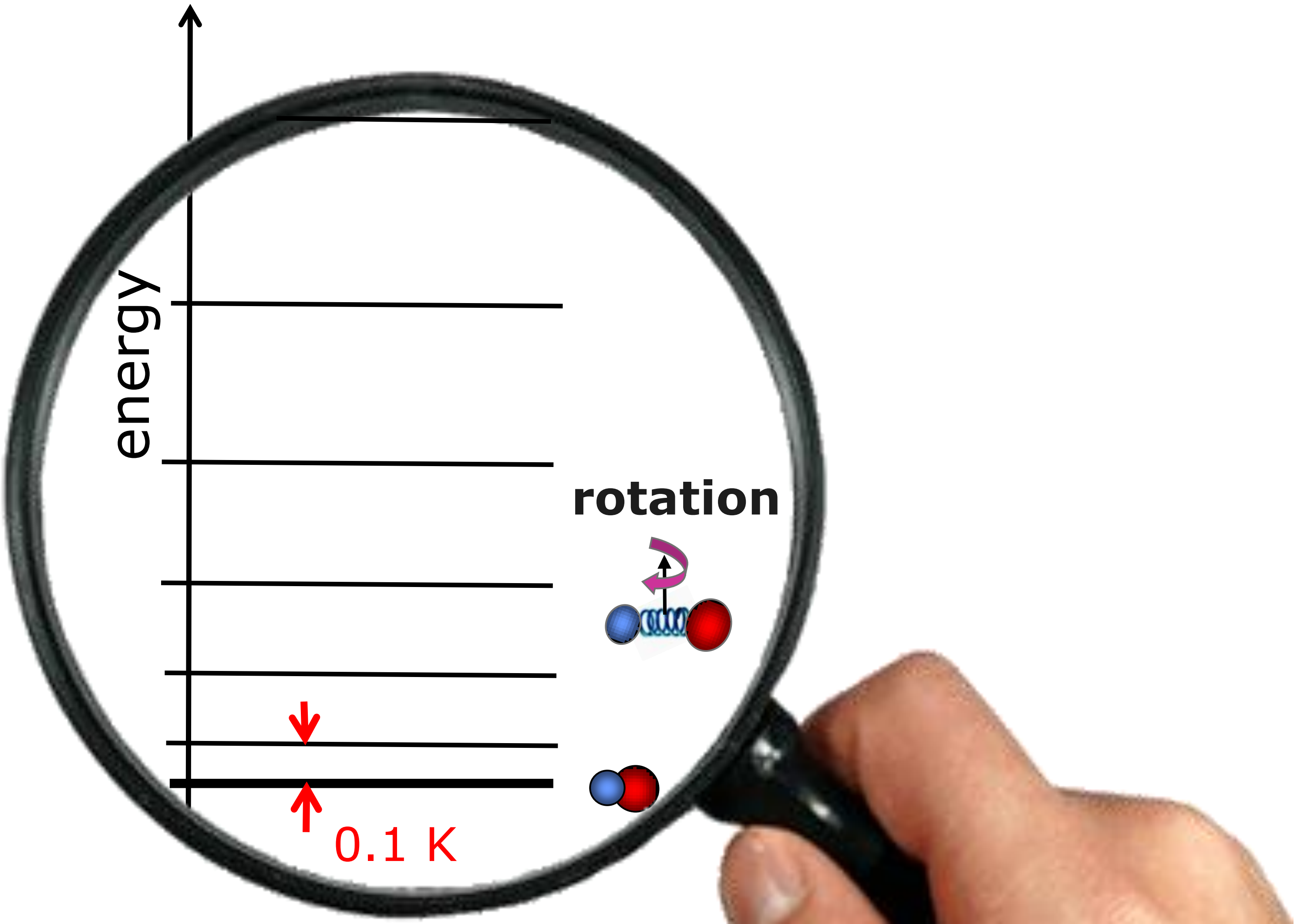


Molecules are complex!

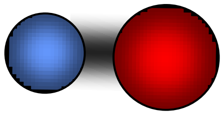


Ultracold molecules: The challenge

Molecules are complex!



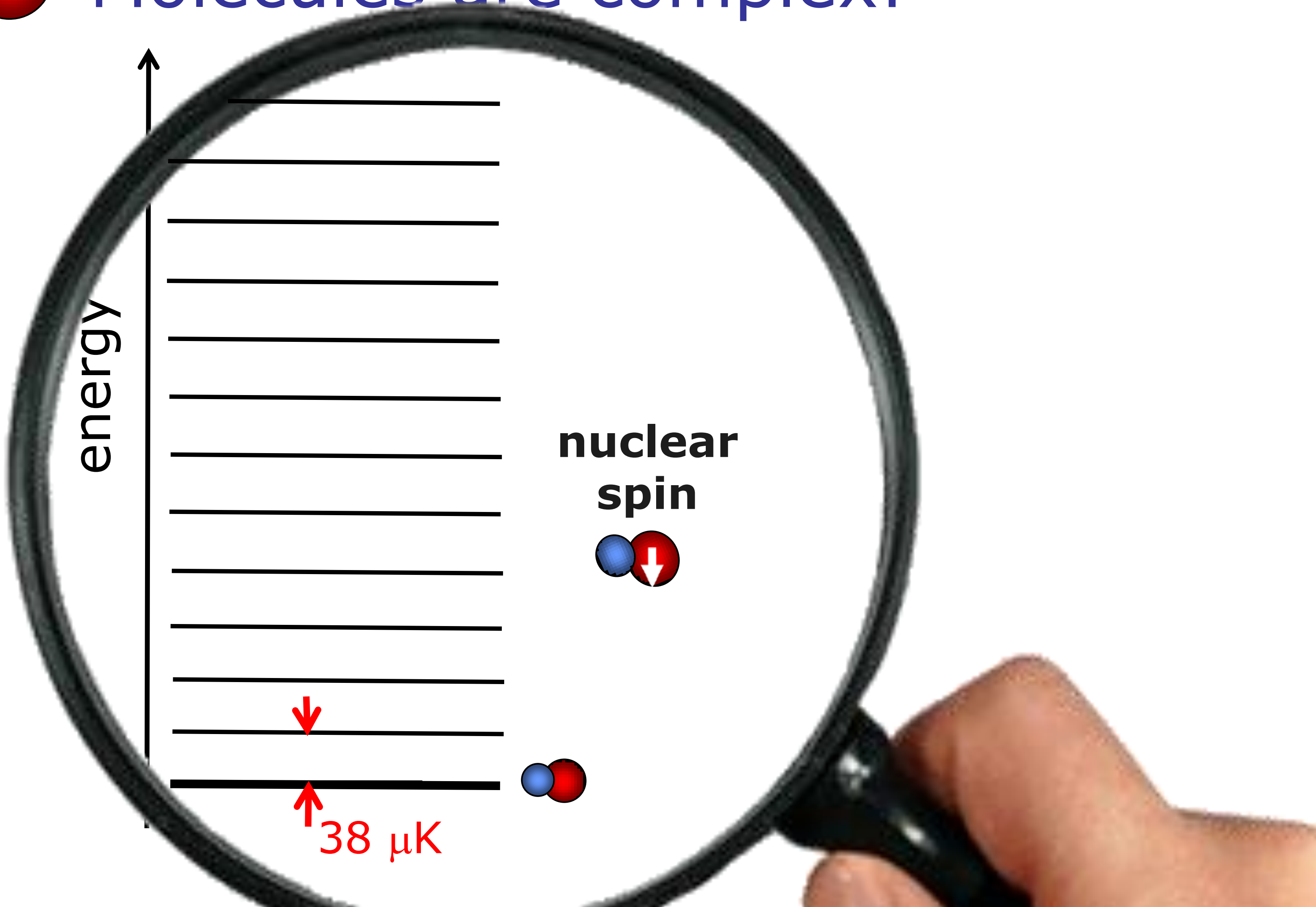
Ultracold molecules: The challenge



Molecules are complex!

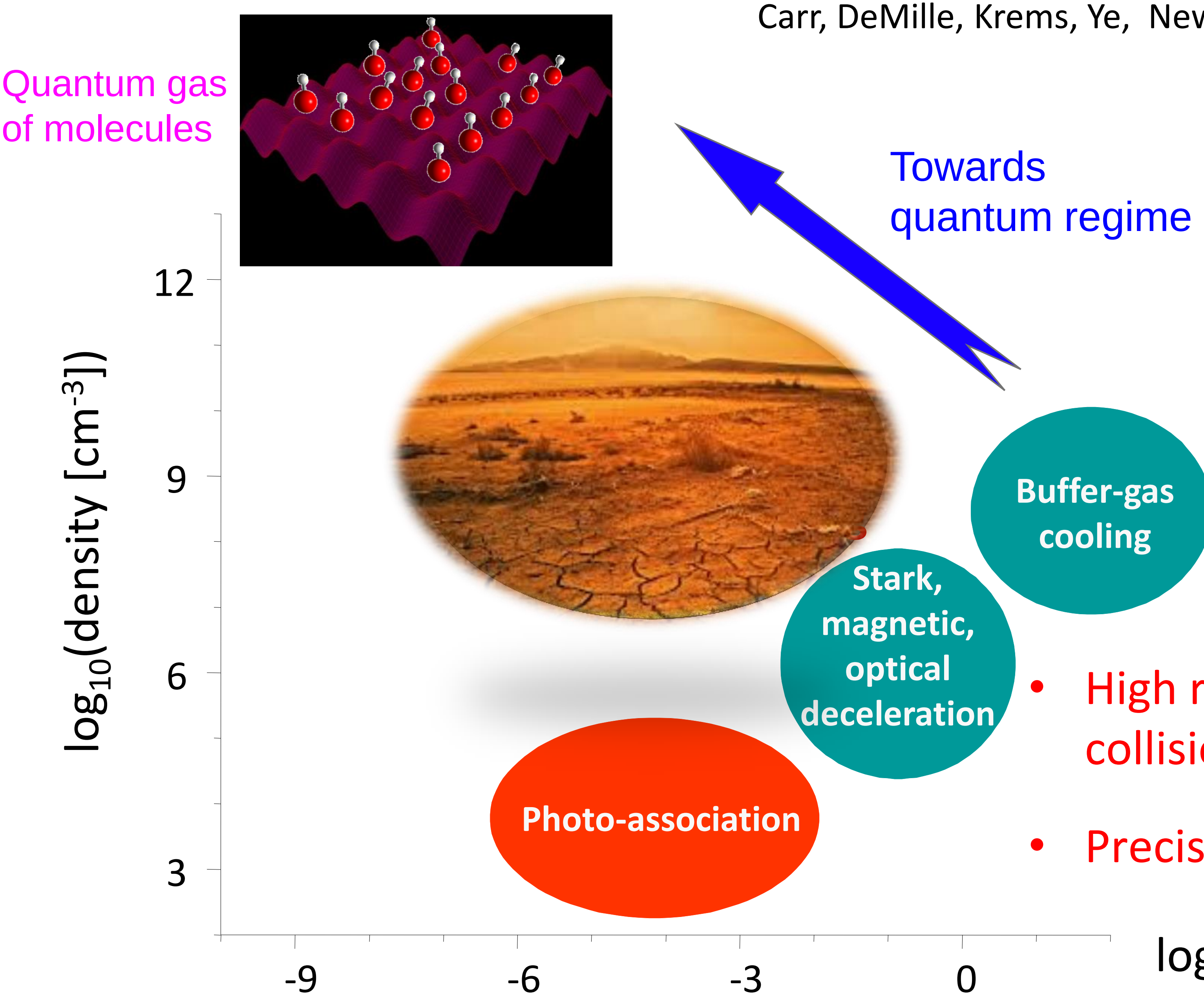
Ultracold molecules: The challenge

Molecules are complex!



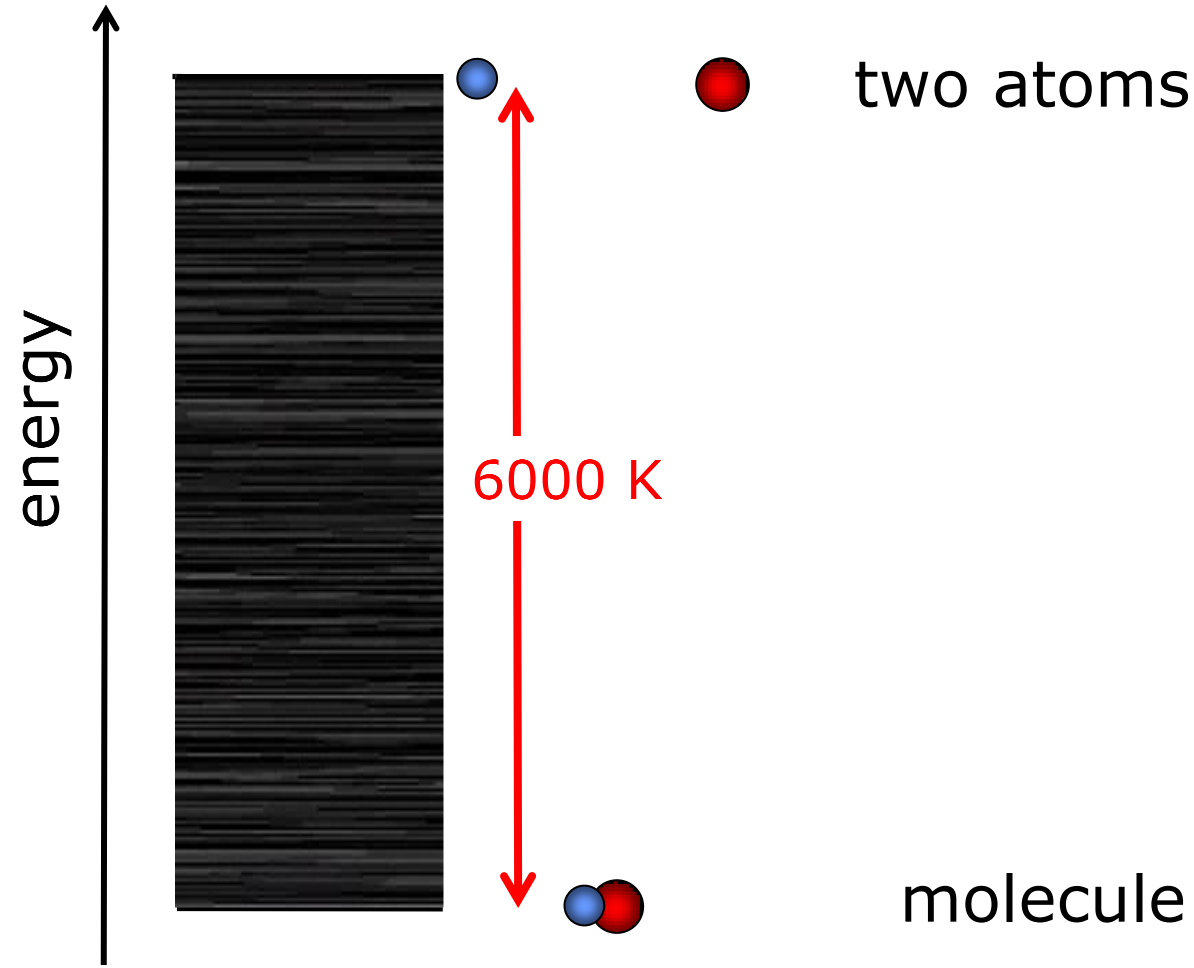
Technology for making cold molecules

Carr, DeMille, Krems, Ye, New. J. Phys. 2009.

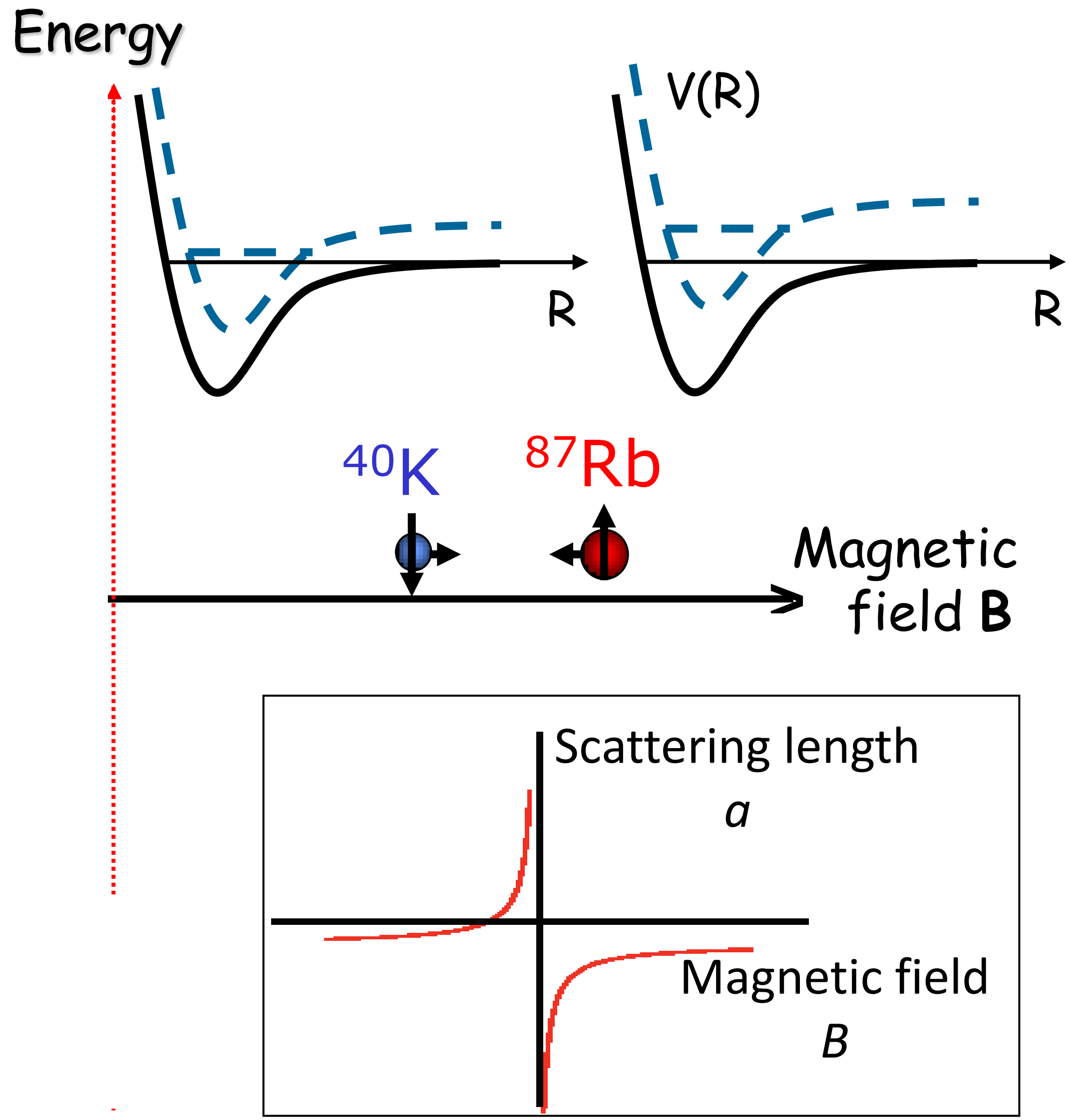


- High resolution collisions/reactions
- Precision test

Associate ultracold atoms into molecules



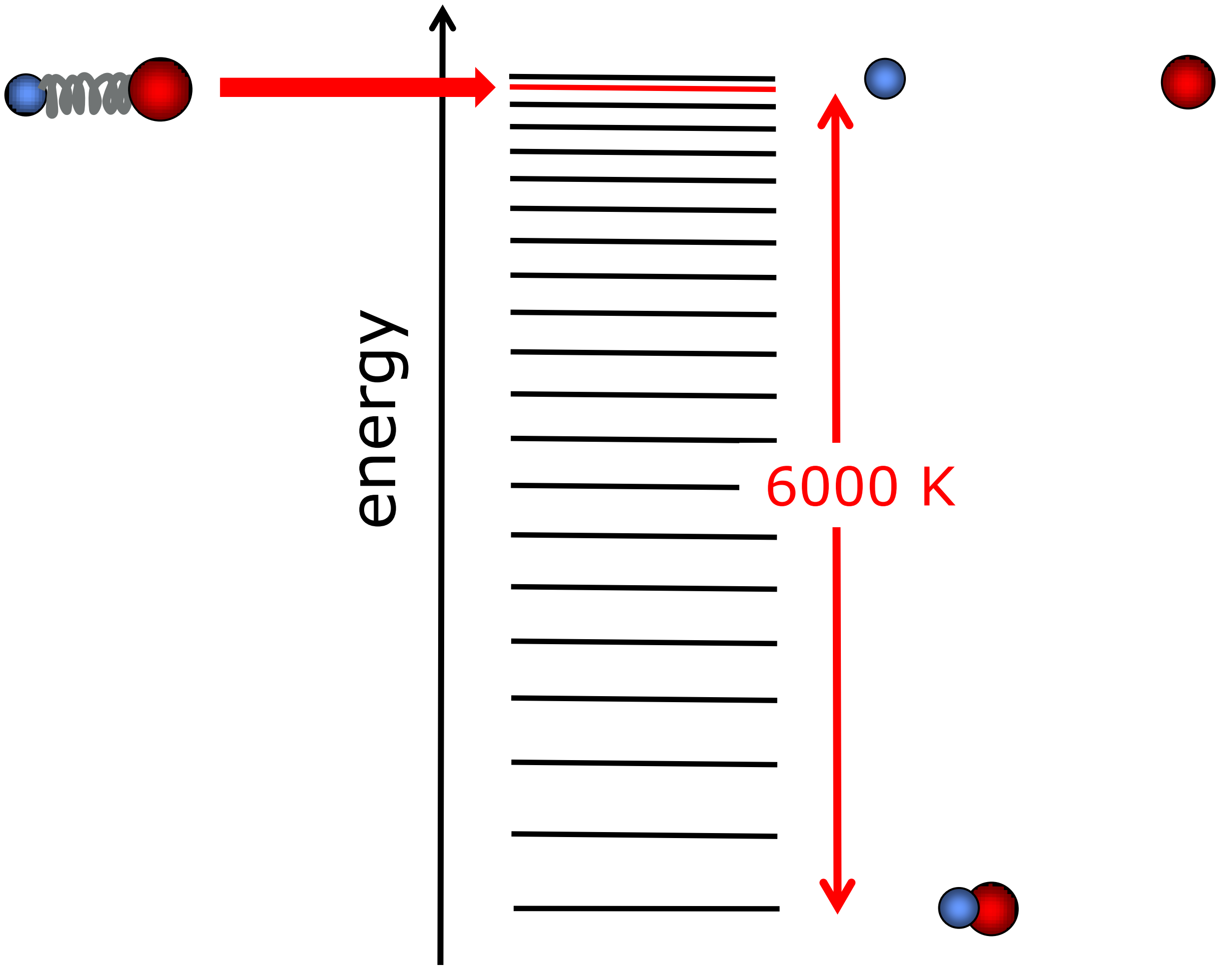
Make Feshbach molecules



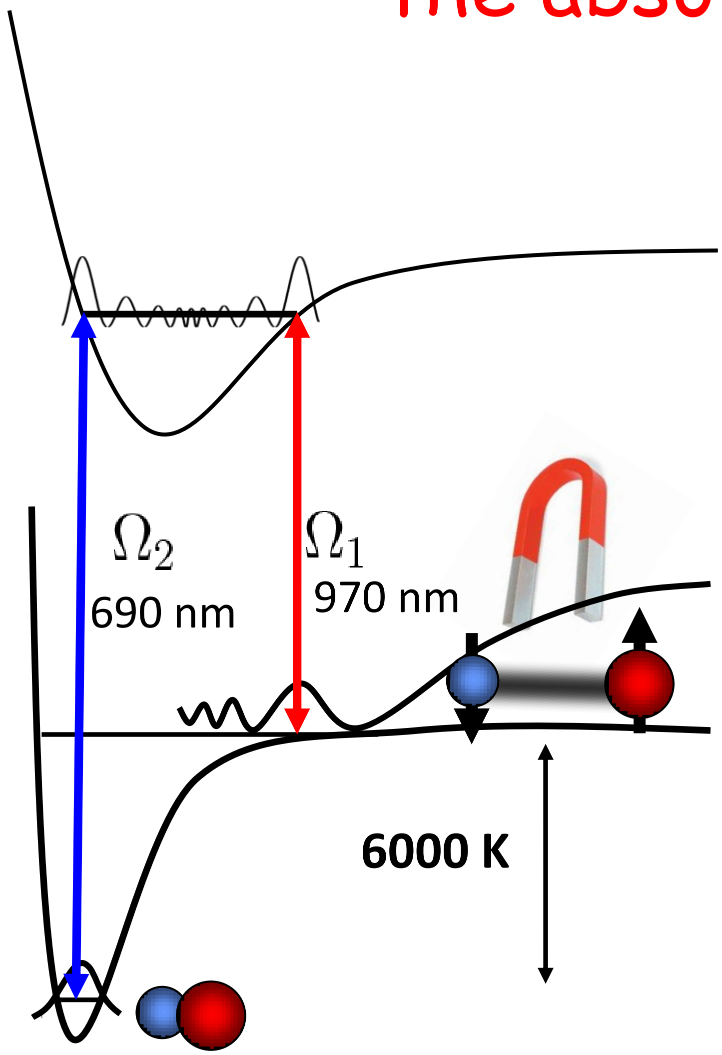
Interaction tuned by scattering resonance

Weakly bound molecules

- no dipole moment
- losses

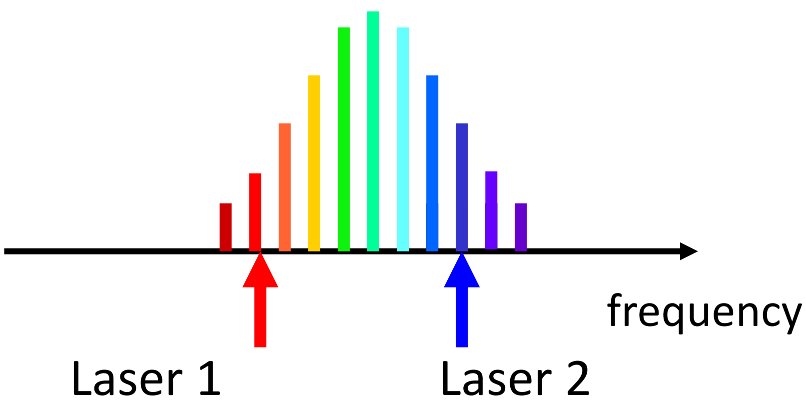


Coherent two-photon transfer - the absolute ground state



(entropy-less chemistry)

Fully coherent, >90% efficiency



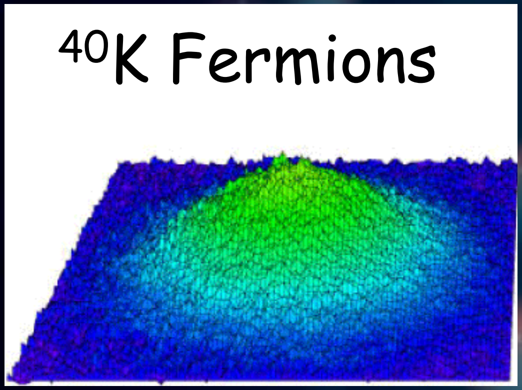
Beat note 125 THz

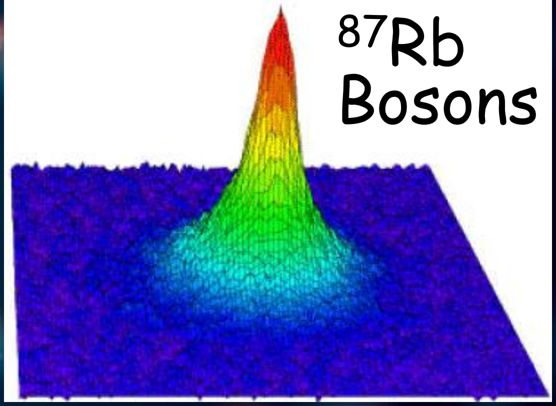
36 nuclear spin states: We populate & control single state

S. Ospelkaus *et al.*, Phys. Rev. Lett. **104**, 030402 (2010).

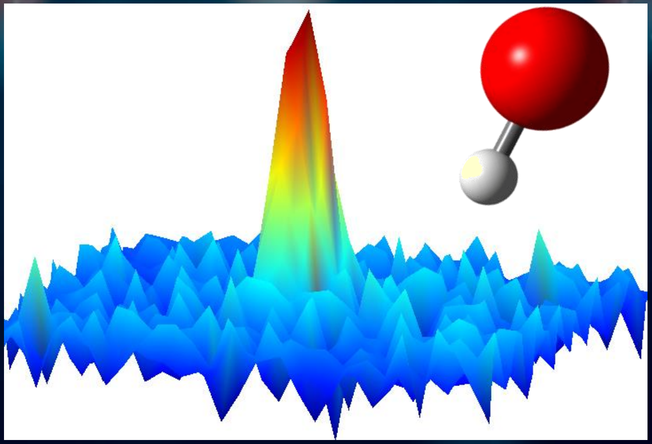
Polar molecules in the quantum regime

- Temperature ~ 100 nK
- Density ~$10^{12}/cm^3$
- T/T_F ~ 1.3





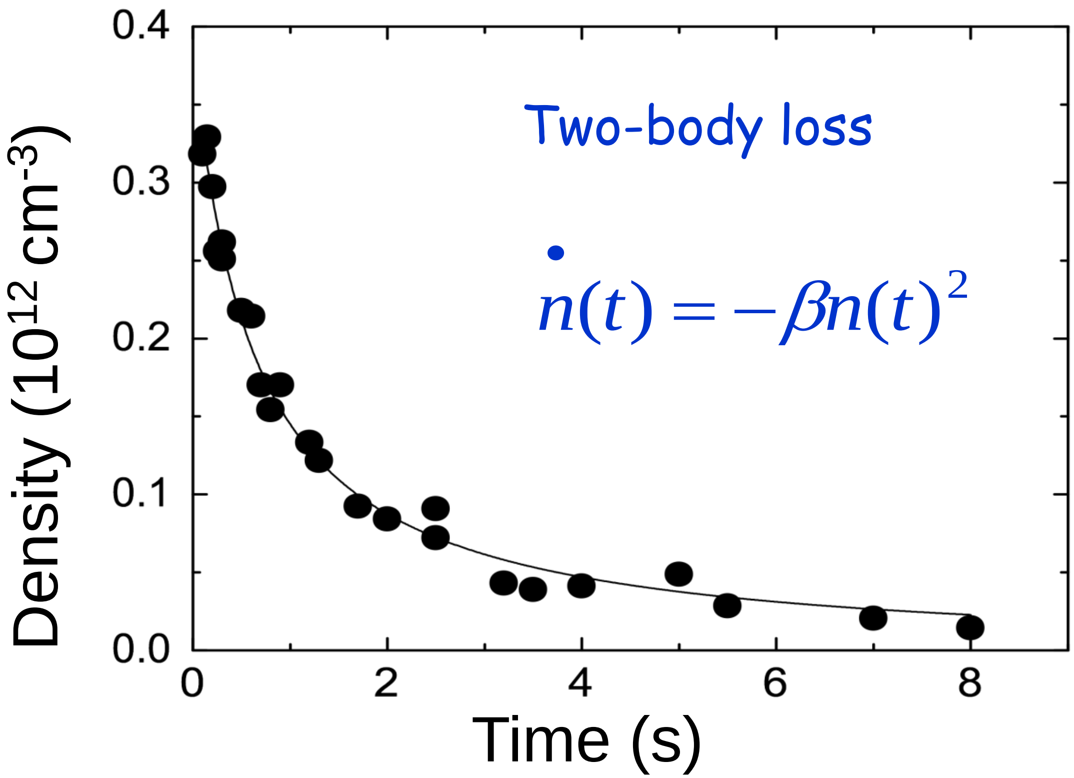
K.-K. Ni *et al.*,
Science 322, 231 (2008).

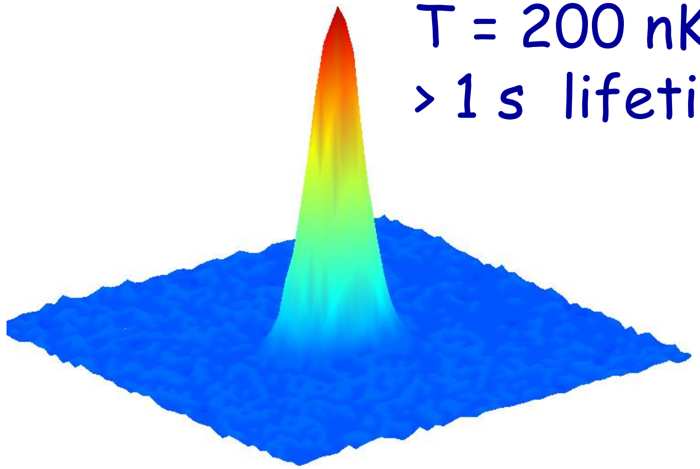


KRb molecules
(Dipole
~0.5 Debye)

Chemistry near absolute zero

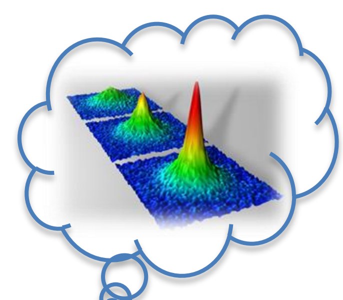
Trapped molecules in the lowest energy state (electronic, vibrational, rotational, hyperfine)



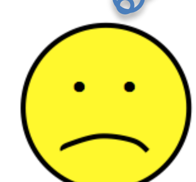


T = 200 nK

> 1 s lifetime

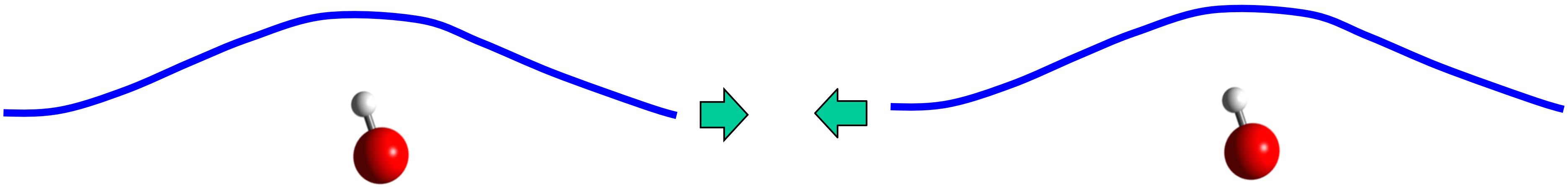


$KRb + KRb \rightarrow K_2 + Rb_2$

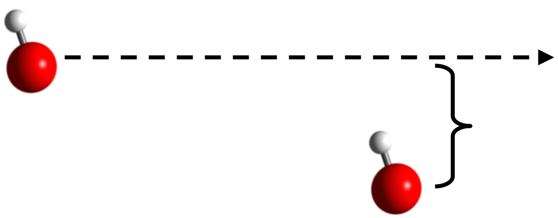


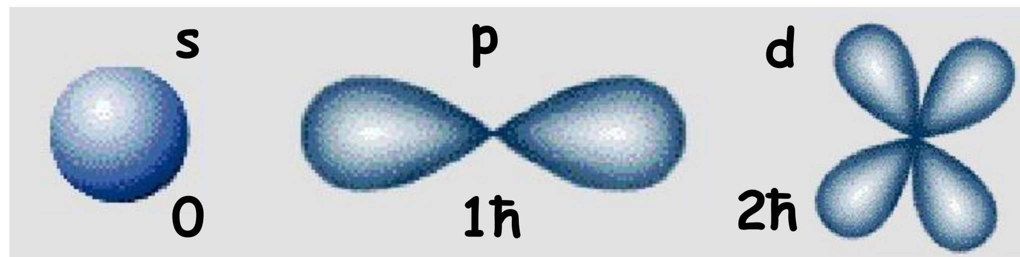
Cold collisions between identical Fermions

(1) Particles behave like waves

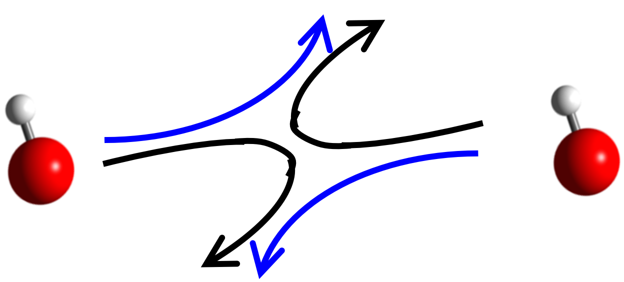


(2) Angular momentum is quantized

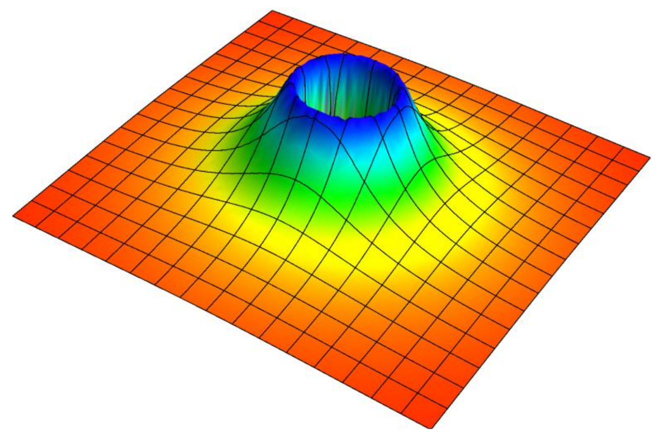




(3) Quantum statistics matter

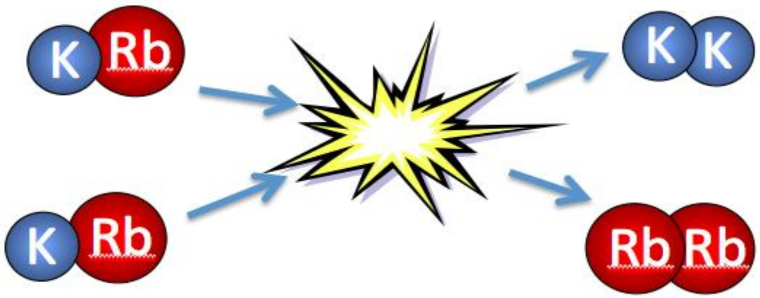


$$|\psi_0\rangle|\psi_1\rangle - |\psi_1\rangle|\psi_0\rangle$$



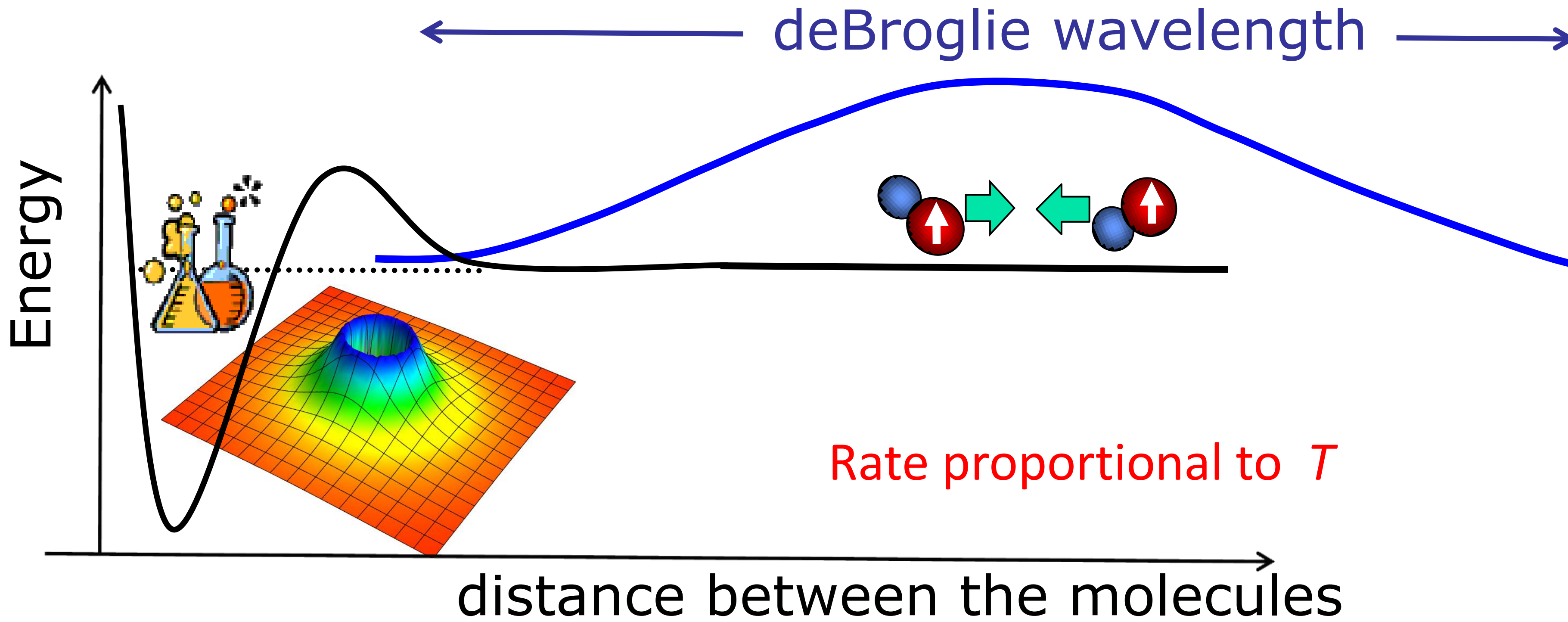
Fermions ⇨ L = 1, *p*-wave collisions

Ultracold quantum chemistry

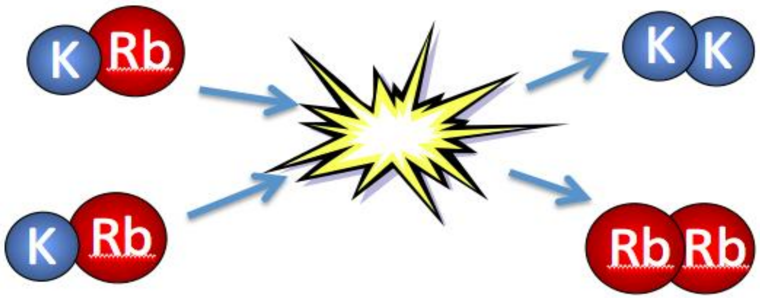


Ospelkaus *et al.*,
Science **327**, 853 (2010).

At low T, the quantum statistics of fermionic molecules suppresses chemical reaction!

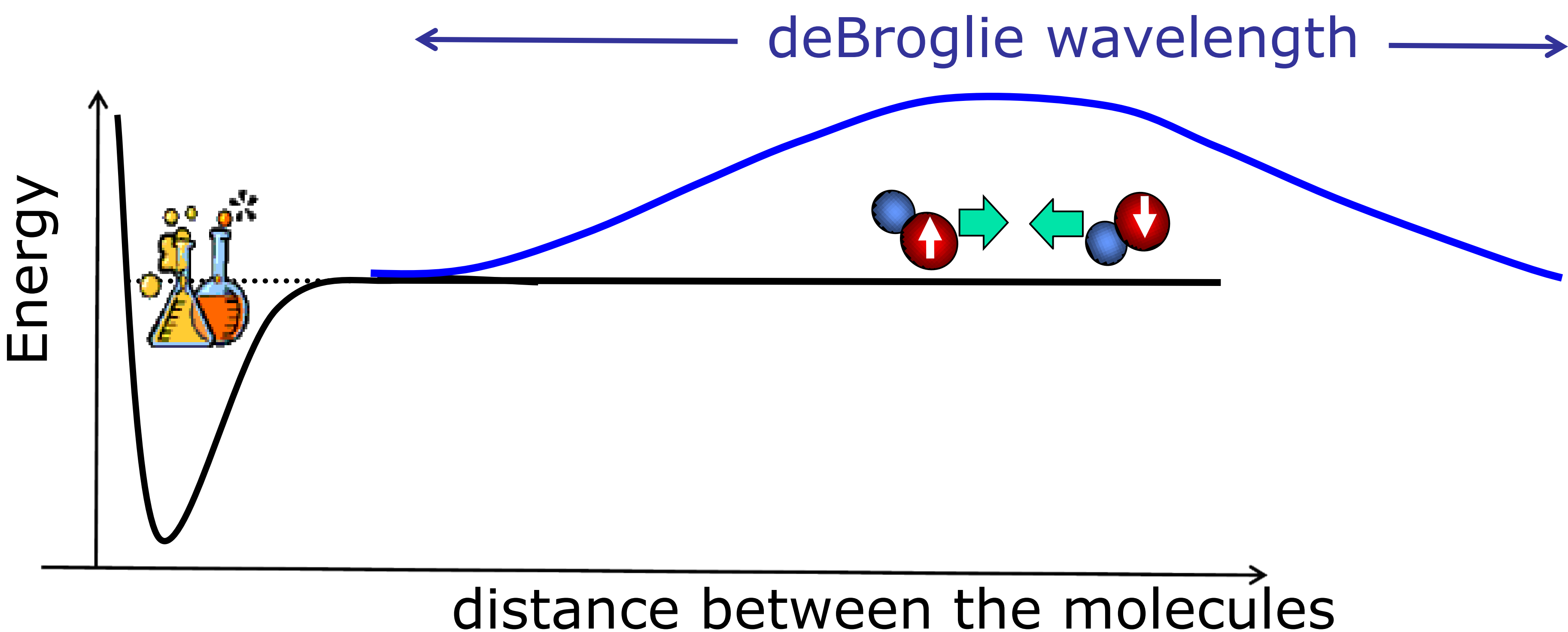


Ultracold quantum chemistry



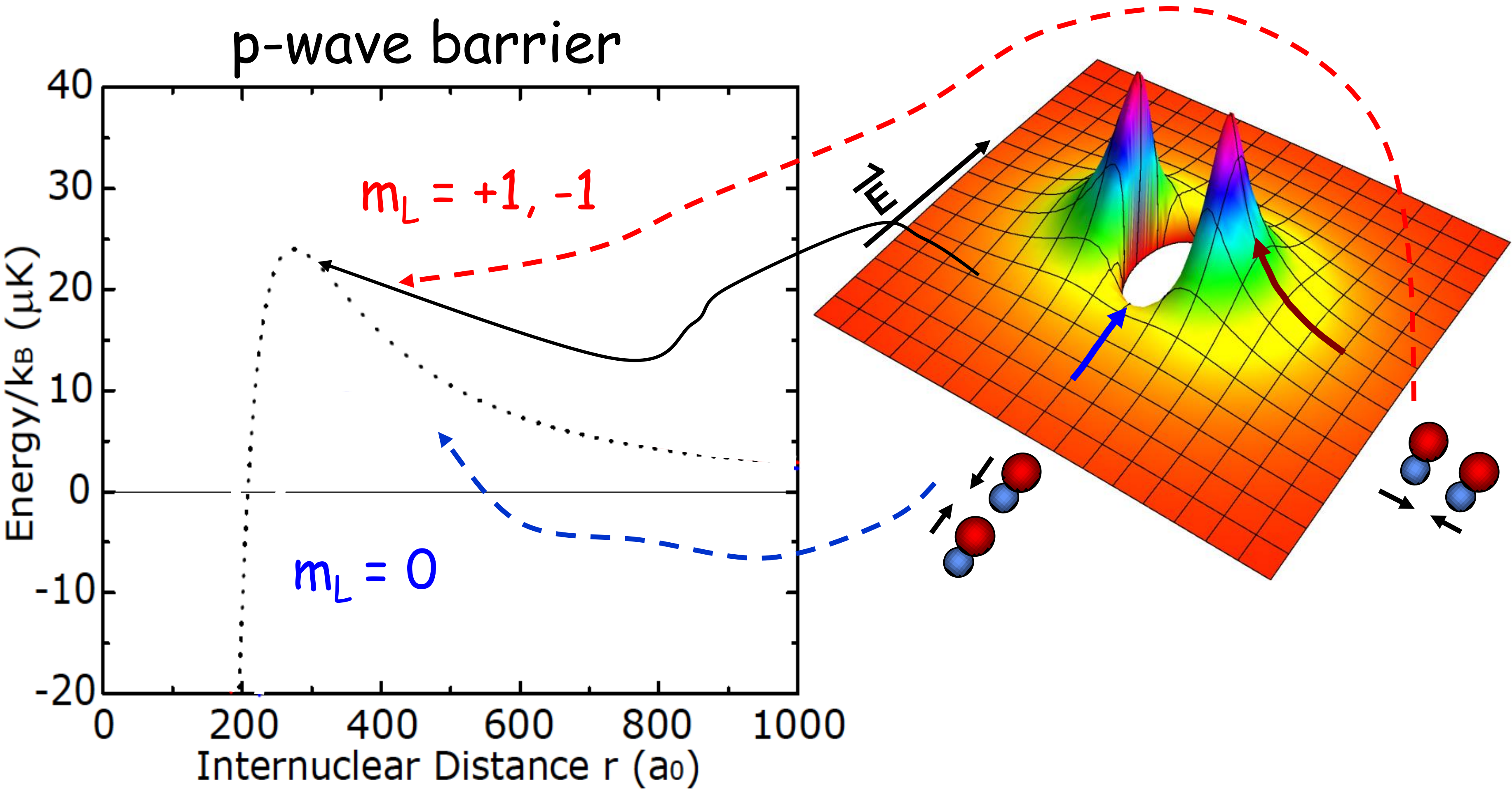
Ospelkaus *et al.*,
Science **327**, 853 (2010).

Distinguishable molecules do not enjoy the suppression
→ rate is x 100 higher !



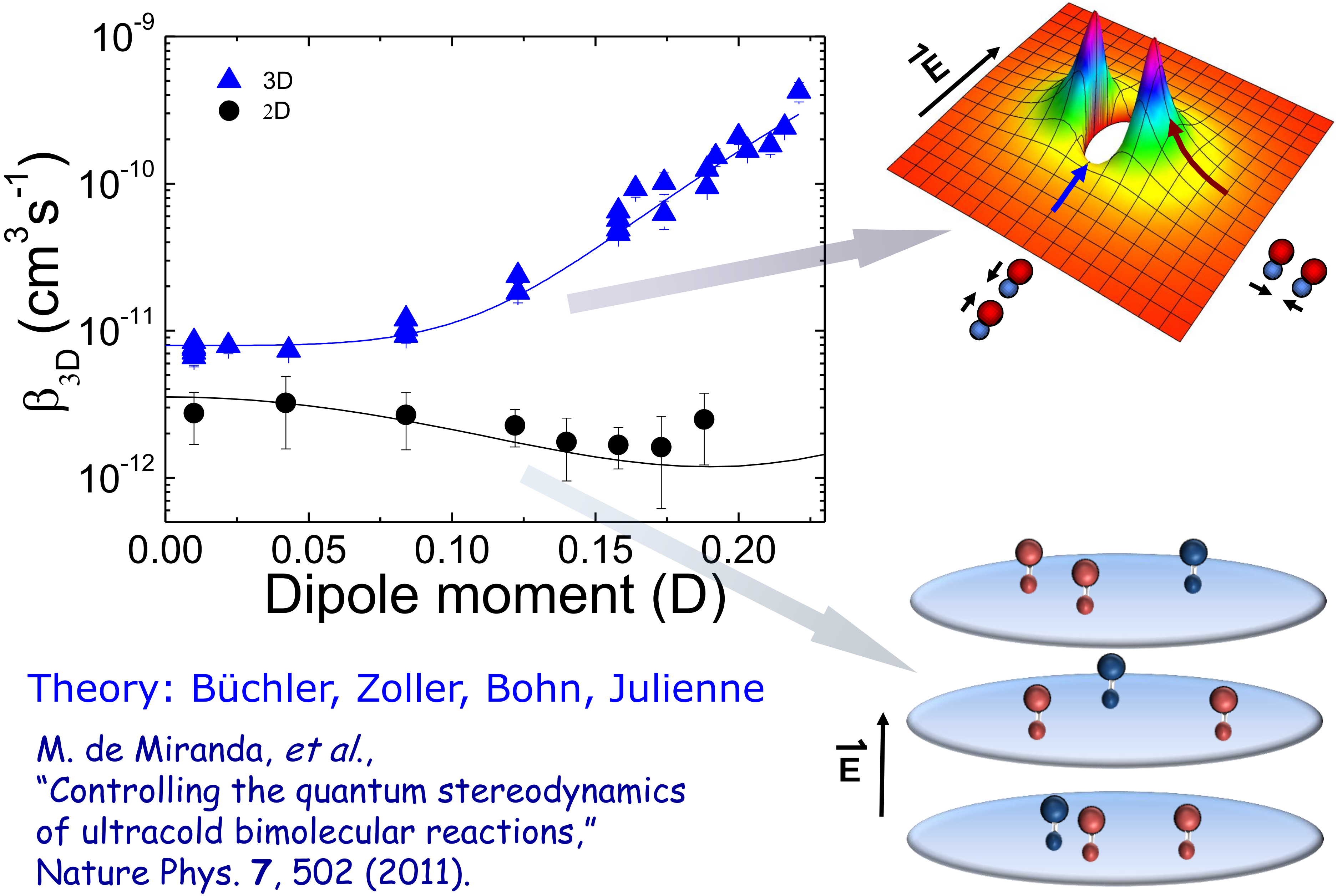
Anisotropic dipolar collisions

K.-K. Ni *et al.*, Nature **464**, 1324 (2010).



Collisions under a single partial wave ($L = 1\hbar$).

2D geometry – loss suppression

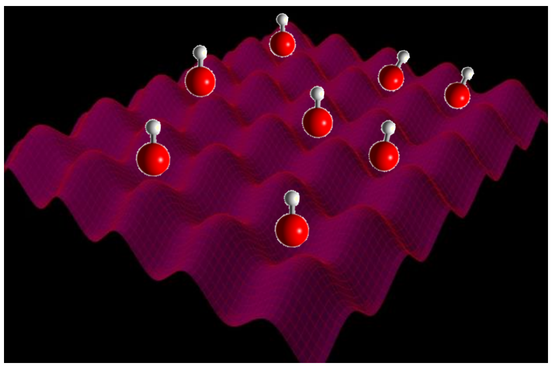


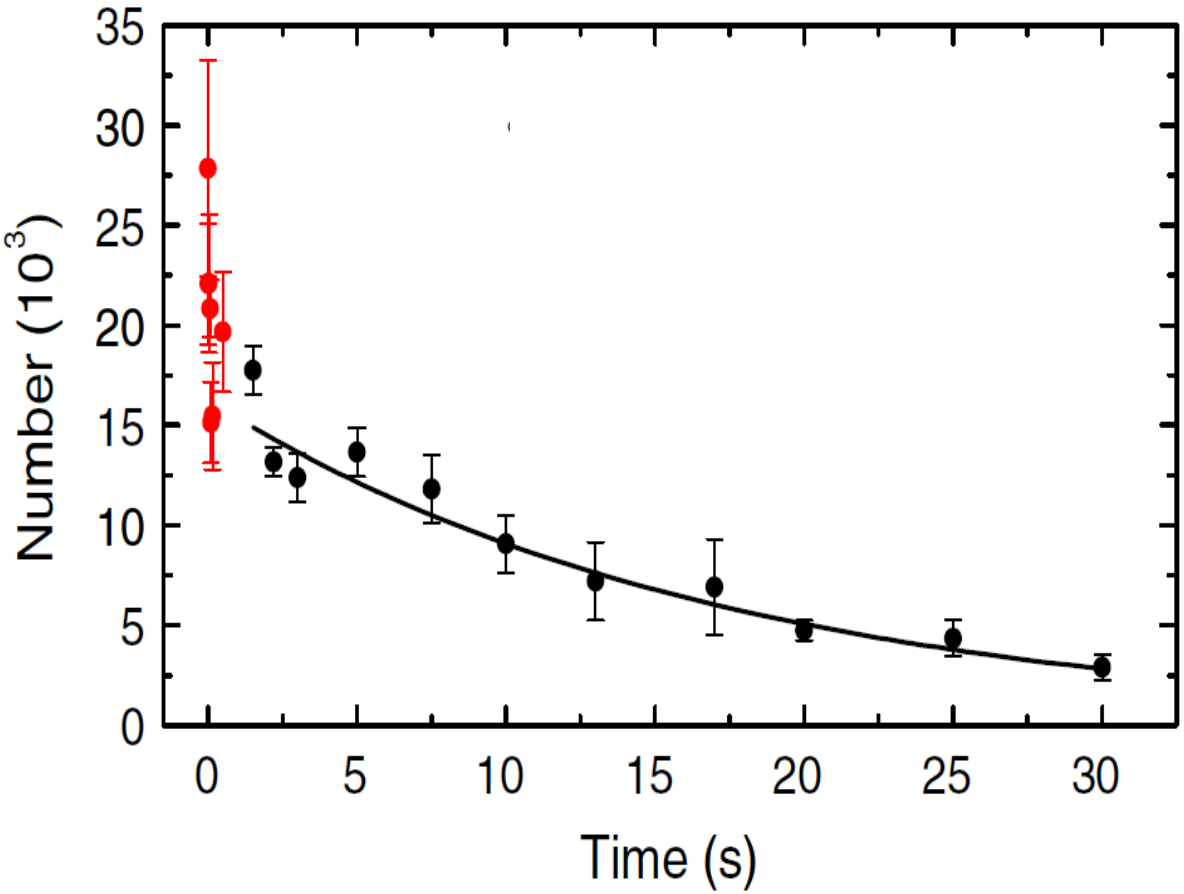
Theory: Büchler, Zoller, Bohn, Julienne

M. de Miranda, *et al.*,
"Controlling the quantum stereodynamics of ultracold bimolecular reactions,"
Nature Phys. **7**, 502 (2011).

3D optical lattice - suppressing chemical reaction with quantum Zeno effect

Lifetime ~ 20 s
Filling ~ 5%



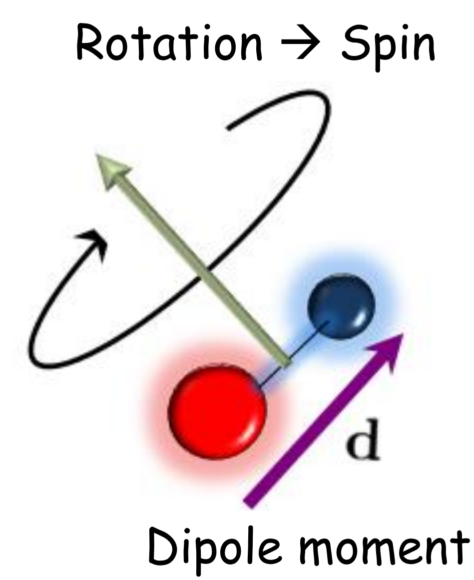


A. Chotia *et al.*, Phys. Rev. Lett. **108**, 080405 (2012).

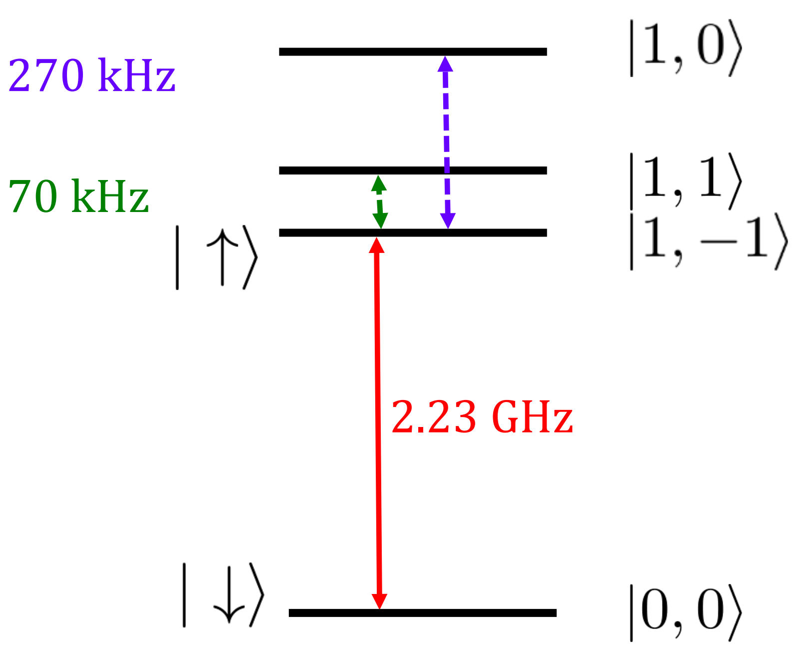
B. Zhu *et al.*, Phys. Rev. Lett. **112**, 070404 (2014).

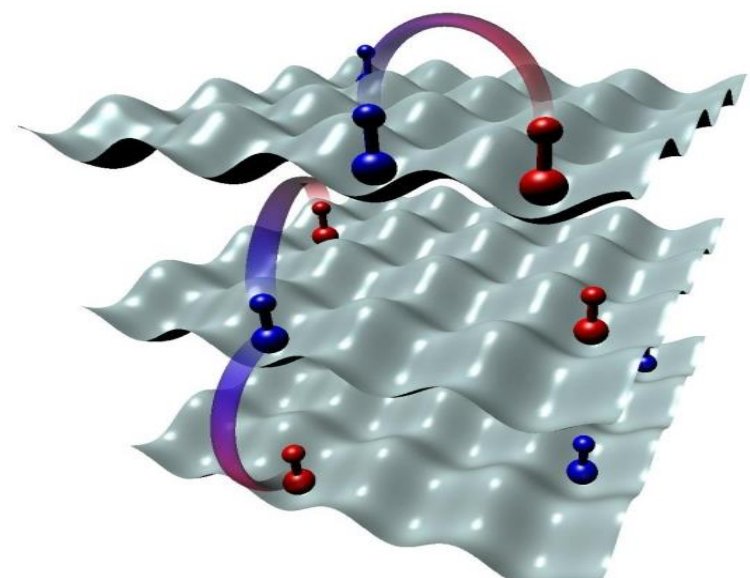
Spin exchange in a lattice of molecules

Barnett *et al*., Phys. Rev. Lett. **96**, 190401 (2006).
Micheli *et al*., Nature Phys. **2**, 341 (2006).
Gorshkov *et al*., Phys. Rev. Lett. **107**, 115301 (2011).



- Long-range dipolar interactions for direct (~kHz) spin exchanges - motion & spin decoupled
- Fully tunable with electromagnetic fields

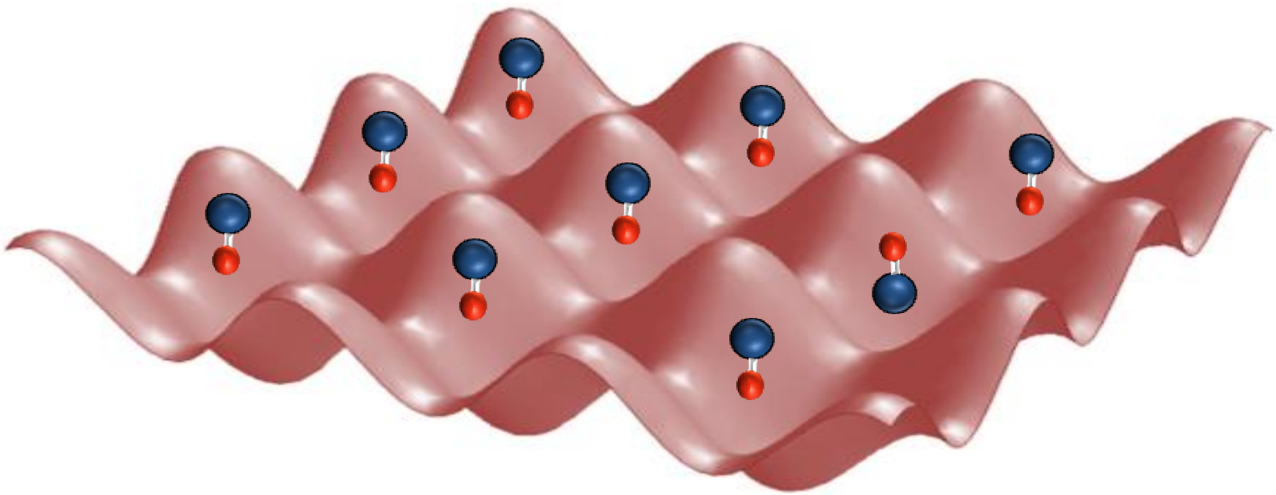




A good system to study many-body quantum localization ?

D. Huse, G. Shlyapnikov, M. Lukin, E. Demler, …

Molecules (material) are physically pinned down,
but spins (excitations) can be exchanged and mobile !

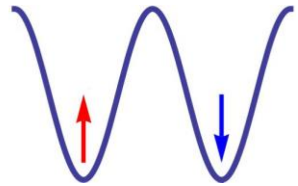


Energy flow in a macro-molecule !

Interaction strength for quantum magnetism

$$\langle\downarrow|\hat{d}|\downarrow\rangle = \langle\uparrow|\hat{d}|\uparrow\rangle = 0 \qquad \langle\downarrow|\hat{d}|\uparrow\rangle \neq 0$$

$$H = \sum_{i>j} V_{dd}(\mathbf{r}_i - \mathbf{r}_j)\left[J_z S_i^z S_j^z + \frac{J_\perp}{2}\left(S_i^+ S_j^- + S_i^- S_j^+\right)\right]$$



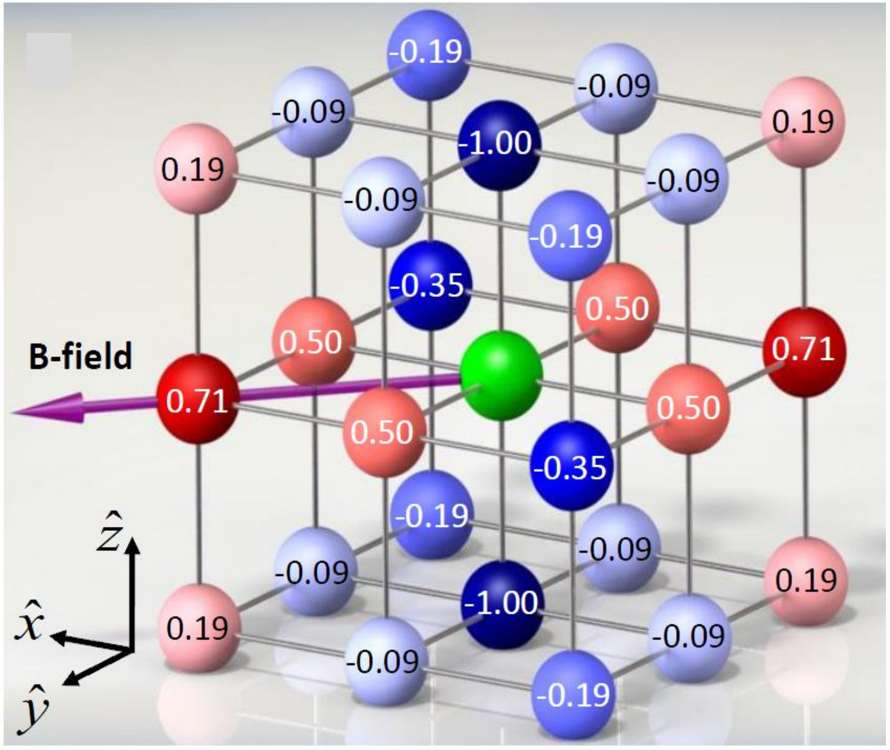
$$= S_i^x S_j^x + S_i^y S_j^y$$

Flip-flop term

$$\frac{1 - 3\cos^2\theta}{|\mathbf{r_i} - \mathbf{r_j}|^3}$$

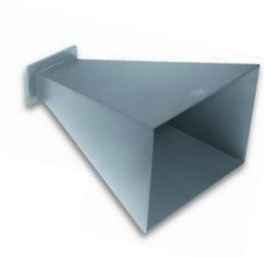
$$\frac{J_\perp}{h} = \frac{d_{\uparrow\downarrow}^2}{4\pi\epsilon_0 h a_{\mathrm{lat}}^3}$$

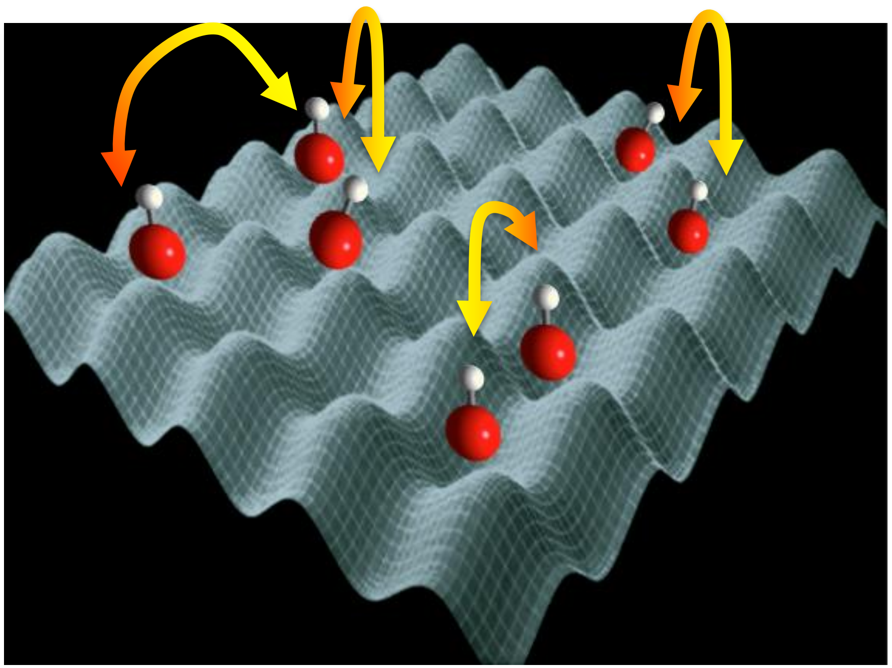
The oscillation frequency for a pair of molecules is $J_\perp/2h$.

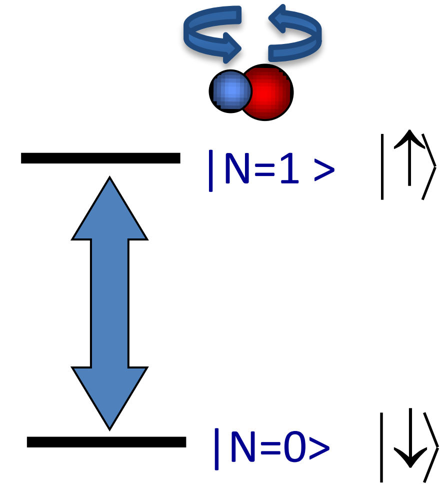


A Dipolar Spin-Lattice Model

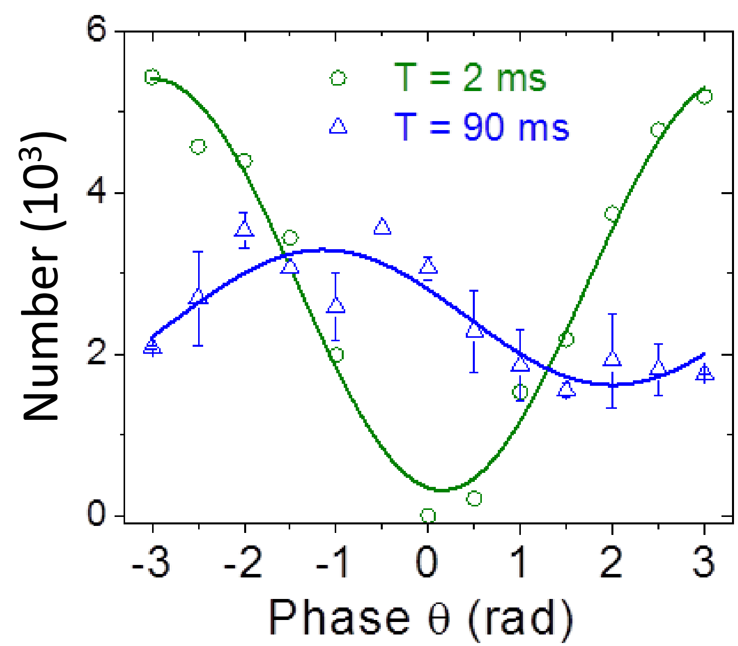
B. Yan *et al.*, Nature **501**, 521 (2013).



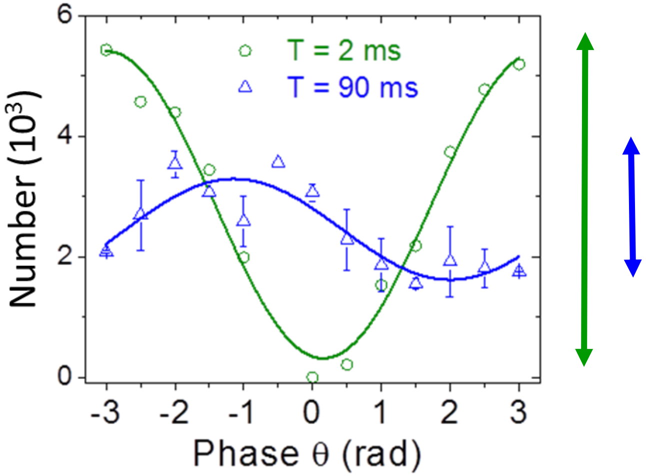


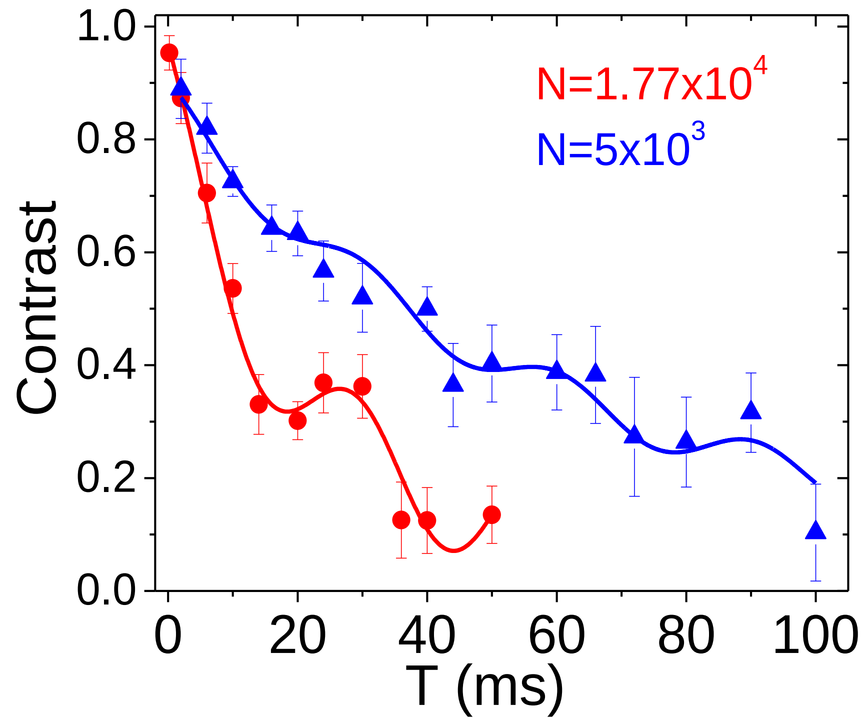


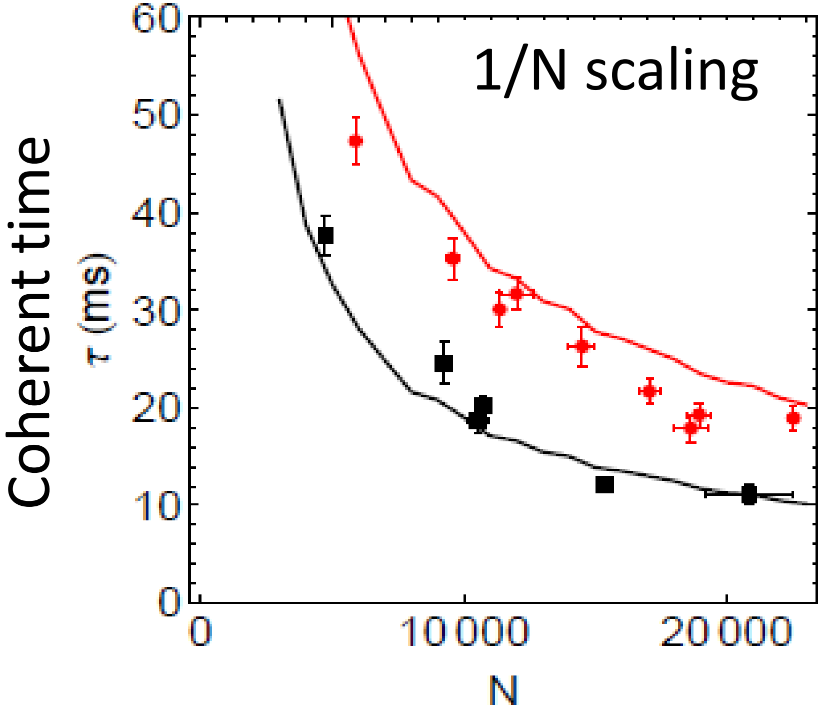
- Start with N=0. $|\downarrow\rangle$
- Drive a coherent spin superposition. $\frac{1}{\sqrt{2}}\left(|\uparrow\rangle+|\downarrow\rangle\right)$
- Probe spin coherence at T. (Ramsey spectroscopy)



Oscillations due to dipolar interactions







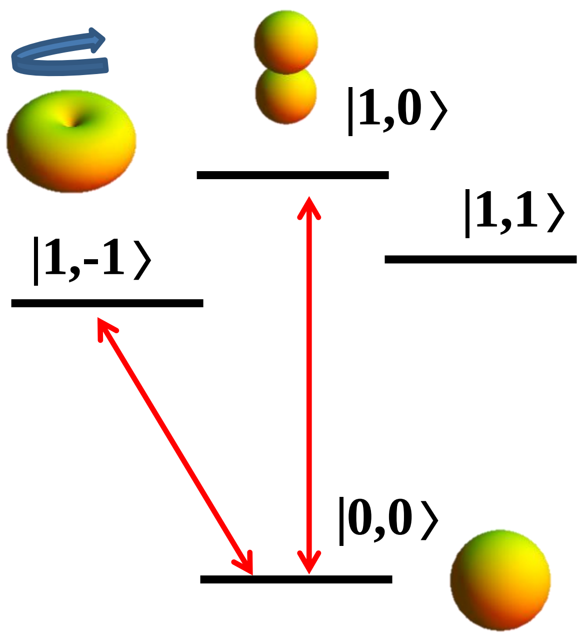
$|1,-1\rangle \leftrightarrow |0,0\rangle$

$|1,0\rangle \leftrightarrow |0,0\rangle$

Oscillation frequencies & decay time both depend on rotational states

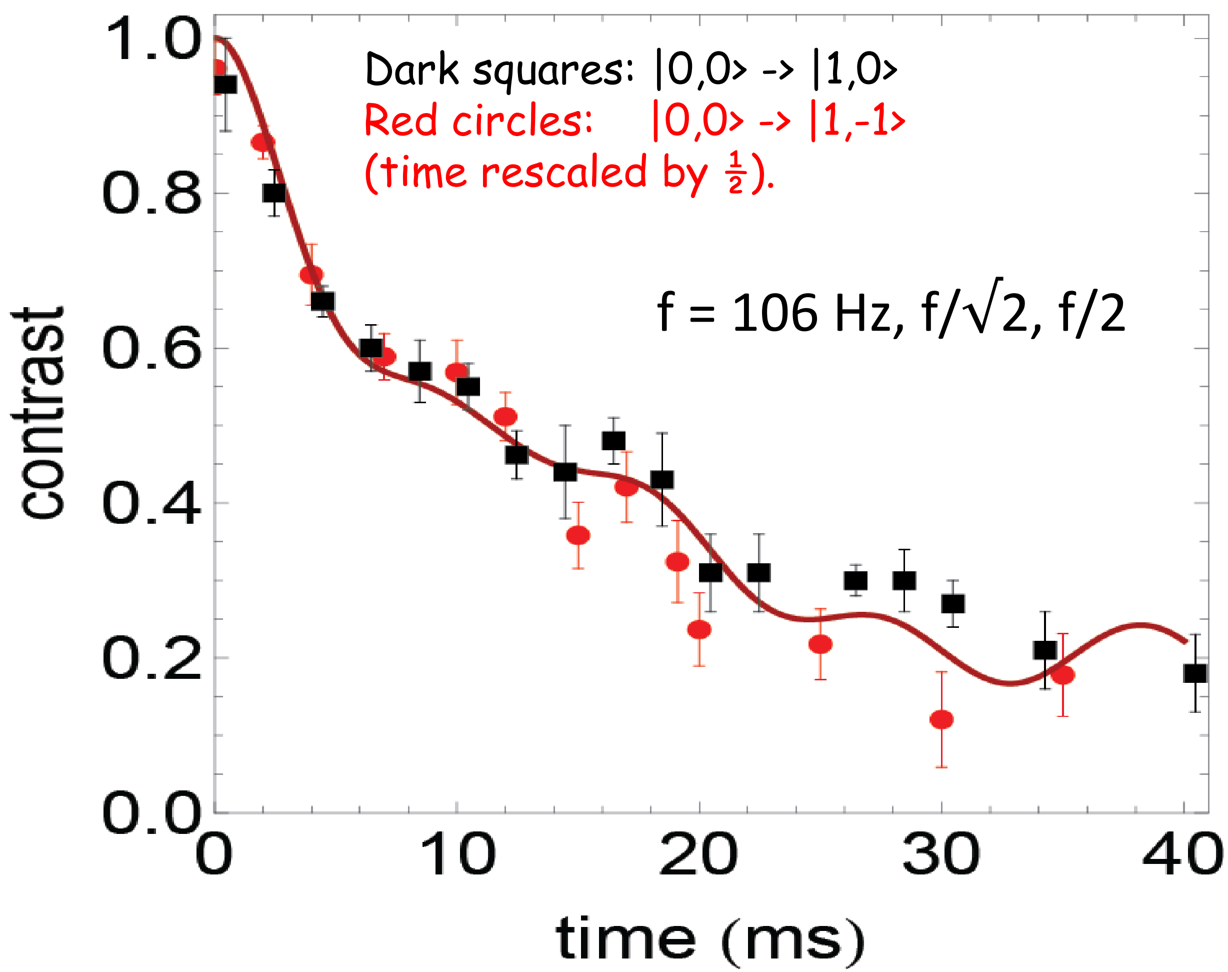
Control dipolar interaction

K. Hazzard *et al.*, Phys. Rev. Lett. **113**, 195302 (2014).



$\frac{J_\perp}{2} \sim$ 102 Hz

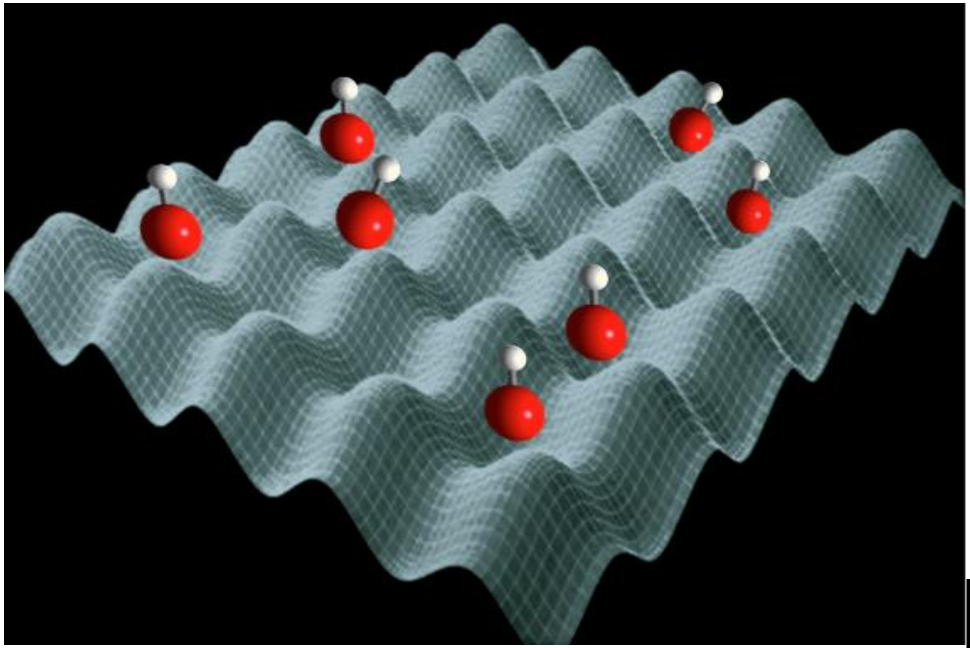
for |0,0> to |1,0>



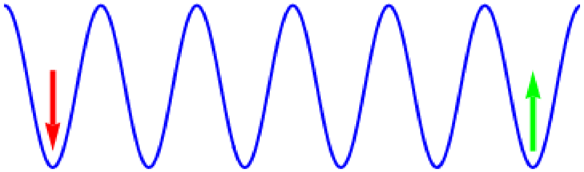
($\frac{J_\perp}{2} \sim$ 51 Hz for|0,0> to |1,-1>)

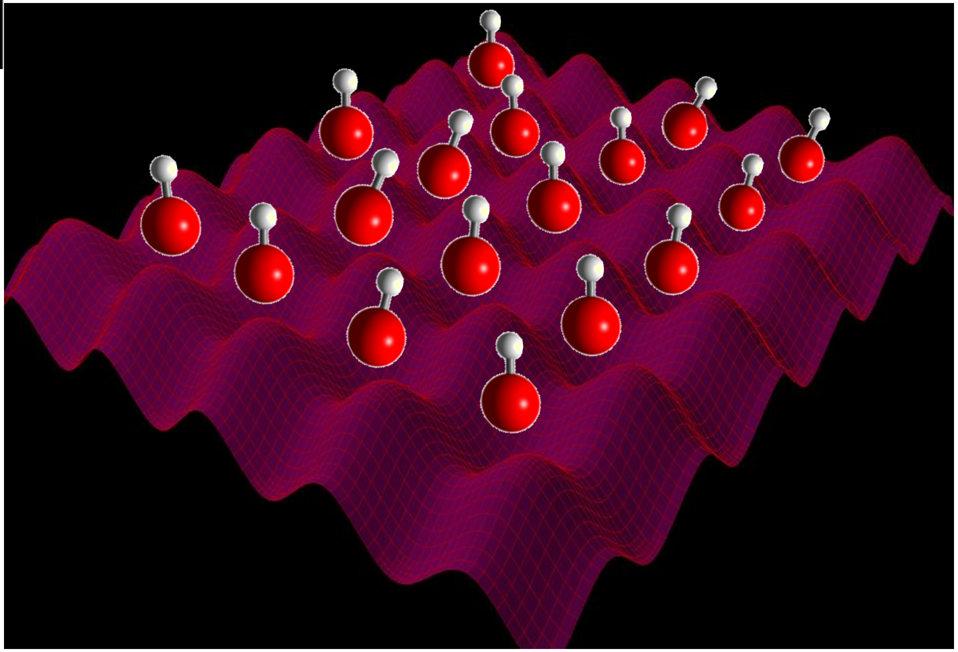
One fitting parameter (filling 5-10%) reproduces the experiment

Highly filled optical lattice

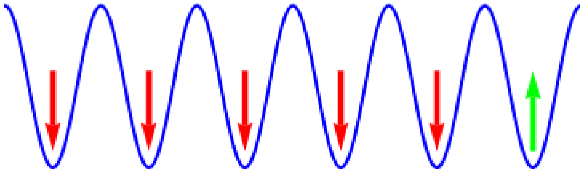


~5% filling in a 3D lattice

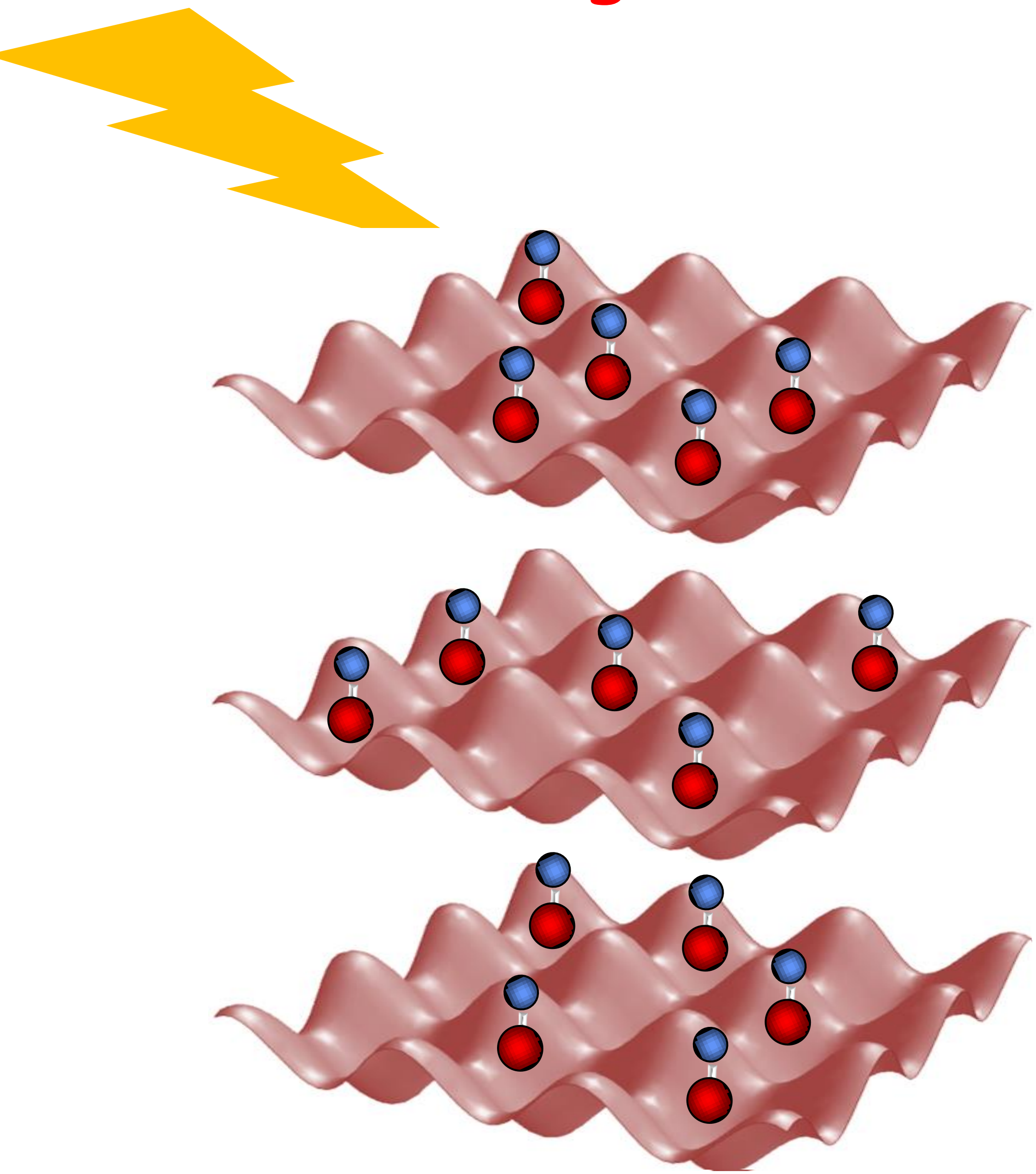




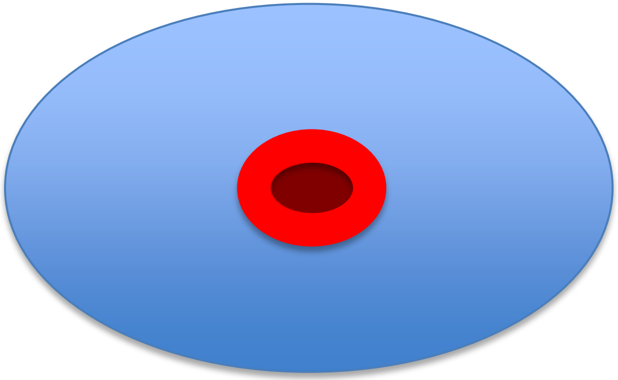
Goal:
A near zero entropy 3D lattice

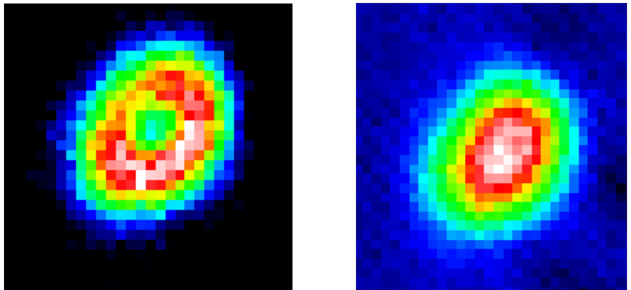


Creating molecules in a 3D lattice



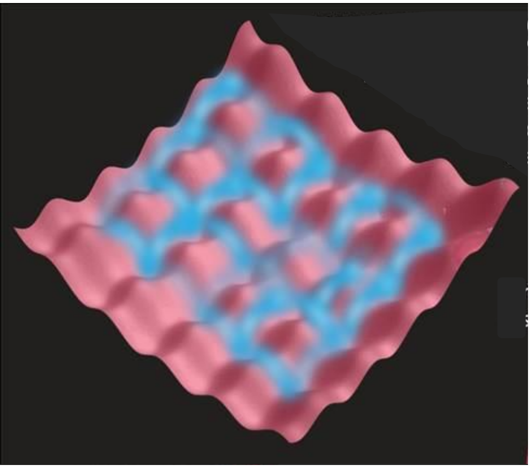
1. Rb MOTT insulator
2. Add lots of K atoms (tune Rb – K interaction energy)
3. Magnetic association & Raman transfer

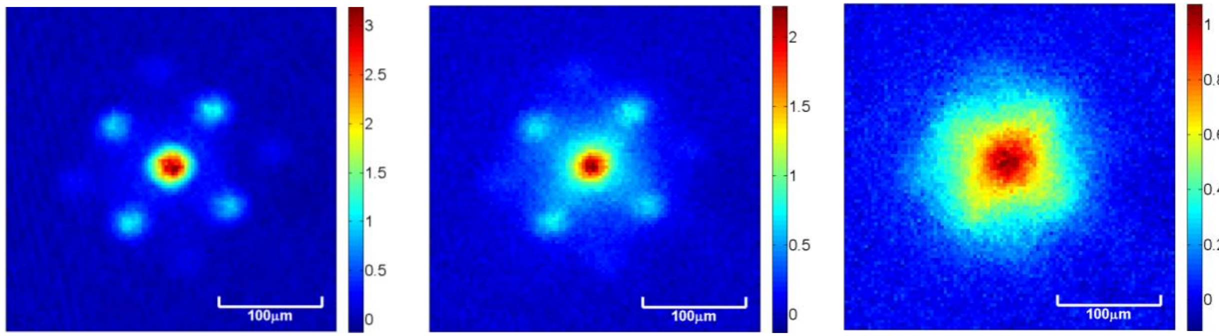




Rb Mott insulator imaged *in-situ*

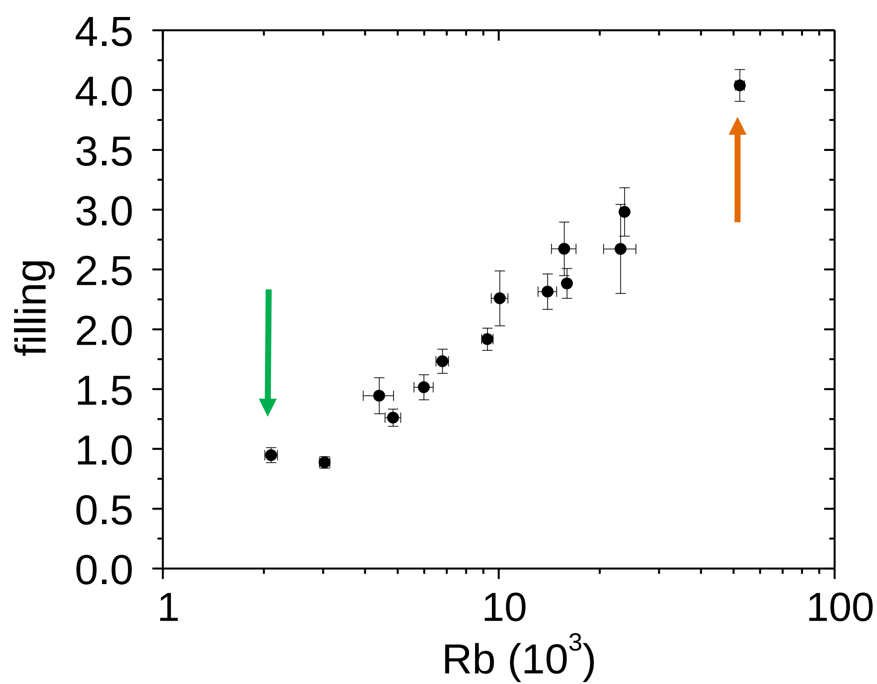
A superfluid BEC phase transition to a MOTT insulator

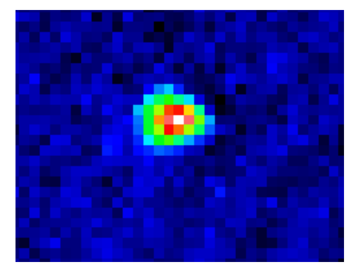




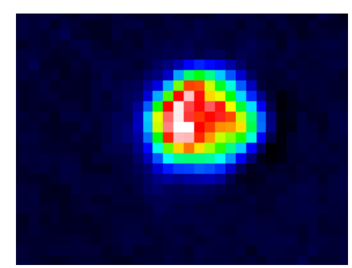
12 E_{rec} 18 E_{rec} 24 E_{rec}

Lattice depth →



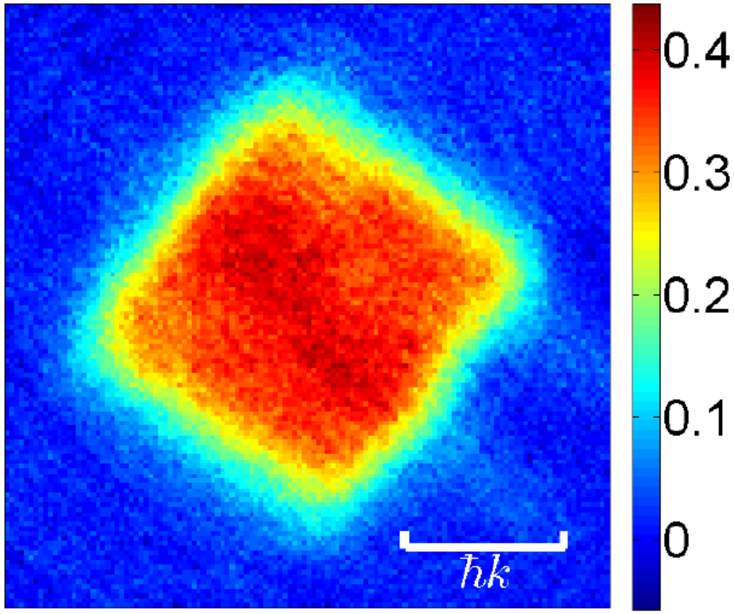


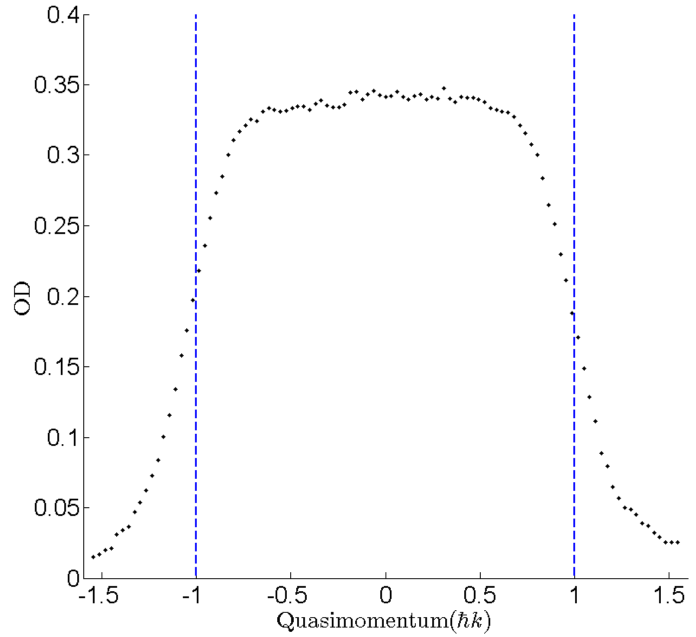
2000 Rb

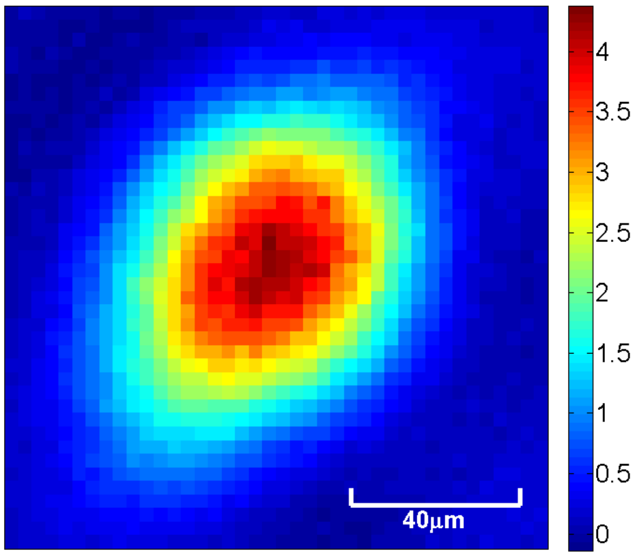


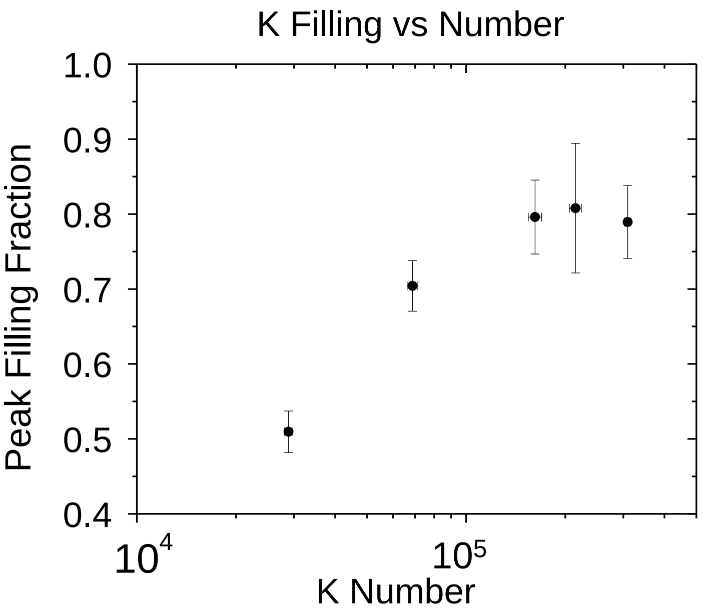
50,000 Rb

Imaging of K in momentum & real space

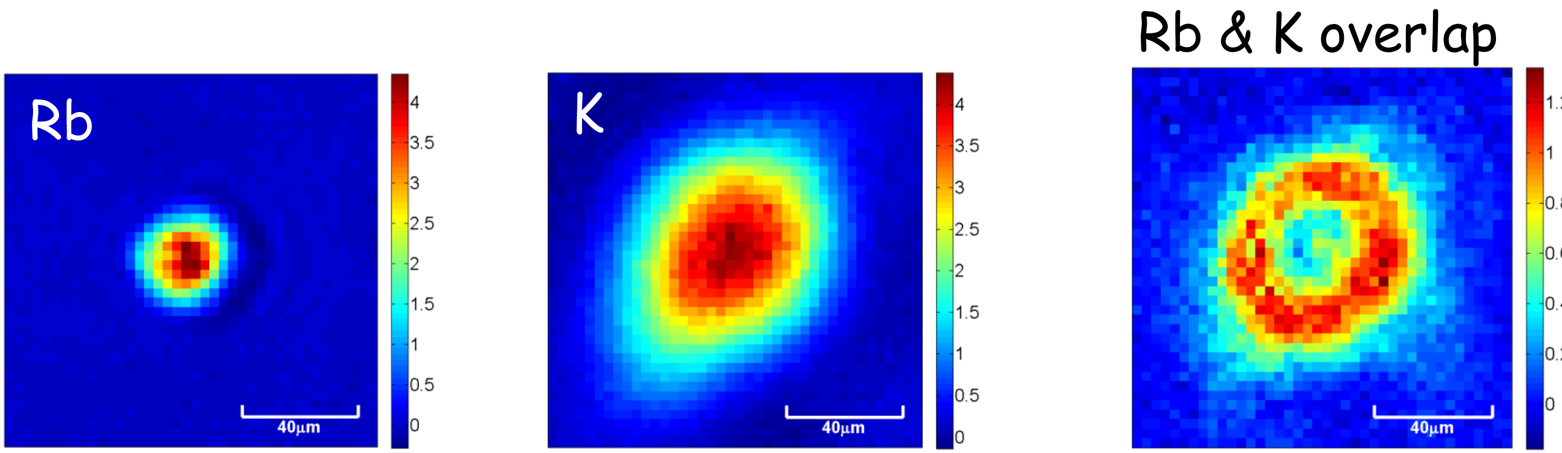


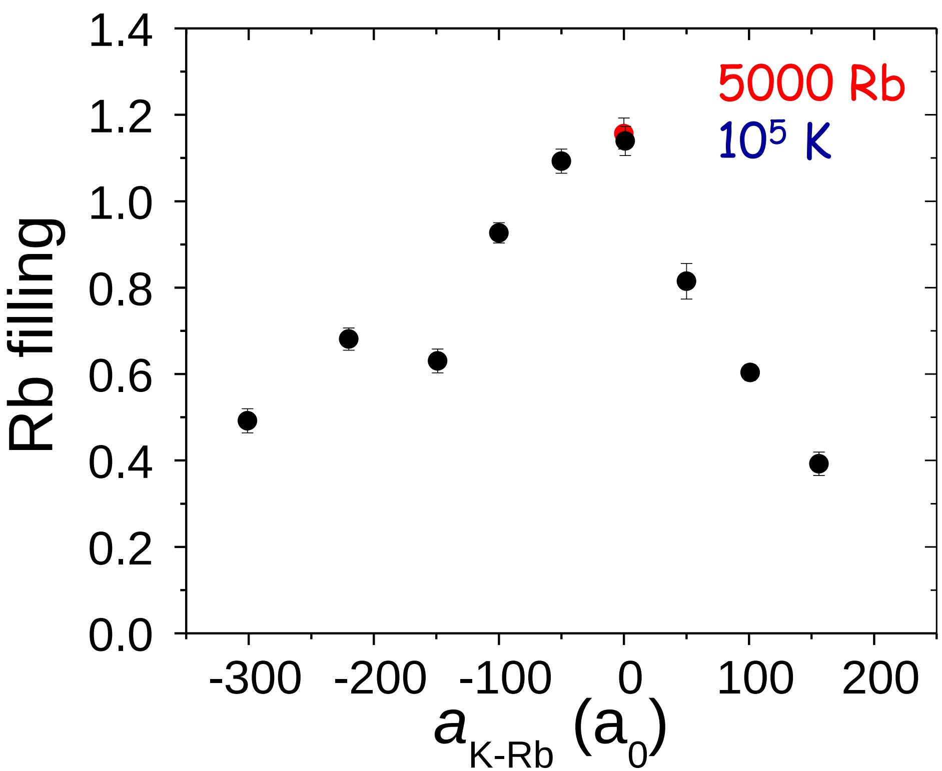






Overlap of Rb and K

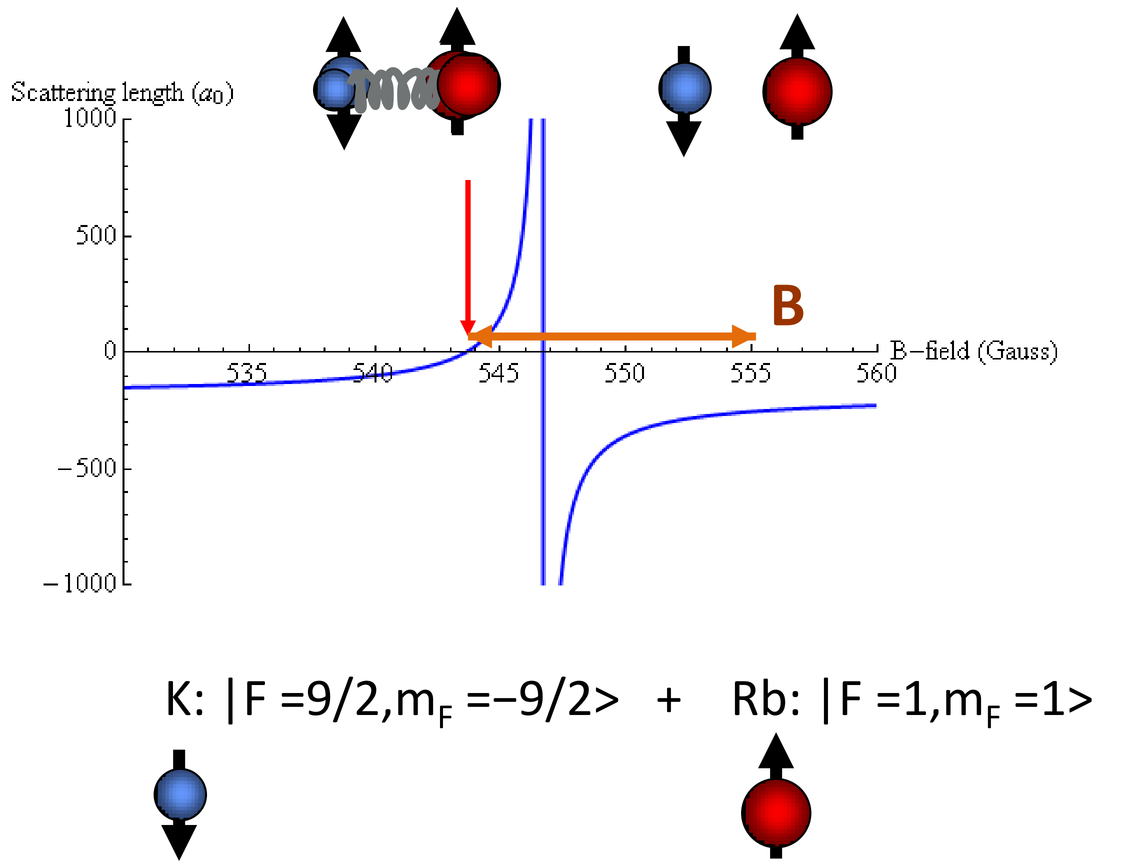




- Vary a_{KRb} before loading lattice
- At a_{KRb} = 0, Rb MI unaffected by K

Pairing up K-Rb in lattice without heating

- Load the lattice at $a_{KRB} = 0$
- Jumping across the resonance dilutes the filling (populating higher bands)
- Flip to a noninteracting spin state (|9/2,-7/2>) to avoid resonance when ramping B
- Flip back to |9/2,-9/2>, then proceed with Feshbach association

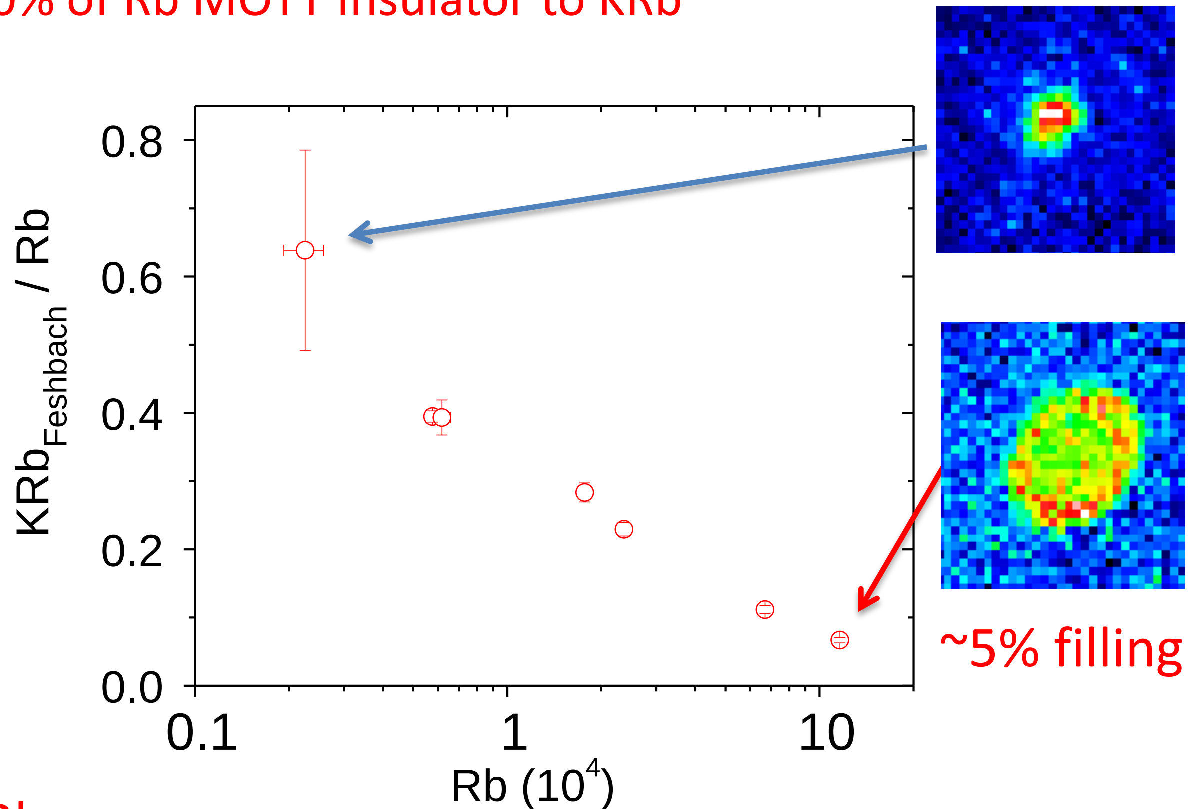


A low entropy lattice of molecules

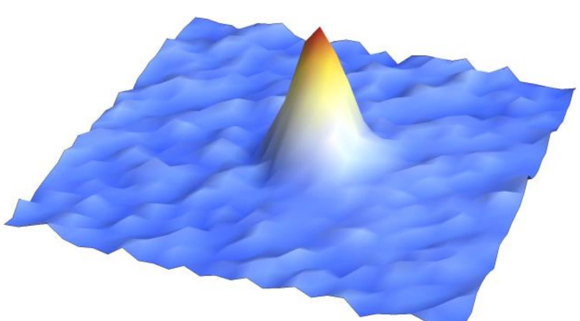
Convert > 60% of Rb MOTT Insulator to KRb

- For BEC of a few 10^3 Rb, the peak filling of Rb ~ 1
- To measure KRb, dissociate the molecules & count the numbers of K = Rb

Image of KRb

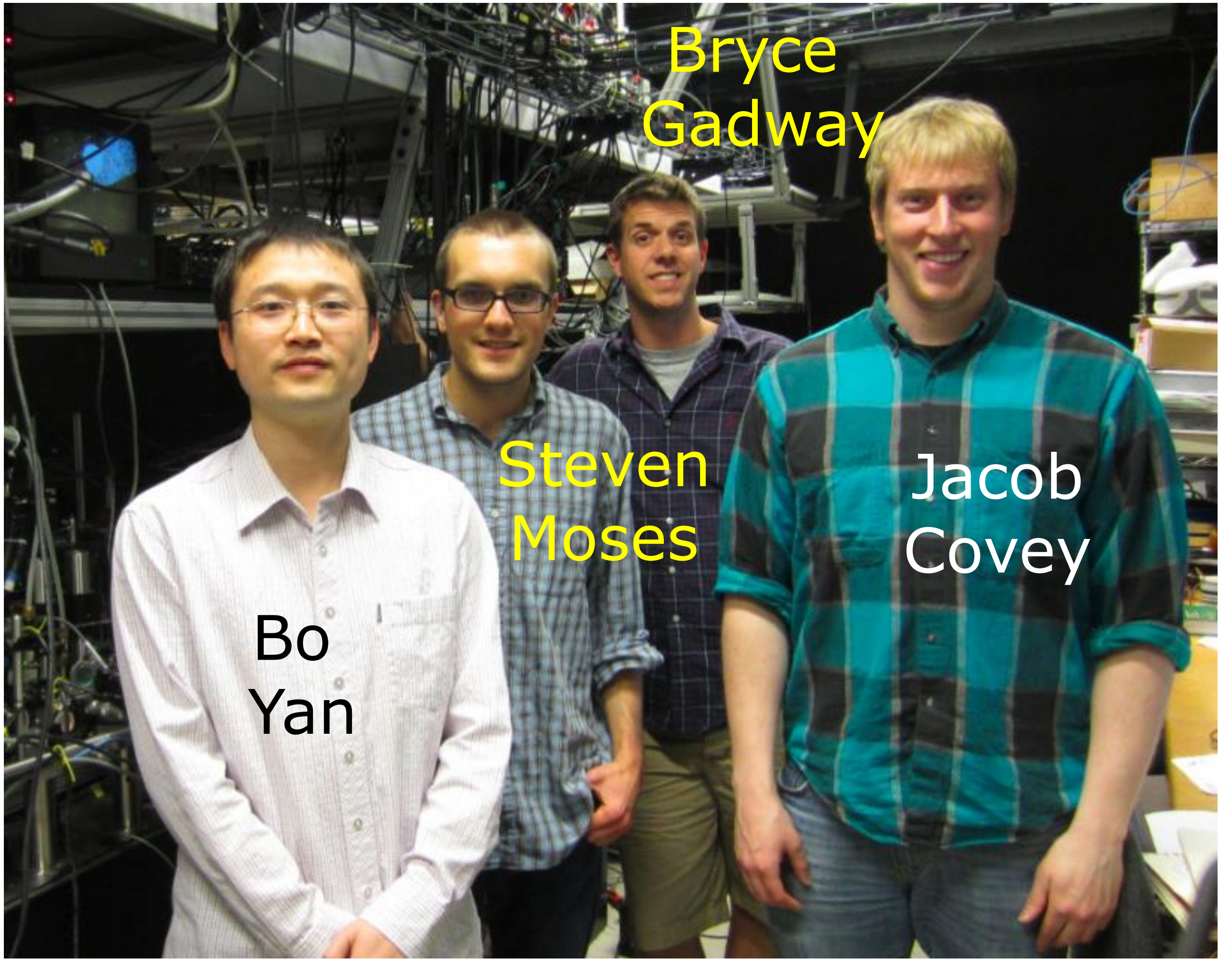


Ground state KRb,
~ 40% filling in 3D lattice



(entropy/molecule ~ 1.7 k_B)

Special Thanks (KRb team):



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