The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2030-27

Conference on Research Frontiers in Ultra-Cold Atoms

4 - 8 May 2009

Ultracold polar molecules

OSPELKAUS SCHWARZER Silke
JILA
National Institute of Standards and Technology NIST
and Department of Physics University of Colorado at Boulder, 80309-0440
Boulder CO
U.S.A.

Preparing an ultracold gas of polar molecules

Silke Ospelkaus
JILA, NIST and University of Colorado, Boulder

Kang Kuen Ni
Marcio Miranda
Brian Neyenhuis
Dajun Wang
Avi Pe'er
Joshua Zirbel

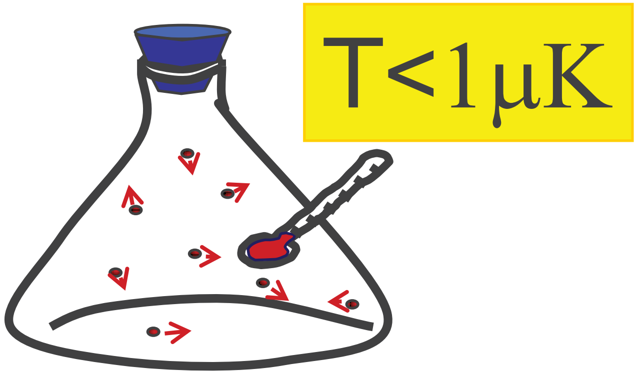
Jun Ye
Deborah Jin

Theory support: Svetlana Kotochigova and Paul Julienne

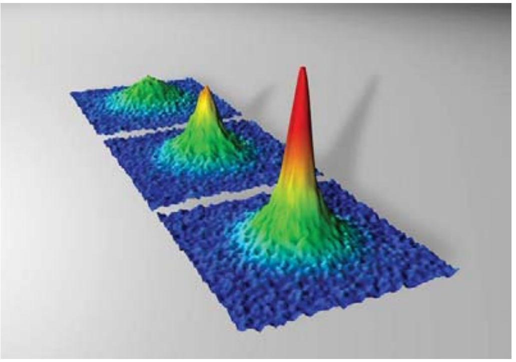
Outline

- Why make ultracold polar molecules?
- The challenge and our approach
- Properties of polar molecular gas
- Outlook

Ultracold atomic quantum gases



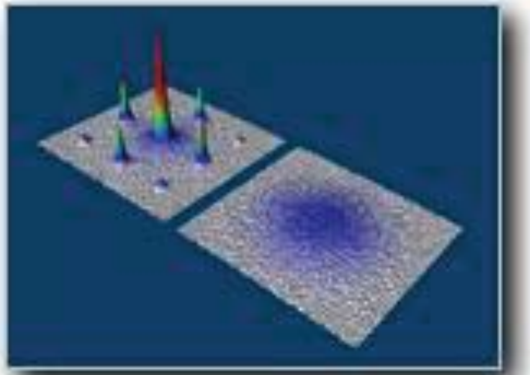
Bose-Einstein condensation
Fermi gases



http://jilawww.colorado.edu/~jin/publications/images/3Dview-white-9_001.jpg

Strongly correlated systems

- Superfluidity in Fermi gases
- Quantum phase transitions with fermions / bosons in optical lattices
- …

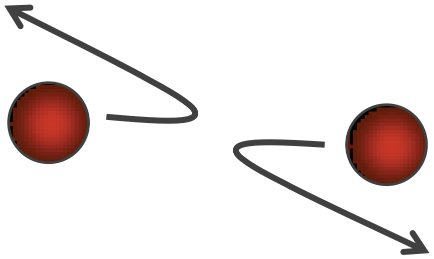


http://www.quantum.physik.uni-mainz.de/bec/gallery/mottadditional1.jpg

Interactions are the key!

- **Atoms:**
  contact interaction

  isotropic
  short ranged $\delta(R)$



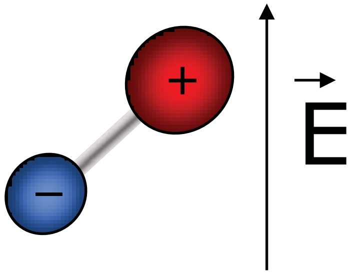
Why polar molecules?

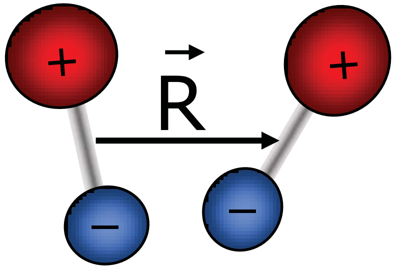
- **Polar molecules:**

  Permanent electric dipole moment

  Dipole-dipole interaction

  - Long-range *~1/*R^3
  - Anisotropic
  - Tunable

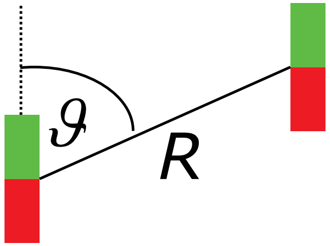




Why polar molecules?

Atoms

Magnetic dipoles



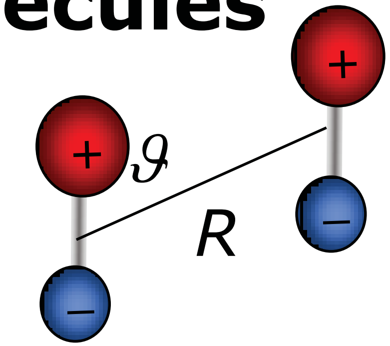
d ~ Bohr magneton

Berkeley, Rb BEC

Stuttgart, Cr BEC

Polar molecules

Electric dipoles



d ~ Debye

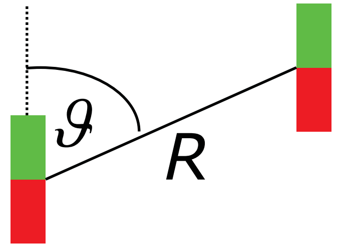
10 000 times stronger!

$$\frac{(\mathrm{Debye})^2}{(\mathrm{Bohr\ magneton})^2} \cdot c^2 = 10^4$$

Why polar molecules?

Atoms

Magnetic dipoles



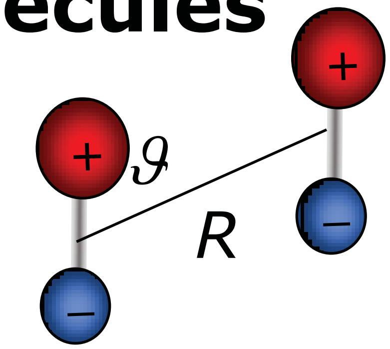
d ~ Bohr magneton

$d=1\mu_B$:
$a_{dd}=2.2a_0$

$<< n^{-1/3}$

Polar molecules

Electric dipoles



d ~ Debye

d=1 Debye
$a_{dd}=50000a_0$

Long-range!

Length scale

$n^{-1/3}=(5000\text{-}20\ 000)\ a_0$

$$a_{dd} = md^2 \big/ 4\pi\hbar^2\varepsilon_0$$

Perpectives with ultracold polar molecules – Quantum physics

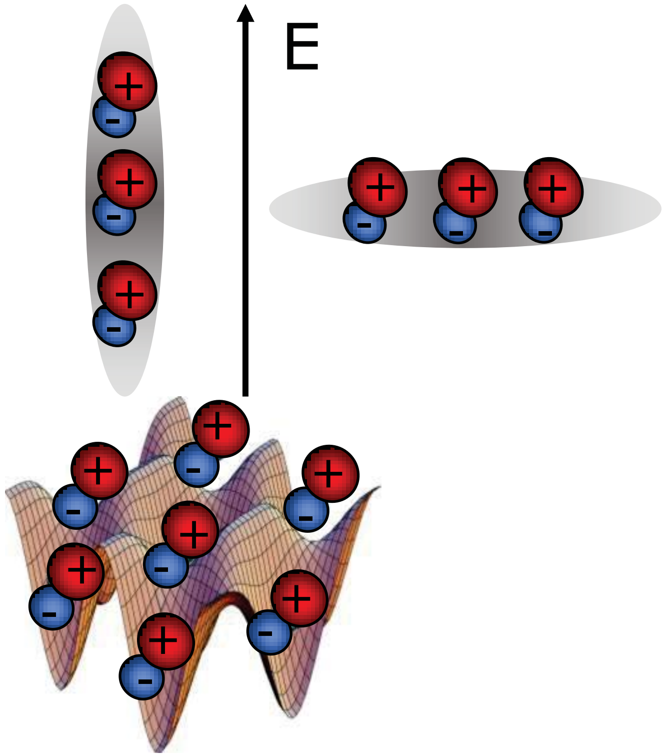
- **Quantum information**
  (strong dipolar interactions, long coherence time)

  D. DeMille, PRL 88,067901(2001)

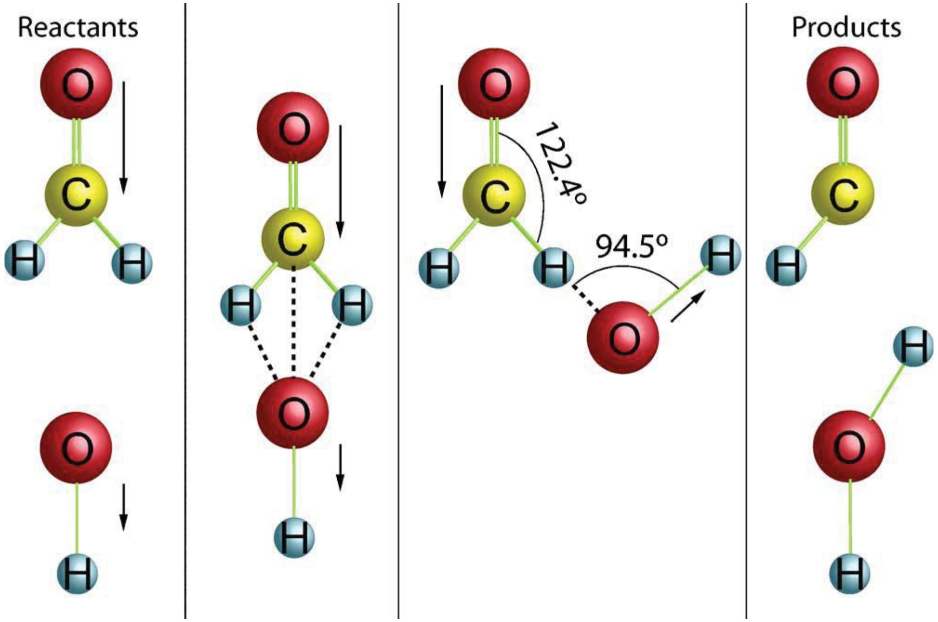
- **Quantum degeneracy**
  (e.g. BEC/Fermi gases with anisotropic interactions)

- **Dipolar phase transition**
  (Condensed matter systems and beyond)

  Reviews e.g.
  M. Baranov, Physics Reports 464, 71-111(2008)
  G. Pupillo et al., arxiv: 0805.1896 (2008)



Perspectives with ultracold polar molecules – Ultracold chemistry



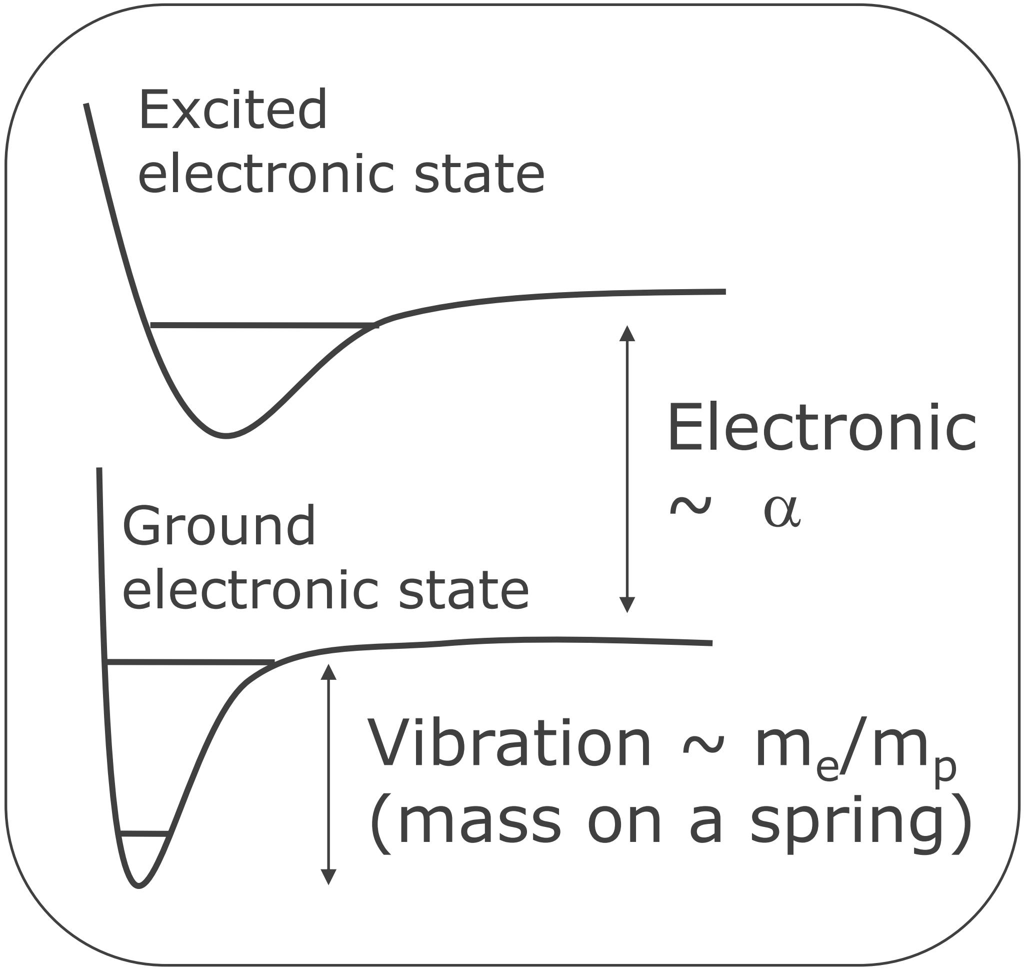
E. R. Hudson *et al.*, Phys. Rev. A **73**, 063404 (2006)

Controlled molecular collisions
Ultracold chemical reactions

- Molecules in single quantum states
- precise control of internal and external degrees of freedom

Review: e.g. R.V. Krems, PCCP 10, 4079 (2008)

Ultracold molecules:
Precision measurements



Excited
electronic state

Electronic
$\sim \alpha$

Ground
electronic state

Vibration $\sim m_e/m_p$
(mass on a spring)

- Ultrahigh resolution spectroscopy
- Molecular interferometry

- Search for eEDM
- Time variation of fundamental constants

What are the requirements?

- Single internal quantum state, and long-lived
- Dipolar interaction energy comparable to kinetic energy

$$\boxed{d^2 / R^3 \propto k_B T}$$

***Need** low temperature and high density*

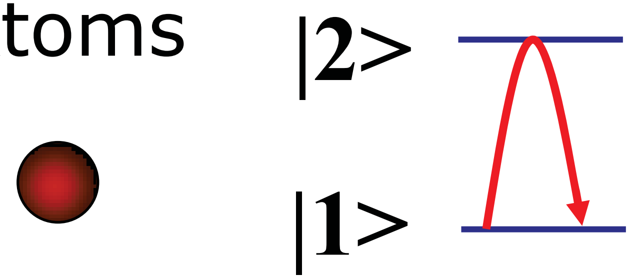
➡ a quantum degenerate gas!

Ultracold molecules – a challenge

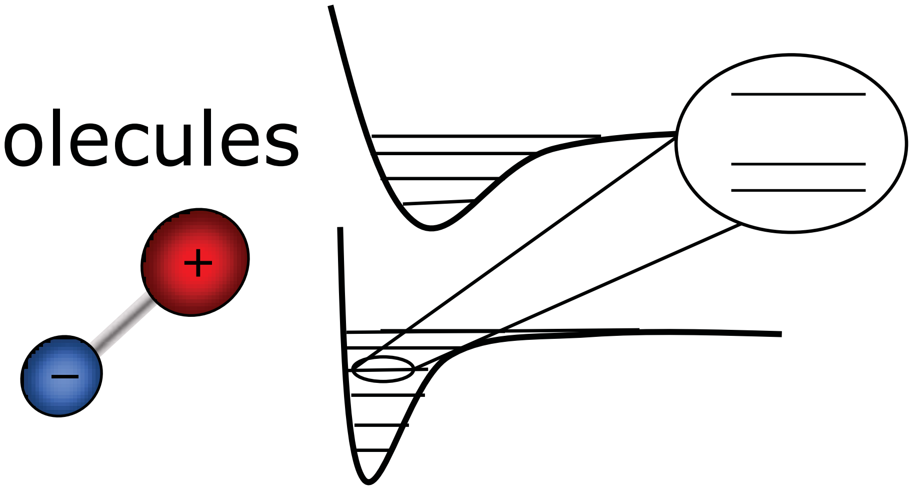
"A diatomic molecule is a molecule with one atom too many!"

– Arthur Schawlow, co-inventor of laser
and pioneer of laser spectroscopy

Atoms

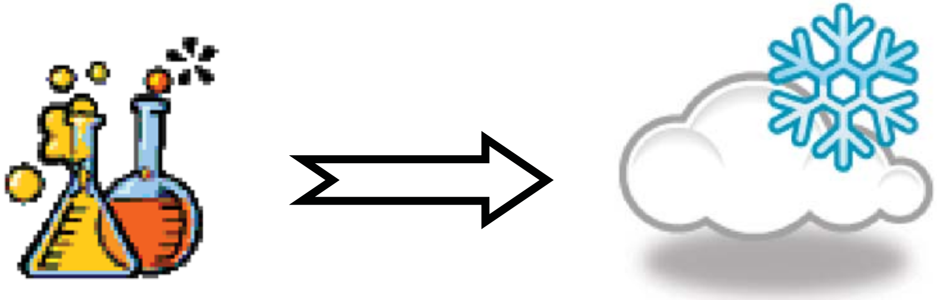


Molecules



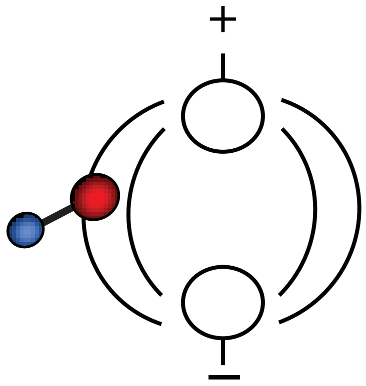
What has been achieved?

Direct cooling of ground state polar molecules

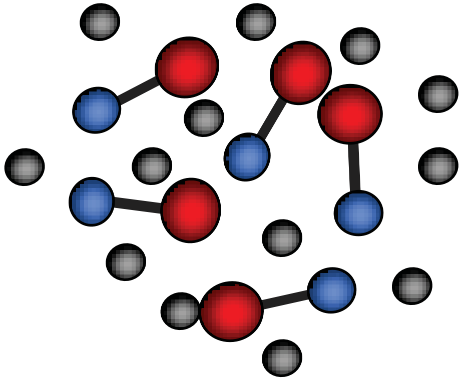


Stark deceleration

Buffer gas cooling



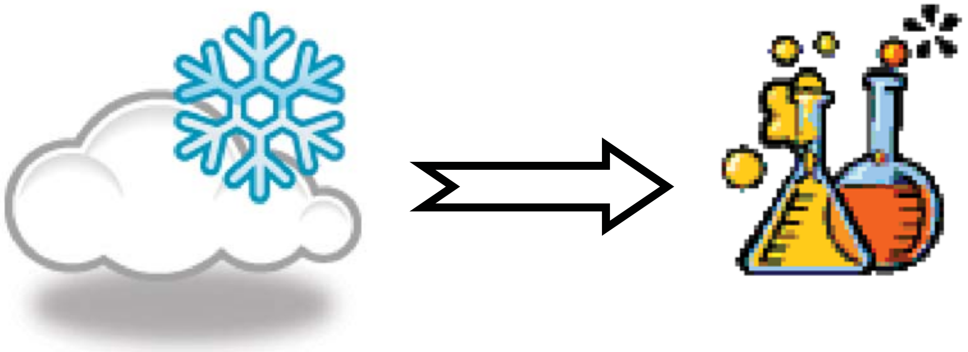
Temperature: 1 mK
Densities ~10^6/cm^3
$\rho=10^{-13}$



J. Doyle at Harvard, G. Meijer in Berlin, G. Rempe in Munich, J. Ye at JILA,…..

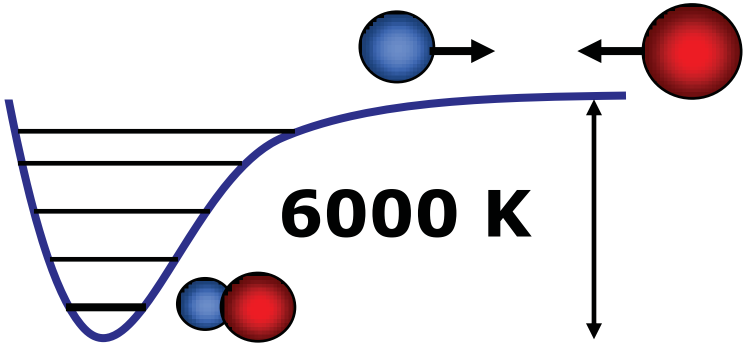
How to make ultracold polar molecules?

Pairing of ultracold atoms

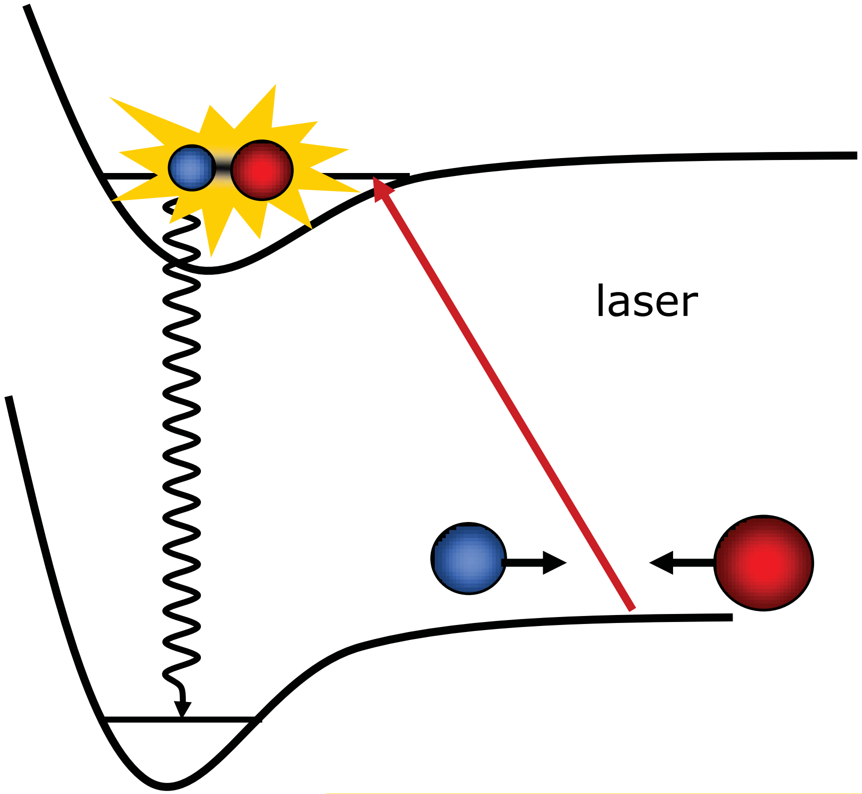


Advantage: Start ultracold
(@ few hundred nK).

Challenge: Stay ultracold.



Pairing of ultracold atoms
Photoassociation



- Light carries away the binding energy!
- Rovibrational ground state **polar** molecules

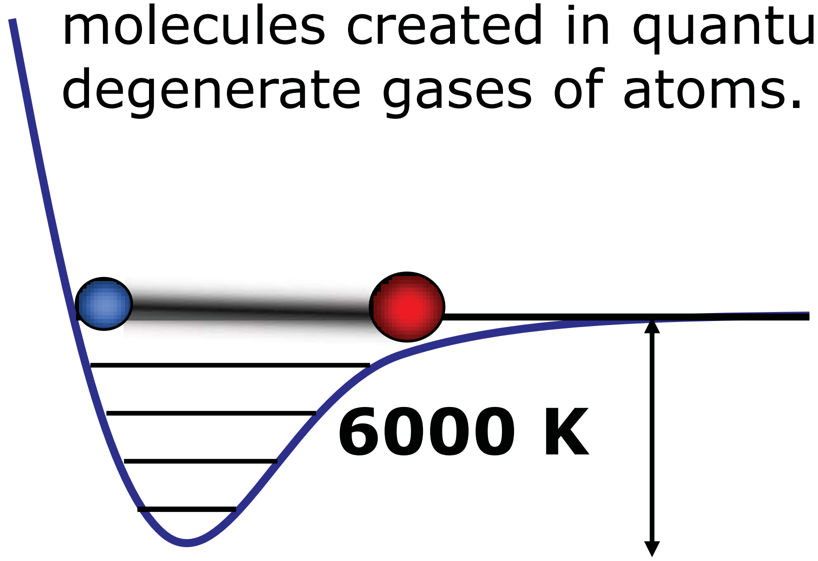
- **But:** Recoil kick (300nK)
- Several vibrational/rotational states
- Low production rate

Estimate: T=250μK, n=10^5/cm^3, $\rho=10^{-13}$,

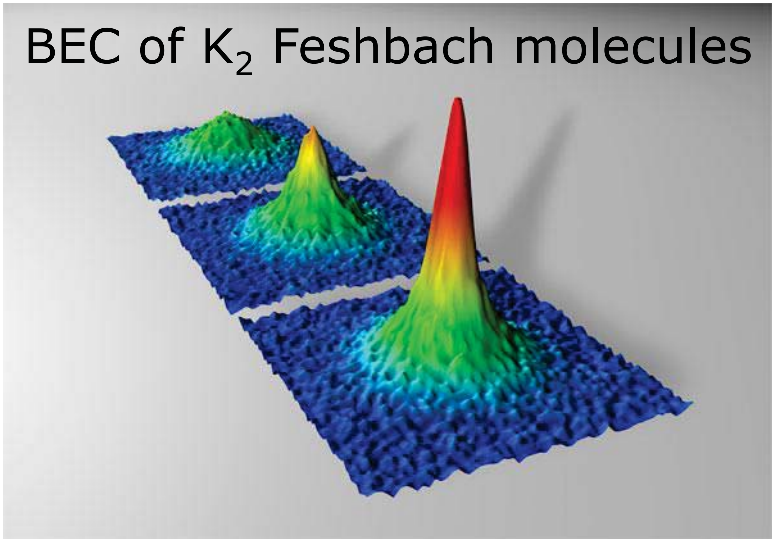
DeMille at Yale, Weidemuller in Freiburg/Heidelberg,…..

Pairing of ultracold atoms: Feshbach molecules

Large, weakly bound “Feshbach” molecules created in quantum degenerate gases of atoms.



BEC of K_2 Feshbach molecules



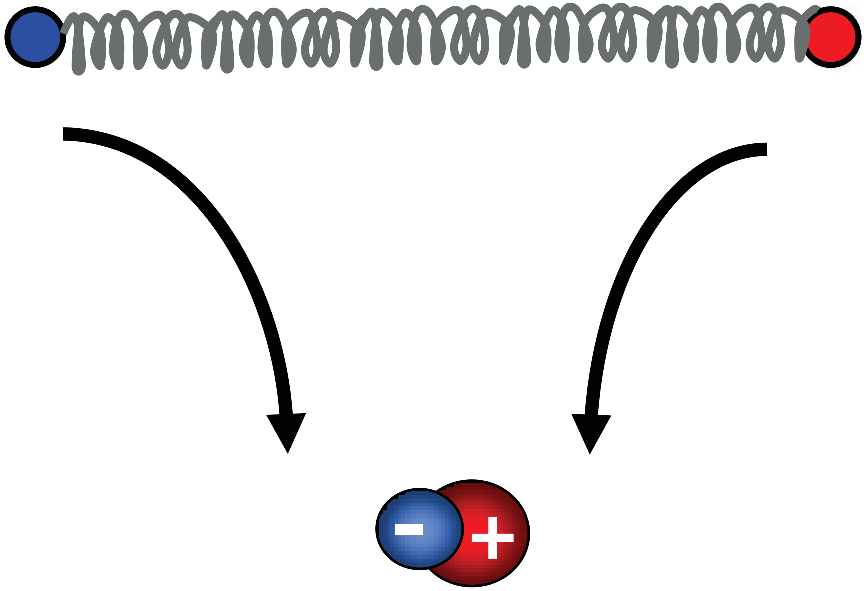
D.S. Jin, JILA, Boulder
BEC of Li_2: R. Grimm, W. Ketterle, ….

- Least bound vibrational level
- well defined quantum state!
- Weakly bound
- Large and floppy

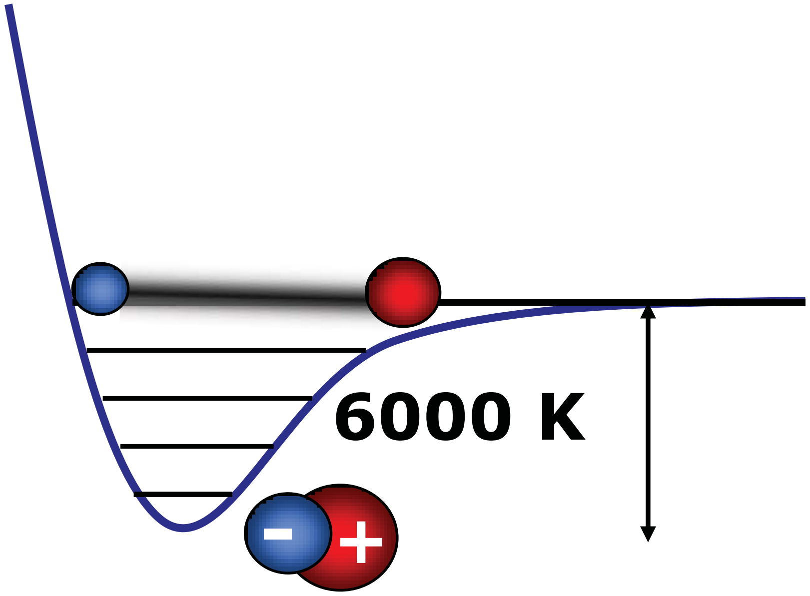
Dipole moment d=0

Shrink the molecules

Feshbach molecules

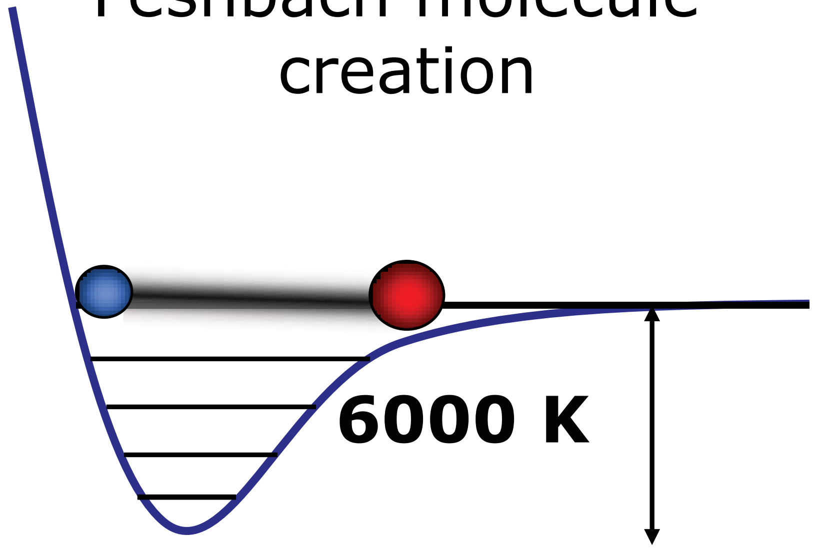


Small, tightly bound,
polar molecules



Our approach

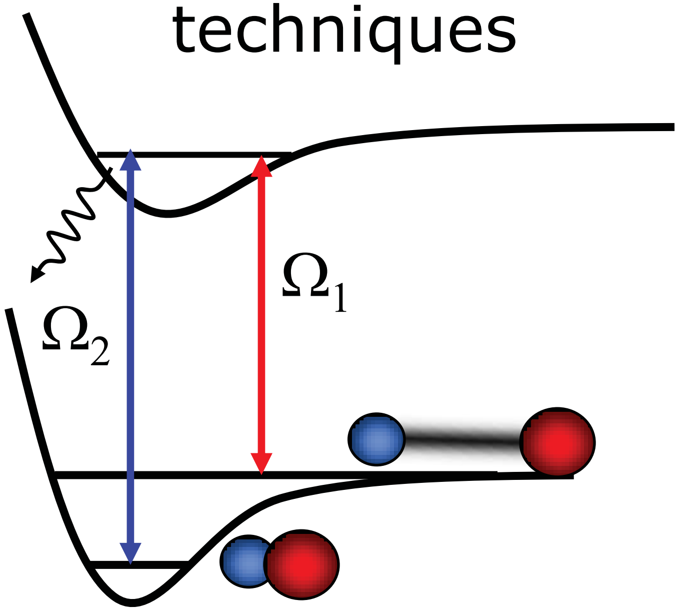
Feshbach molecule creation



Negligible dipole moment

+

Coherent state transfer techniques

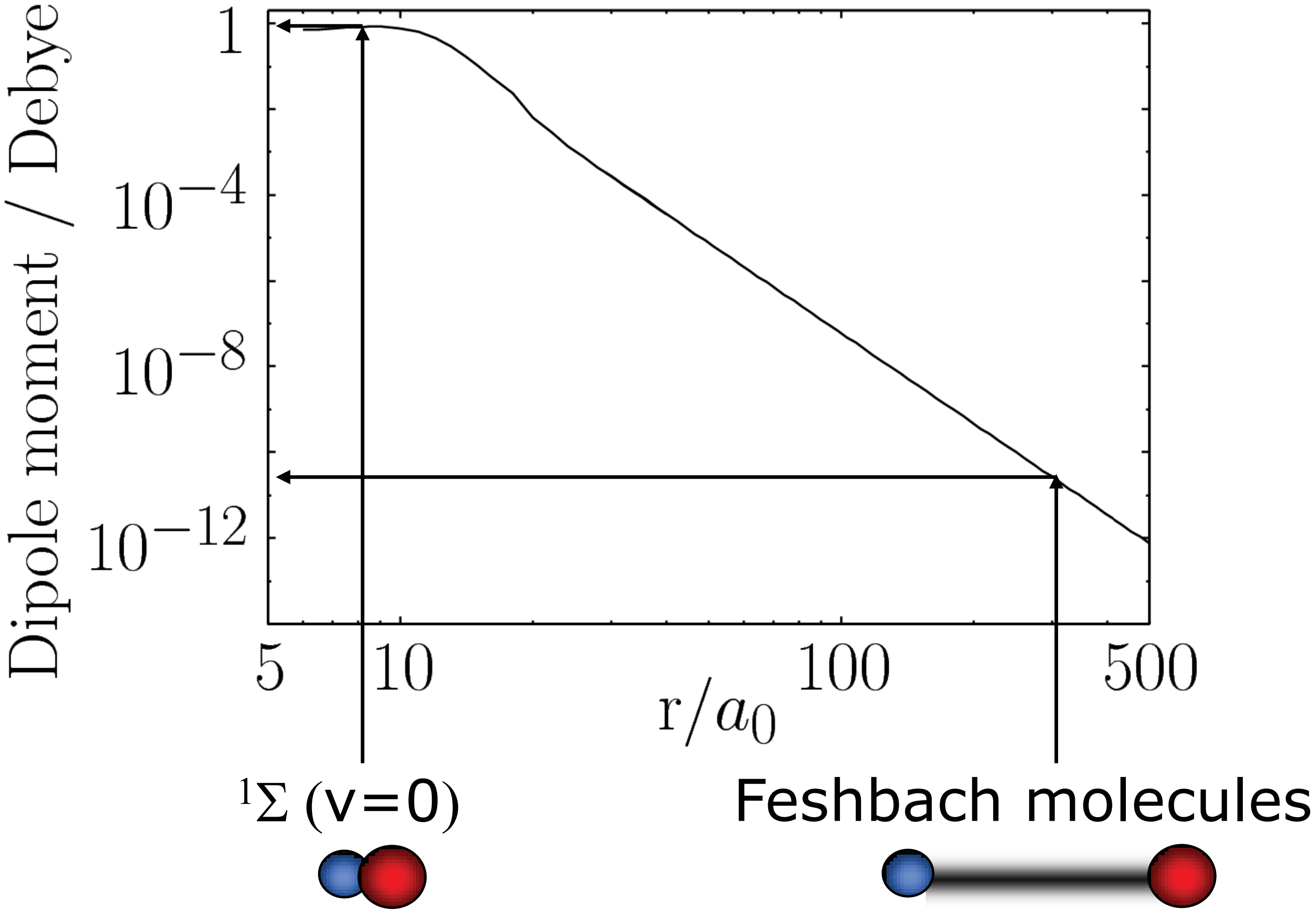


Significant dipole moment

Preserve phase-space density through coherent transfer

Non-polar molecules: J. Hecker Denschlag / R. Grimm in Rb_2 and C. Nagerl in Cs_2

KRb dipole moment

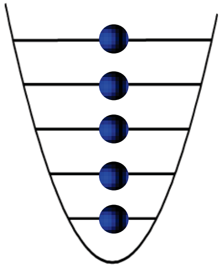


$^1\Sigma$ (v=0)

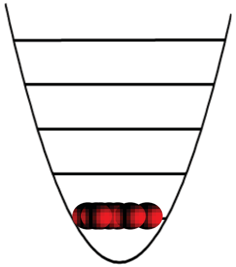
Feshbach molecules

Our system

^{40}K



Mixture of ^{40}K and ^{87}Rb
T=300 nK, $n=10^{13}/cm^3$, $\rho=0.2$
trapped in an optical potential



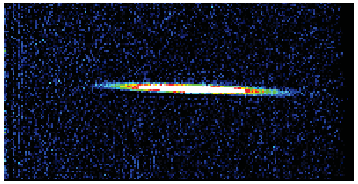
^{87}Rb

Weakly bound KRb Feshbach molecules

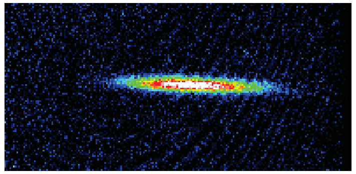
Binding energy ~ 14μK
Size ~ 300 a_0
(size of ground state KRb 7a_0)

Seeing the trapped Feshbach molecules

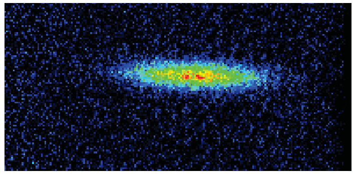
1ms



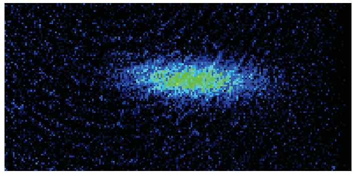
3ms

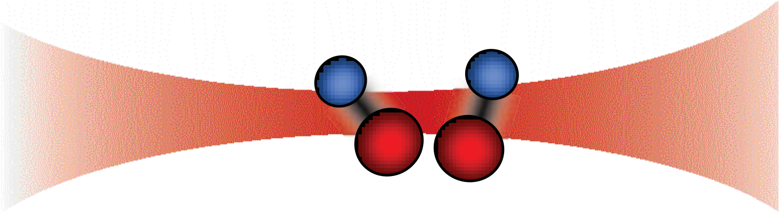


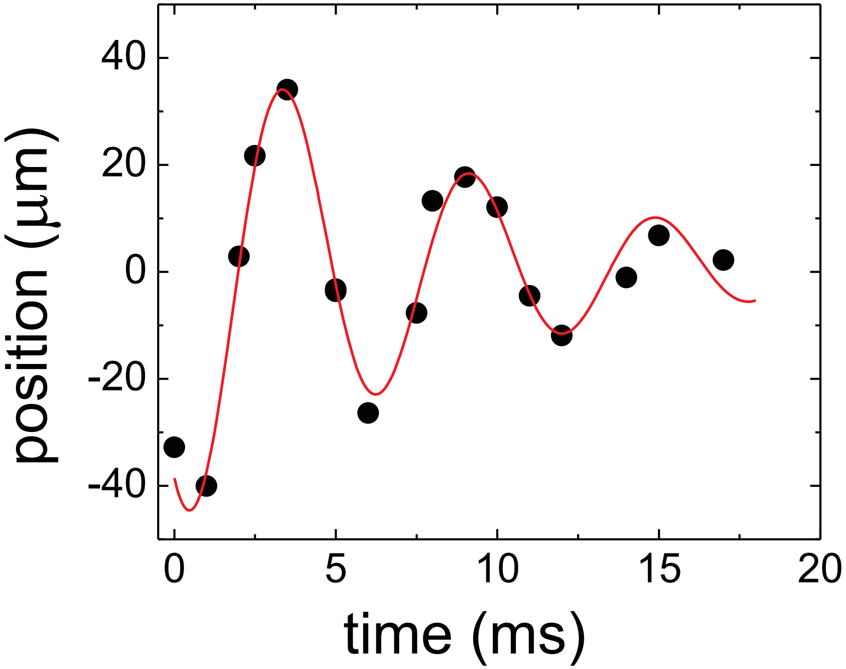
6ms



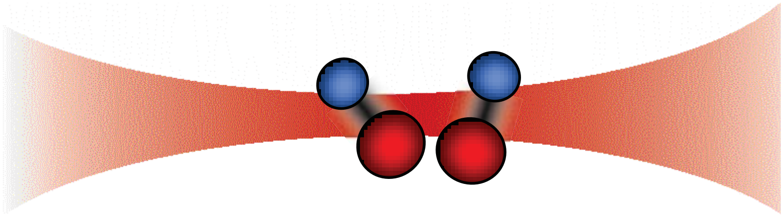
9ms







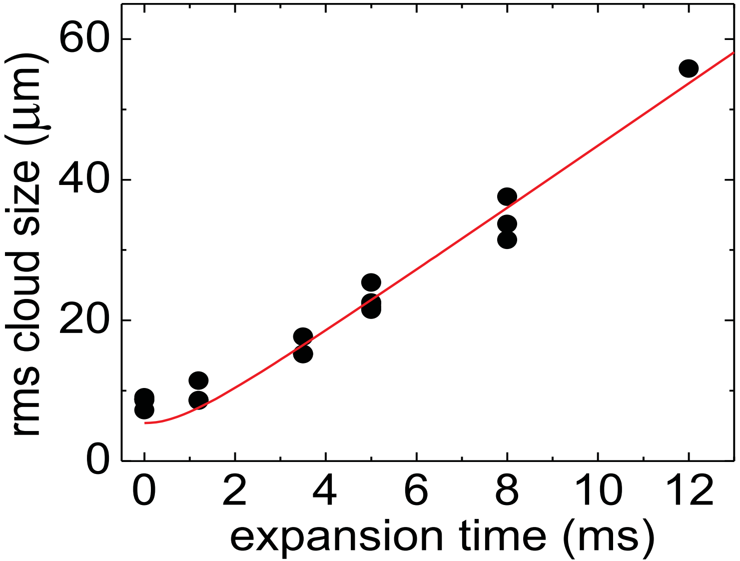
Properties of KRb Feshbach molecules



5 x 10^4 molecules trapped in an optical potential

J. Zirbel et al., PRA 78, 013416 (2008)

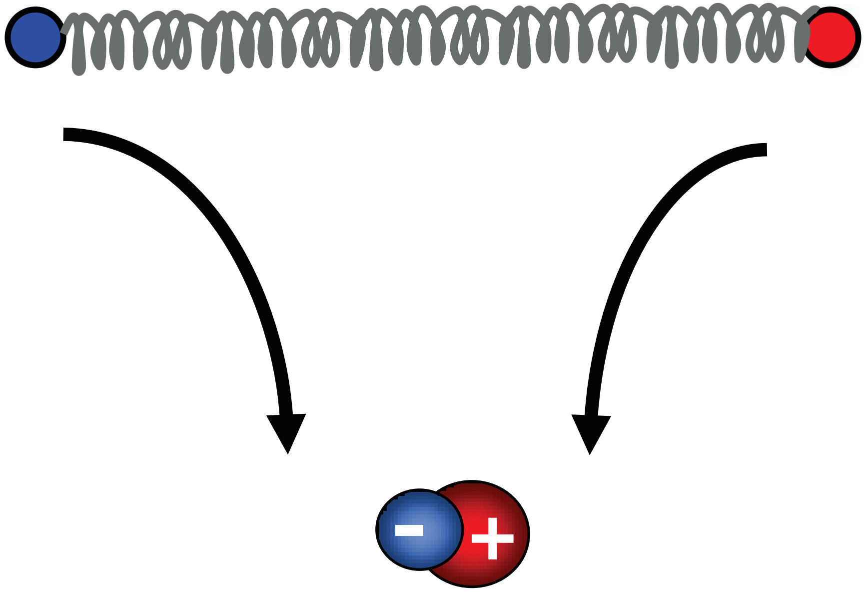
- Expansion energy ~400nK
- $T/T_F=3$
- Density~10^{12}/cm^3
- ρ =0.01



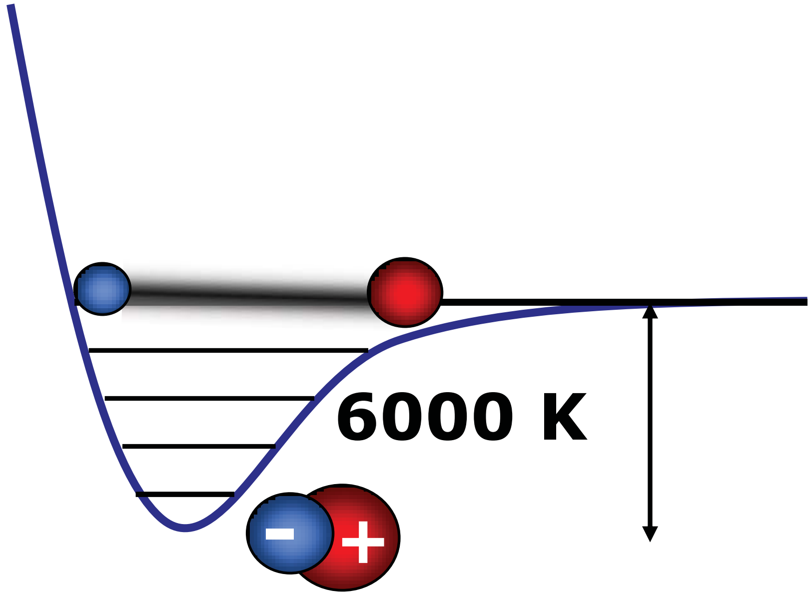
Electric dipole moment = 5 x 10^{-11} Debye ≈ 0

Shrink the molecules

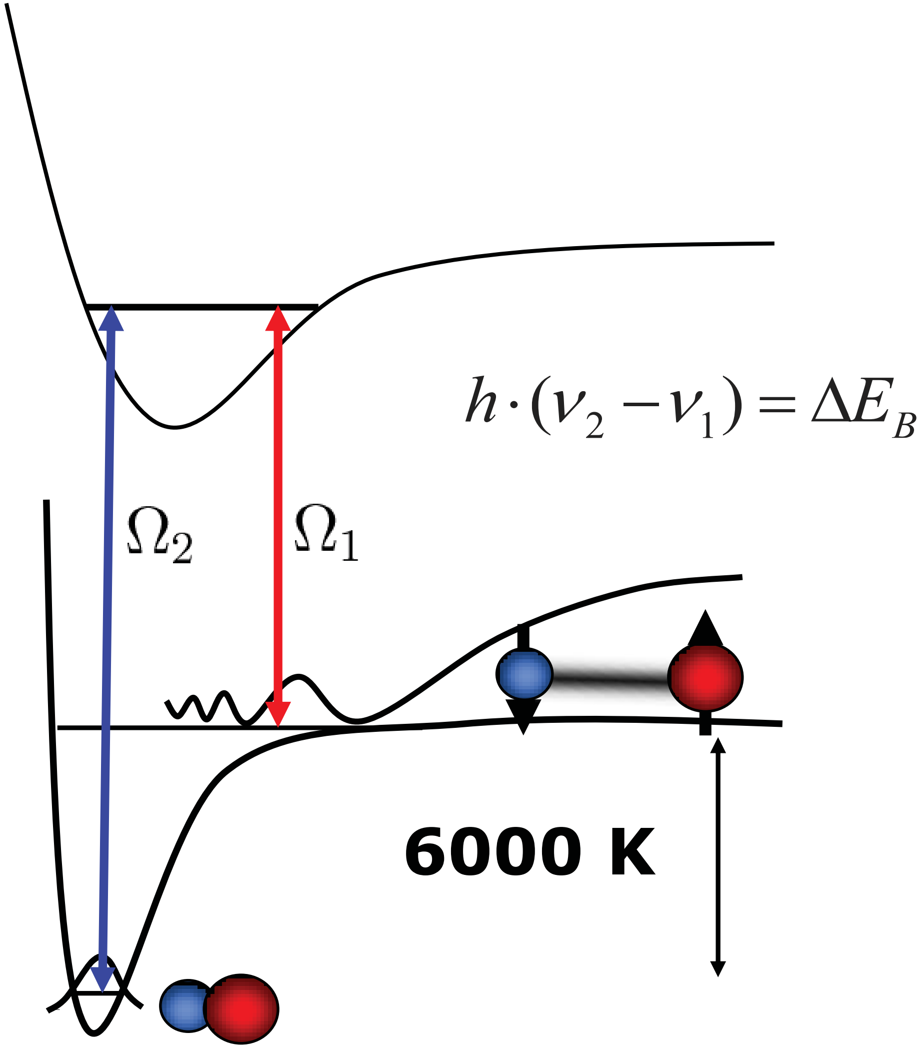
Feshbach molecules



Small, tightly bound,
polar molecules



Coherent two-photon transfer to the rovibrational ground-state



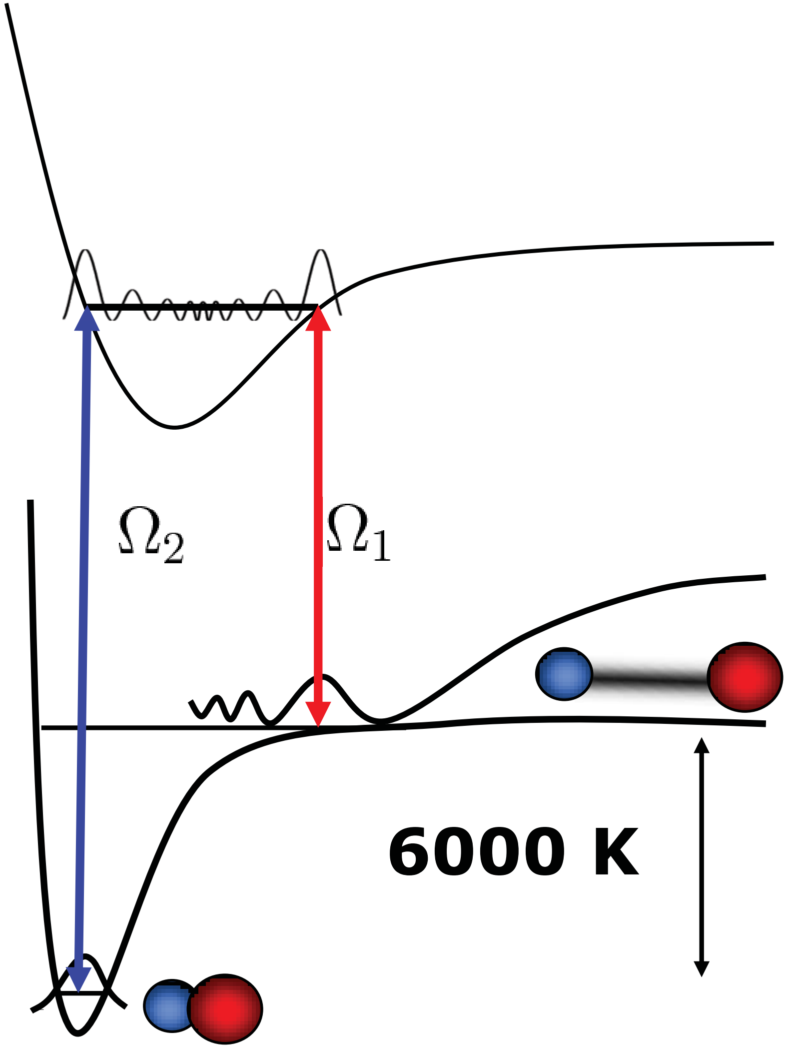
$$h \cdot (\nu_2 - \nu_1) = \Delta E_B$$

Control internal degrees of freedom (quantum state)

Challenges:

- Wave function overlap (Franck-Condon Overlap)
- Bridging ~125 THz (~6000K) with a phase coherent laser system

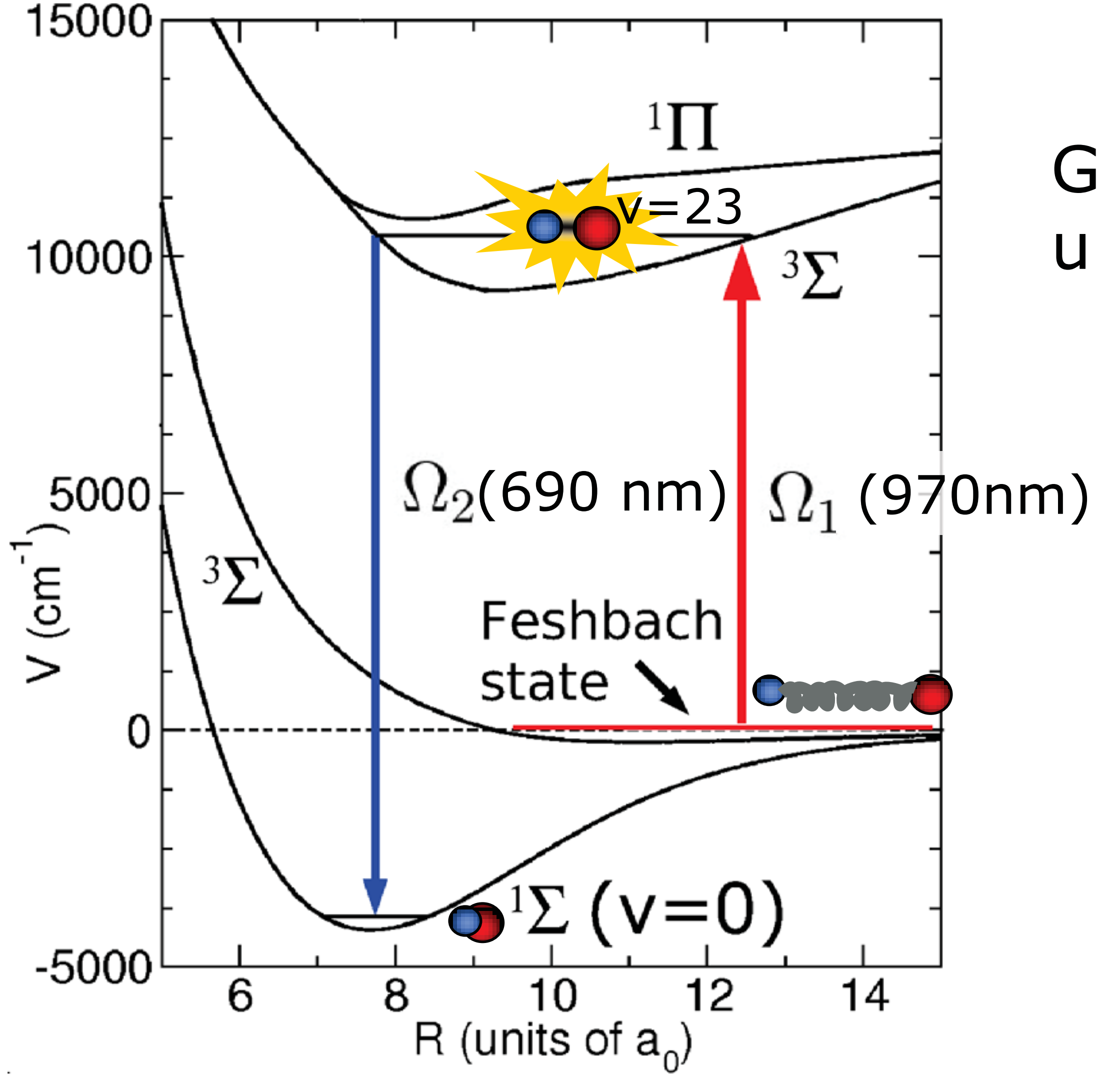
Coherent two-photon transfer to the rovibrational ground-state



Challenges:

- Wave function overlap (Franck-Condon Overlap)
- Bridging ~125 THz (~6000K) with a phase coherent laser system

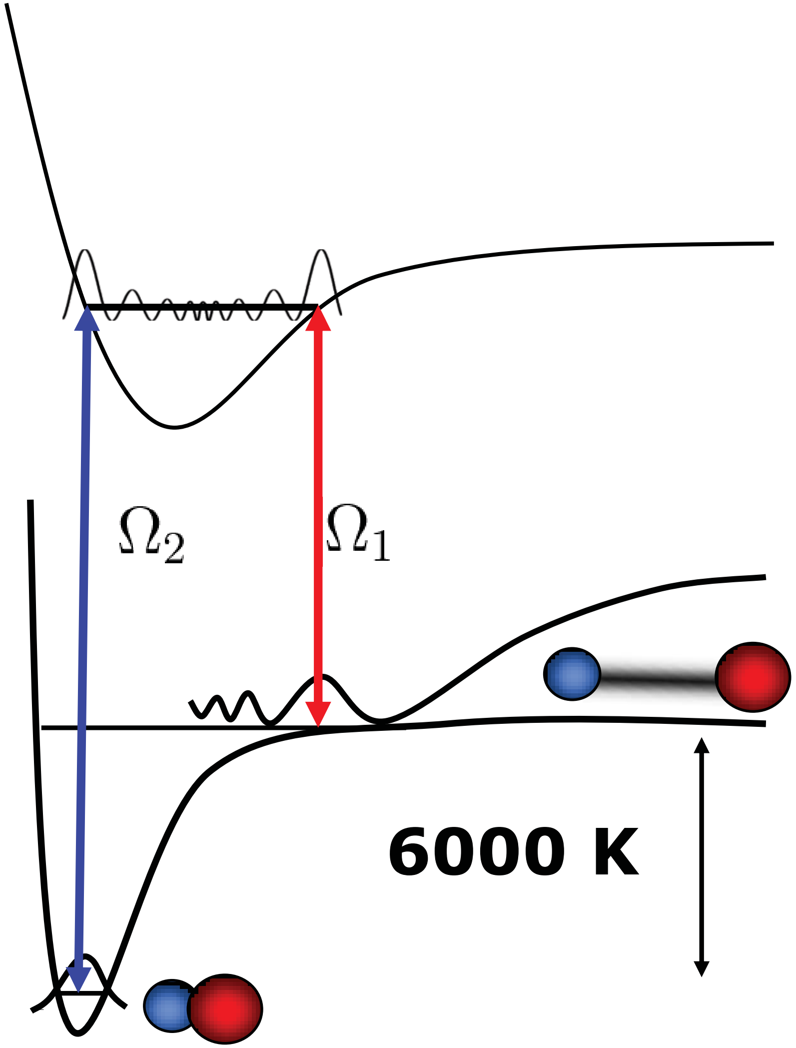
Coherent two-photon transfer: Wavefunction overlap



Good Franck-Condon for both up and down transitions.

Triplet Singlet Mixing

Coherent two-photon transfer

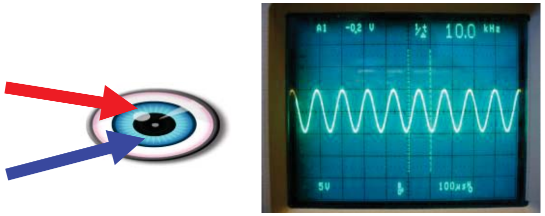


Challenges:

- Wave function overlap (Franck-Condon Overlap)
- Bridging ~125 THz with a phase coherent laser system

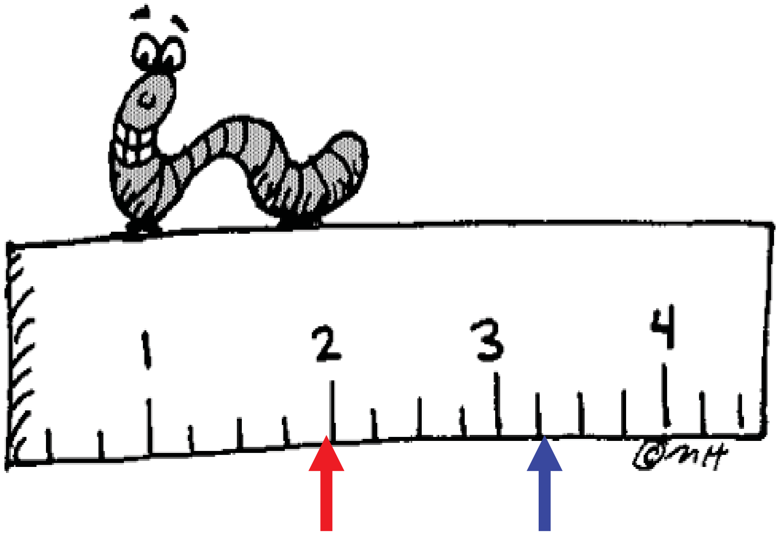
Coherent two-photon transfer

$$h \cdot (\nu_2 - \nu_1) = \Delta E_B$$



Laser 1

Laser 2

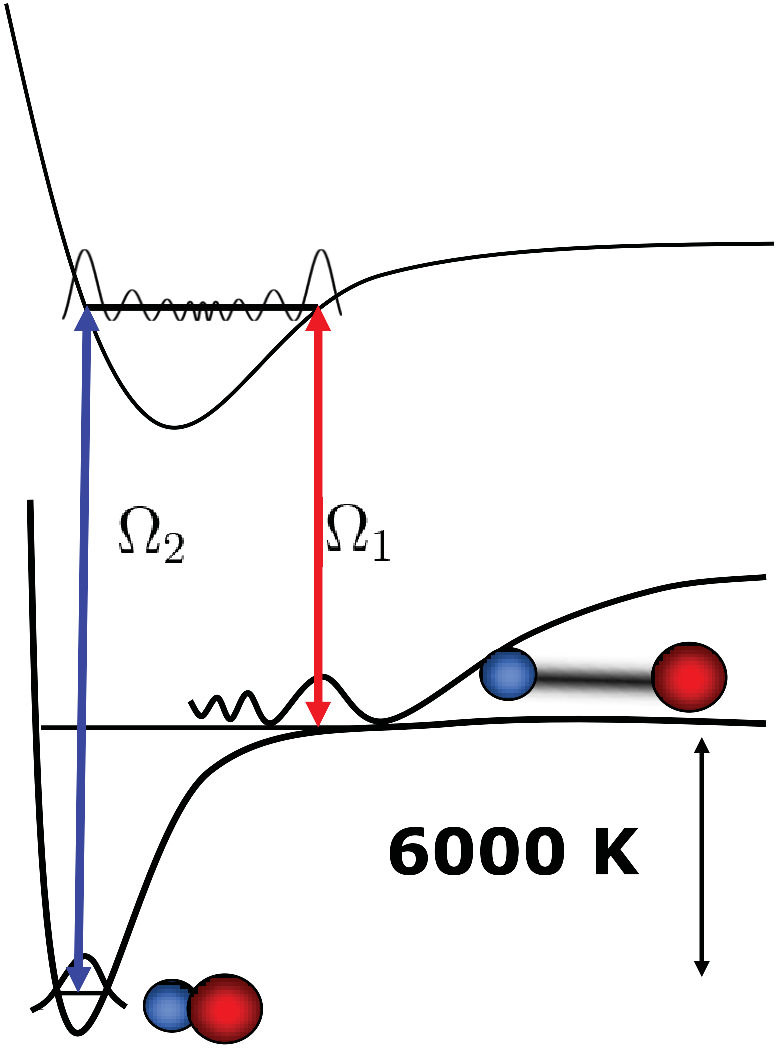


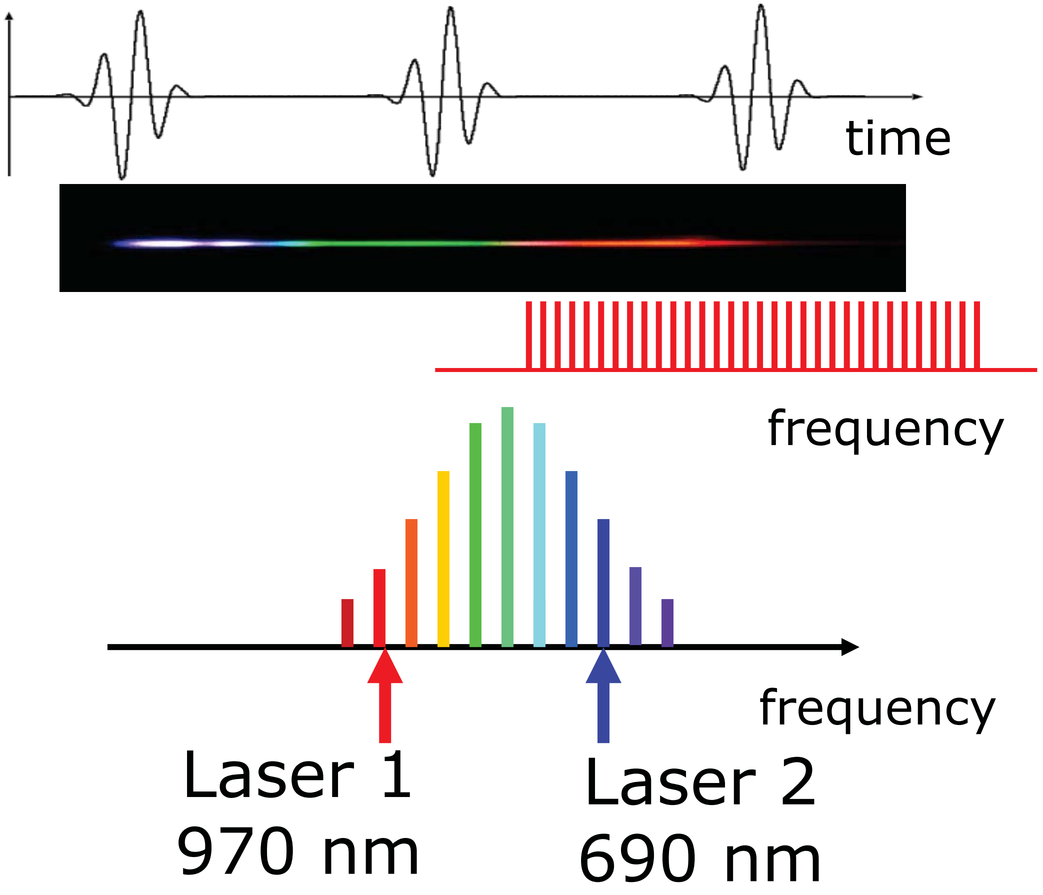
Laser 1

Laser 2

“Frequency ruler”

Frequency comb assisted transfer



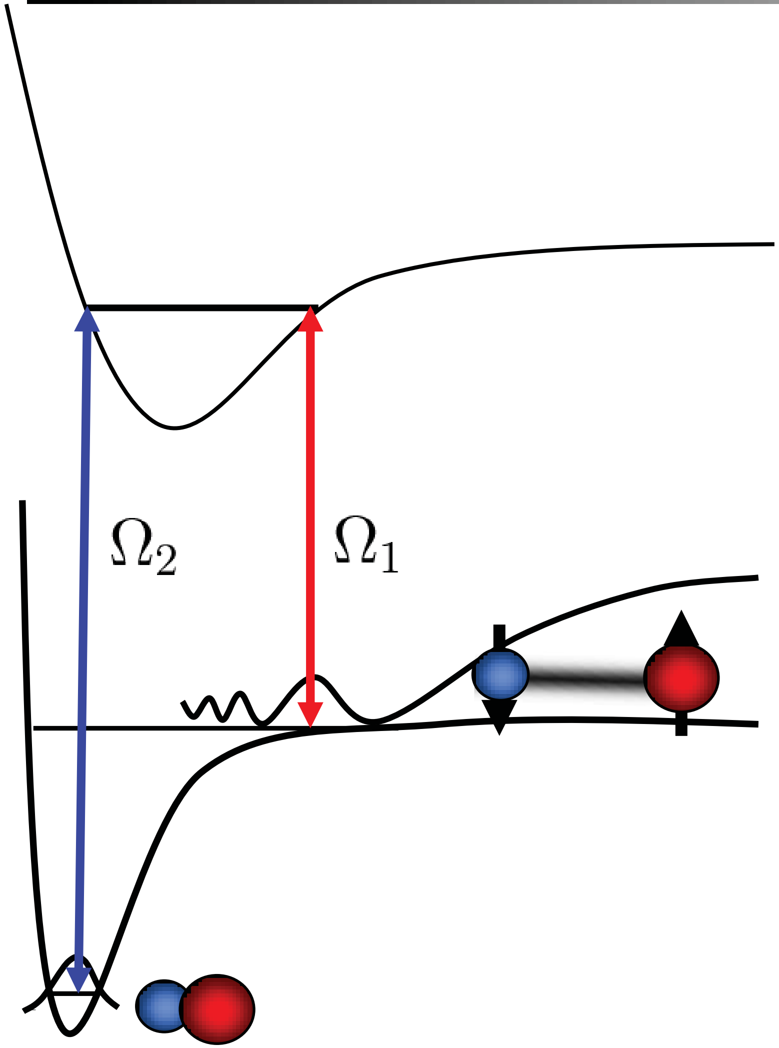


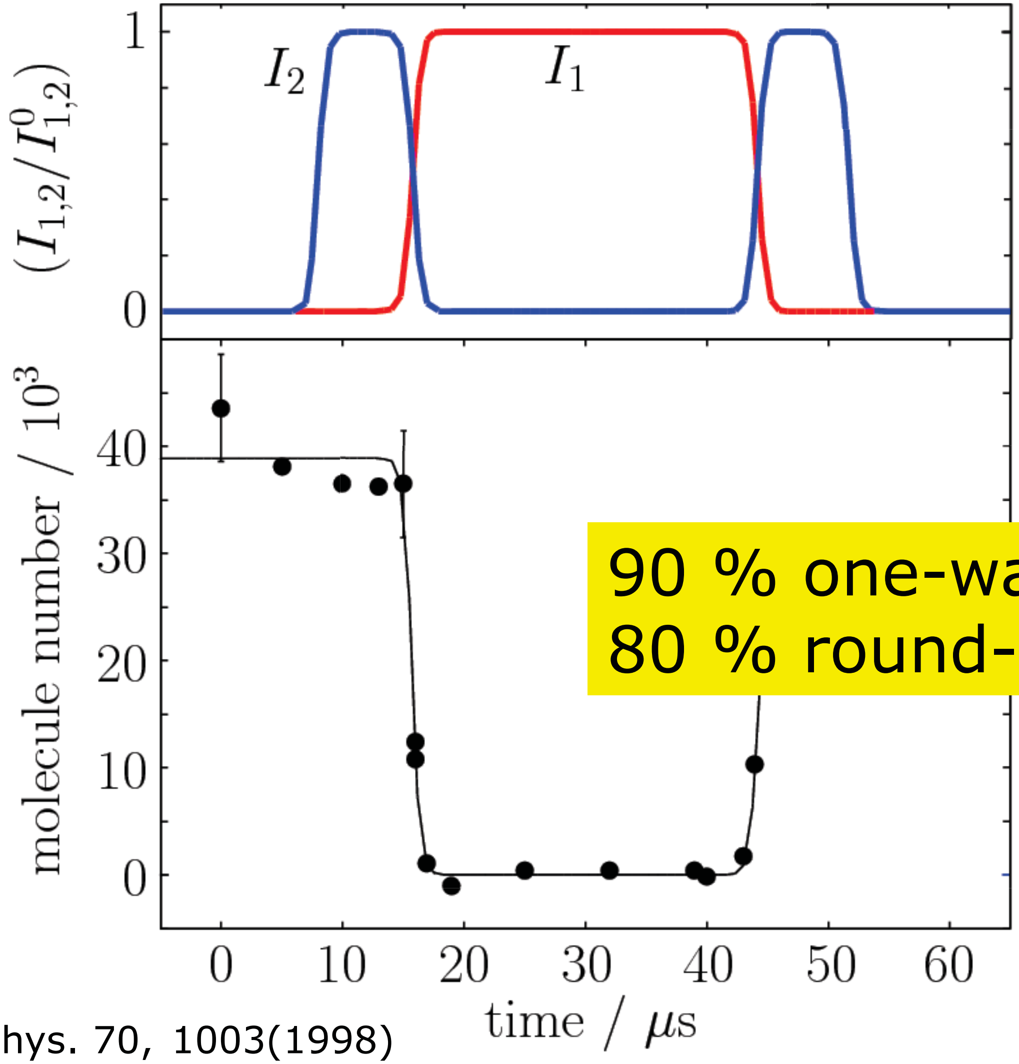
Laser 1
970 nm

Laser 2
690 nm

Beat note 125 THz

Making ground-state polar molecules (STIRAP)

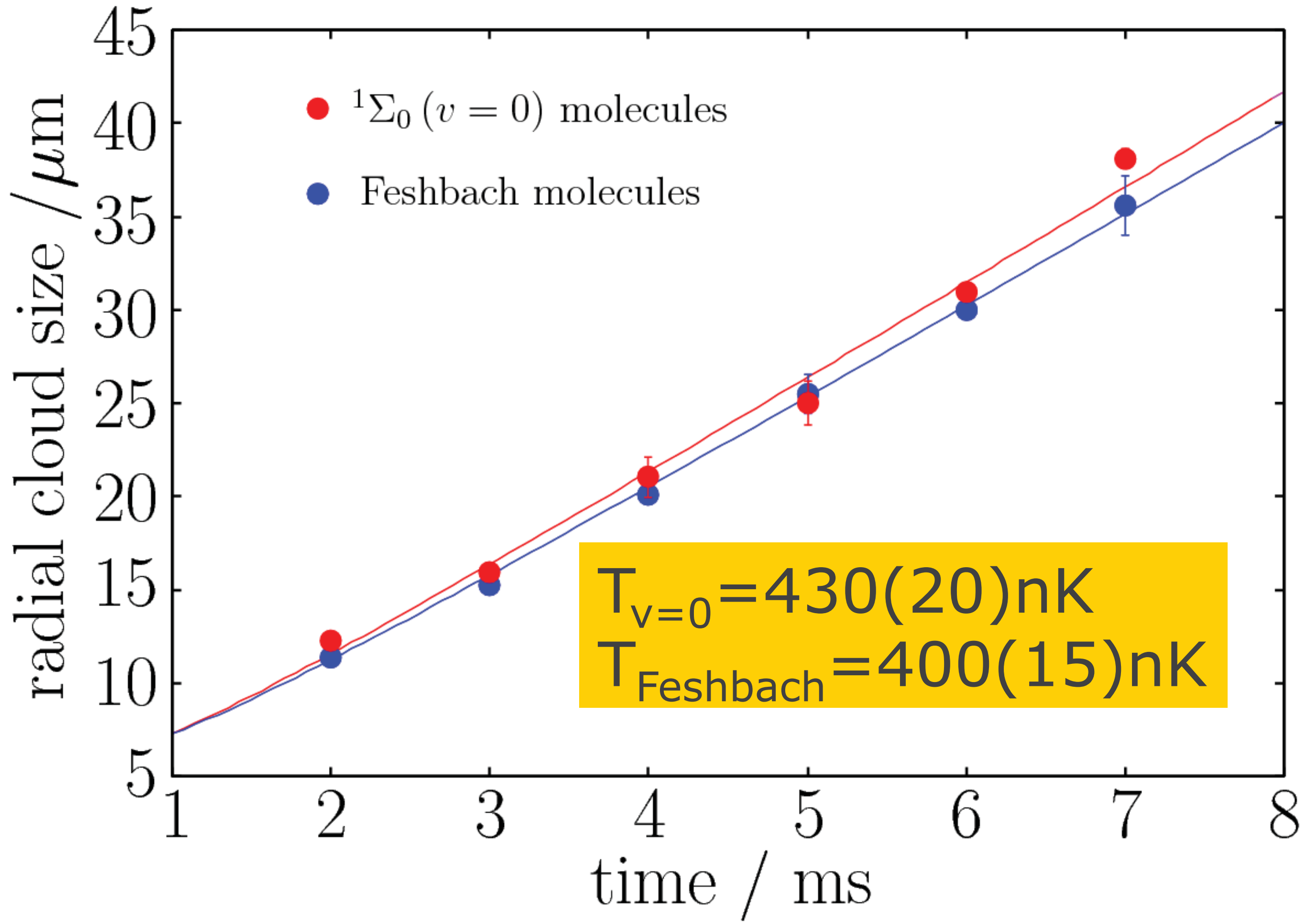




90 % one-way
80 % round-trip

STIRAP: K. Bergmann et al., Rev. Mod. Phys. 70, 1003(1998)

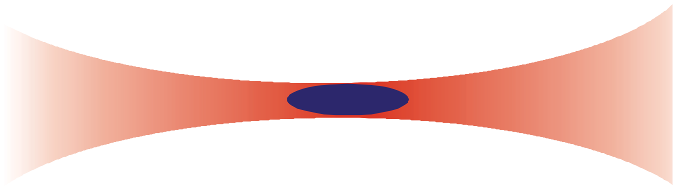
Transfer without heating

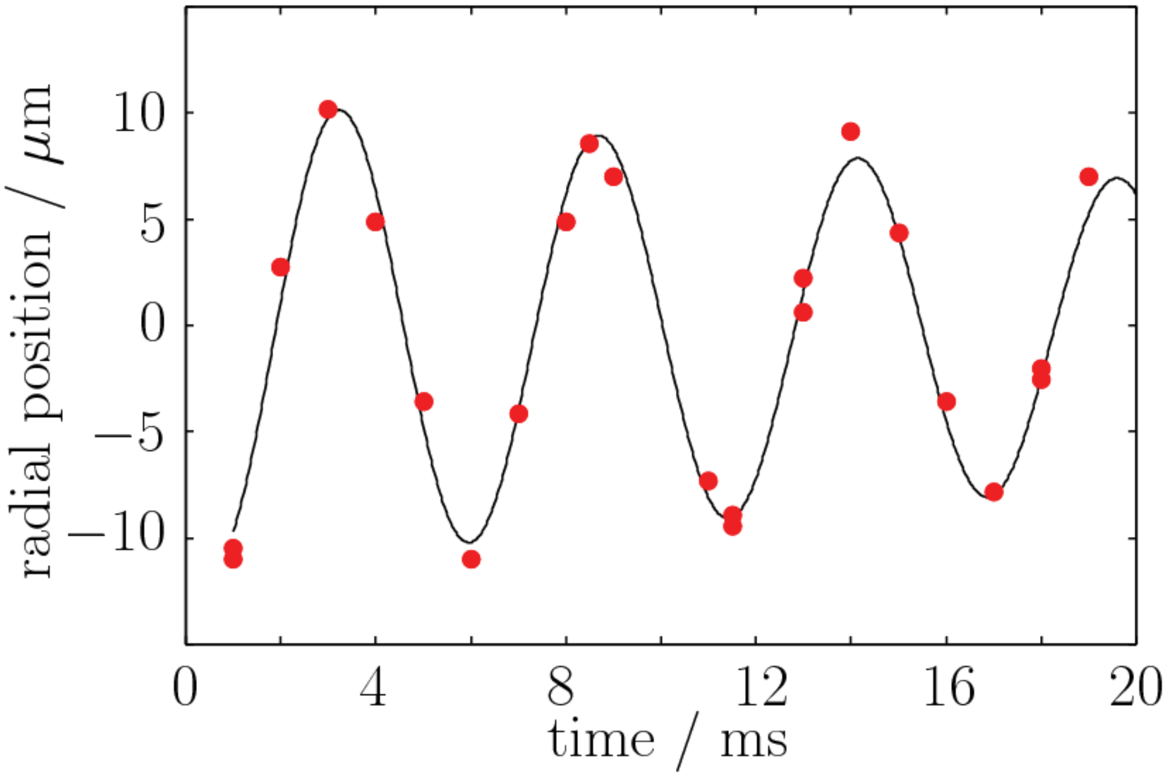


$T_{v=0}$=430(20)nK
T_{Feshbach}=400(15)nK

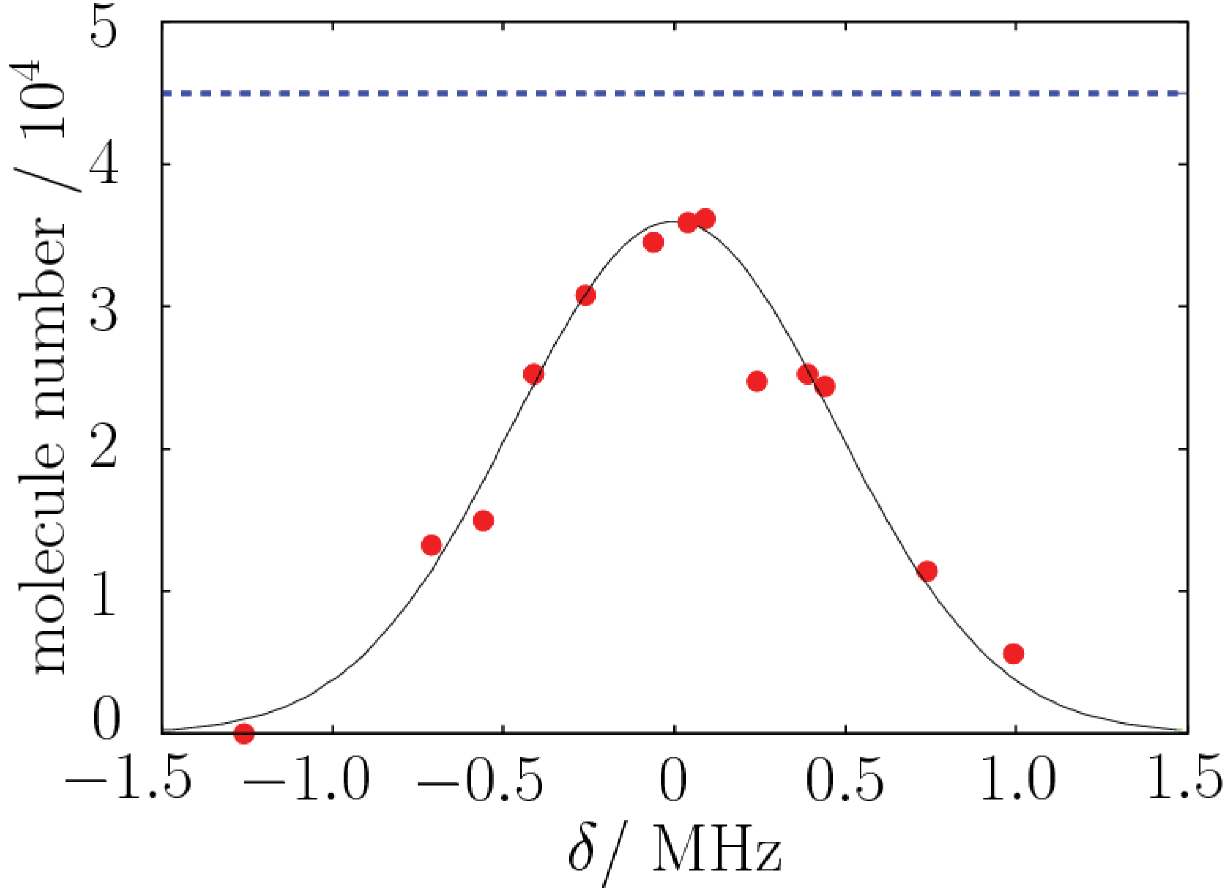
Light carries binding energy away 125 THz (6000 K)!

Trapped molecules!



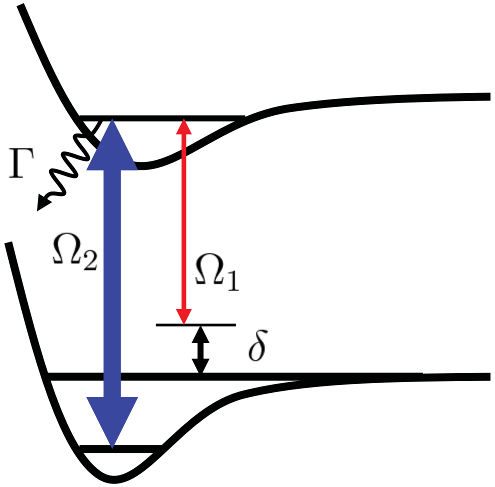


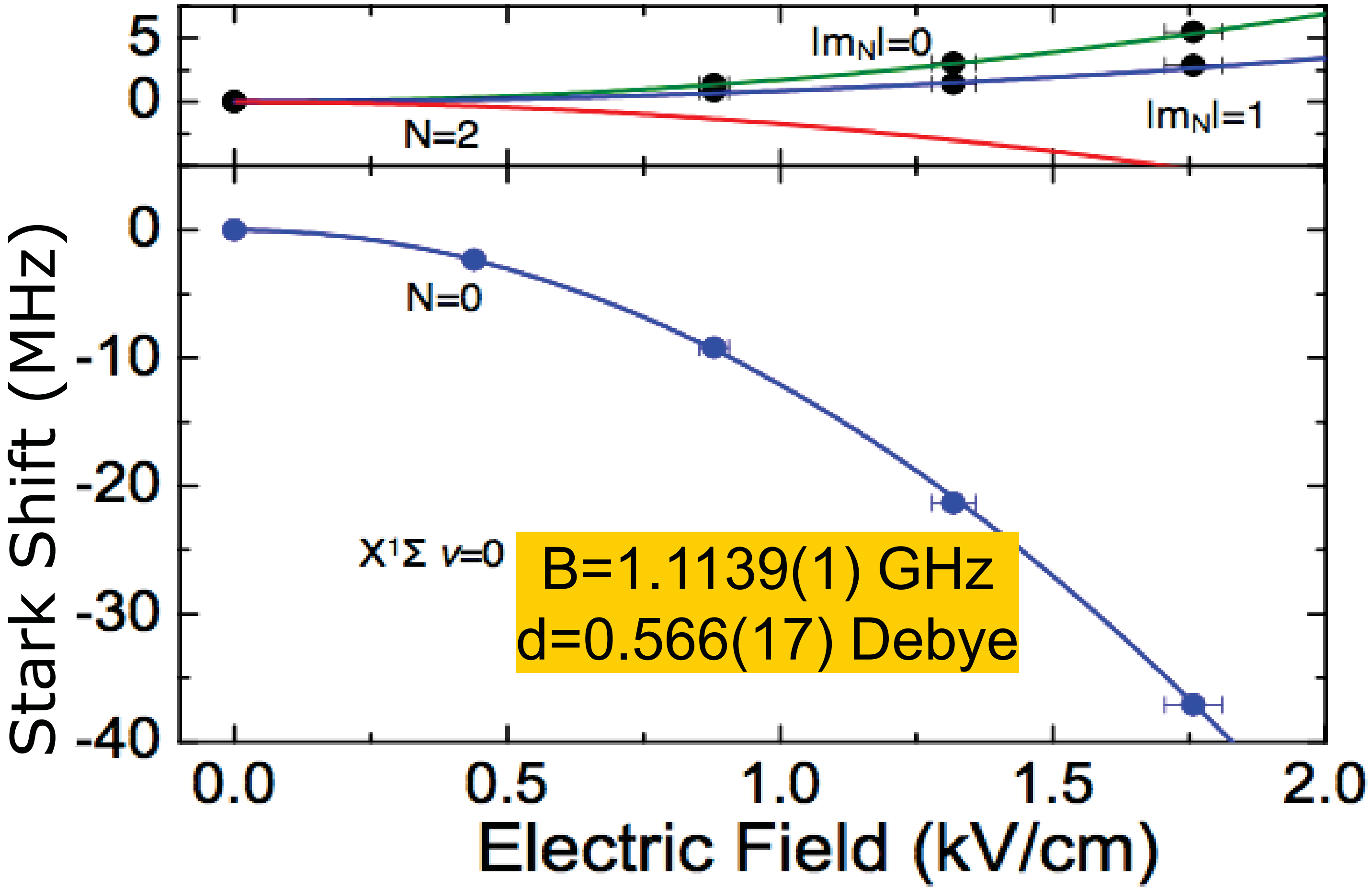
Spectroscopy of the ground state



Binding energy of $X^1\Sigma_0$ ($v = 0$, $N = 0$)
h x 125.319703(1) THz

Stark Spectroscopy

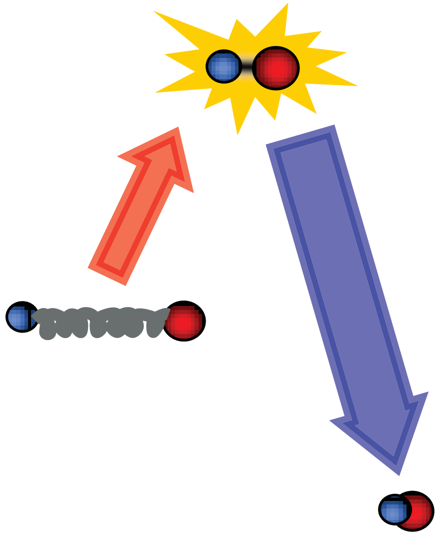




B=1.1139(1) GHz
d=0.566(17) Debye

Properties of ground-state polar molecular gas

4×10^4 rovibrational **ground state polar** molecules trapped in an optical dipole trap



- Temperature ~400nK
- $T/T_F=3$
- Density ~$10^{12}/cm^3$
- $\rho=0.01$
- Dipole moment ~0.5 Debye
- long lived (τ~200ms)

Enhancement of phase-space density by 11 orders of magnitude compared to previous results

K. Ni et al, Science 322, 231 (2008), S. Ospelkaus et al., arxiv: 0901.0533(2009)

What next?

- Collisional properties of fermionic ground state polar molecules

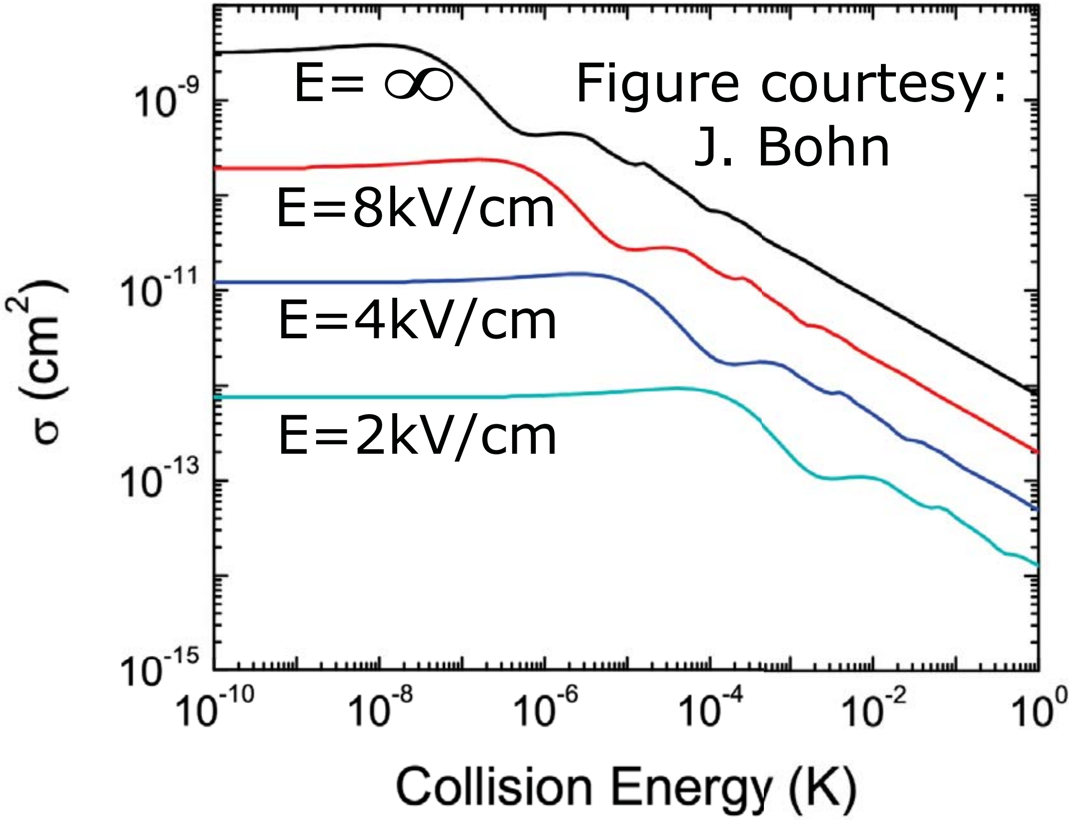
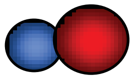


Figure courtesy:
J. Bohn

Fermionic
^{40}K



Bosonic
^{87}Rb

$$V(r) = \xcancel{g\delta(r)} + \frac{d^2}{r^3}(1 - \cos^2\vartheta)$$

Evaporative cooling?

Control of elastic/inelastic collisions?

Conclusions

- Preparation of a near-quantum degenerate gas of polar rovibrational ground state molecules
- Dipole moment 0.566(17) Debye
- Enhancement of phase space density 11 orders of magnitude