Lecture III: Ultracold molecules – a new frontier

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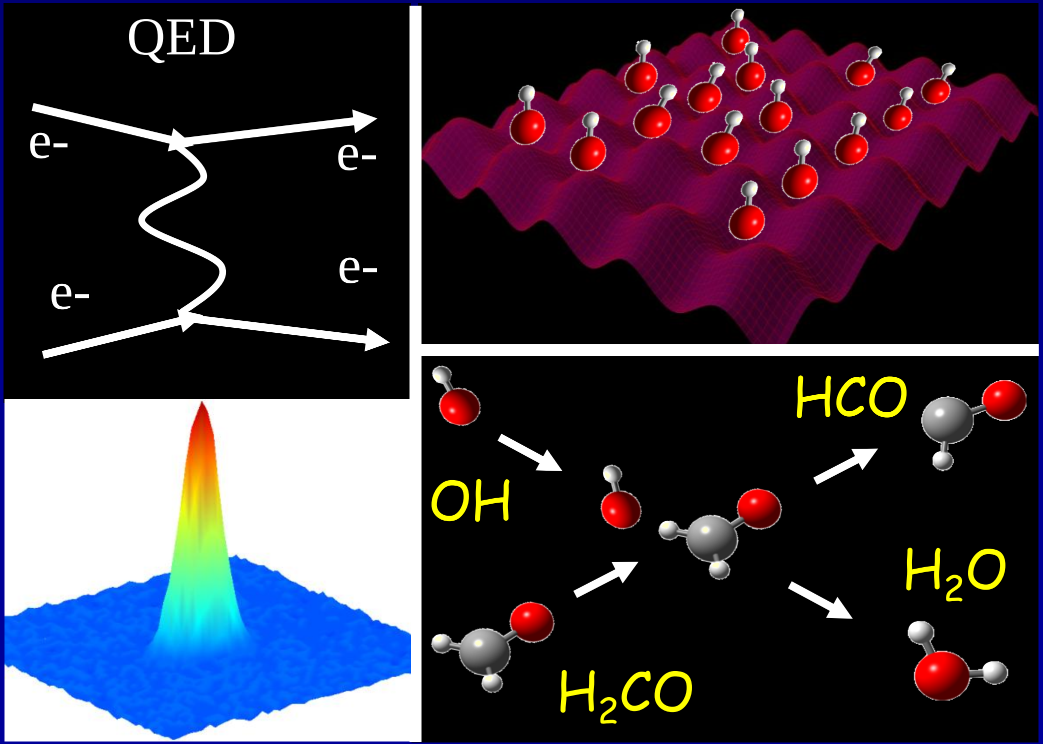
ICAP Summer School, Paris, July 21, 2012



Precision test

Exotic phases

Quantum dipolar gas

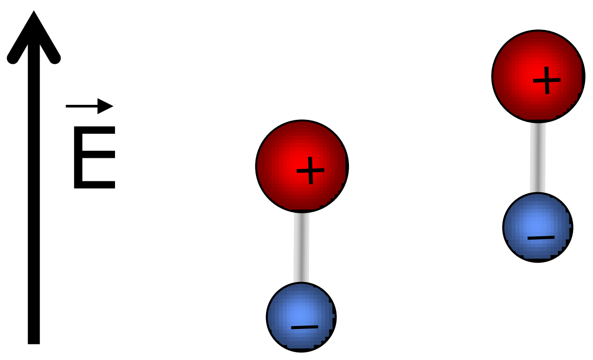
Chemical reactions

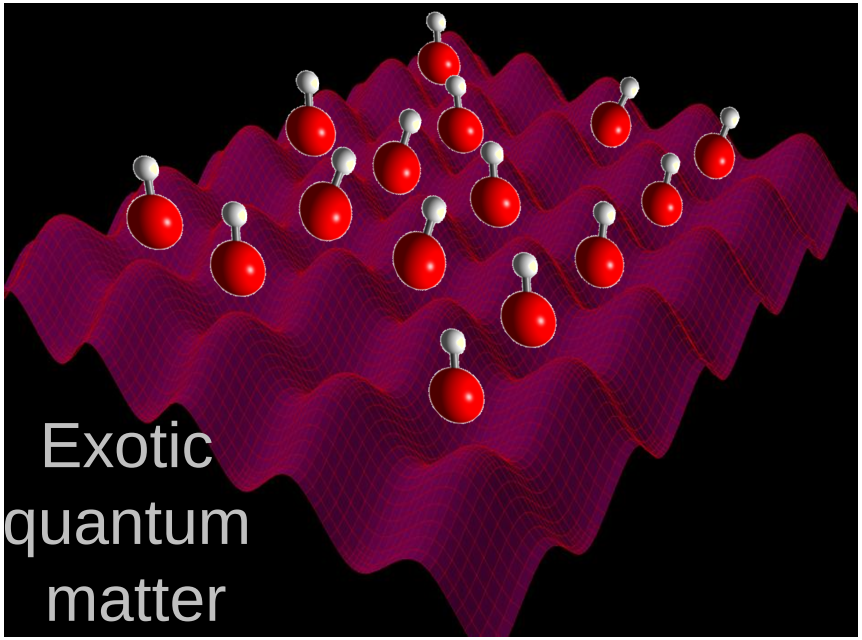
Quantum gas of polar molecules

Extend capability to control quantum systems

What's new (compared to ultracold atoms)?

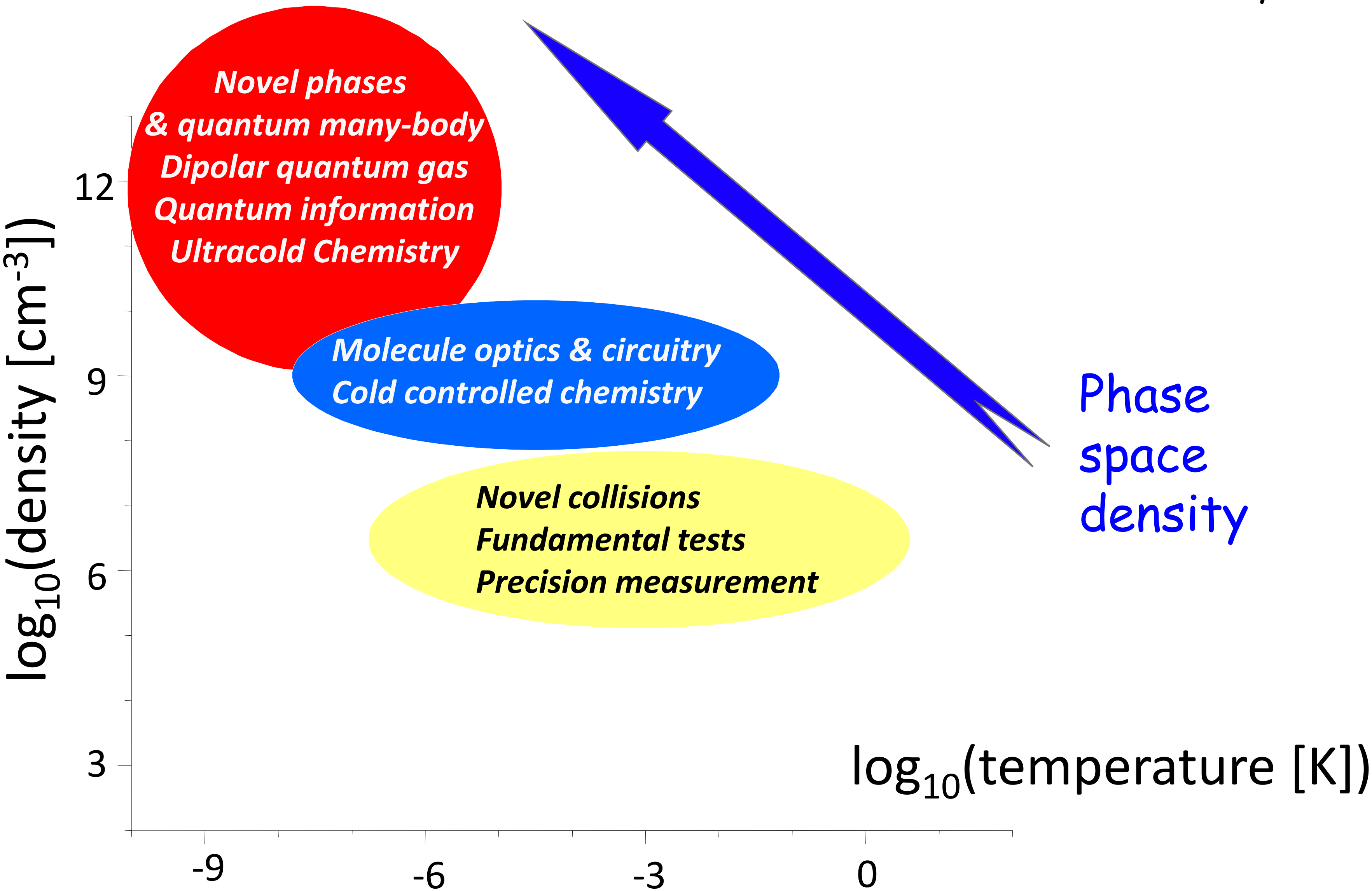
- New internal degrees of freedom:
  vibration, rotation
- Chemistry
- Long-range interactions





Science with cold molecules

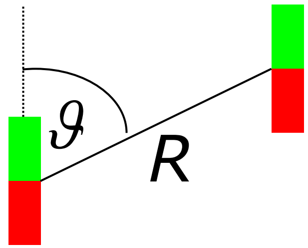
Carr, DeMille, Krems, Ye, New. J. Phys. 2009.



Dipolar quantum systems

Atoms

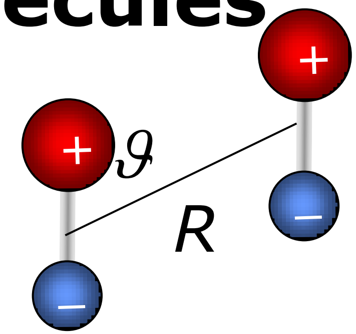
Magnetic dipoles



d ~ Bohr magneton

Polar molecules

Electric dipoles



d ~ Debye

$E_I \sim 10^{-3}$ - 10^{-1} nK
@ $n=10^{12}$-10^{14}/cm^3

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

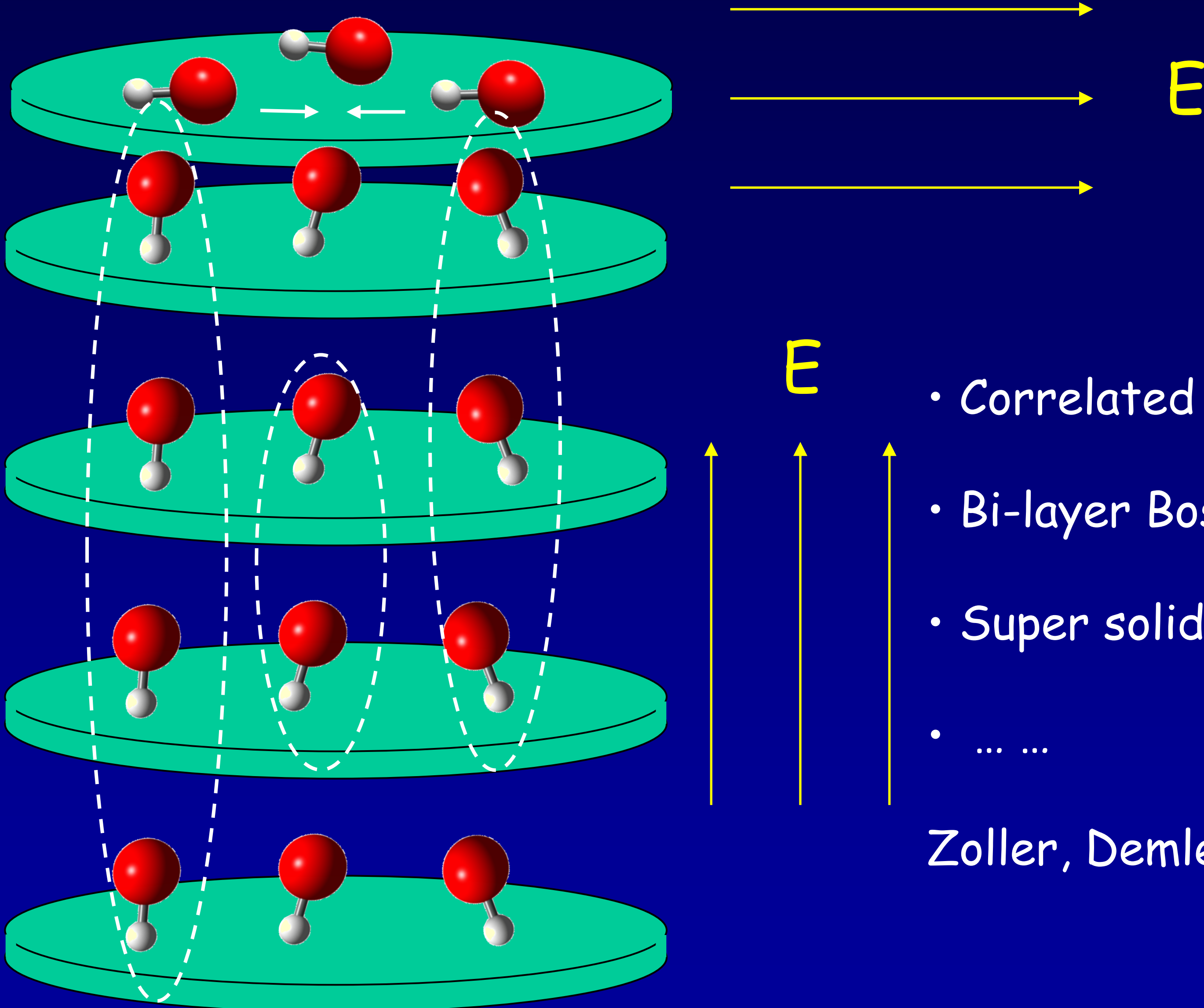
Controllable

$E_I \sim 10$ - 1000 nK
@ $n=10^{12}$-10^{14}/cm^3

Quantum degeneracy

$$\frac{d_1 \cdot d_2}{R^3} \sim k_B T$$

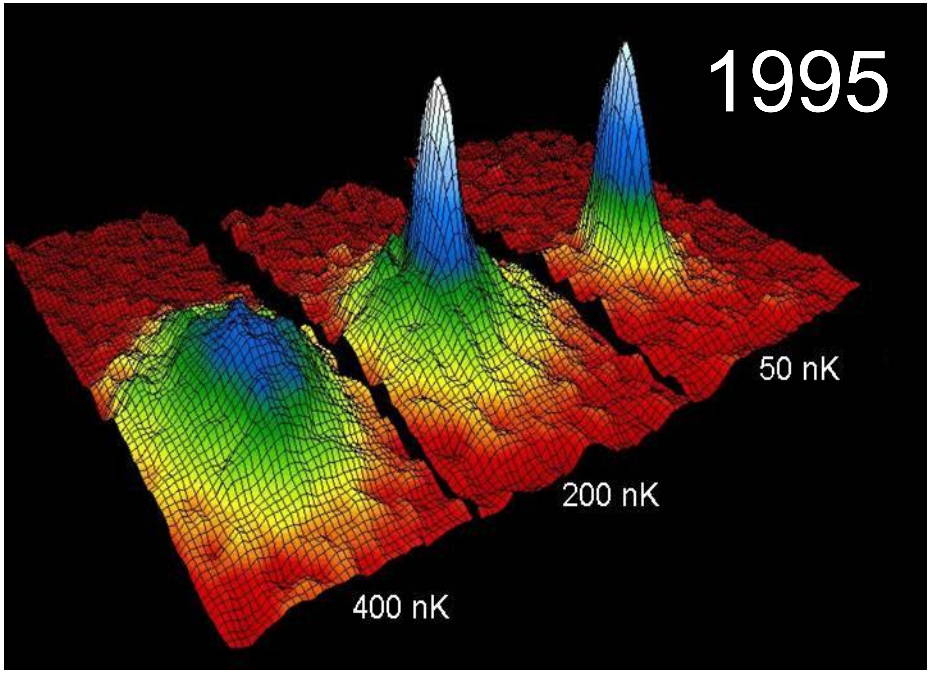
New quantum phases and dynamics



- Correlated Fermi pairs
- Bi-layer Bose condensation?
- Super solids?
- … …

Zoller, Demler, Santos, … …

Atom vs. molecule



Bose-Einstein Condensation

T = 100 nK

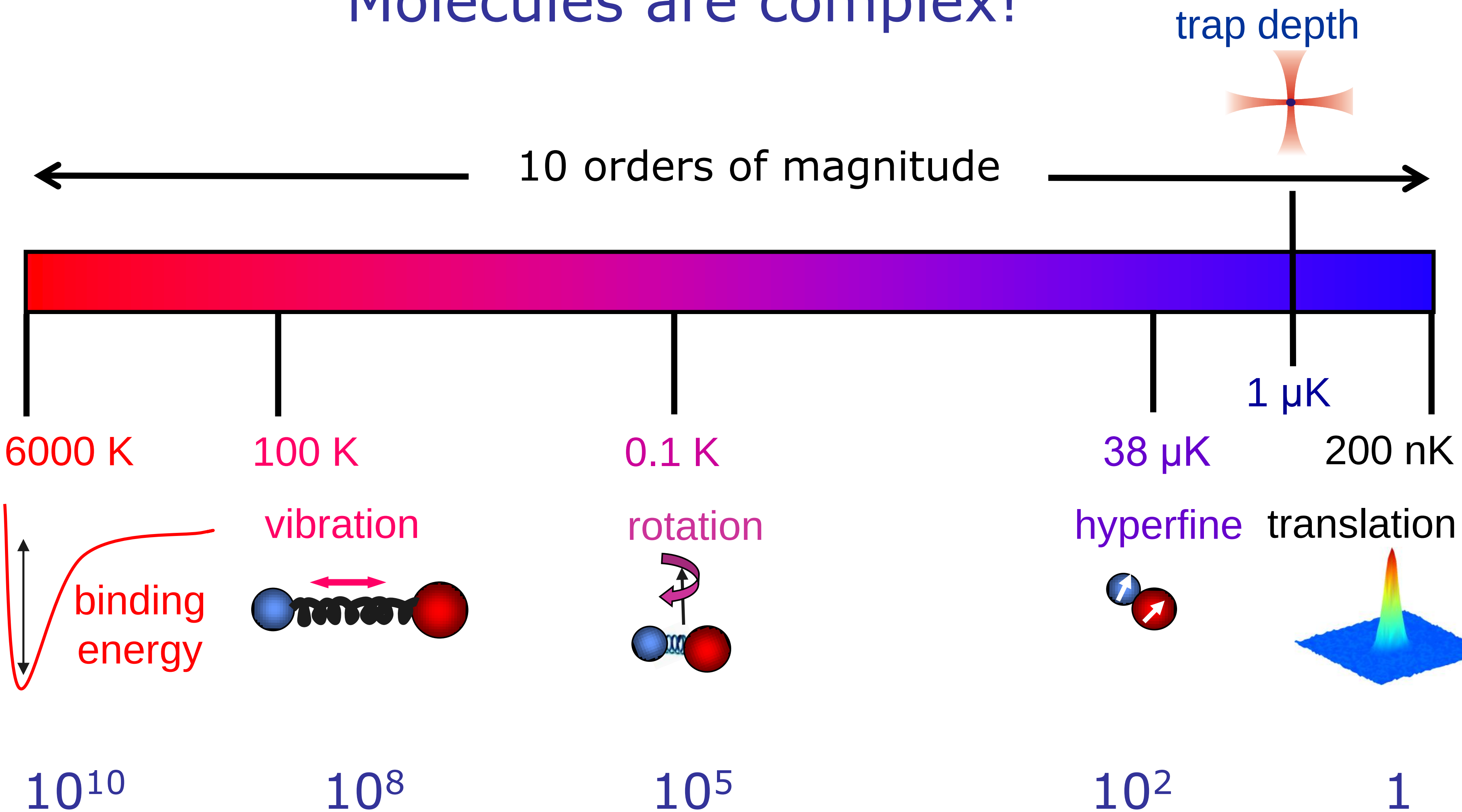
N = 10^6 atoms

n = 10^{13} cm^{-3}

Molecules (pre-2008):
T = 100 mK, n = 10^6 cm^{-3}

Ultracold molecules: The challenge

Molecules are complex!



How do you cool molecules?

Cooling stable molecules

Chemistry
(make molecules)

→

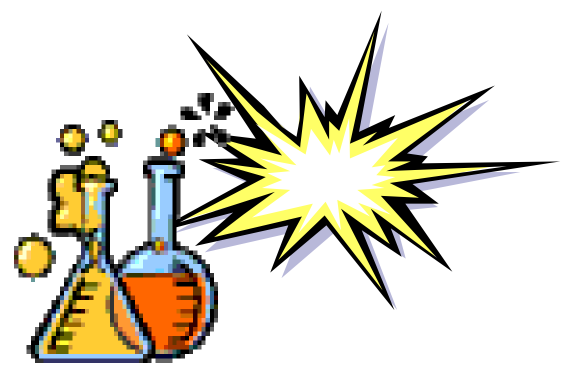
Cooling

OR

Pairing ultracold atoms

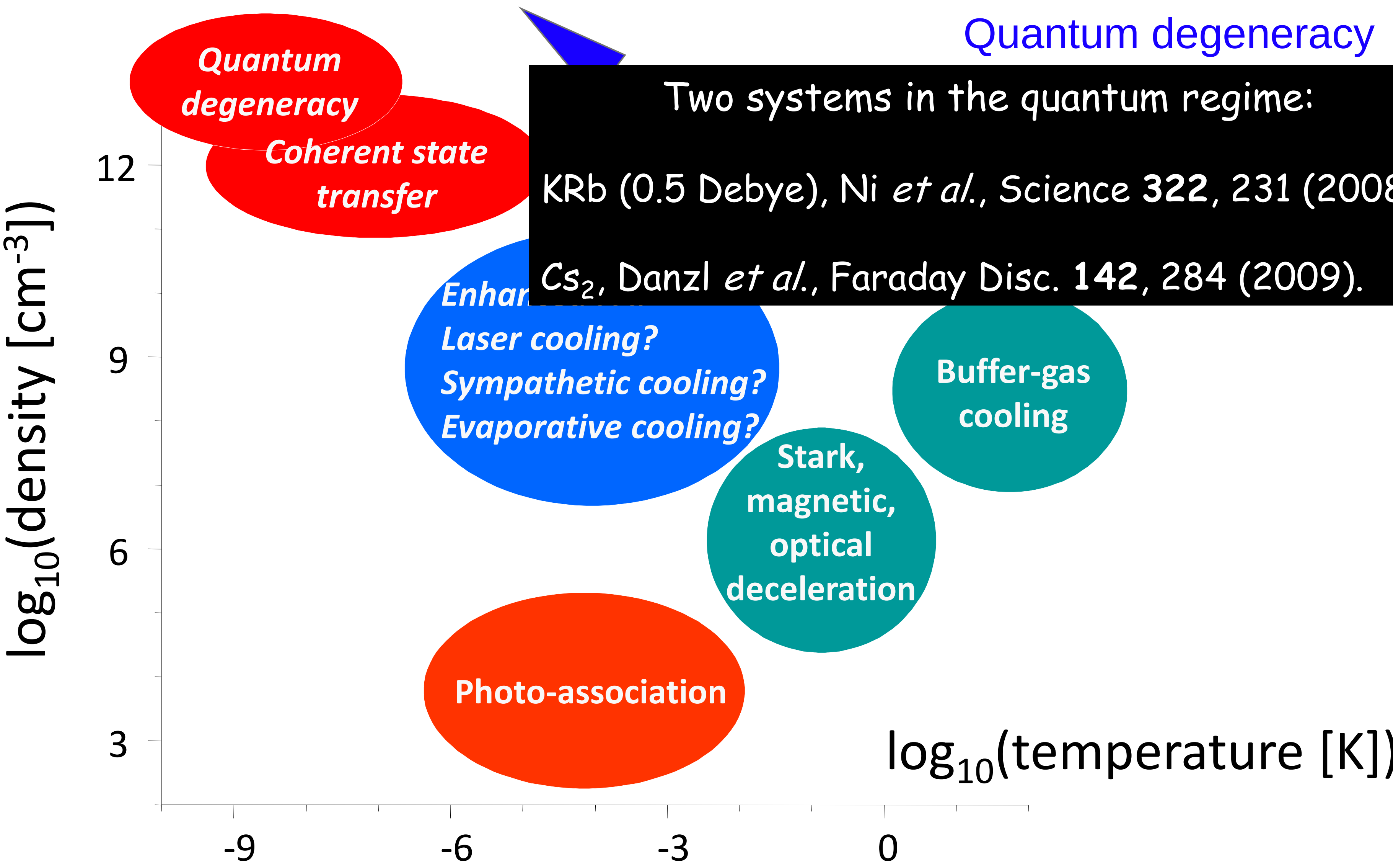
Cooling

→



Chemistry
(make molecules)

Technology for cold molecules

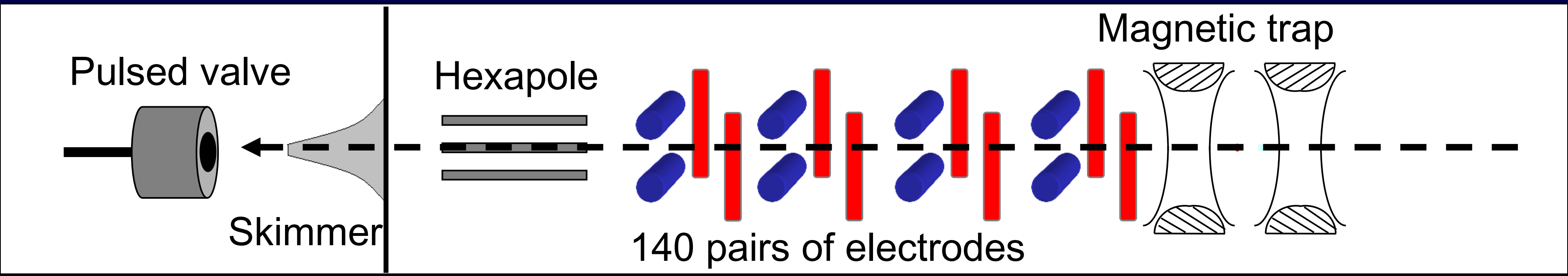


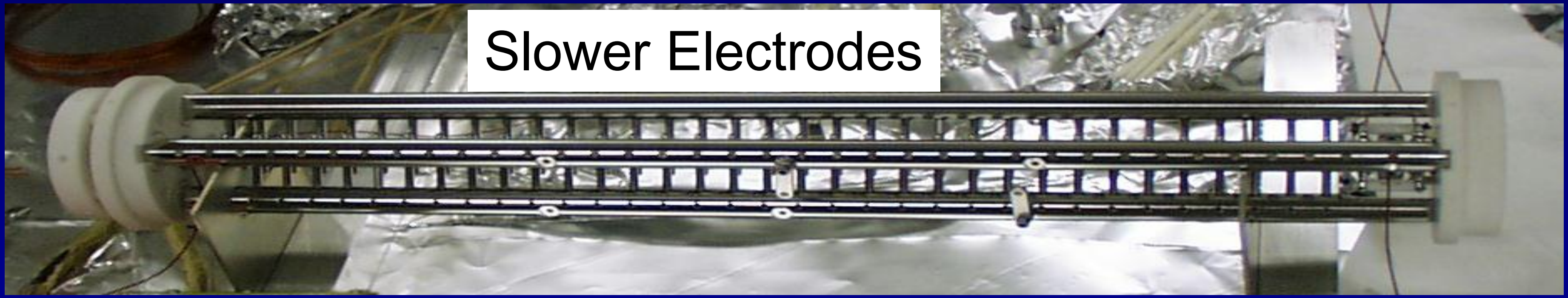
Two systems in the quantum regime:

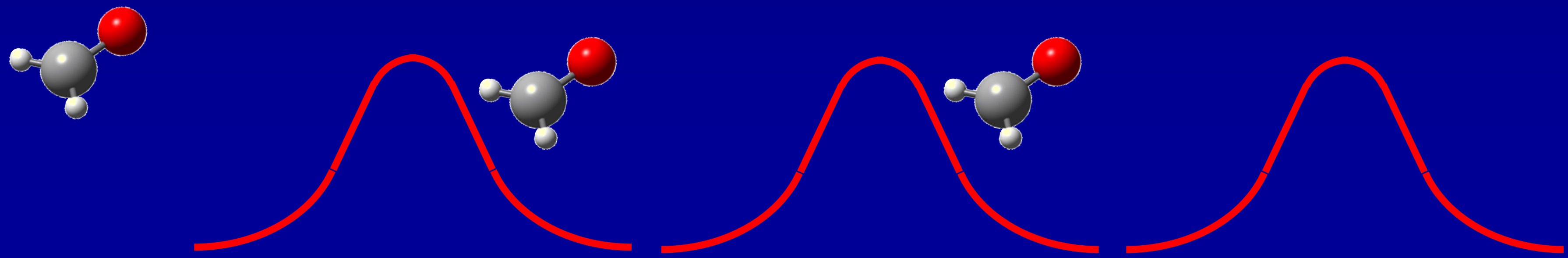
KRb (0.5 Debye), Ni *et al.*, Science **322**, 231 (2008)

Cs_2, Danzl *et al.*, Faraday Disc. **142**, 284 (2009).

Deceleration of ground-state molecules

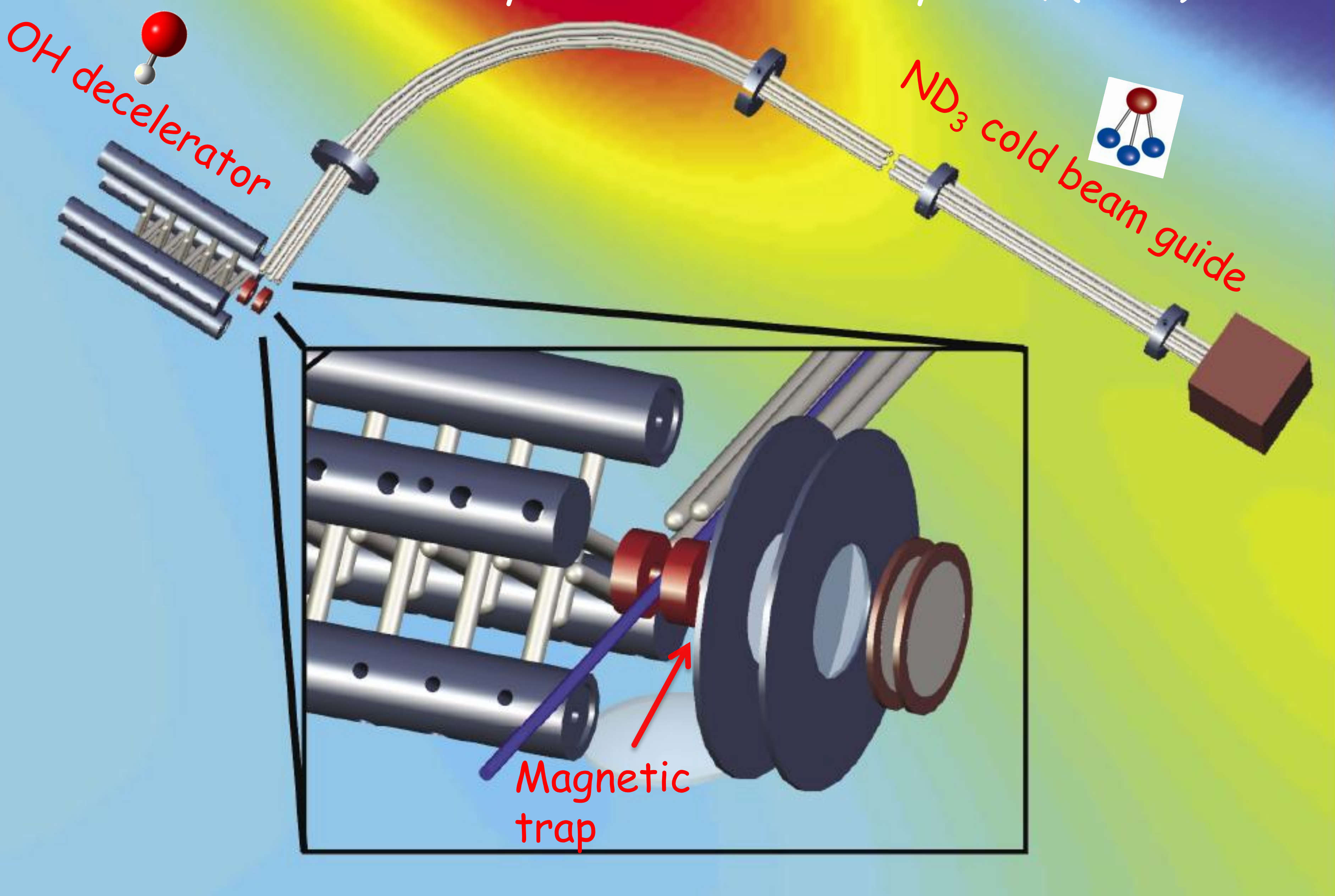




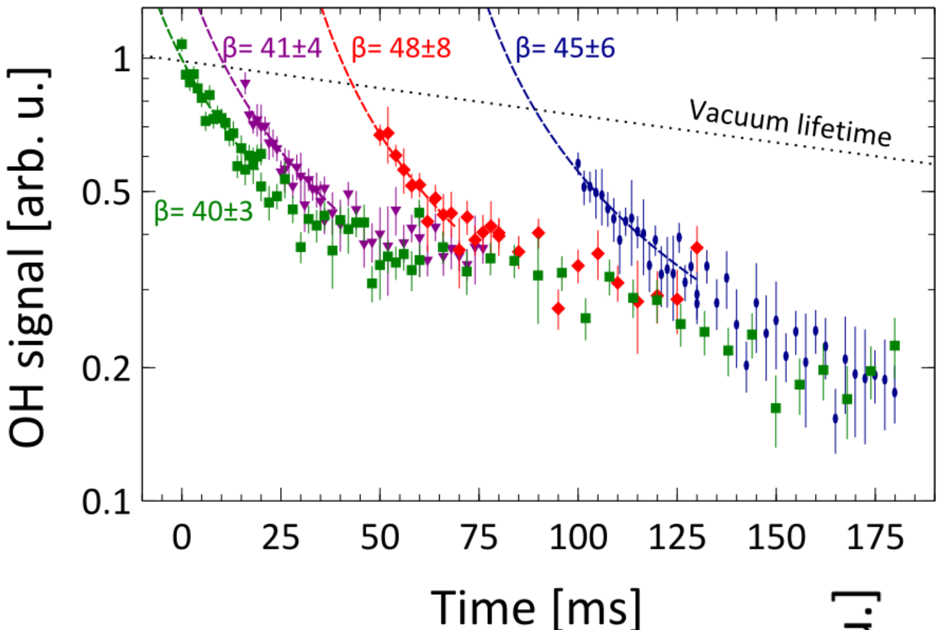


Dipolar collisions between OH & ND_3

Phys. Chem. Chem. Phys. 13, (2011) Cover

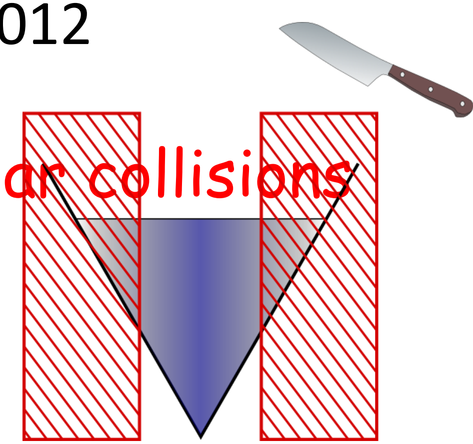


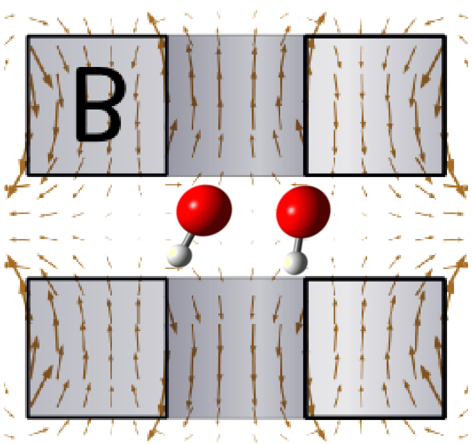
Evaporative cooling of OH



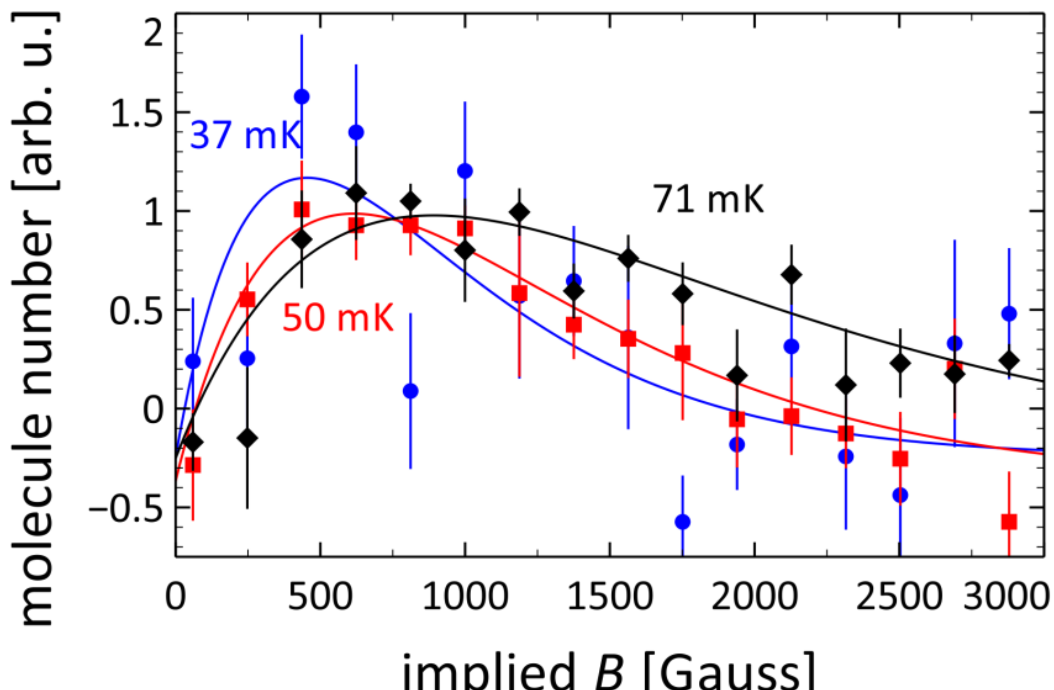
Data: May 2012

Inelastic dipolar collisions



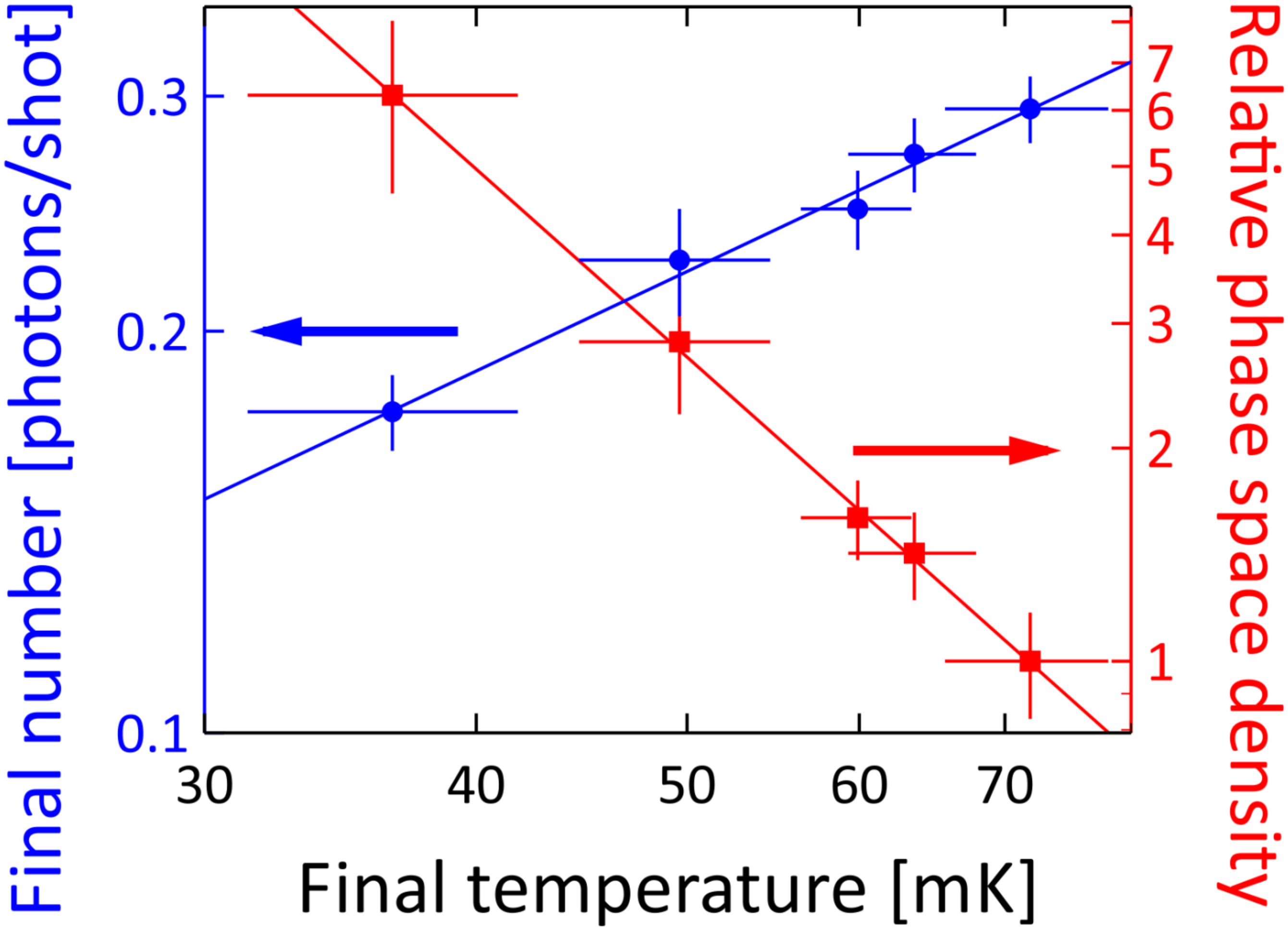


Evaporative cooling

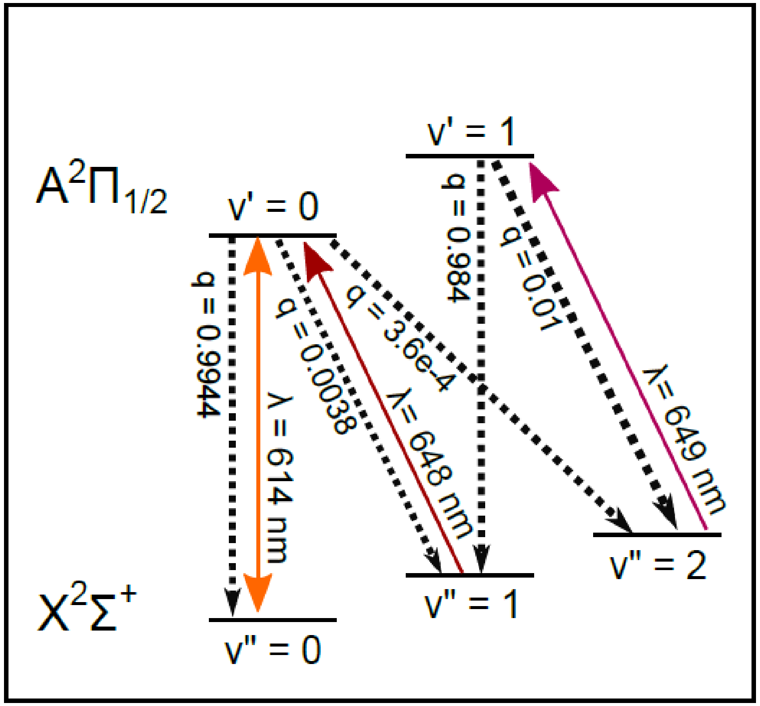


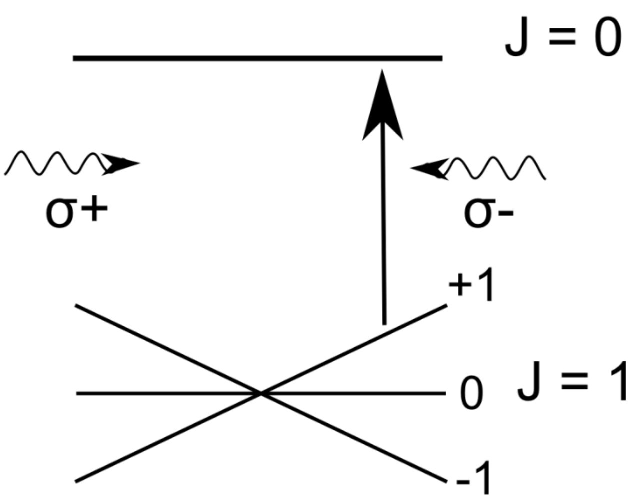
Sawyer et al.,
Phys. Rev. Lett. 98, 253002 (2007).
Phys. Rev. Lett. 101, 203203 (2008).

Evaporative cooling!

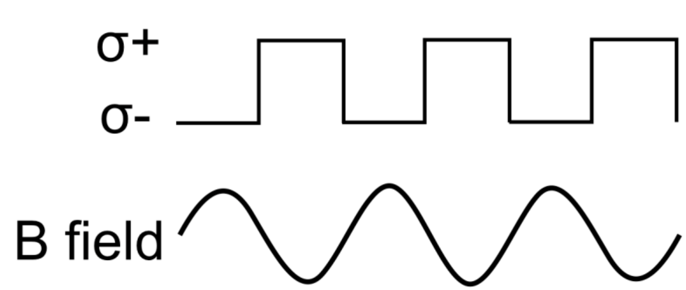


A magneto-optic trap (MOT) for molecules



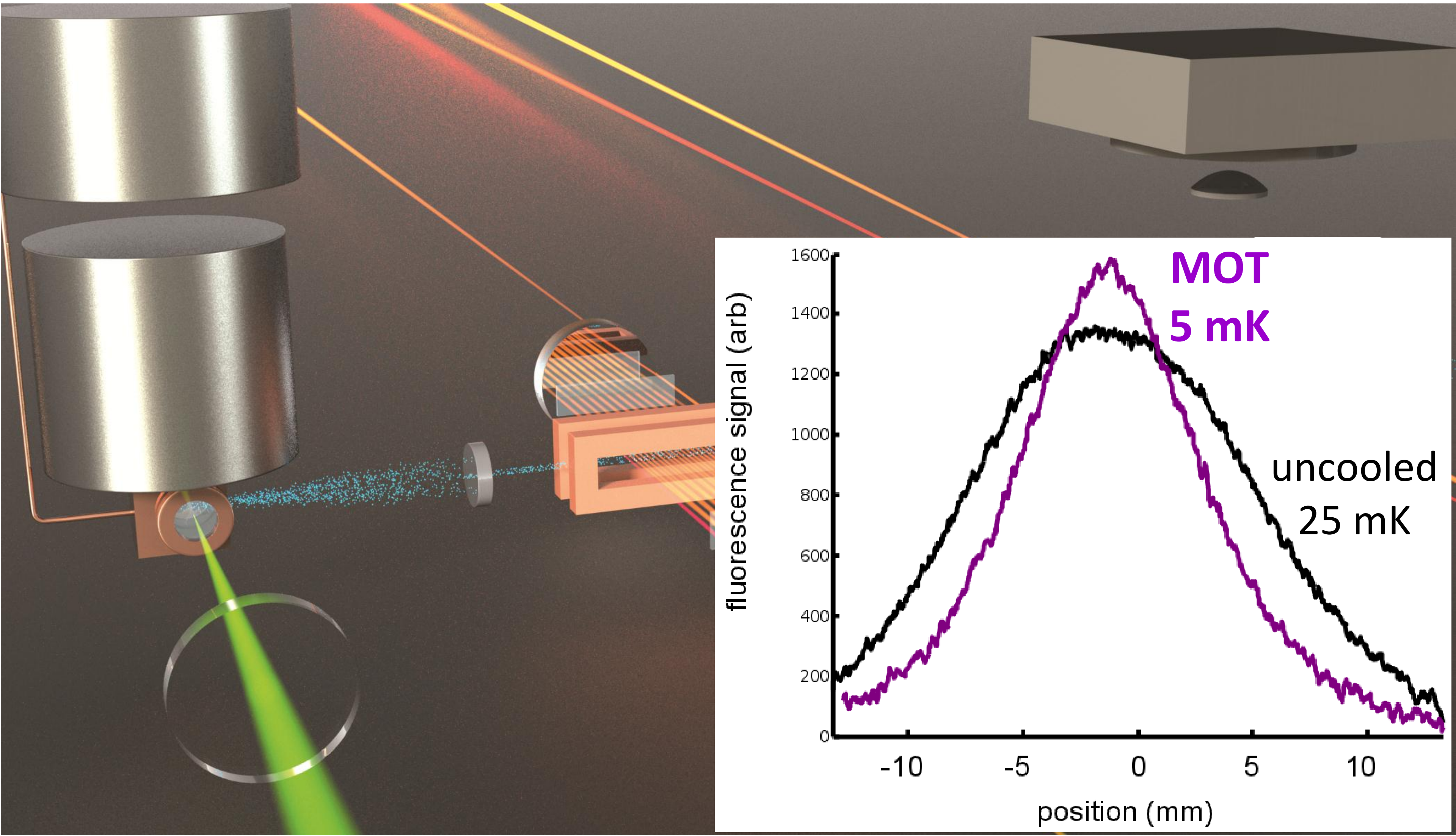


Remixing of Zeeman Levels



A magneto-optic trap (MOT) for YO molecules

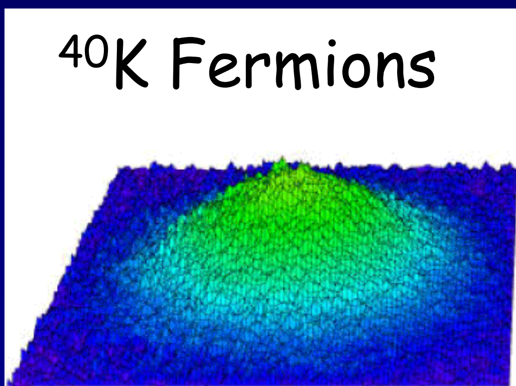
Stuhl et al., Phys. Rev. Lett. 101, 243002 (2008): First proposal
DeMille et al., Nature (2010): demonstration of 1D laser cooling

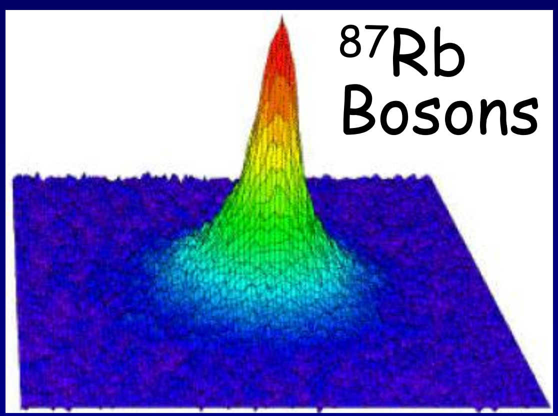


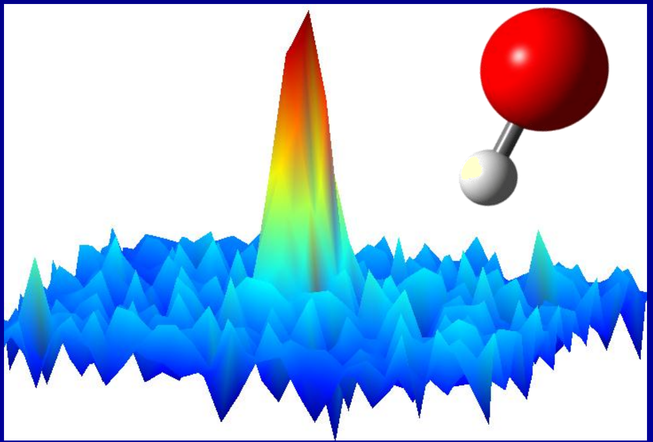
Quantum gas of polar molecules

10000 times colder, 1000000 times more dense than other results for polar molecules!

- Density $\sim 10^{12}/cm^3$
- $\rho \sim 0.2$ (10^{11} enhancement)





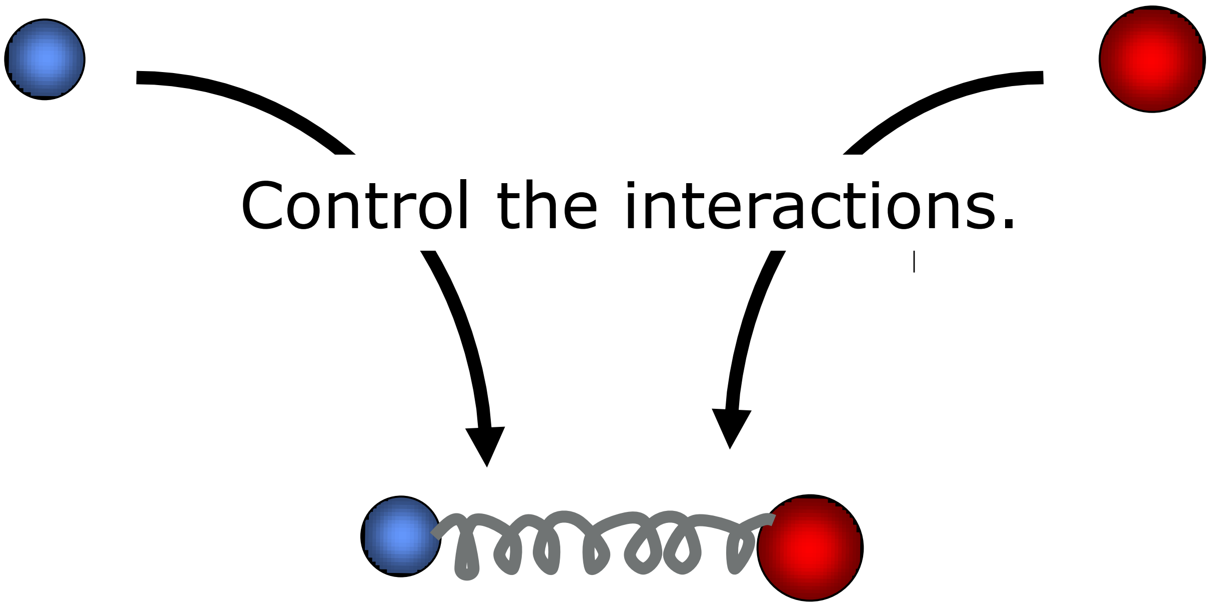


K. Ni *et al.*,
Science 322, 231 (2008).

KRb molecules
(Dipole
~0.5 Debye)

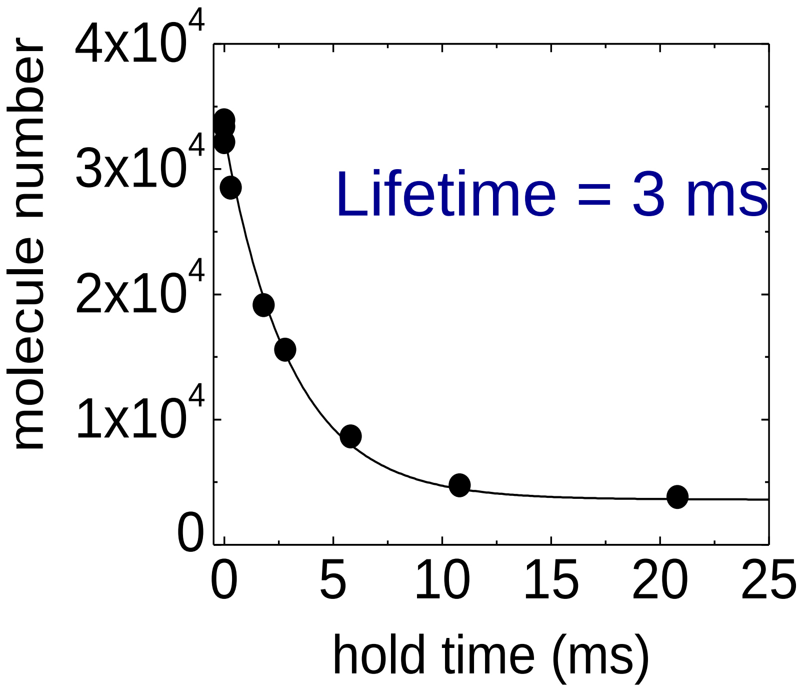
Convert a pair of atoms into a molecule

^{40}K Start with ultracold atoms. ^{87}Rb



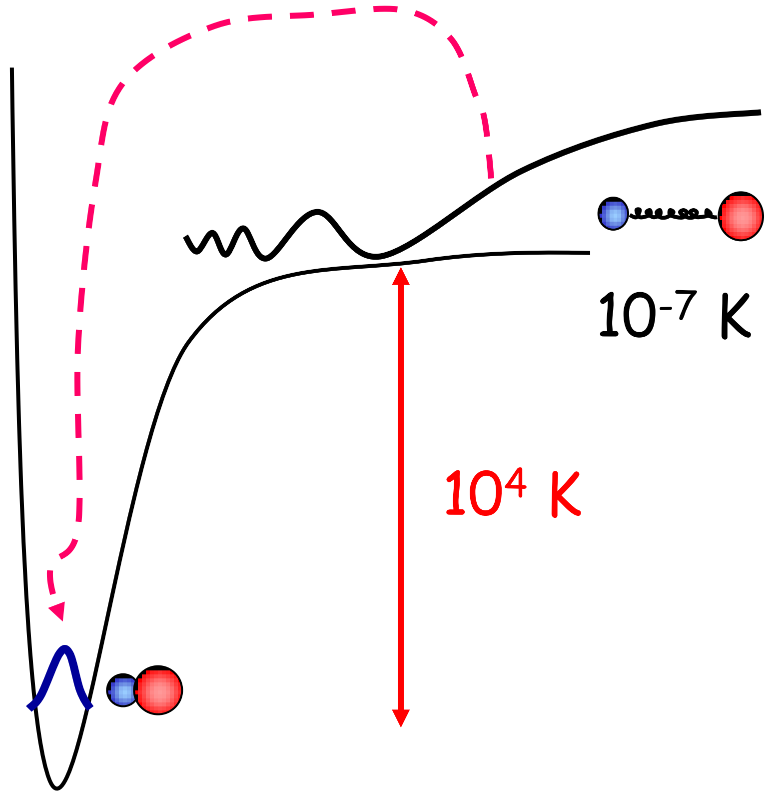
Make large, floppy molecules

Weakly bound molecule lifetime



atoms	100 s
weakly bound molecules	0.003 s

Shrink molecules without heat?

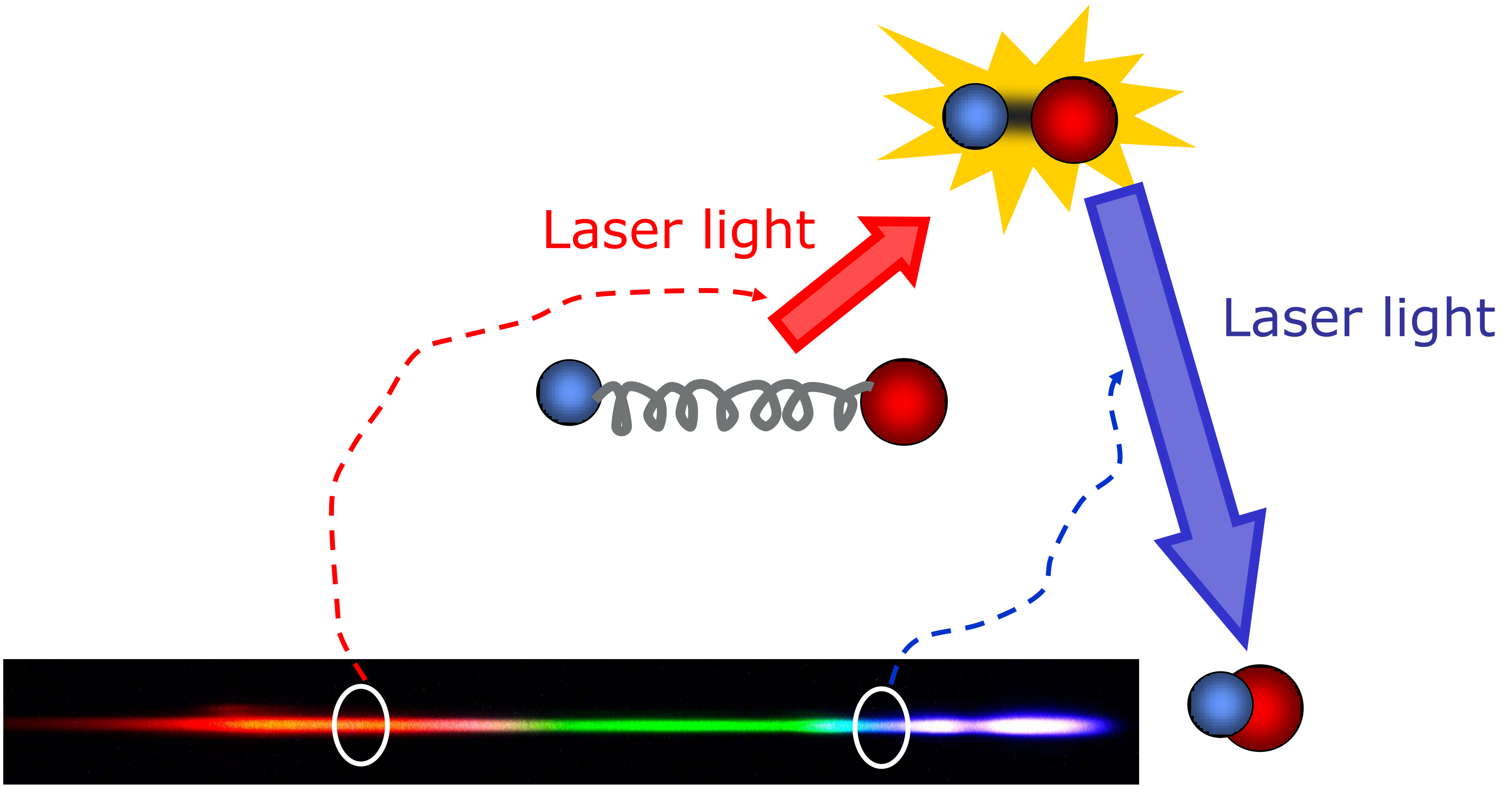


Translation energy
~ 10^{-7} K,

Zero entropy increase

Light provides the answer

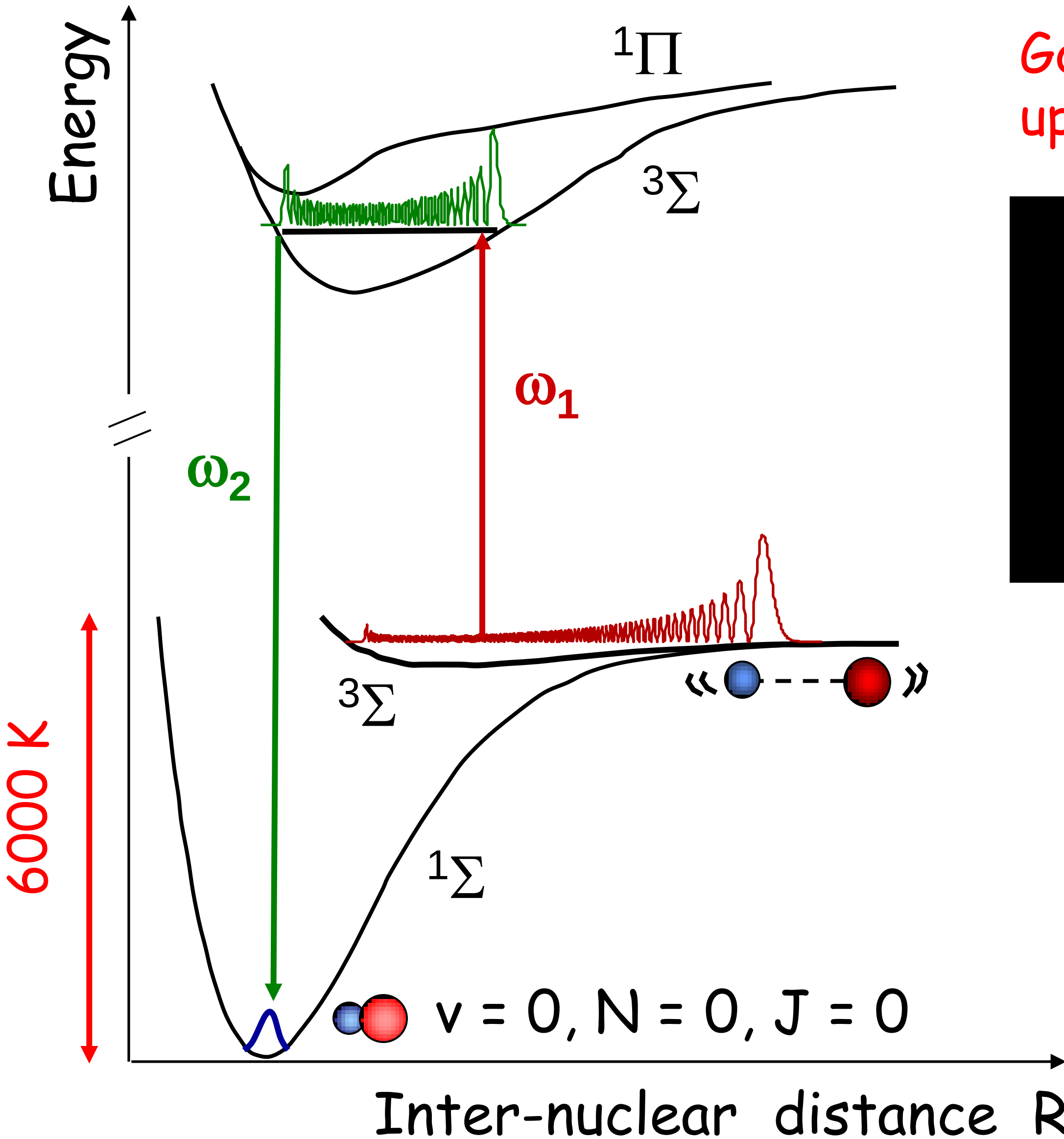
Photons carry away the energy!



Coherent two-photon transfer

Ospelkaus et al., Nature Phys. **4**, 622 (2008)

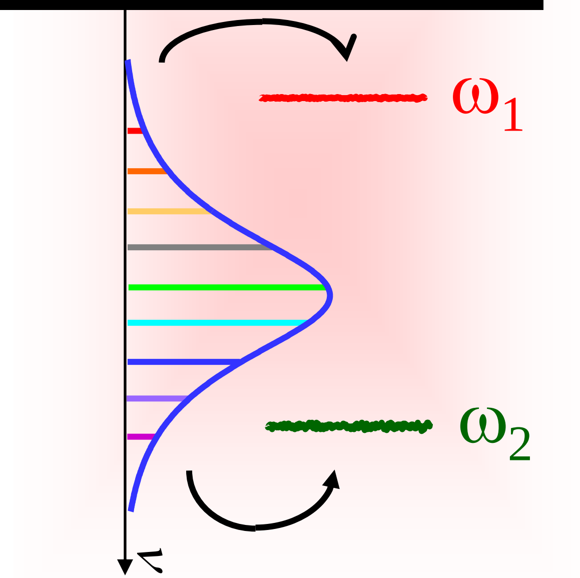
Ni et al., Science **322**, 231 (2008)



Good Franck-Condon for both up and down transitions.

Population transfer

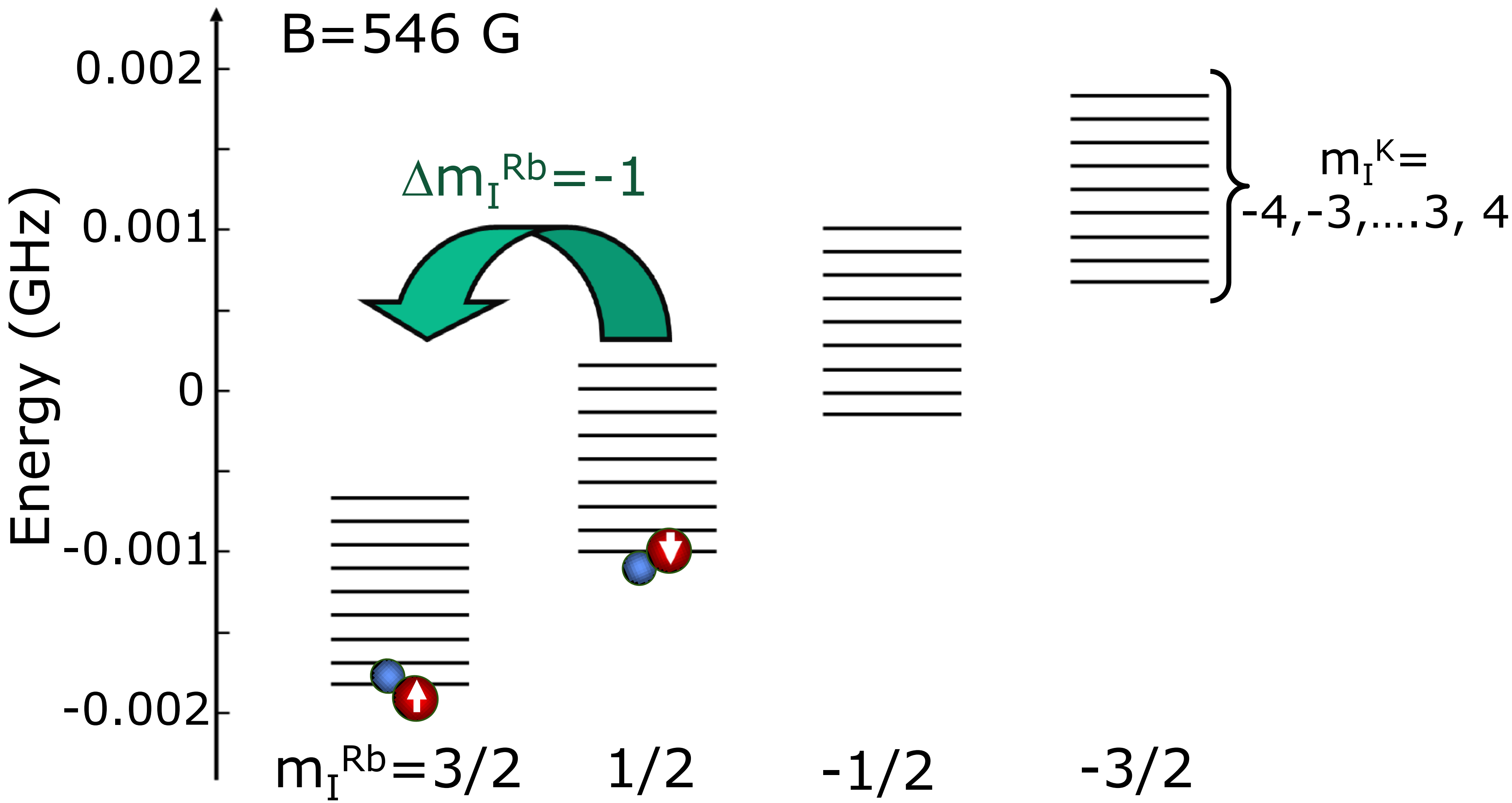
- 92% efficiency
- Fully coherent (no heating)



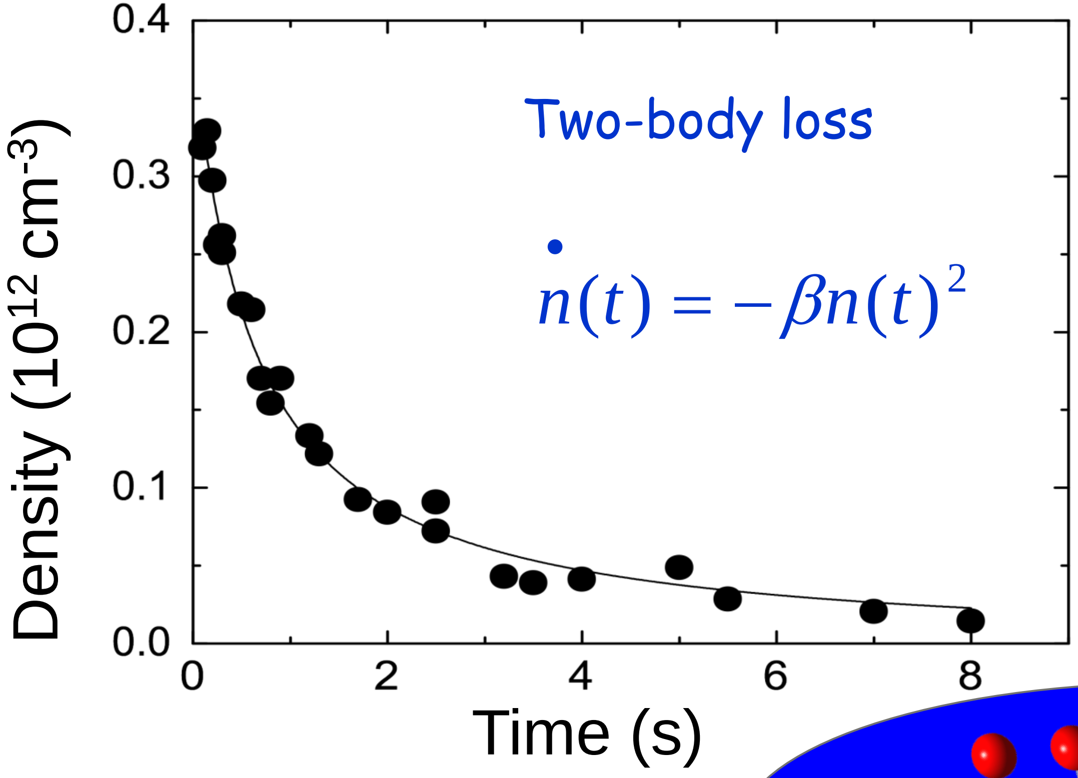
Hyperfine structure for $^1\Sigma$ (v=0, N=0)

S. Ospelkaus et al., PRL **104**, 030402 (2010).

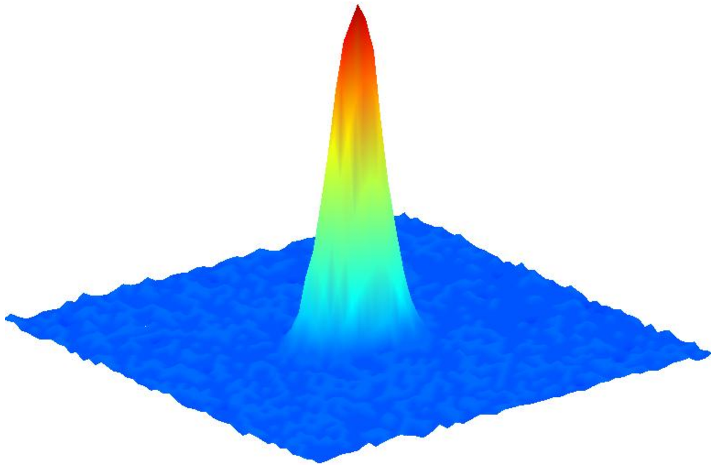
$I^{Rb}=3/2$ $I^{K}=4$ 36 states

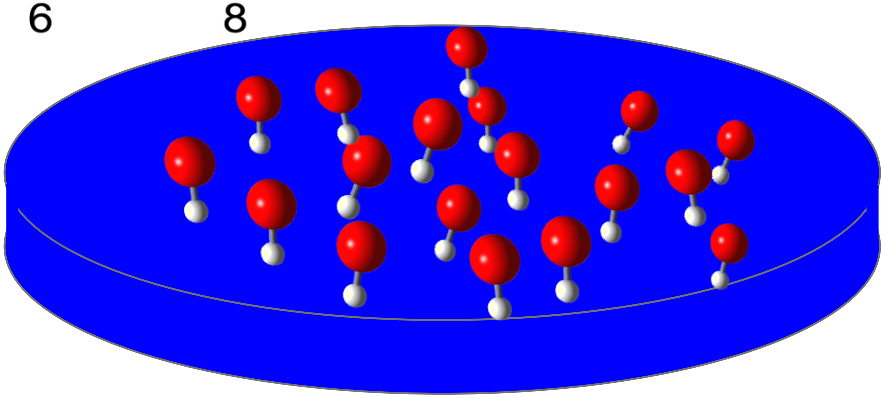


Trapped molecules in the lowest energy state (electronic, vibrational, rotational, hyperfine)

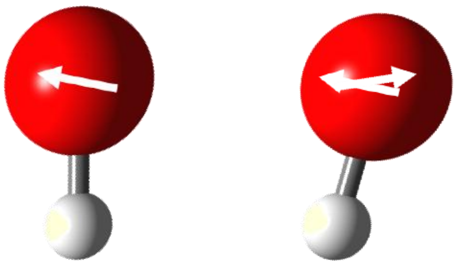


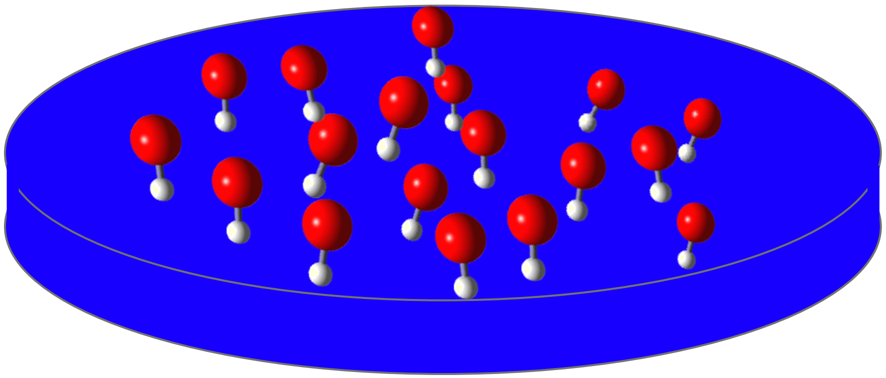
T = 200 nK
> 1 s lifetime





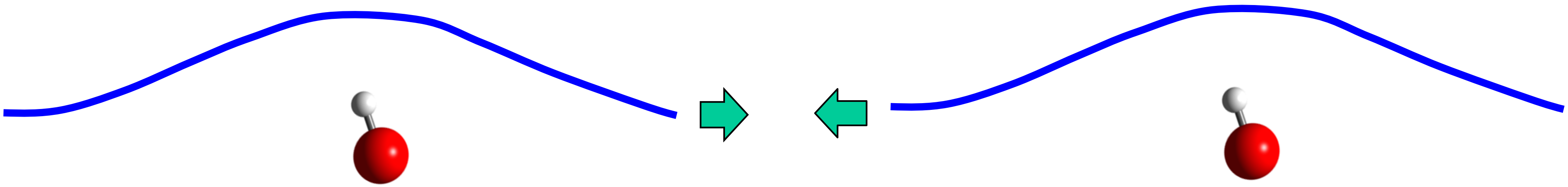
Molecular quantum statistics



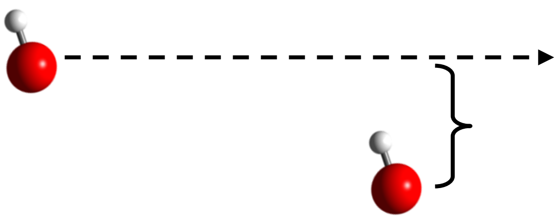


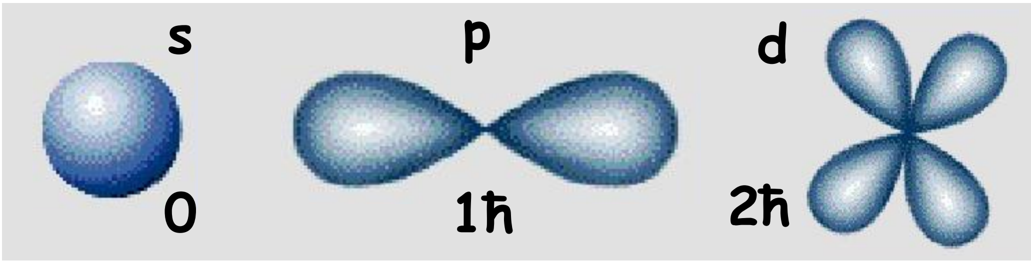
Cold collisions between identical Fermions

(1) Particles behave like waves

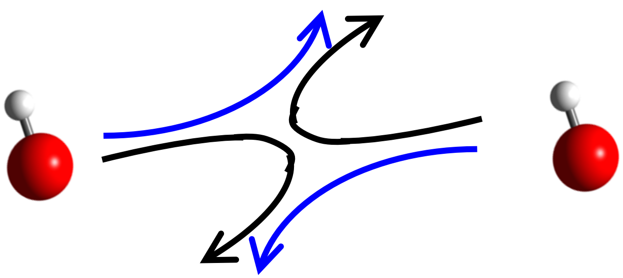


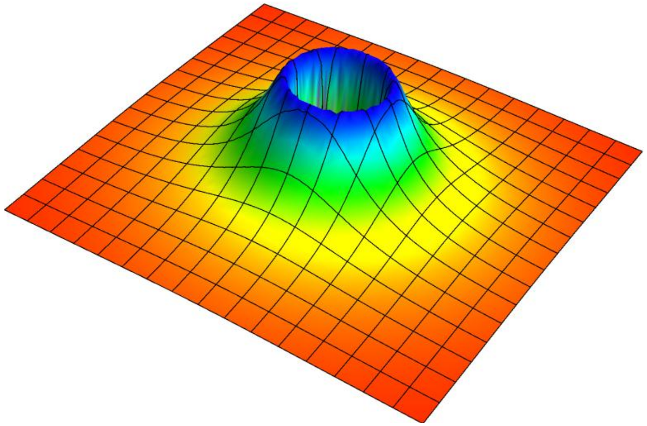
(2) Angular momentum is quantized





(3) Quantum statistics matter





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

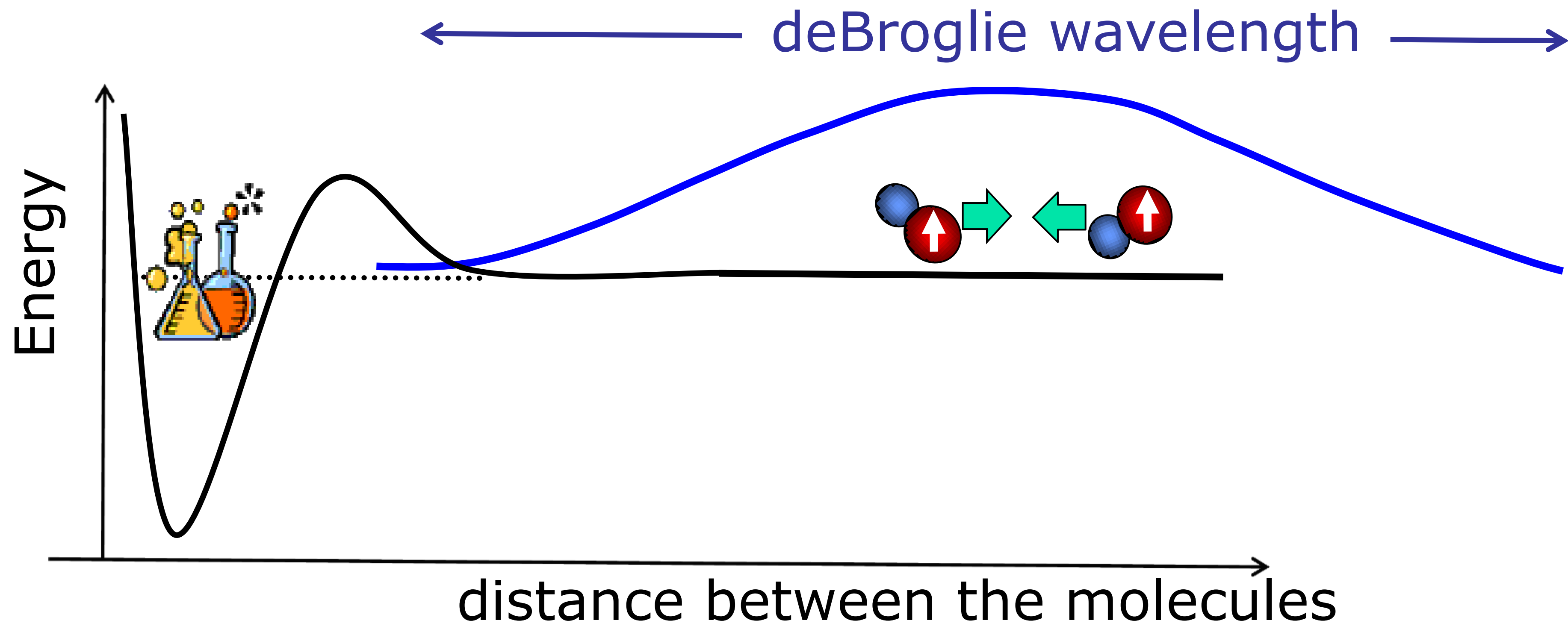
Fermions ⇨ L = 1, *p*-wave collisions

Ultracold quantum chemistry

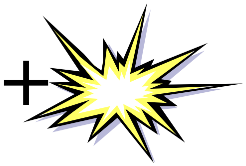
KRb+ KRb → K_2+Rb_2 +

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

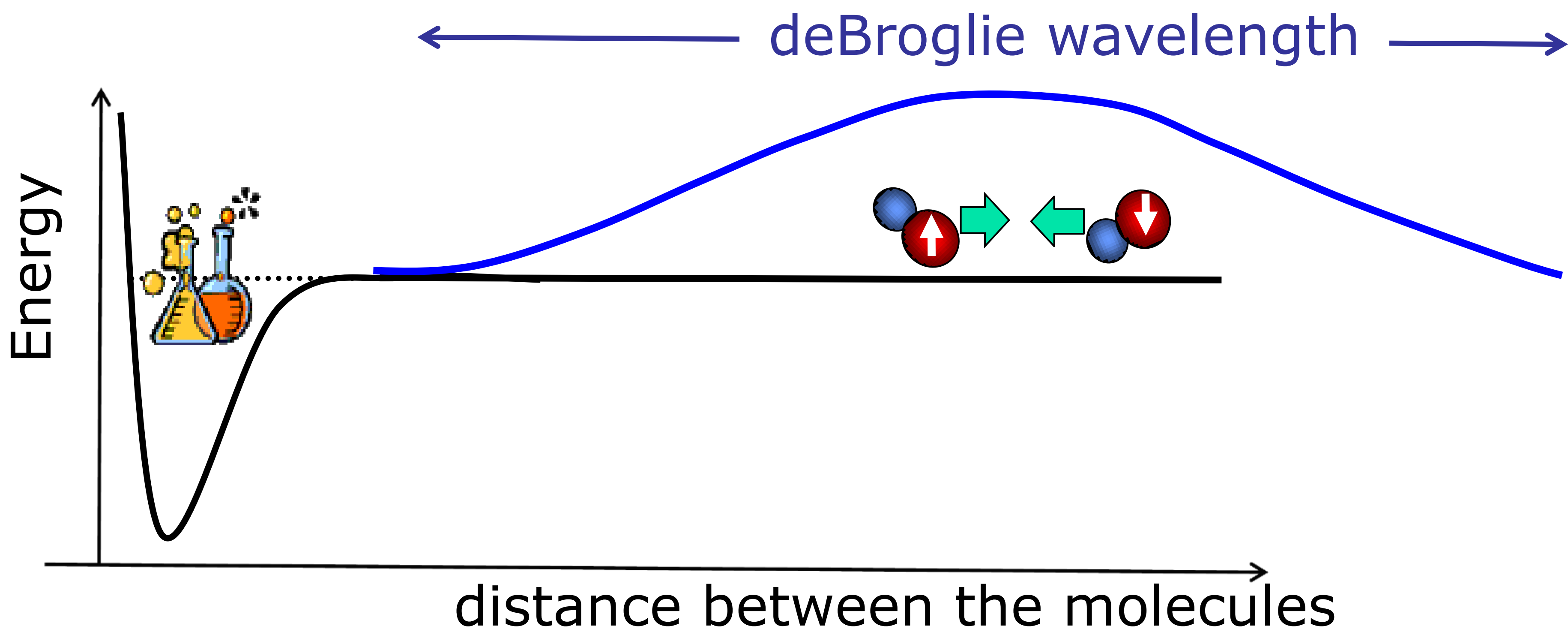
At low T, the quantum statistics of fermionic molecules suppresses chemical reaction rate!



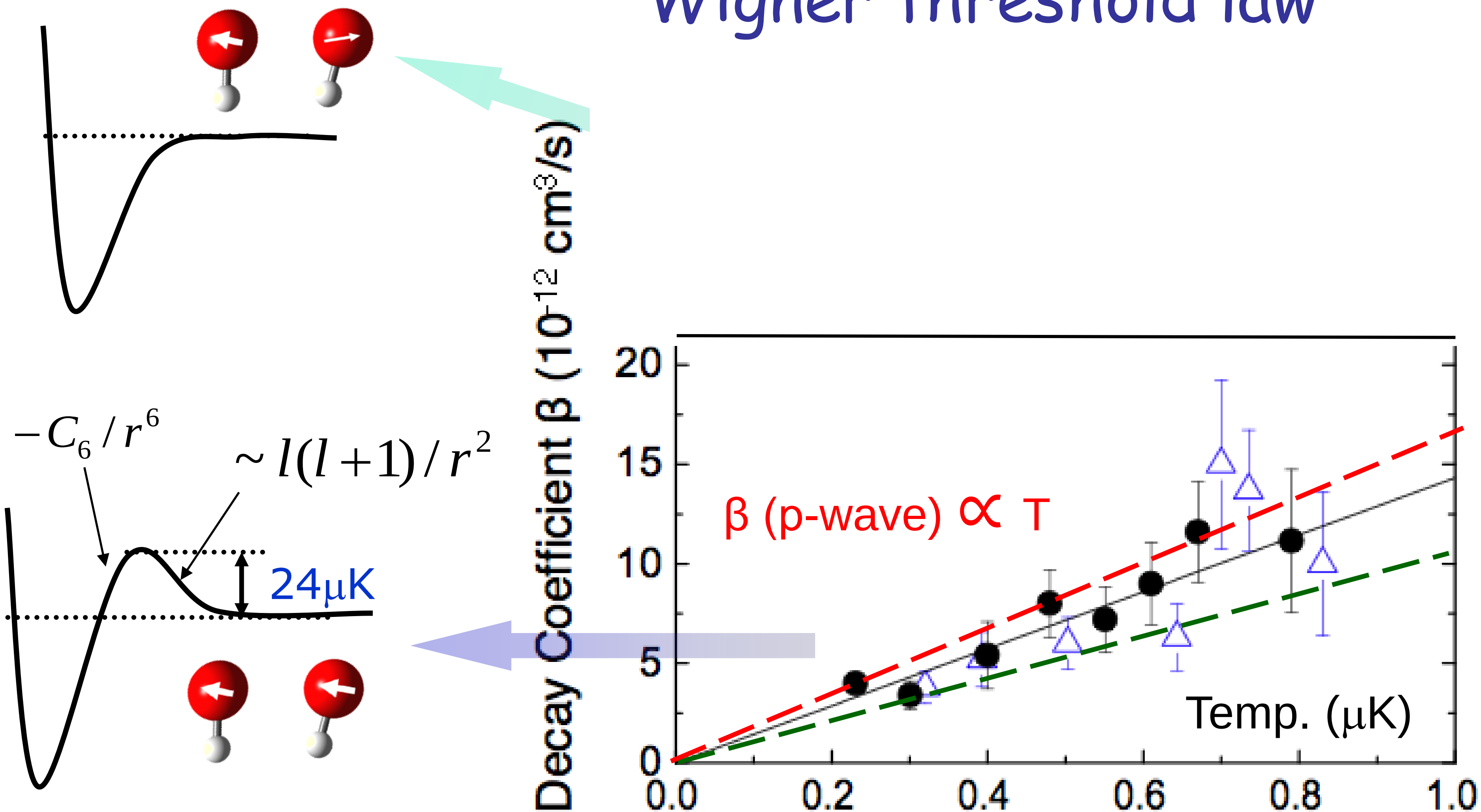
Ultracold quantum chemistry

KRb+ KRb → K_2+Rb_2 + 

Distinguishable molecules do not enjoy the suppression



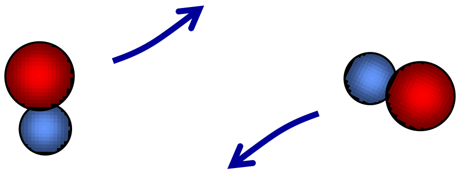
Bimolecular reactions under Wigner threshold law



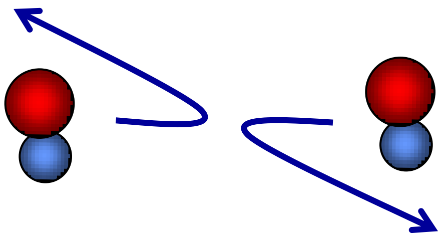
β (p)= 1.2(3)x10^{-5}cm^3/(s K) T

Dipolar molecular collisions

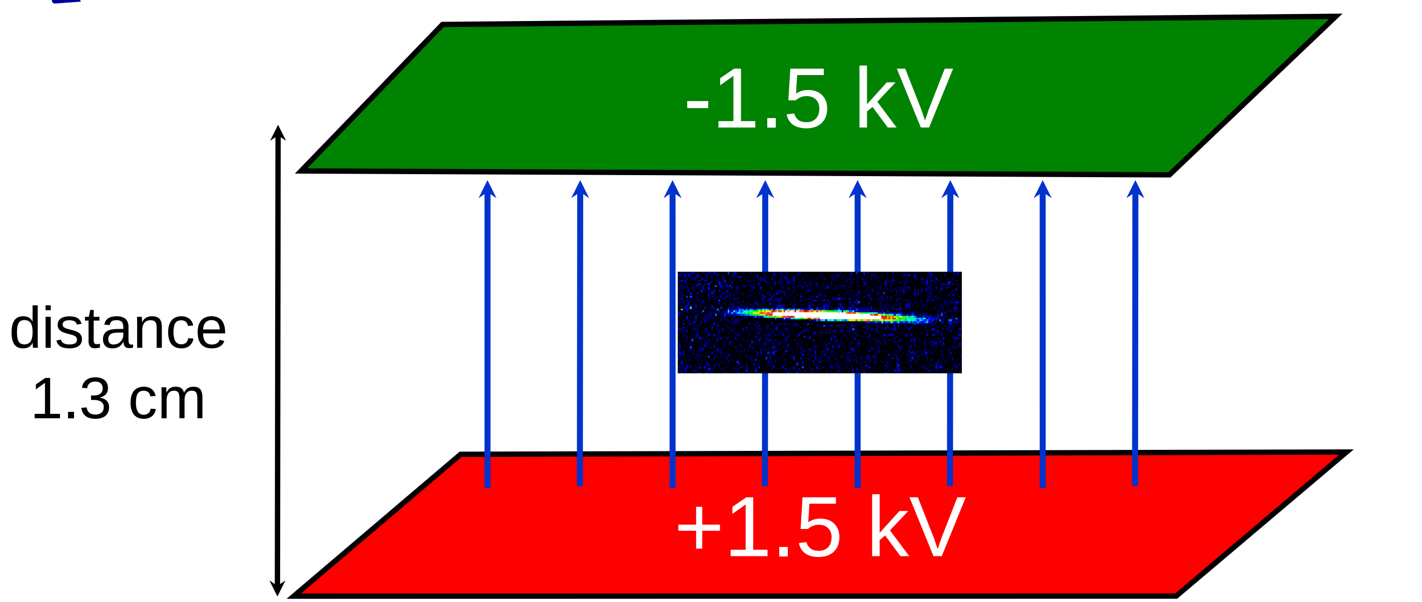
K.-K. Ni *et al.*, Nature **464**, 1324 (2010).



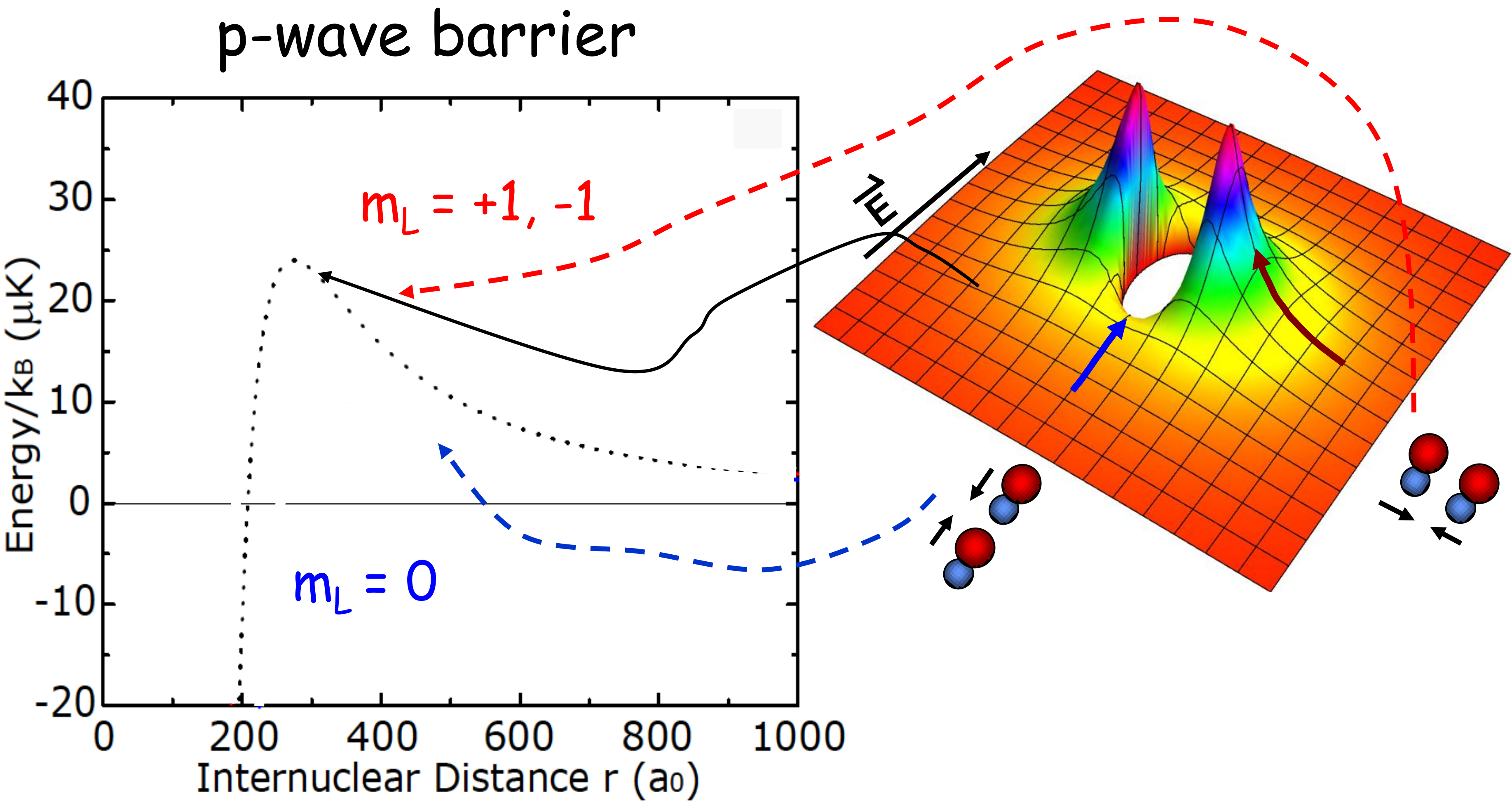
E = 0 (no induced dipoles) → p-wave suppression



Dipolar interaction "turns on" collisions - anisotopic, long range



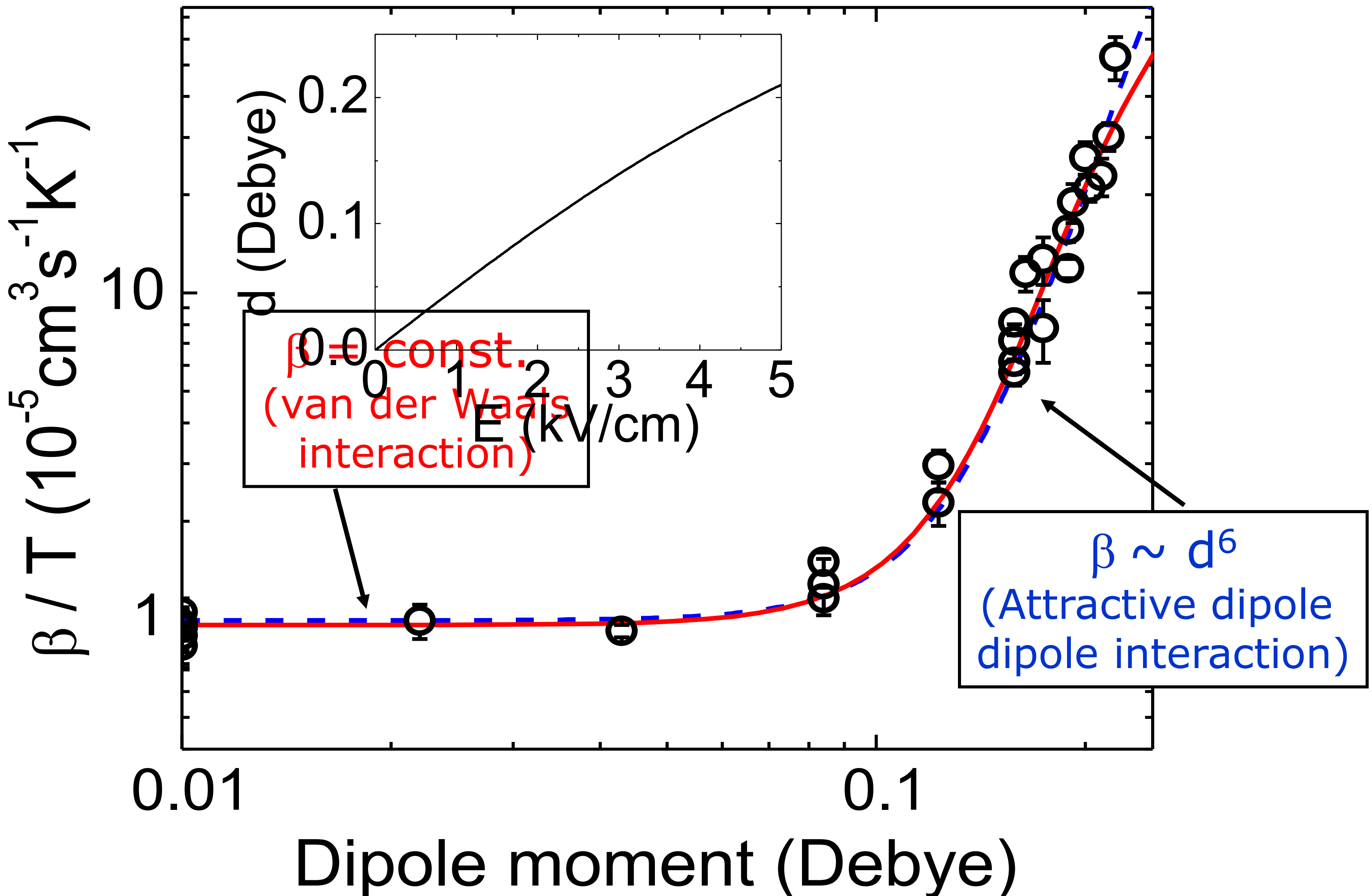
Anisotropic dipolar collisions



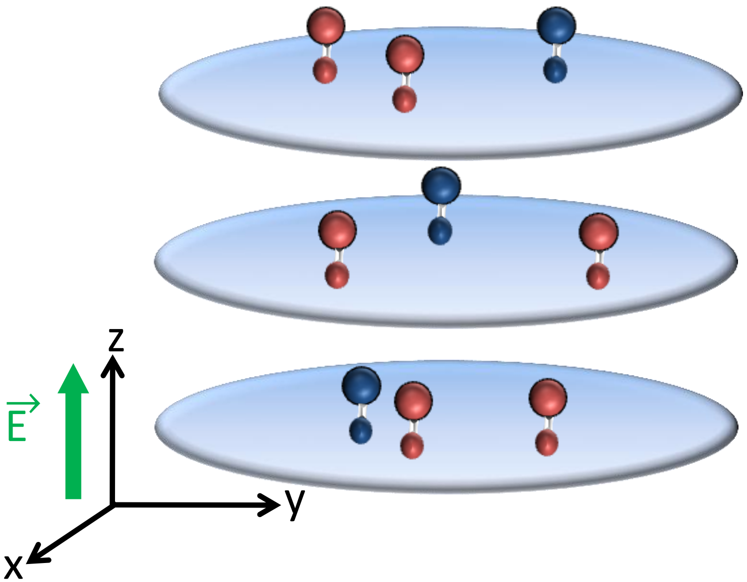
Collisions in 3D space average over different channels.

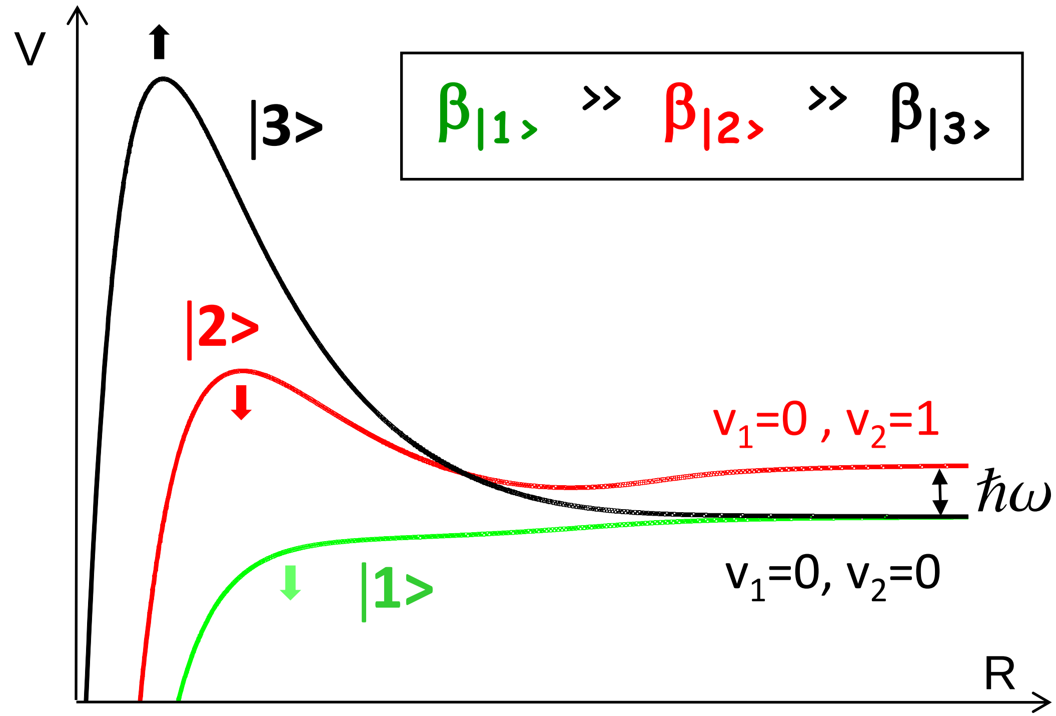
Control the inelastic collisions with d

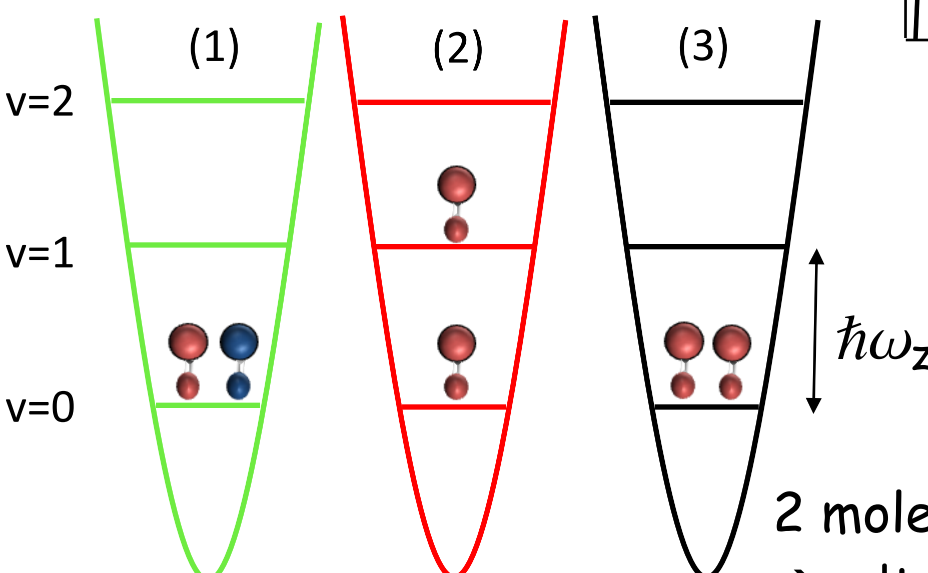
Long-range potential $V(R) = \frac{\hbar^2 L(L+1)}{2\mu R^2} - \frac{C_6}{R^6}$



2D quantum gas - suppress losses



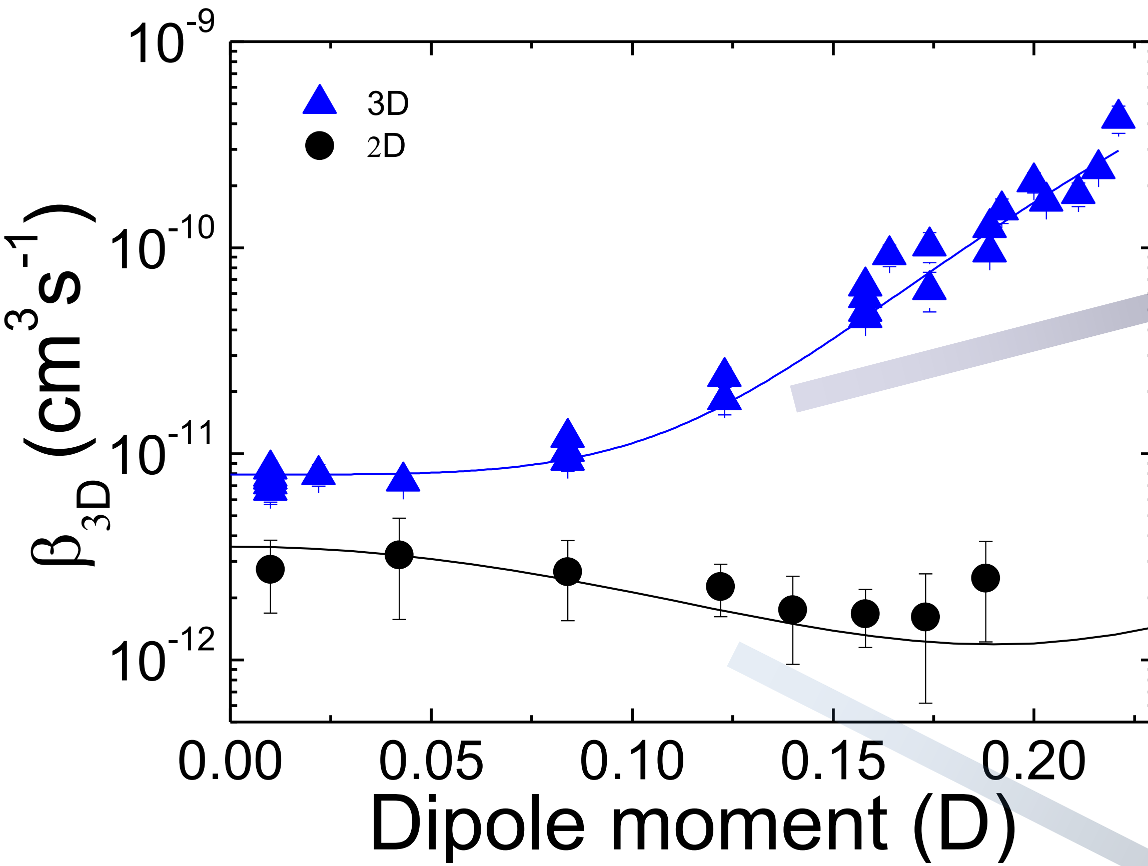


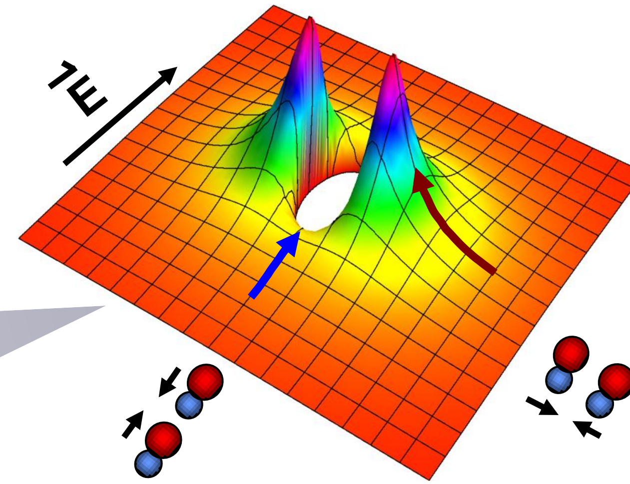


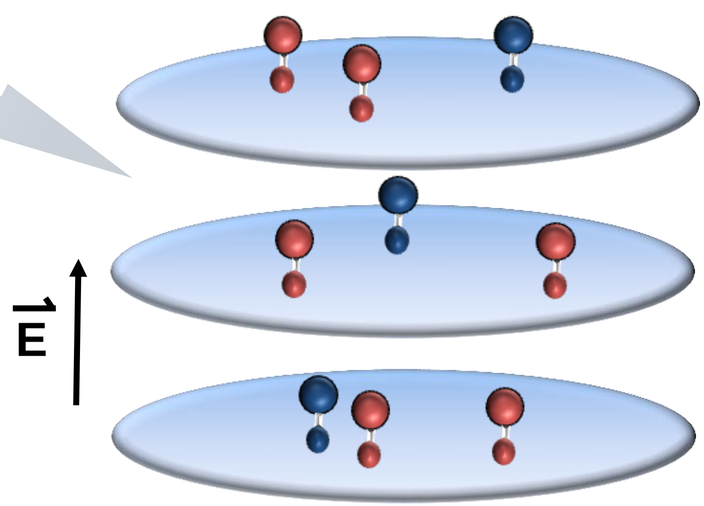
Quantized stereo-dynamics of chemical reactions

2 molecules in the same internal & |v> states

→ $|L = 1, m_L = \pm 1 \rangle$



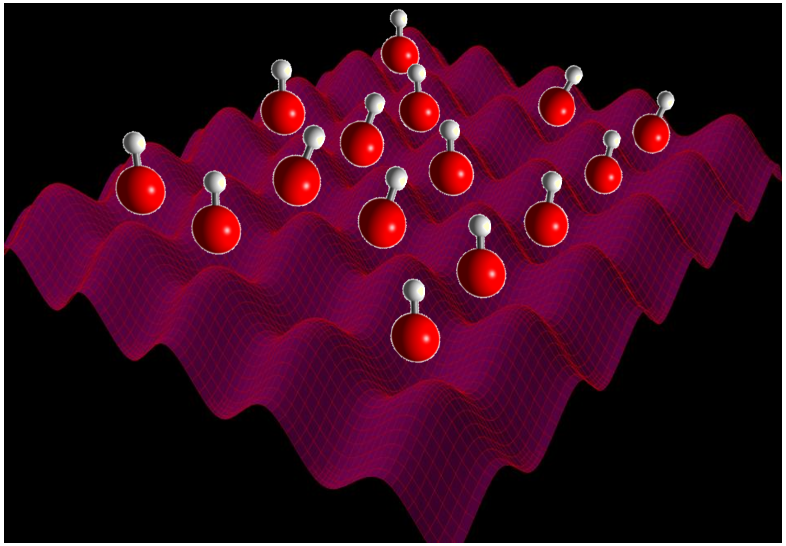


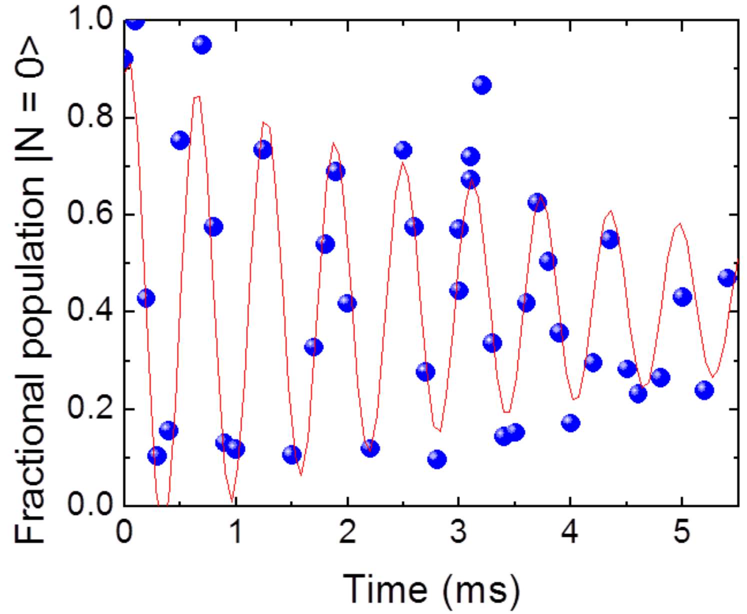


M. de Miranda, *et al.*,
"Controlling the quantum stereodynamics of ultracold bimolecular reactions,"
Nat. Phys. **7**, 502 (2011).

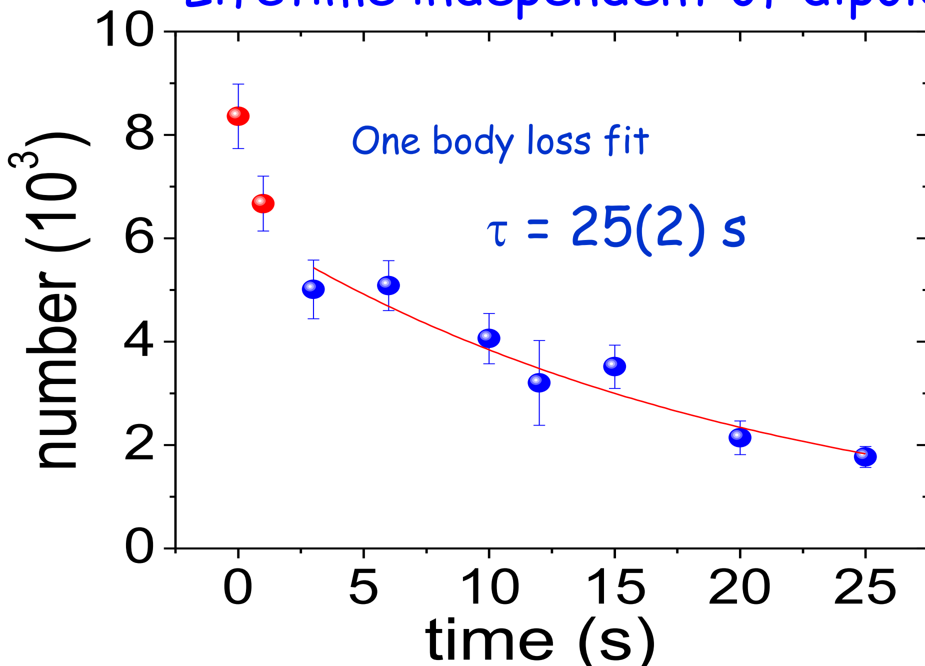
Polar molecules in 3D lattice

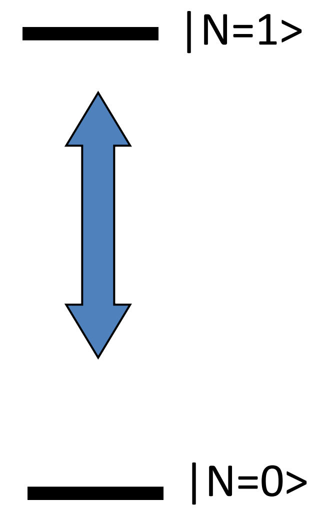
Chotia *et al.*, Phys. Rev. Lett. 108, 080405 (2012).





Lifetime independent of dipole





Cold molecules:

Debbie Jin

Bo Yan
Brian Neyenhuis
Steven Moses
Jake Covey

Matt Hummon
Ben Stuhl
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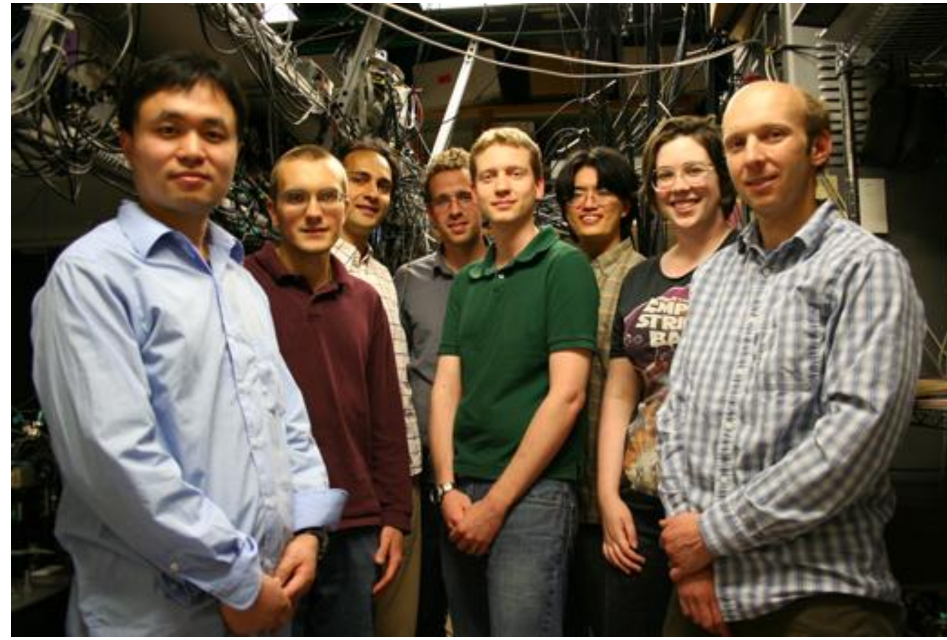

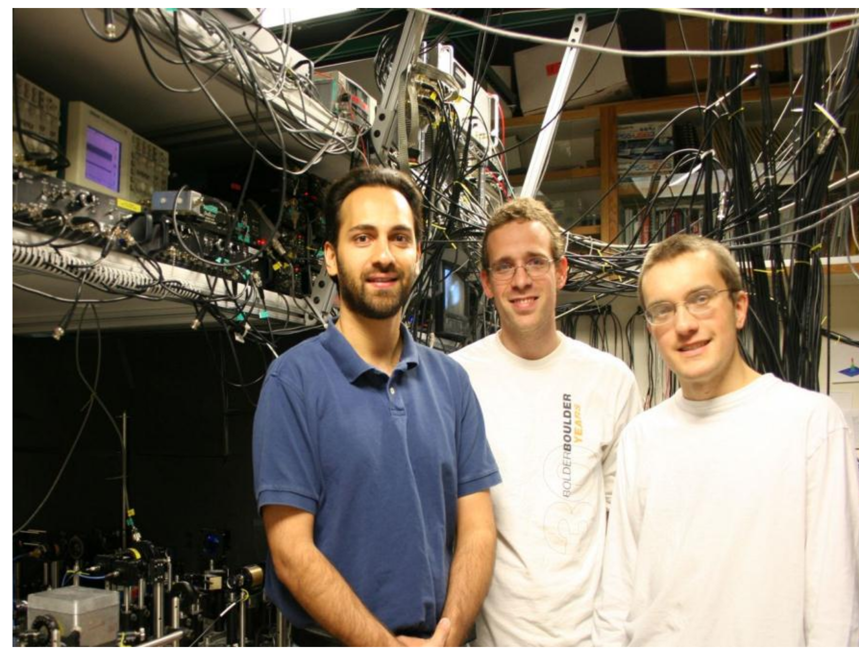

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