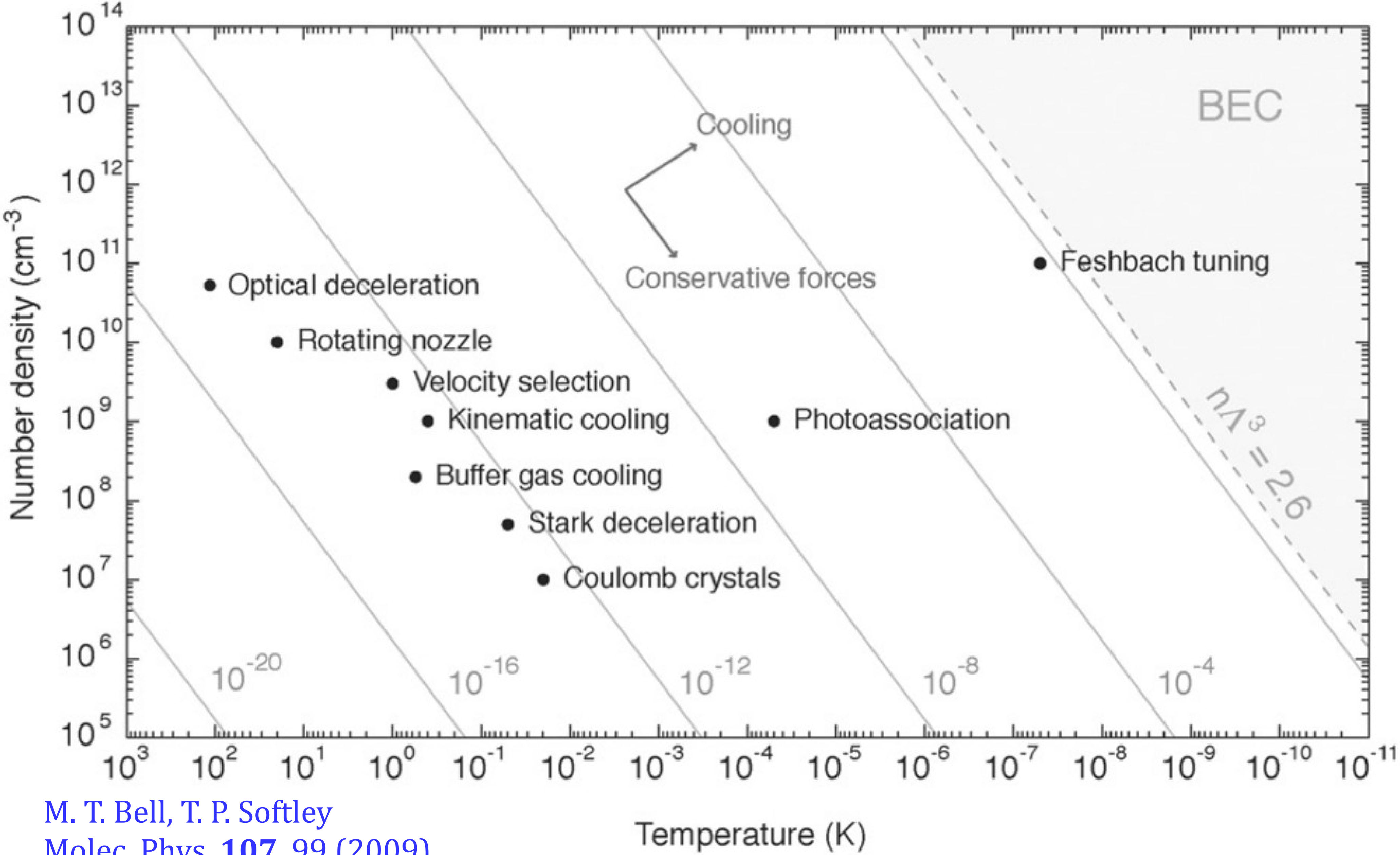
# Experimental techniques for cooling of molecules

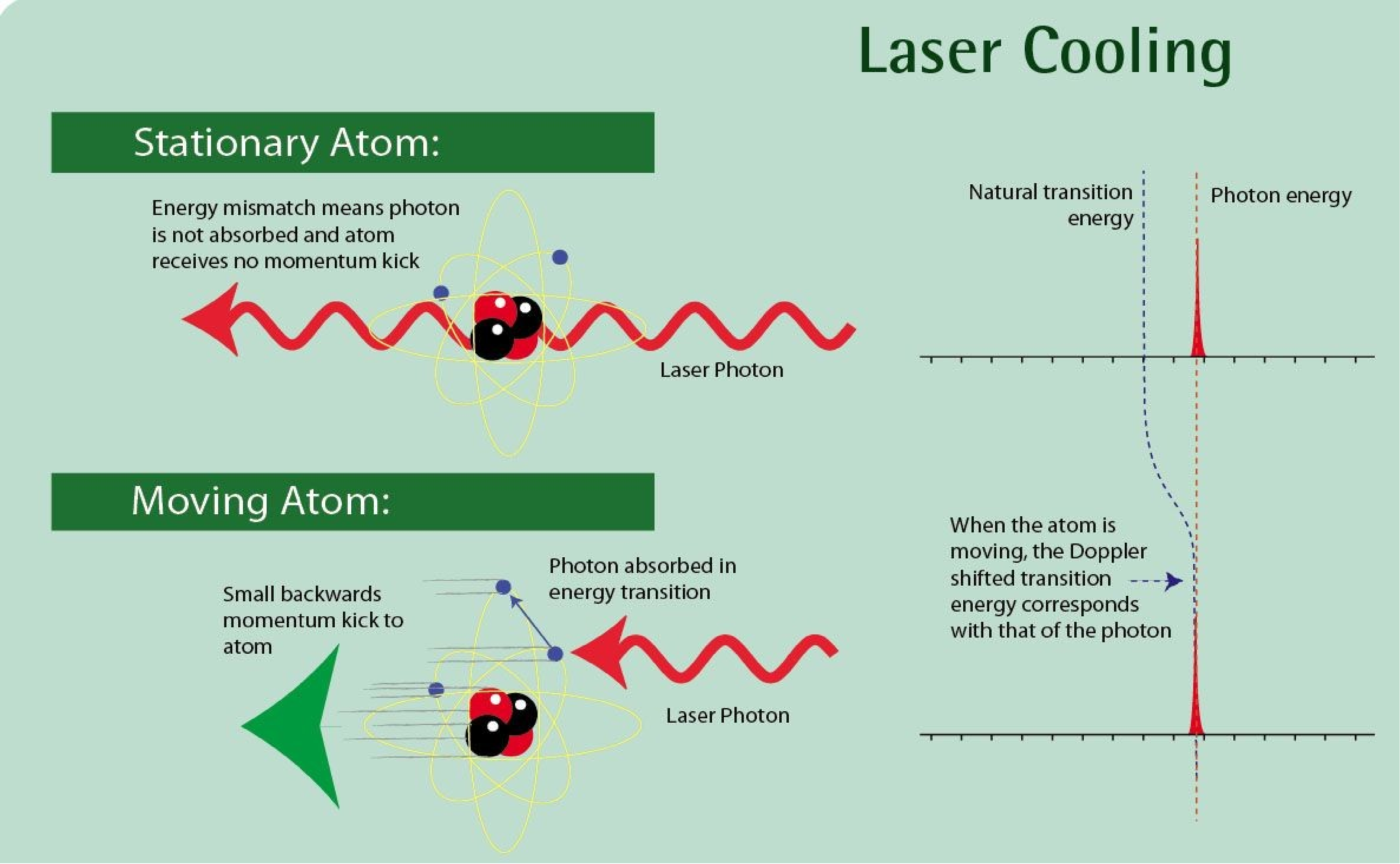
# Experimental techniques to produce ultracold molecules



M. T. Bell, T. P. Softley
Molec. Phys. **107**, 99 (2009)

# Molecular beam deceleration

# Laser cooling of atoms



These scheme works for atoms.

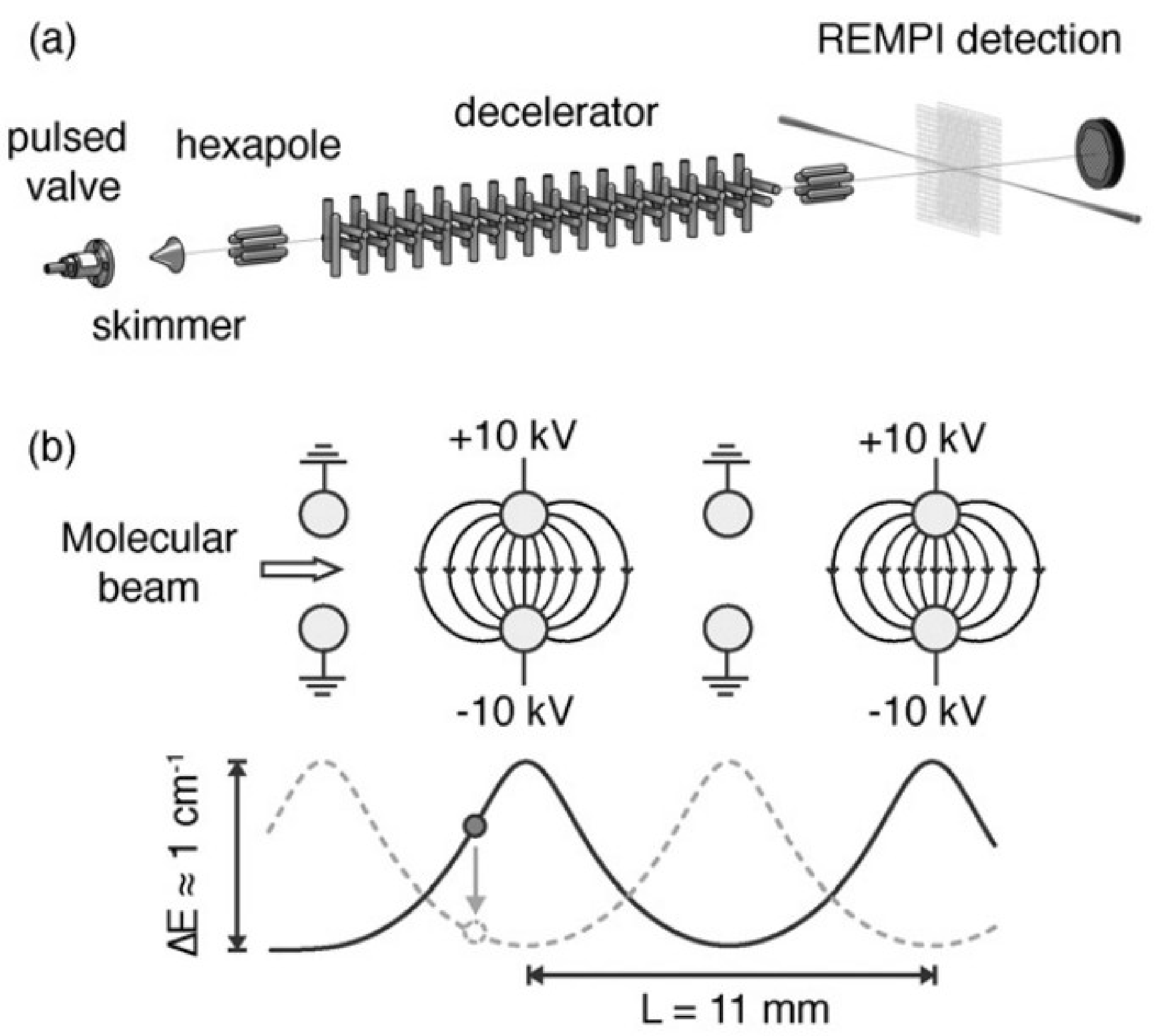
It is inefficient for molecules, having many “shelve” states.

# Stark deceleration

“Low-field seeking” states: quantum states for which the Stark effect produces a positive shift of energy with field.

When molecules enter the region of higher electric field, the “low-field seeking” molecules will climb up along the potential energy, the kinetic energy is reduced, i.e. the molecules slow down.

The field show “travel” with the molecules.



H.L. Bethlem, G. Berden, and G. Meijer, Phys. Rev. Lett. **83**, 1558 (1999).
H.L. Bethlem and G. Meijer, Int. Rev. Phys. Chem. **22**, 73 (2003).

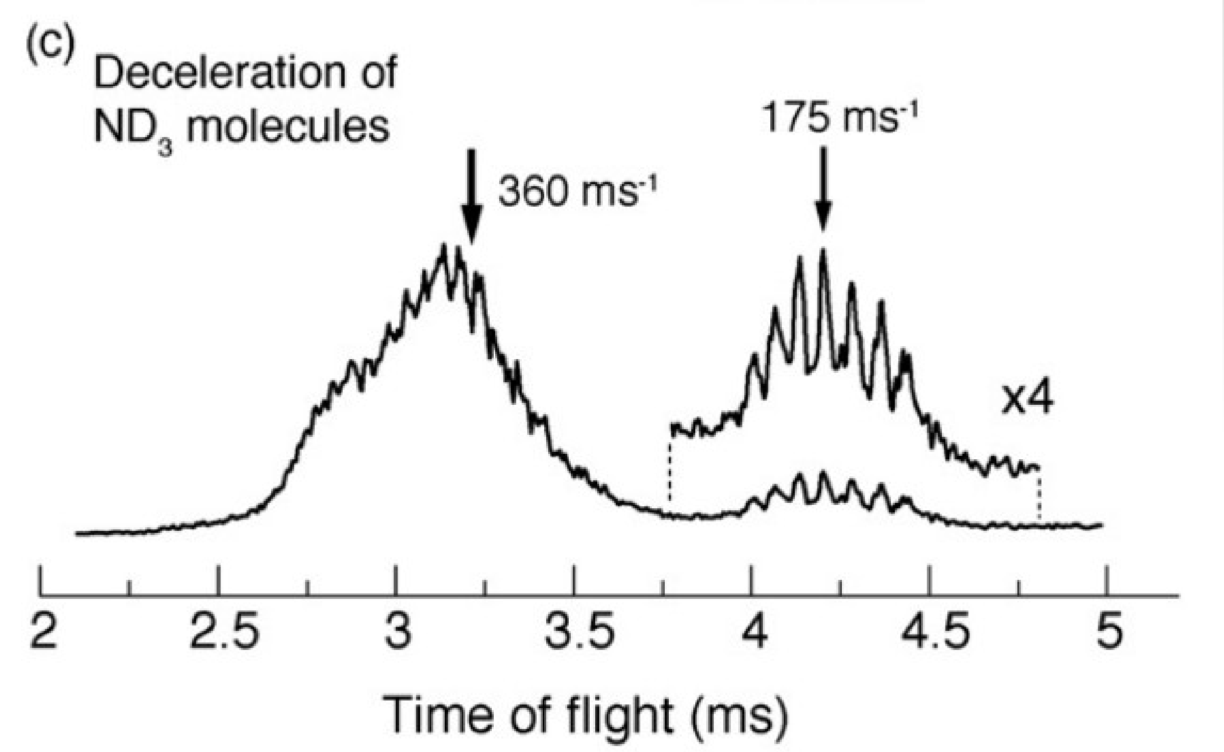
# Stark deceleration

For a molecule with the dipole moment of 1 debye, kinetic energy is reduced by about 2 $cm^{-1}$ ($\Delta T \sim 3K$) per each stage of the setup.

Dozens of stages are needed. The largest setup has 326 stages.

Lowest $T_{long}$ is about 250 mK.

Molecules: CO, OH/OD, $ND_3$, $SO_2$.



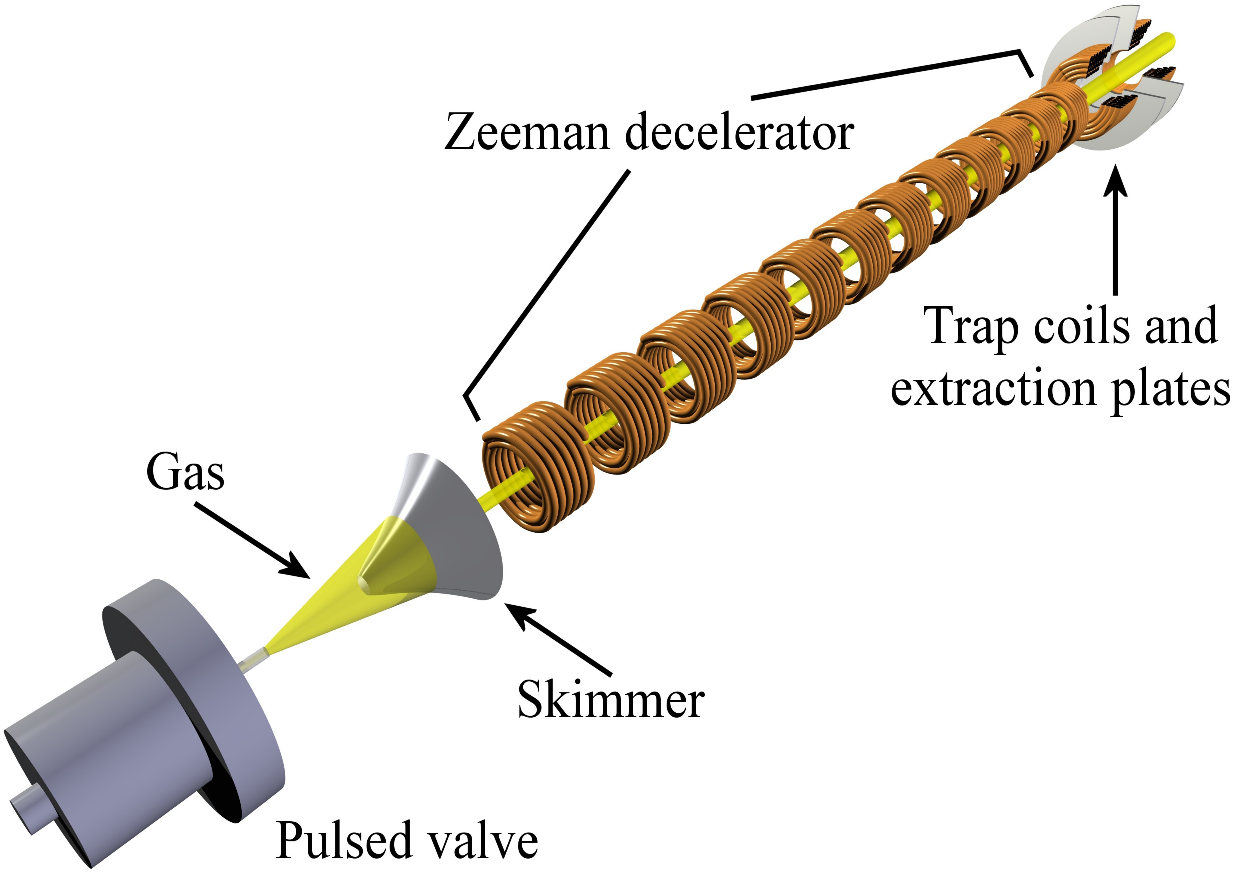
# Zeeman deceleration

Same idea as in th Stark deceleration, but electric field.

First decelerator had 6 stages and used for H.

Pulsed magnetic field of several teslas.

Such decelerators could be used to study radicals.



N. Vanhaecke, U. Meier, M. Andrist, B.H. Meier, and F. Merkt, Phys. Rev. A **75**, 031402 (2007).

# Optical deceleration

Variable electric field, with a variable amplitude $E(\boldsymbol{r},t)$

Polarizable molecule

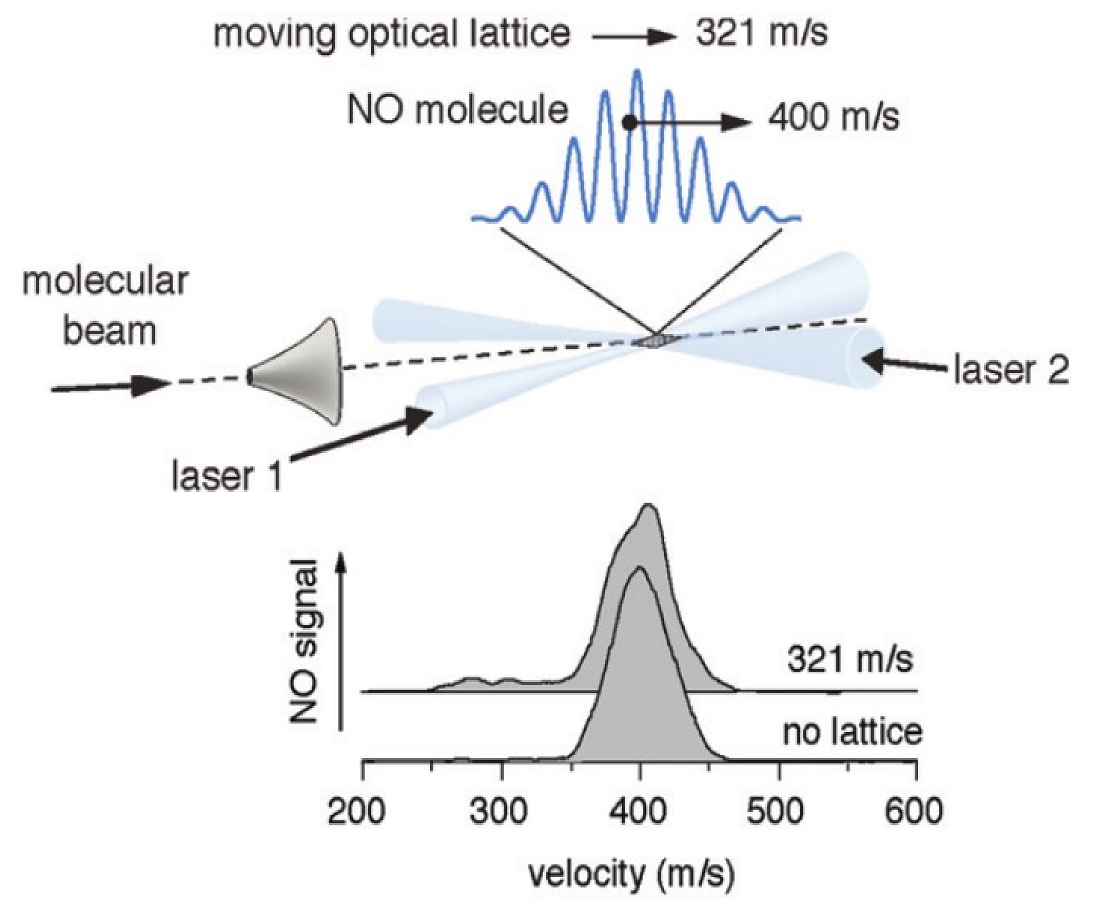
Quasi-static electric potential

$$U(\mathbf{r},t) = -\frac{1}{4}\alpha|E(\mathbf{r},t)|^2$$

α is the averaged polarizability.

The molecule are attracted into the high-field region of space.

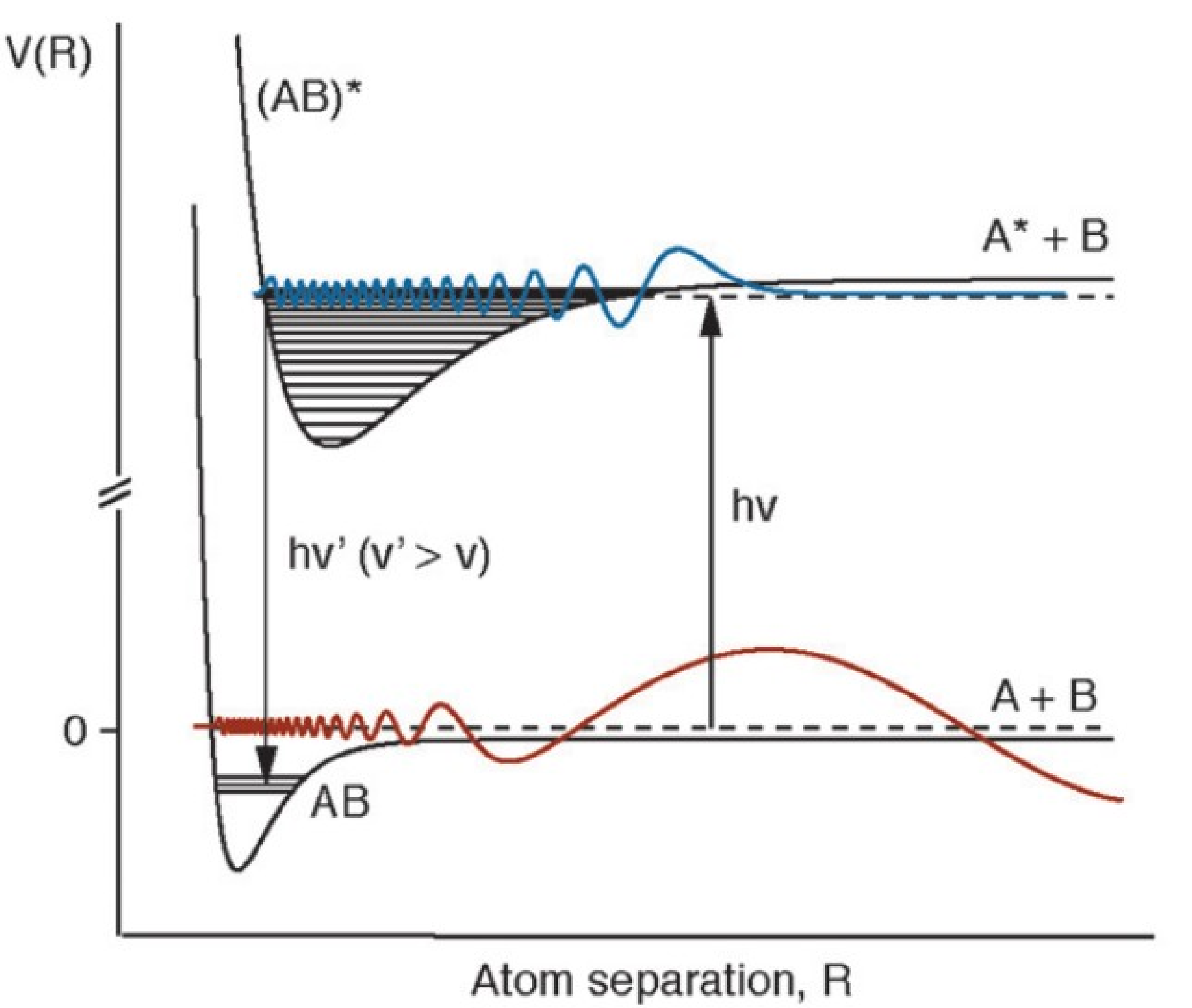
Two counter-propagating lasers form a standing wave (optical lattice).
If laser frequencies are different, the lattice moves.



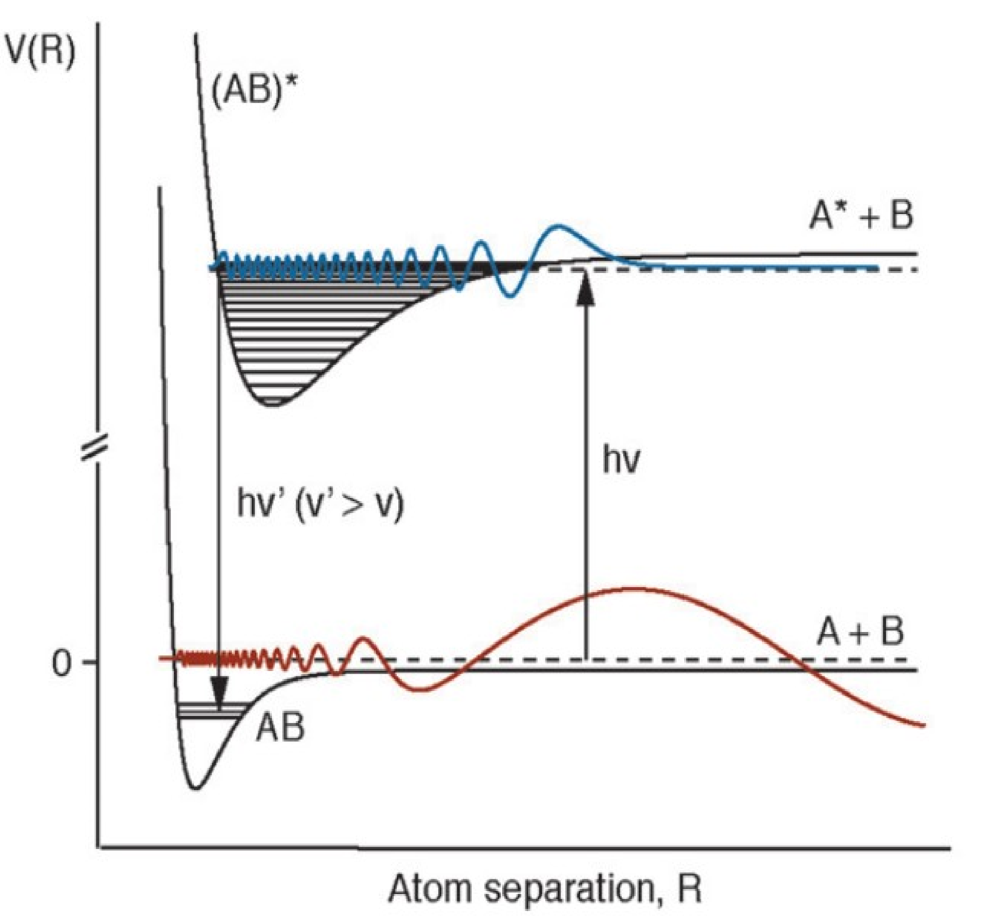
R. Fulton, A.I. Bishop, M.N. Shneider, and P.F. Barker, Nat. Phys. **2**, 465 (2006).

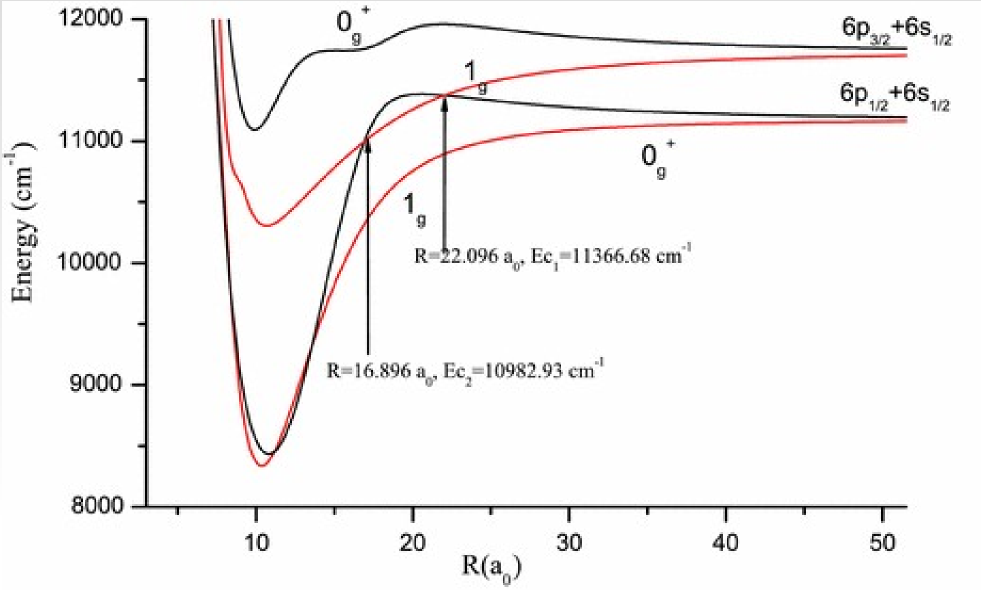
# Forming cold molecules from cold atoms

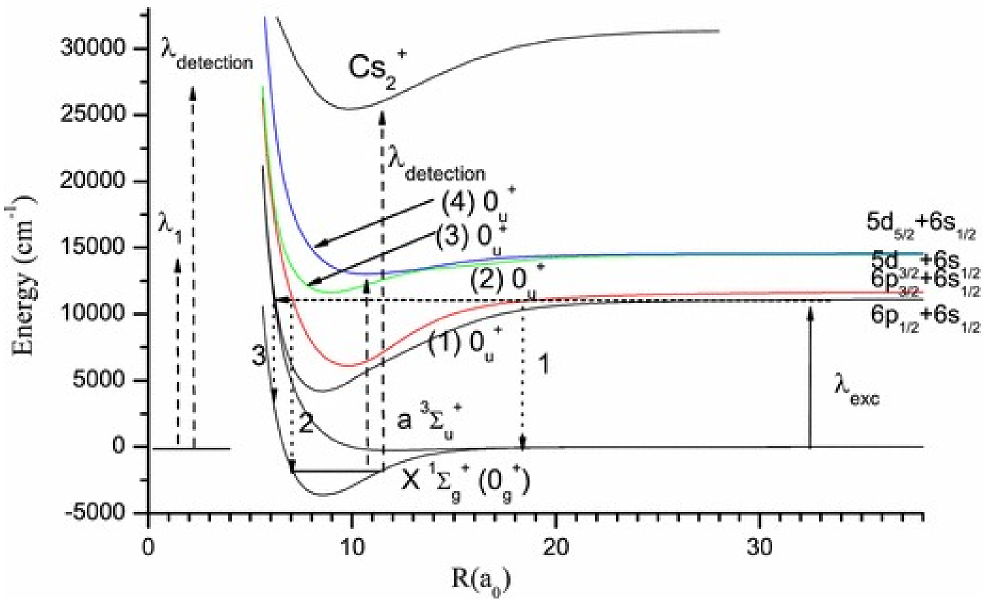
# Photoassociation



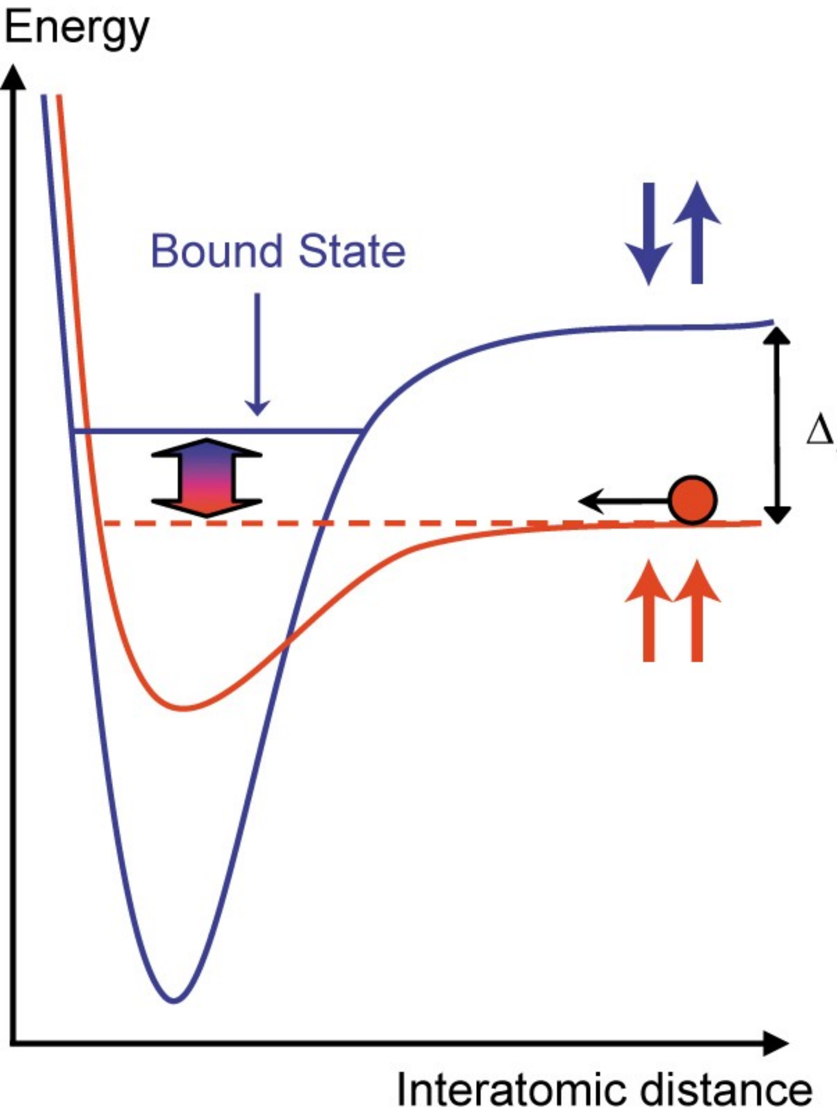
# Photoassociation

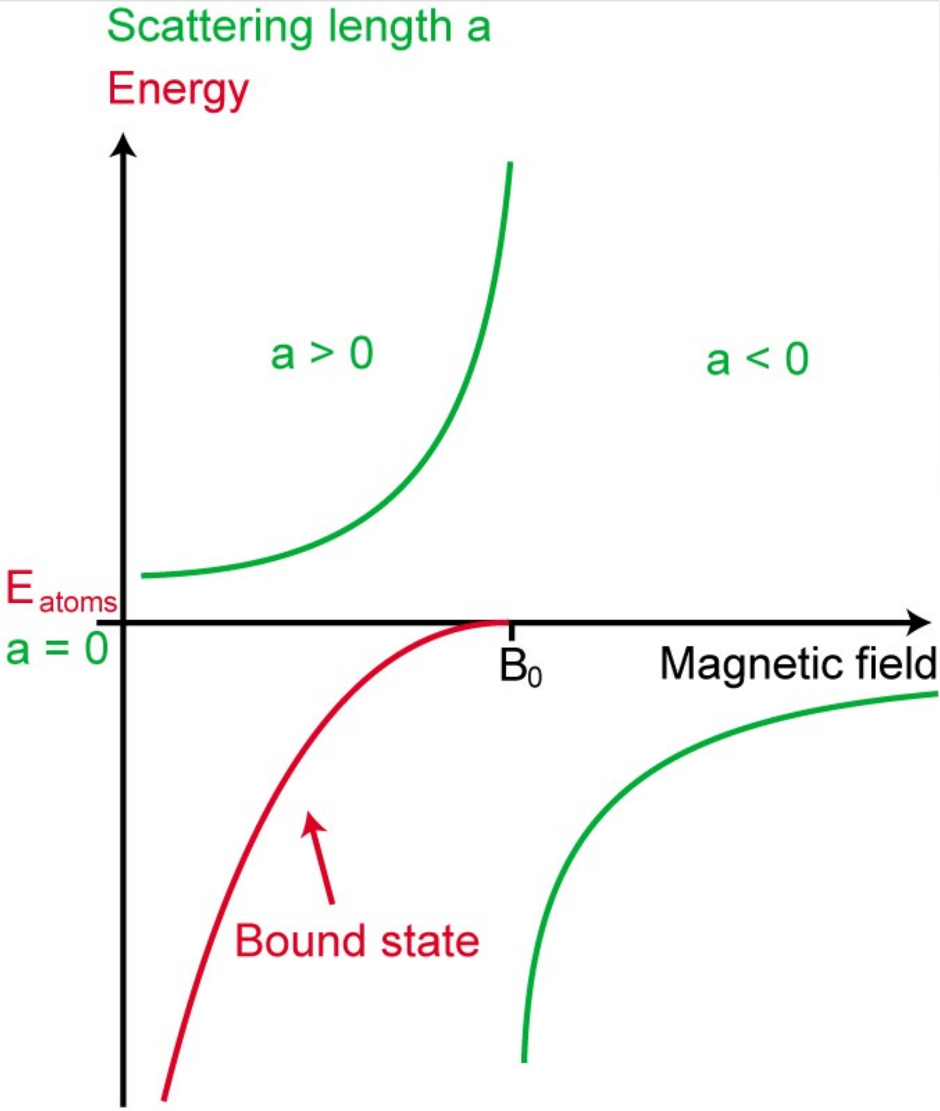




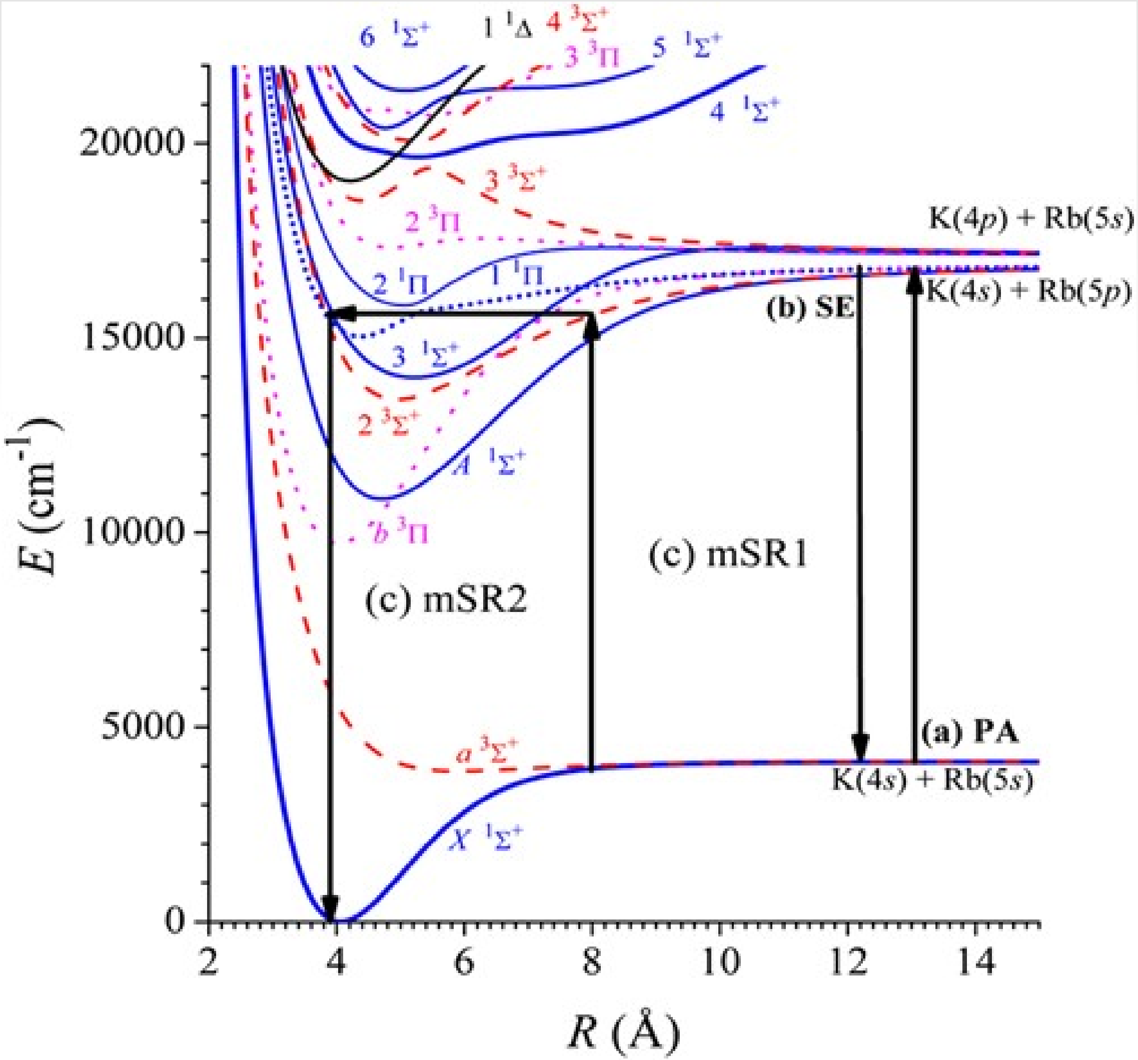


# Magnetic Feshbach resonance



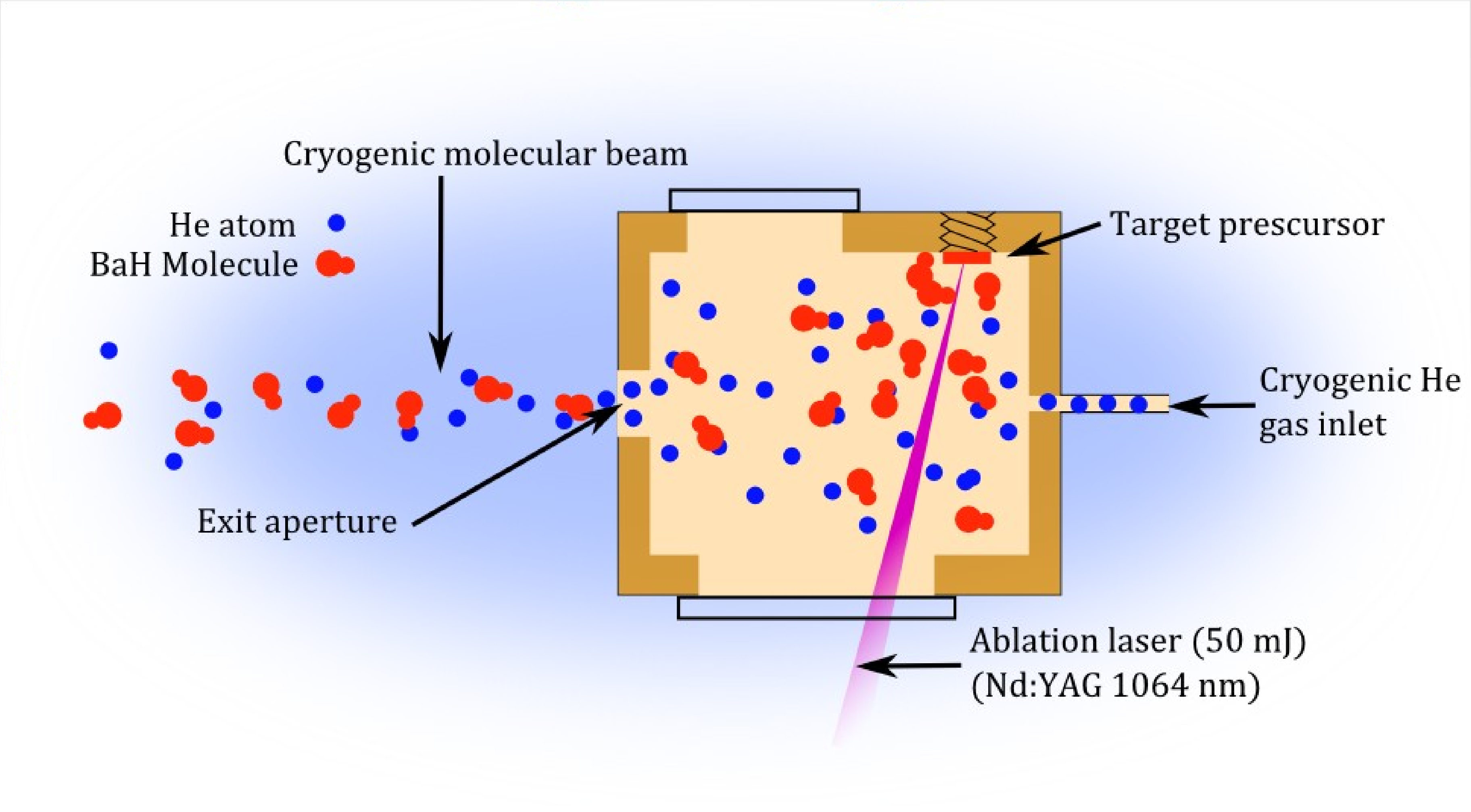


# Transferring population to the vibrational ground state

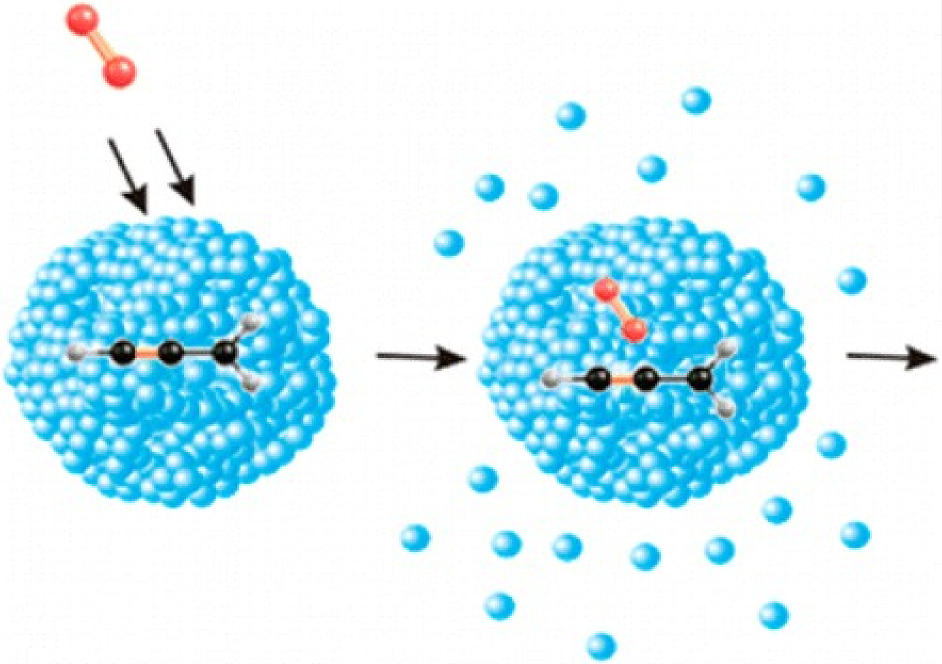


# Collision-based methods

# Buffer-gas cooling



# Superfluid helium droplets



# Trapping and secondary cooling techniques

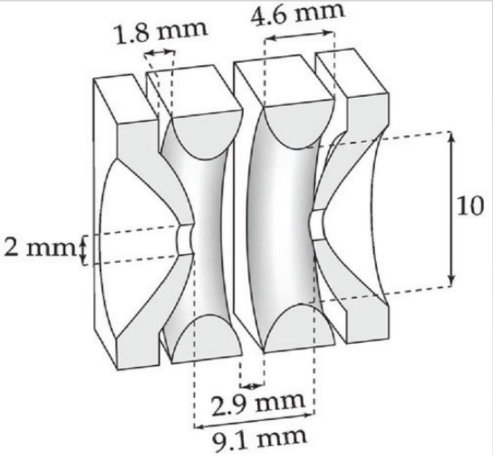
# Electrostatic traps

Polar molecules can be trapped using static inhomogeneous electric fields.

Traps with dipolar, quadrupolar or hexapolar fields.

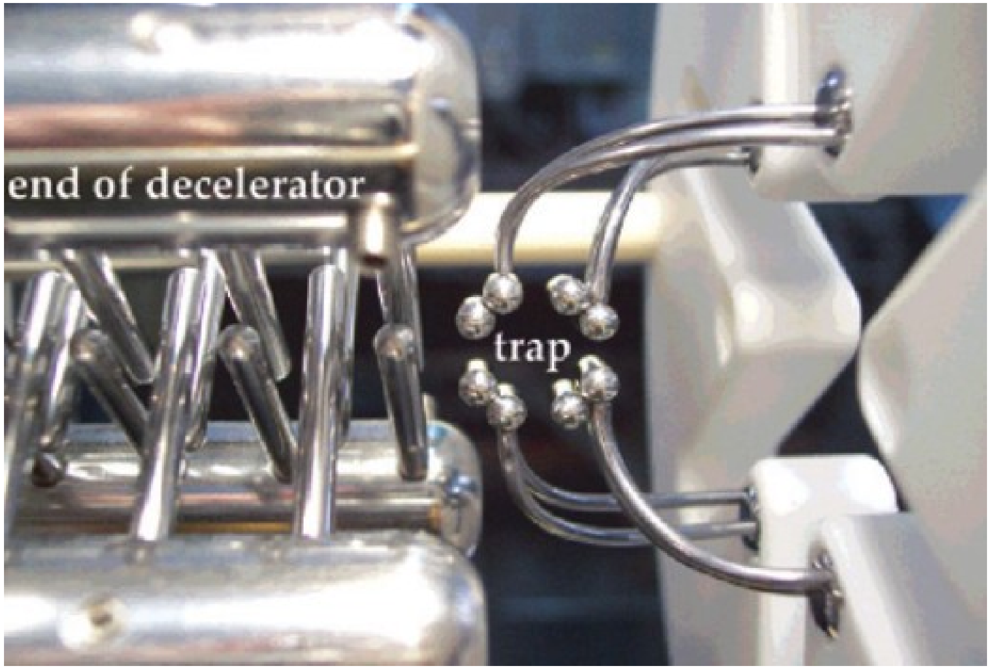
Examples: $ND_3$, OH, NH, CO

Lowest $T$~25 mK



**Electrostatic trapping of ammonia molecules**

Hendrick L. Bethlem, Giel Berden, Floris M. H. Crompvoets, Rienk T. Jongma, André J. A. van Roij & Gerard Meijer



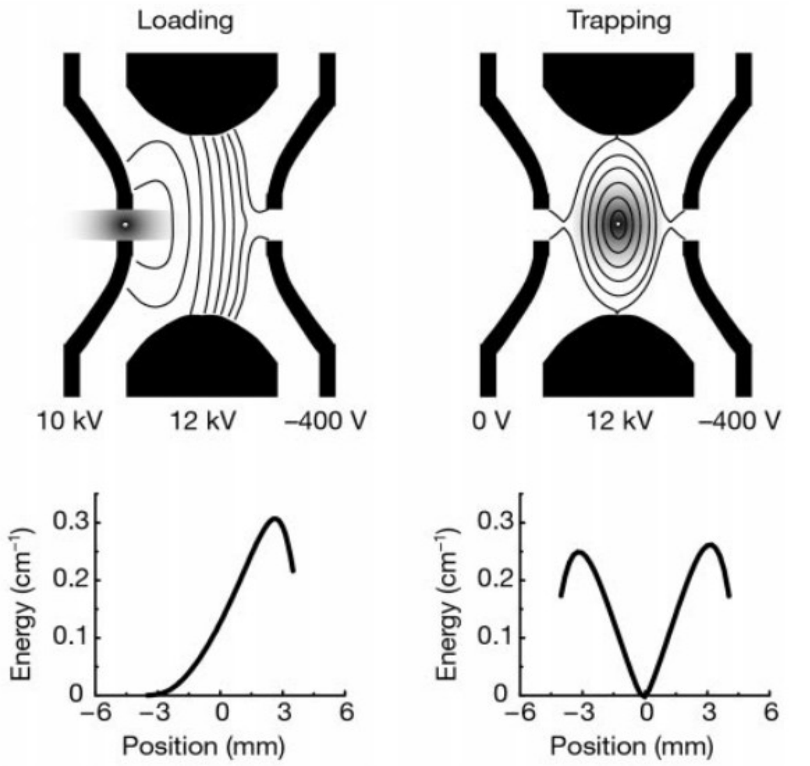


**Figure 2** Configuration of the trap with the voltages as applied during loading and trapping. In the trap, lines of equal electric field are indicated and the cloud of molecules is sketched. The potential energy along the molecular beam axis of the $ND_3$ molecules in the $|J\ K\rangle = |1\ 1\rangle$ state with positive Stark shift is shown for both field geometries.

# Optical traps

Molecules can also be trapped by intense optical fields.

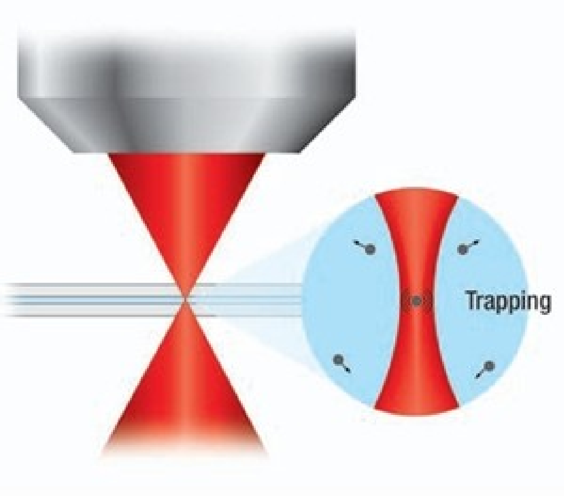
Optical lattice.

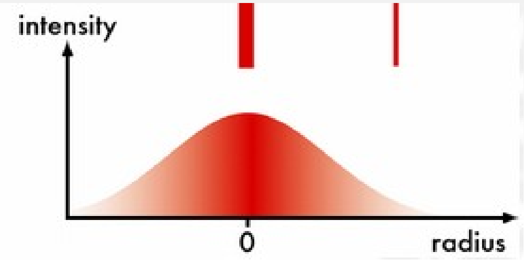
The trapping potential depends on polarizability of the molecule.

As an example, using a 110W $CO_2$ laser, Zahzam et al. produced a trap depth of order 1 mK for $CS_2$ molecules.

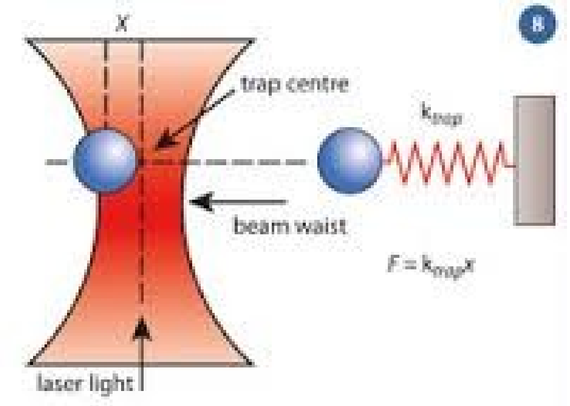
Examples: $CS_2$, RbCs, $Rb_2$, KRb.

Microwave field can also be used. Instead of electronic transitions, rotational transitions are used.





$$U(\mathbf{r},t) = -\frac{1}{4}\alpha|E(\mathbf{r},t)|^2$$

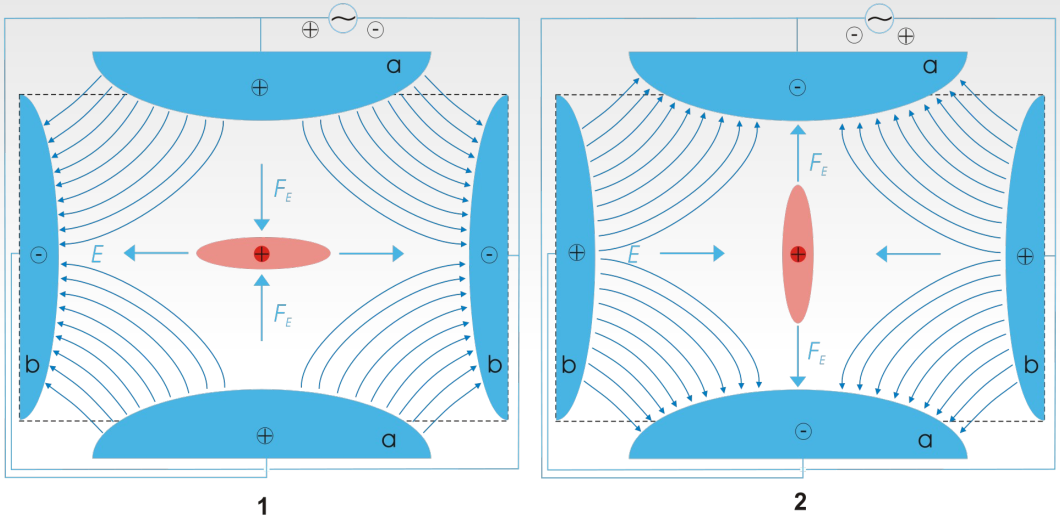


# Ion traps

To trap a positively-charged ion by an electrostatic field, near minimum of the trap, one should have $\nabla \cdot \mathbf{F} < 0.$

It is not possible in free space because of the Laplace equation

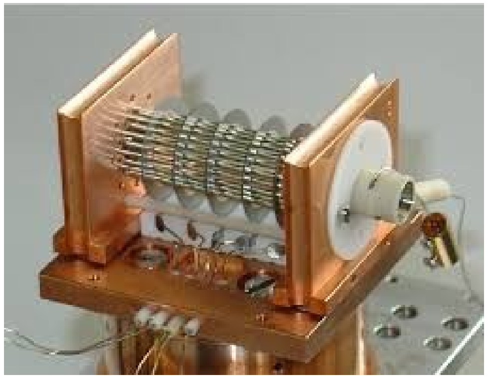
$$\nabla \cdot \nabla = 4\pi\rho$$

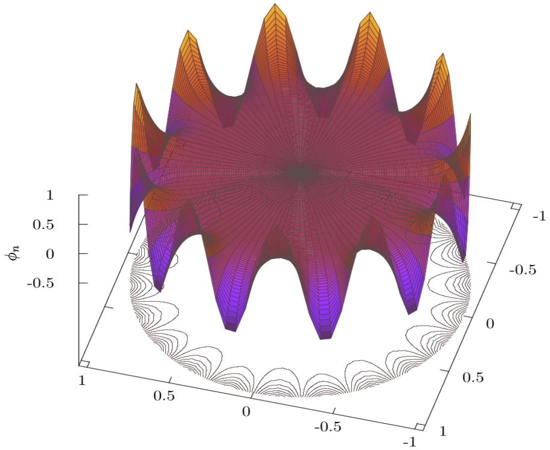


Varying fields are used.

Paul (or quadrupole) traps.

Ions move in the trap: low-frequency (secular) motion and high-frequency (micro) motion.



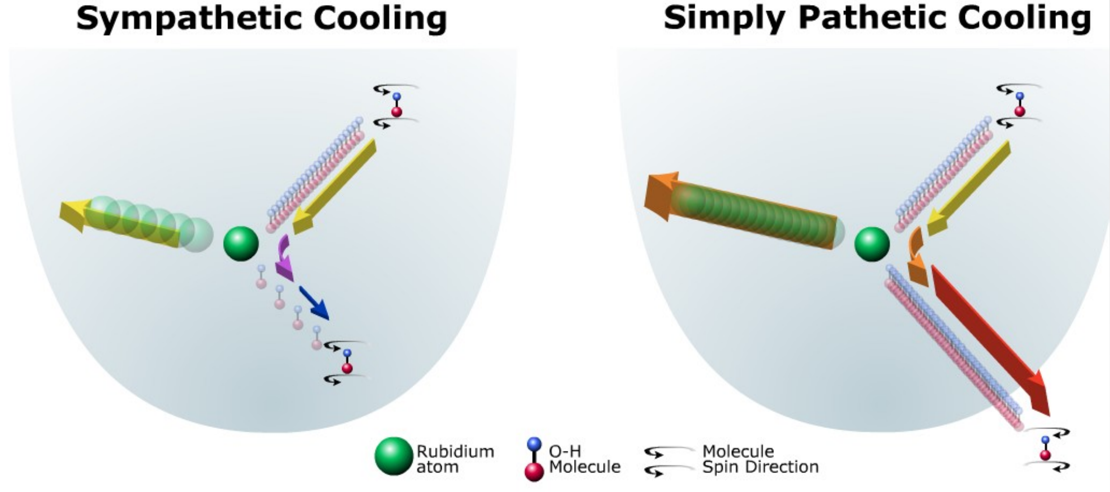


22-pole traps (D. Gerlich)

# Secondary cooling

**Sympathetic cooling:**

Trapped cold molecules or ions might potentially be brought into the ultra-cold regime by placing them in thermal contact with a gas of ultracold atoms.



Problem: inelastic collisions.

**Cavity-assisted laser cooling.**