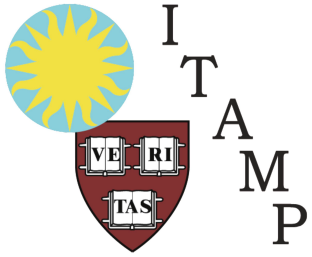
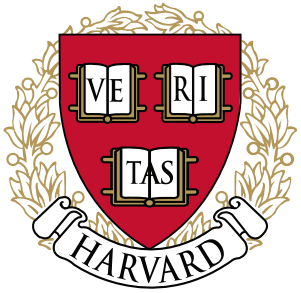




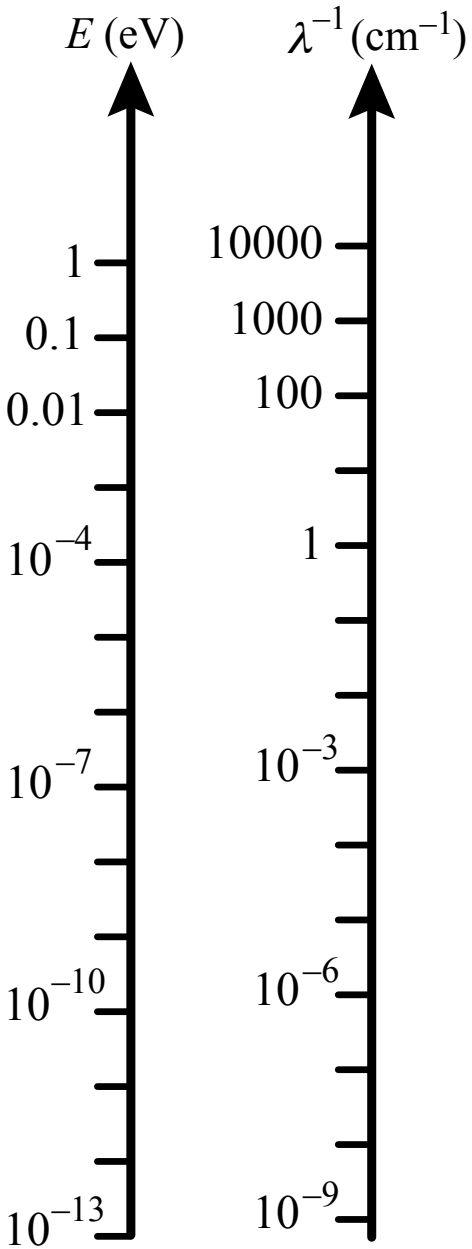
Engineering quantum states in ultracold gases using conservative and nonconservative forces

Mikhail Lemeshko

ITAMP, Harvard-Smithsonian Center for Astrophysics
&
Harvard Physics Department

February 11, 2013

Energy scales of physics and chemistry



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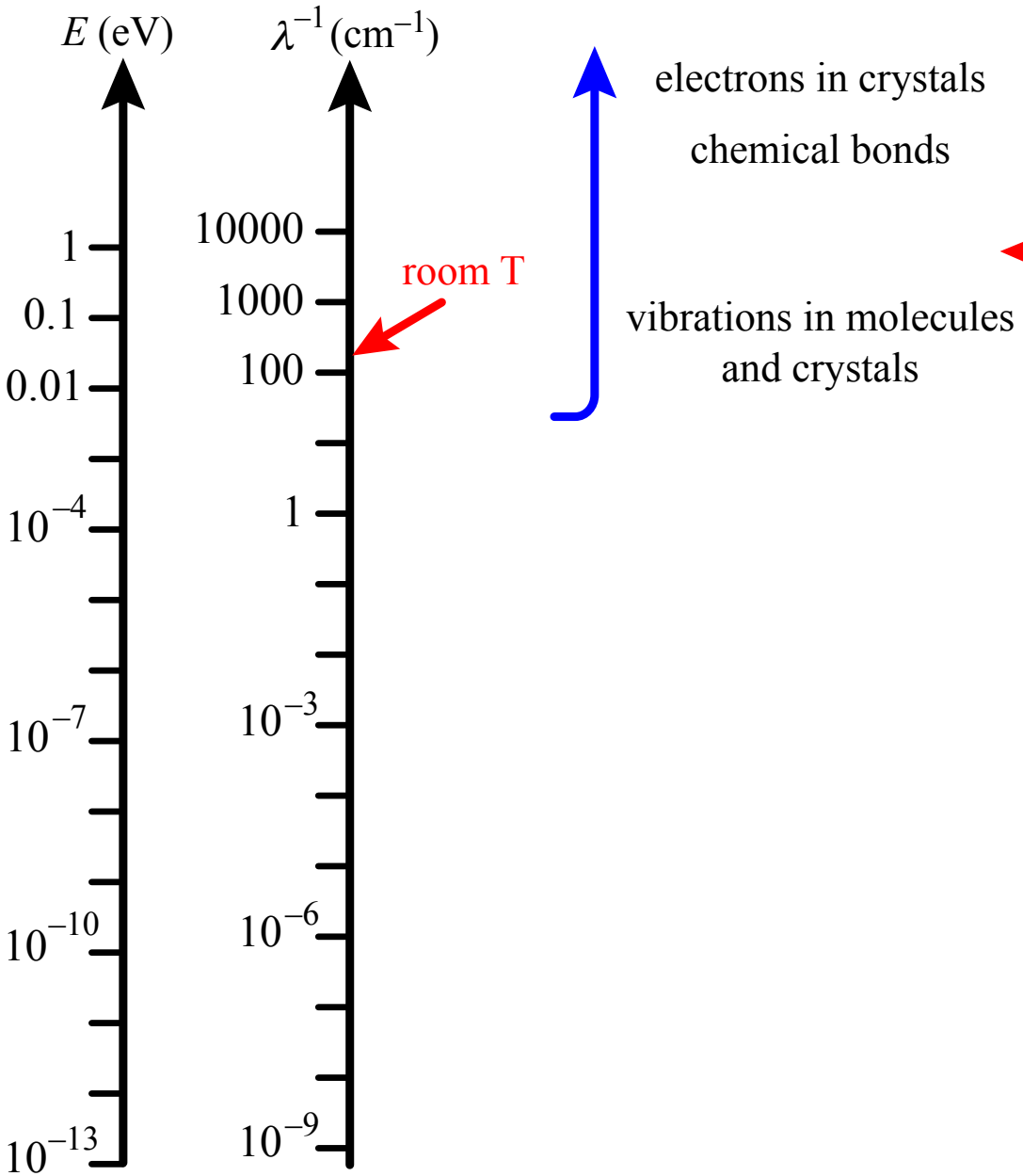

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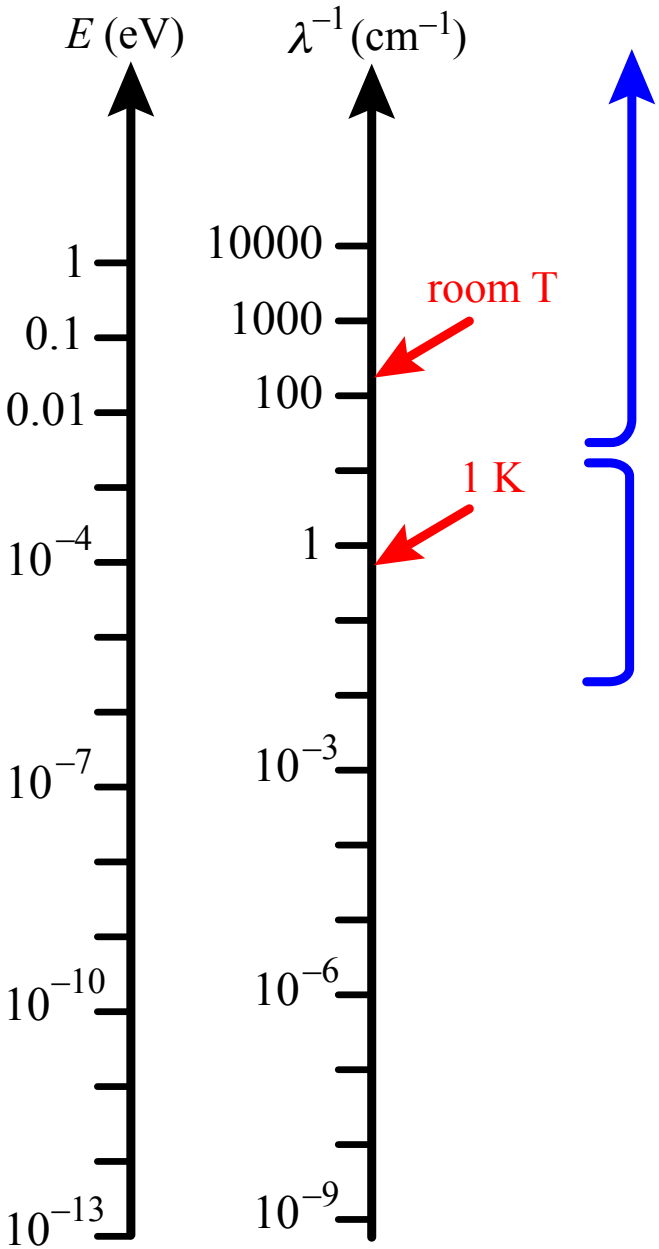


electrons in crystals

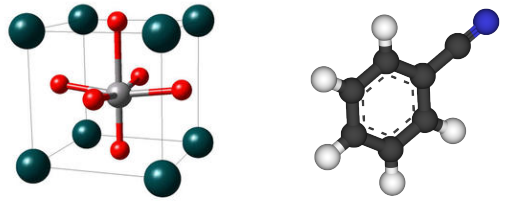
chemical bonds

vibrations in molecules and crystals

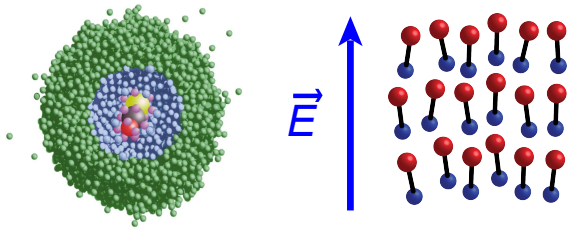
superfluid helium

molecular rotations

a lot of physics and chemistry happens here



precision spectroscopy (He droplets) controlling molecular orientation



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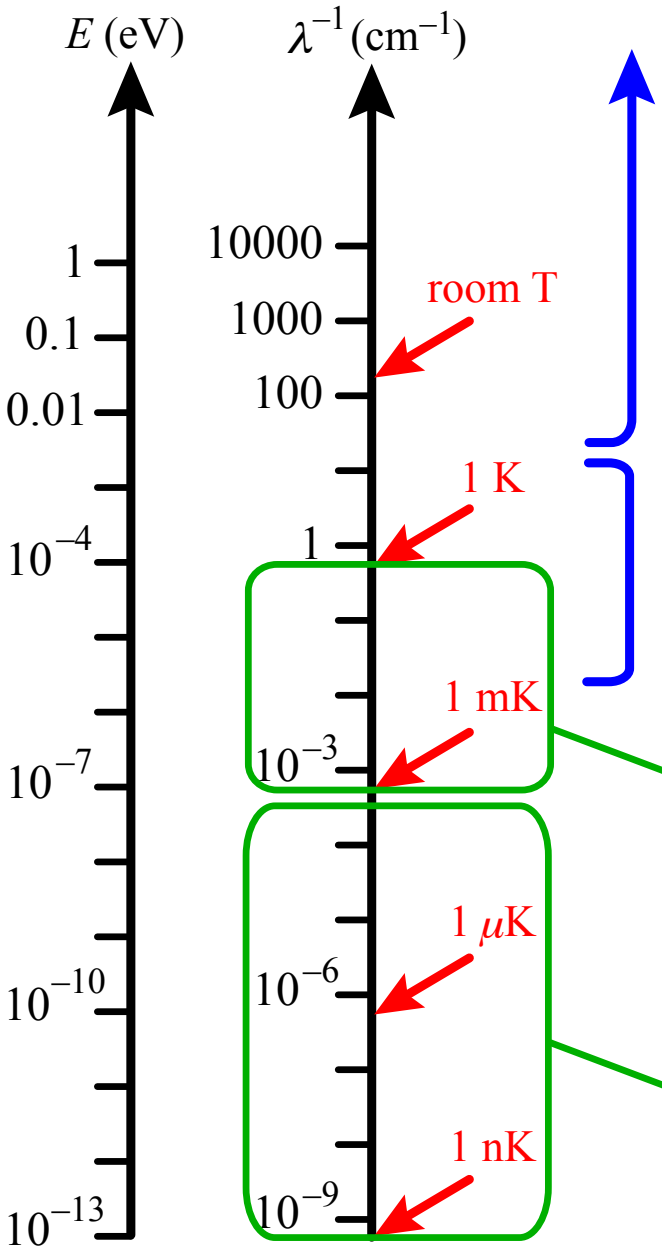

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“cold”

“ultracold”

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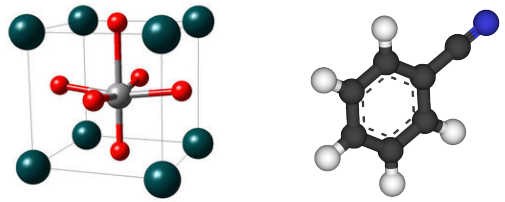

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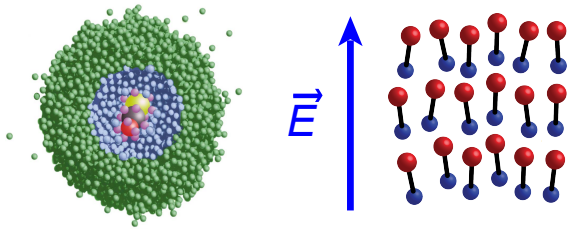
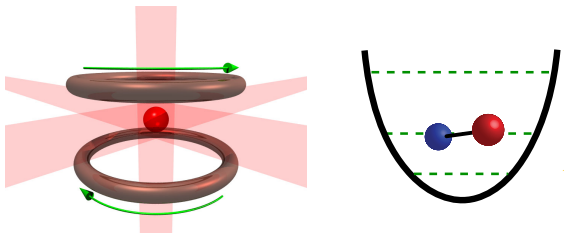


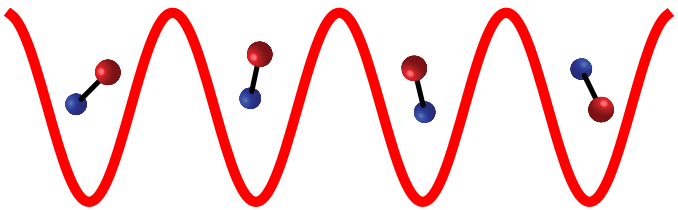
slowing and trapping molecules



Why are cold molecules interesting?

Kinetic energy is so small that molecules can be trapped

Optical lattice: molecules trapped in a periodic laser field



$$\longrightarrow x \qquad V(x) = -\frac{\alpha E^2}{4}\sin^2\left(\frac{2\pi}{\lambda}x\right)$$

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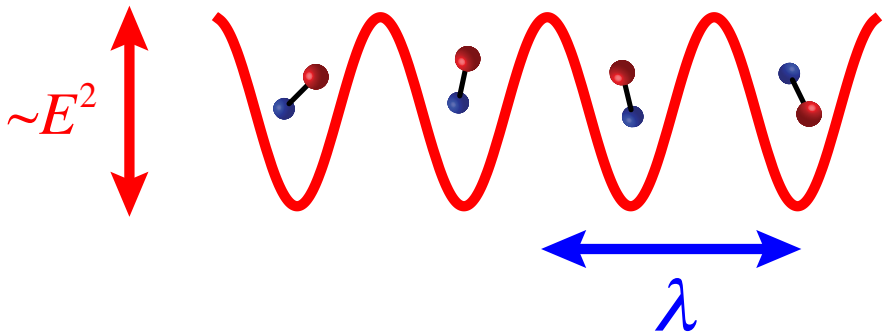

molecular polarizability

laser electric field

$$V(x) = -\frac{\alpha E^2}{4}\sin^2\left(\frac{2\pi}{\lambda}x\right)$$

laser wavelength

Laser intensity: trapping depth

Laser wavelength: distance between the molecules

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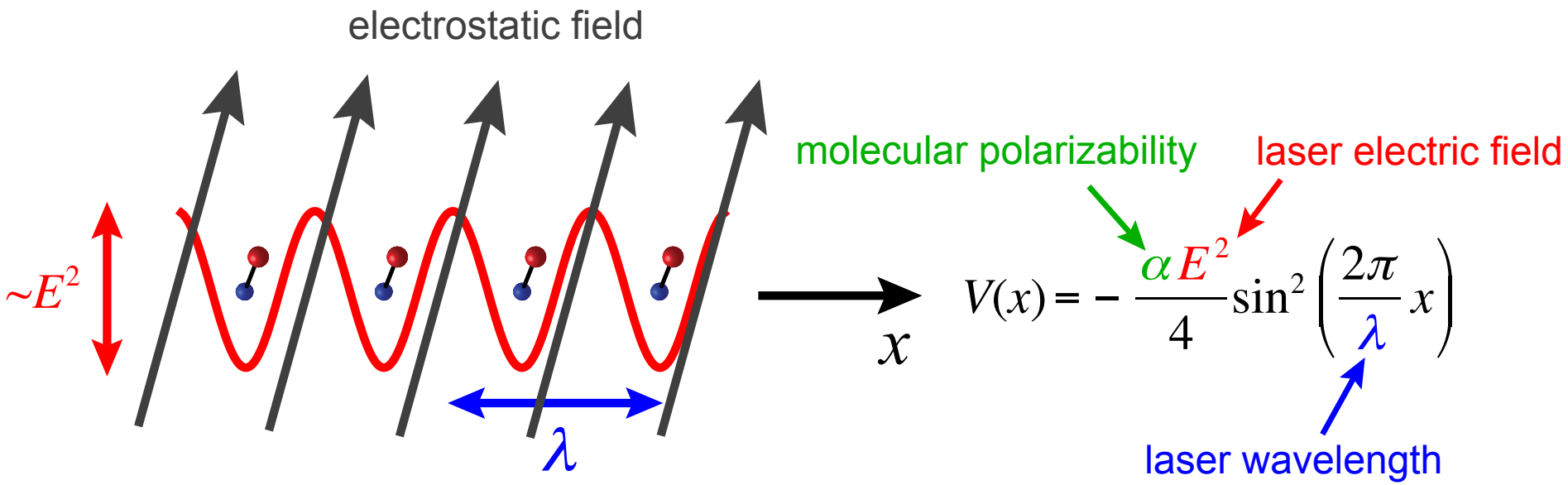


Laser intensity: trapping depth

Laser wavelength: distance between the molecules

Electrostatic field: tuning intermolecular interactions

Molecules in an optical lattice: toolbox for quantum simulation

- Many 'real world' problems are not understood

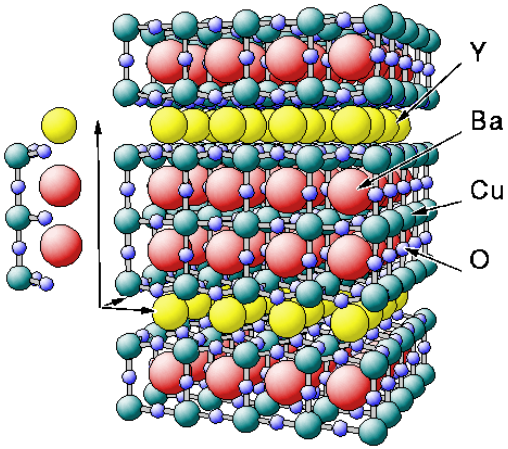
  (high-T_c superconductivity, quantum magnetism, transport in chemistry and biology...)

- Often even the simplest possible models are challenging to solve theoretically

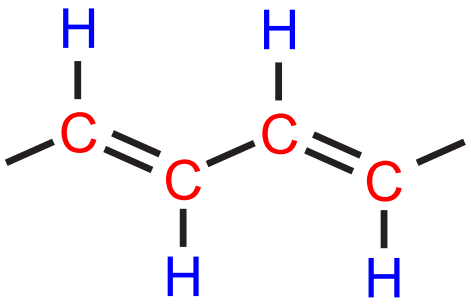
- Quantum simulation: using controllable quantum systems to mimic the behavior of more complex quantum systems (Feynman, 1982)

Molecules in an optical lattice: toolbox for quantum simulation

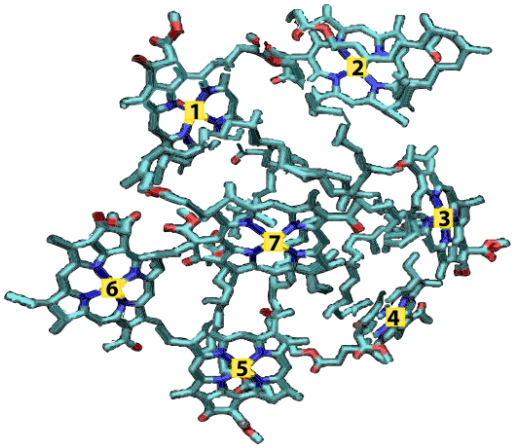
electrons in a crystal



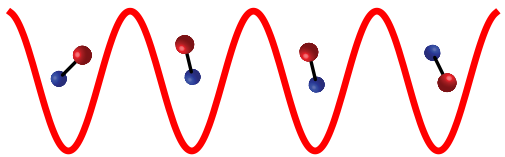
electrons in a polymer



excitons in a photosynthetic complex

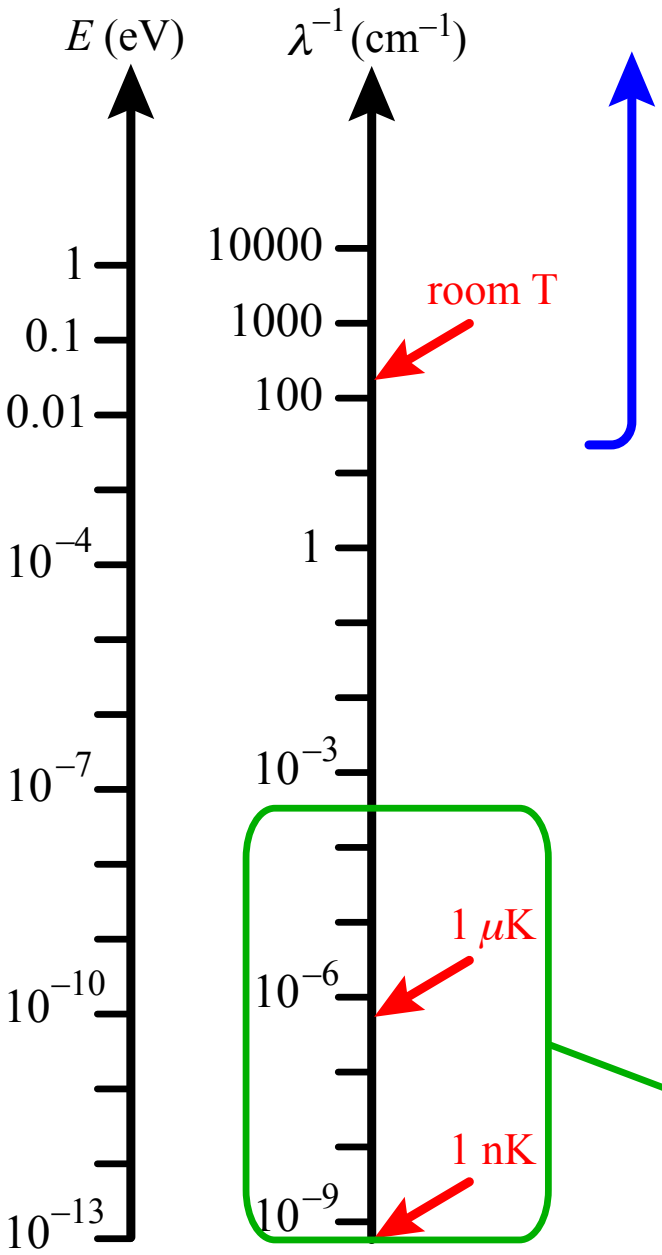


molecules in an optical lattice



engineering realistic model Hamiltonians

Molecules in an optical lattice: toolbox for quantum simulation

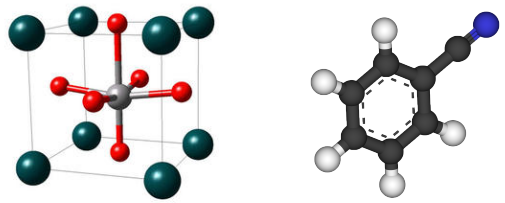


electrons in crystals

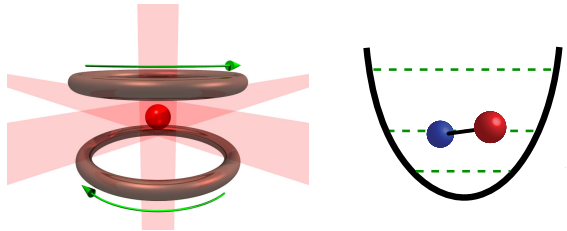
chemical bonds

vibrations in molecules and crystals

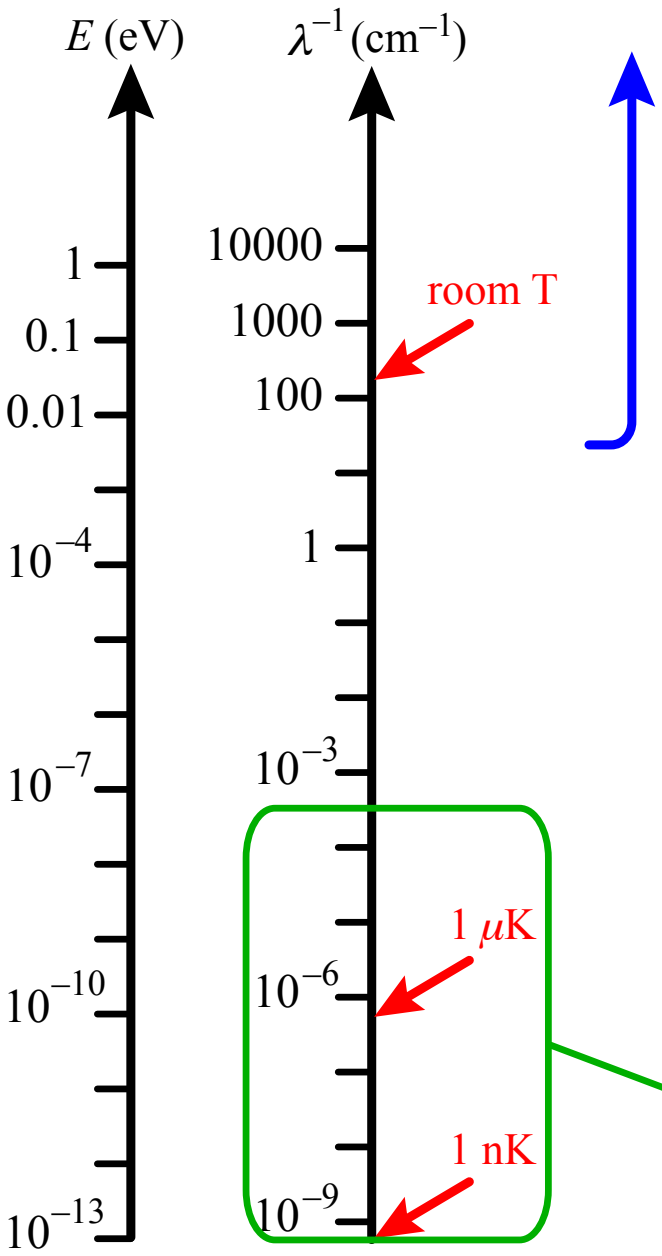
a lot of physics and chemistry happens here



slowing and trapping molecules



Molecules in an optical lattice: toolbox for quantum simulation



electrons in crystals

chemical bonds

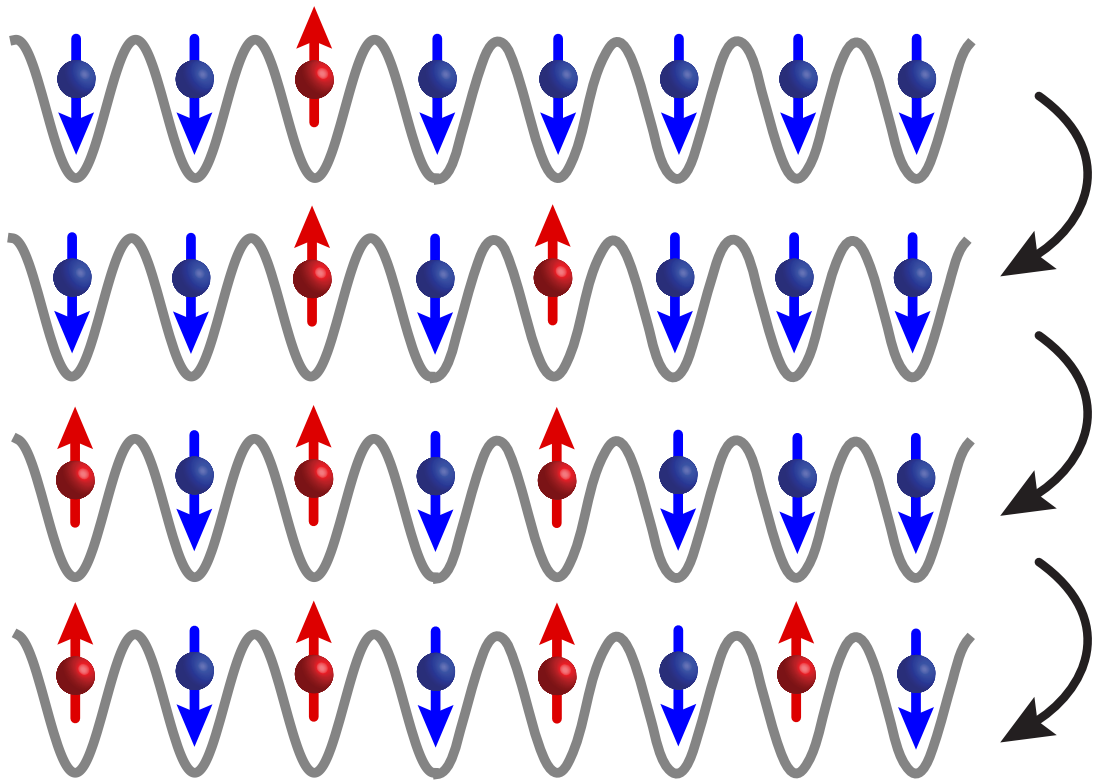
vibrations in molecules and crystals

We can understand this

Theorist's job: proposing and assessing quantum simulators

by making use of this

Simulating spin crystals with cold polar molecules

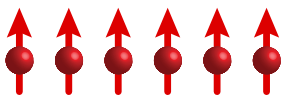


M. Lemeshko, R. Krems, H. Weimer, Phys. Rev. Lett. **109**, 035301 (2012)

What are spin crystals?

Linear chain of spins in transverse and longitudinal magnetic fields (Ising model)

$$H = h_z \sum_i S_z^{(i)} + h_x \sum_i S_x^{(i)} + V \sum_{j<i} \frac{S_z^{(i)} S_z^{(j)}}{|i-j|^3}$$



$i = 1 \;\; 2 \;\; 3 \;\; 4 \;\; 5 \;\; 6 \ldots$

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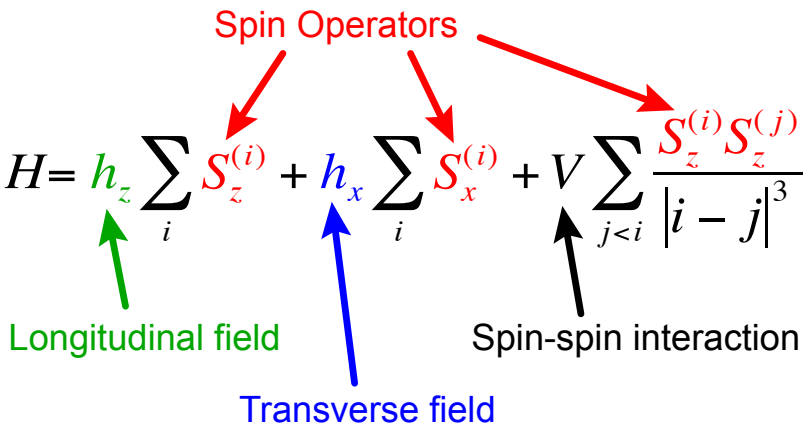

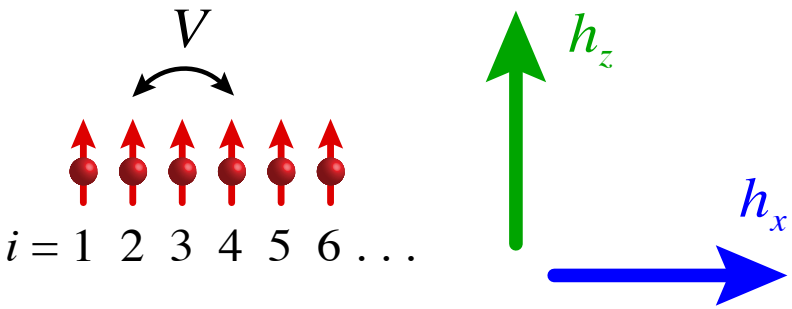

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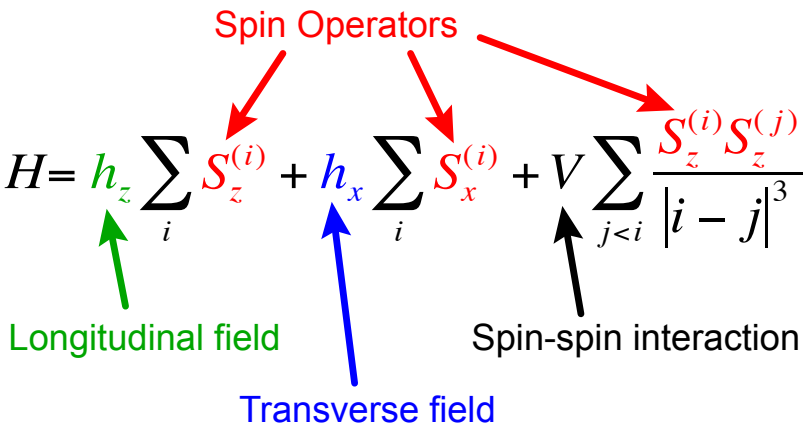
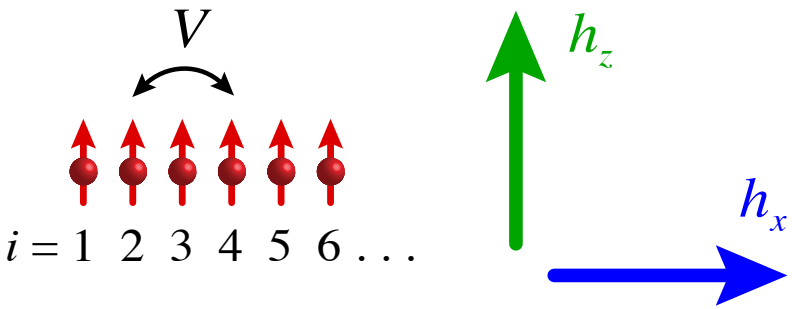
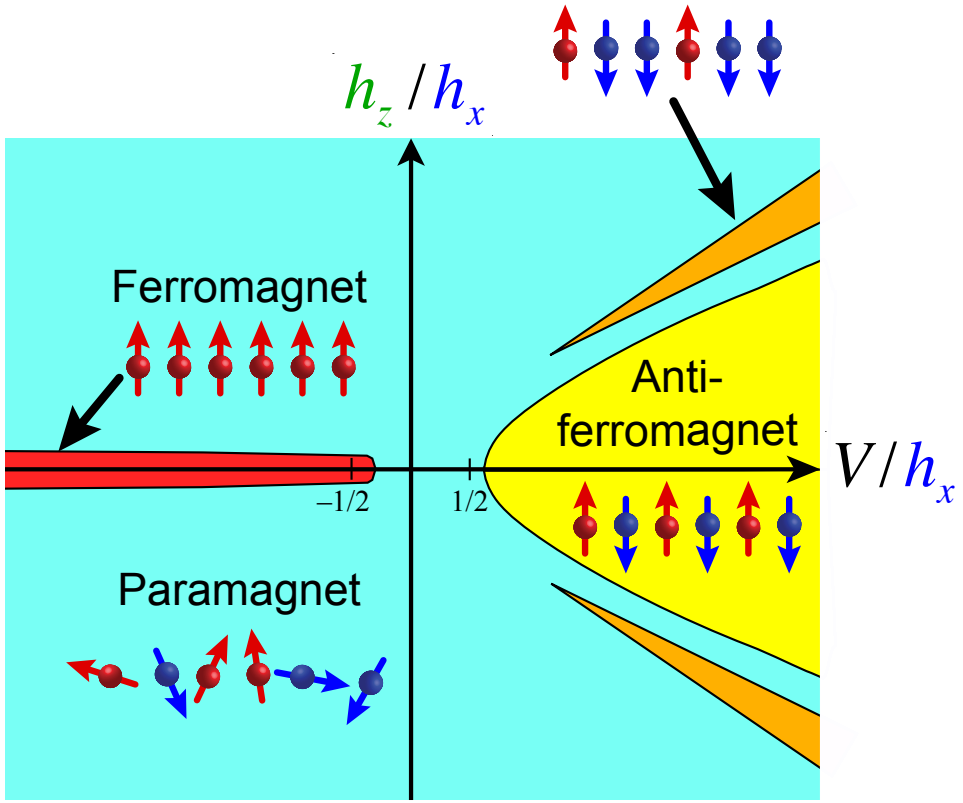
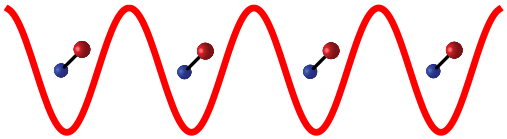






How to simulate spin crystals with cold molecules?

LiCs molecules on a 1D optical lattice



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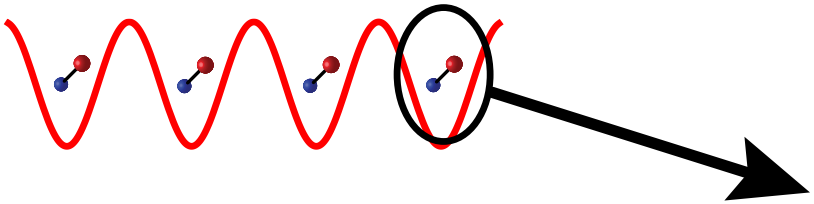
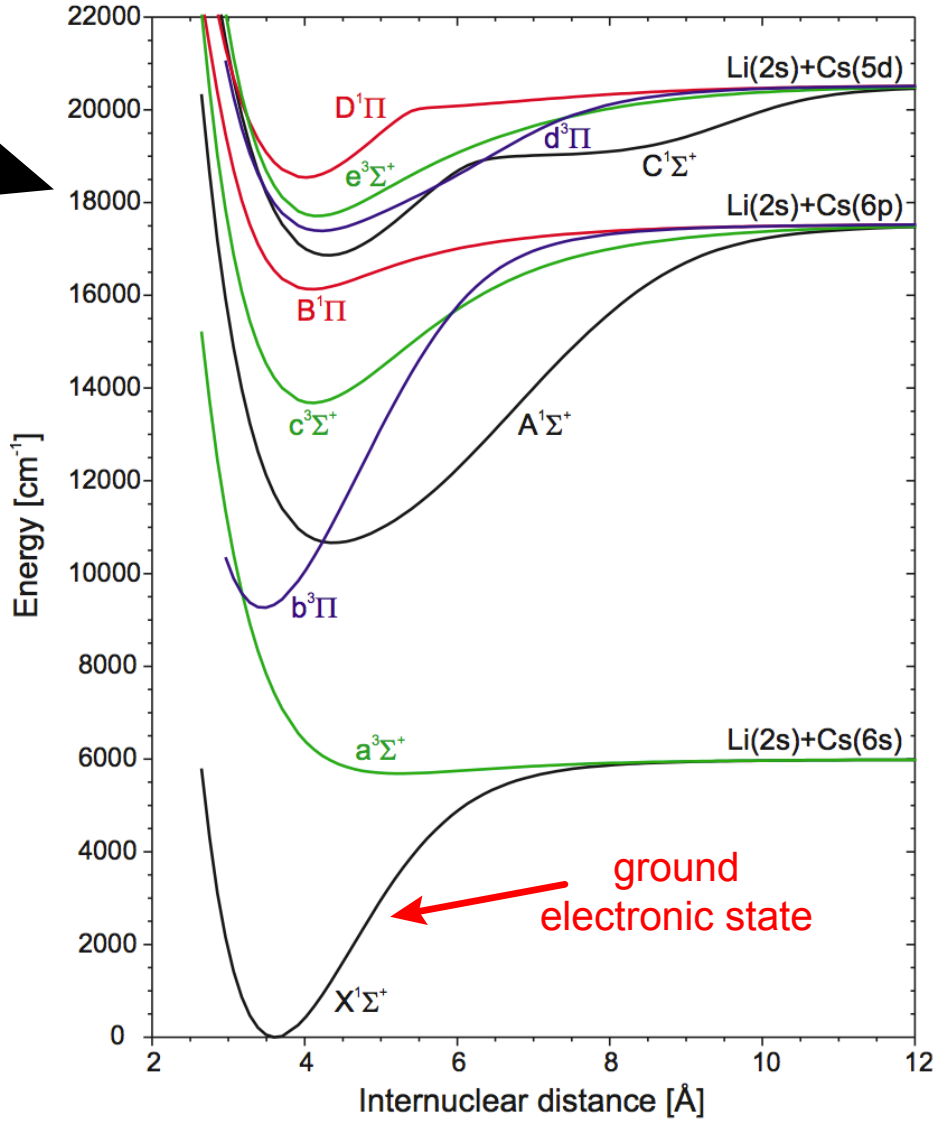


Staanum *et al.*, Phys. Rev. A **75**, 042513 (2007)



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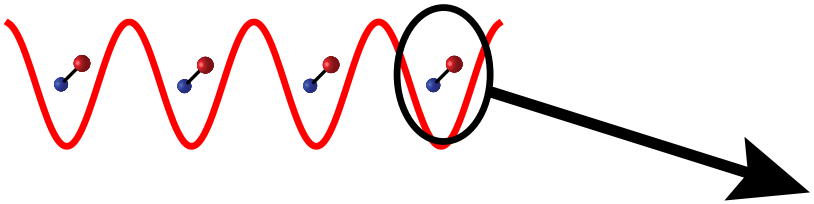

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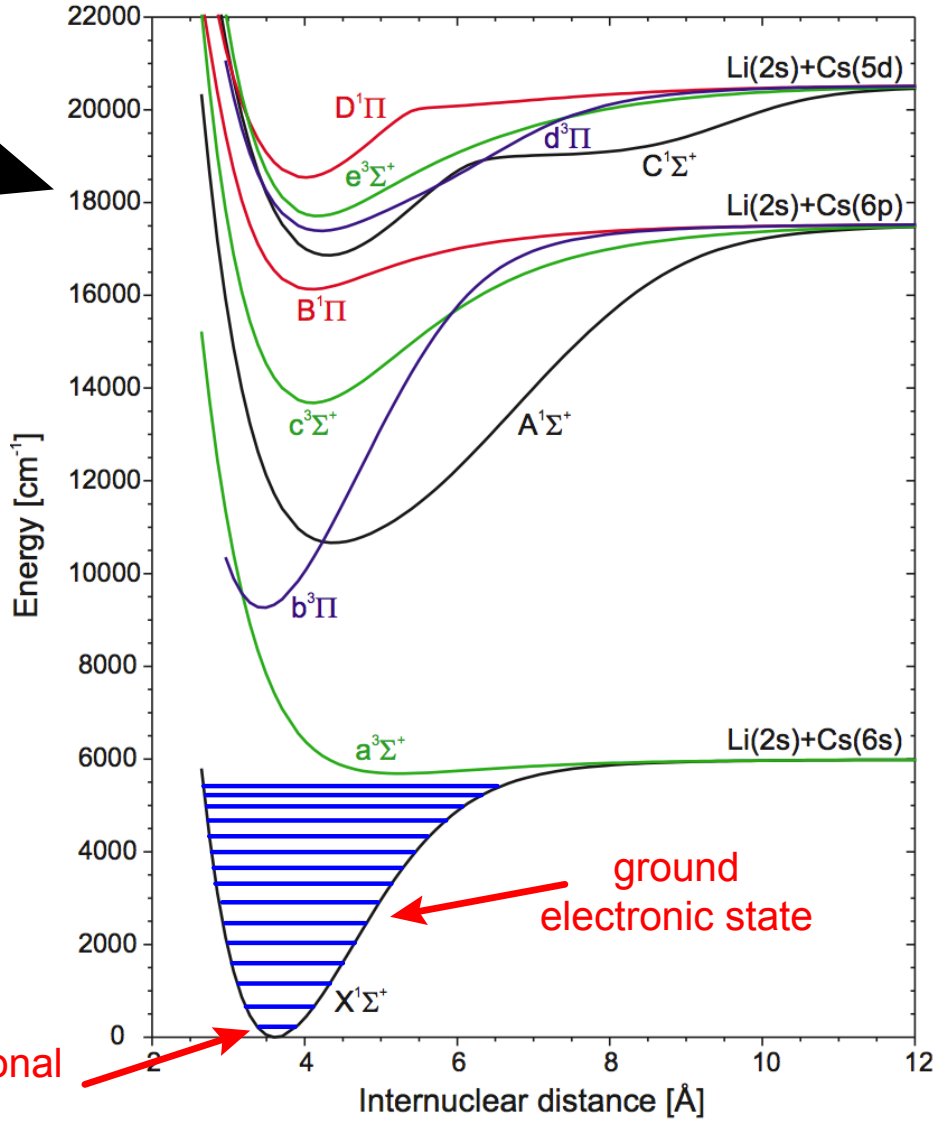

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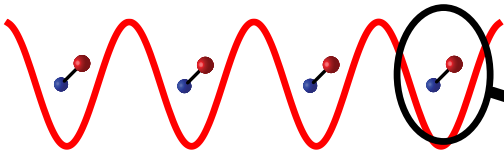


Lowest rotational states (J, M)

$J\,(M{=}0)$

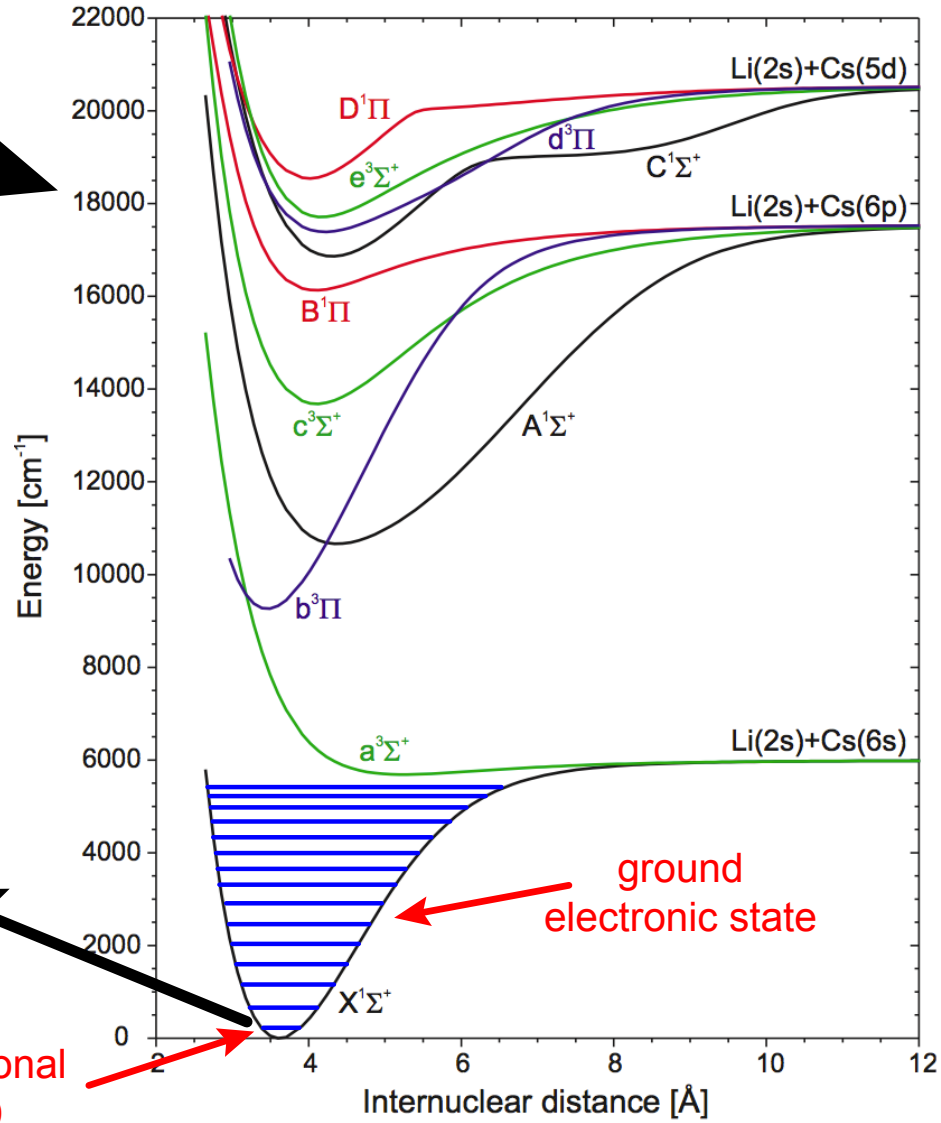
3 —

2 —

1 —

0 —

Staanum *et al.*, Phys. Rev. A **75**, 042513 (2007)



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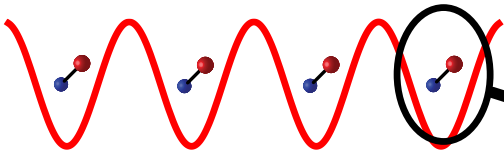

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$J\,(M{=}0)$

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strong field

2

1

0

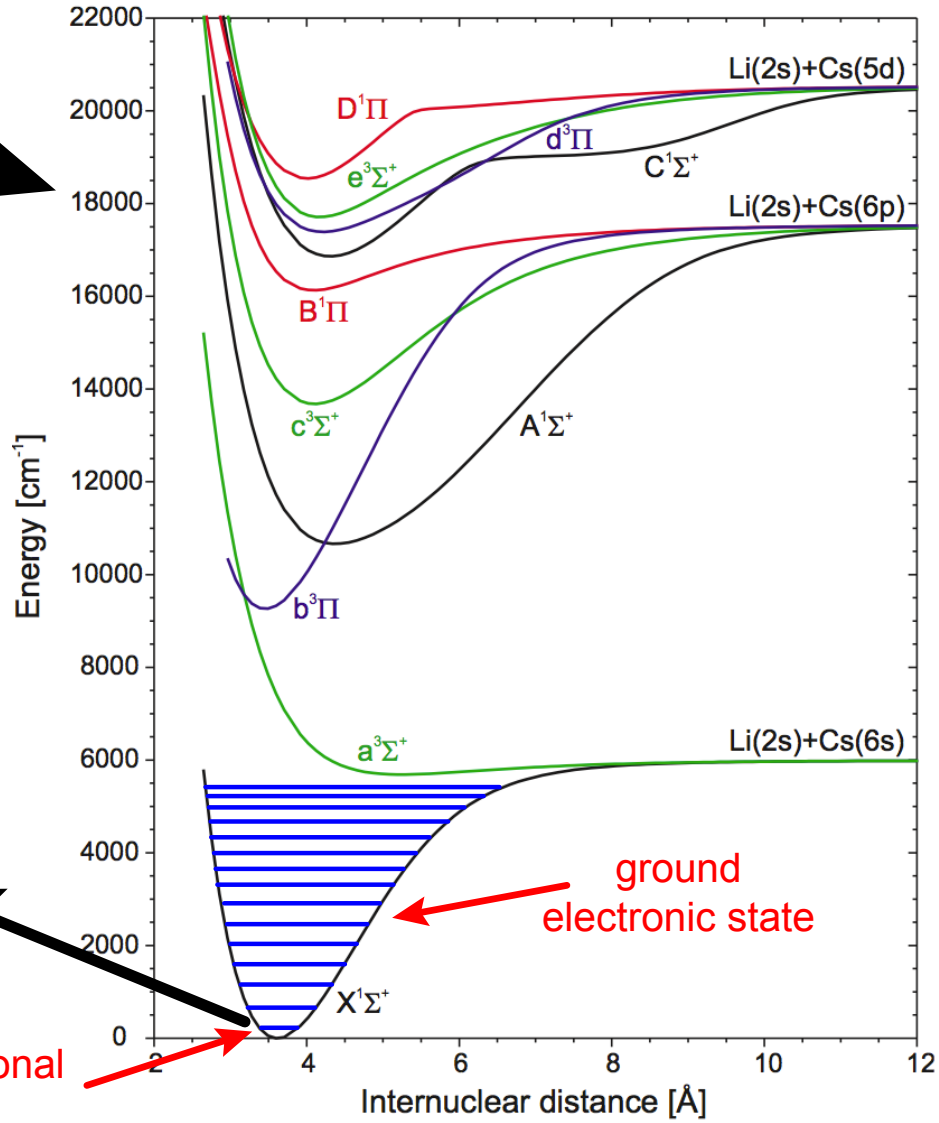
"dressed" states
dipole moment ≠ 0

$2 + 3$

1

0

Staanum *et al.*, Phys. Rev. A **75**, 042513 (2007)



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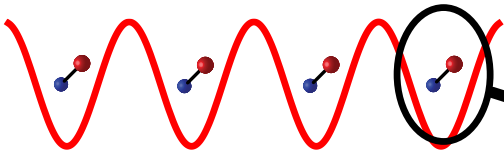

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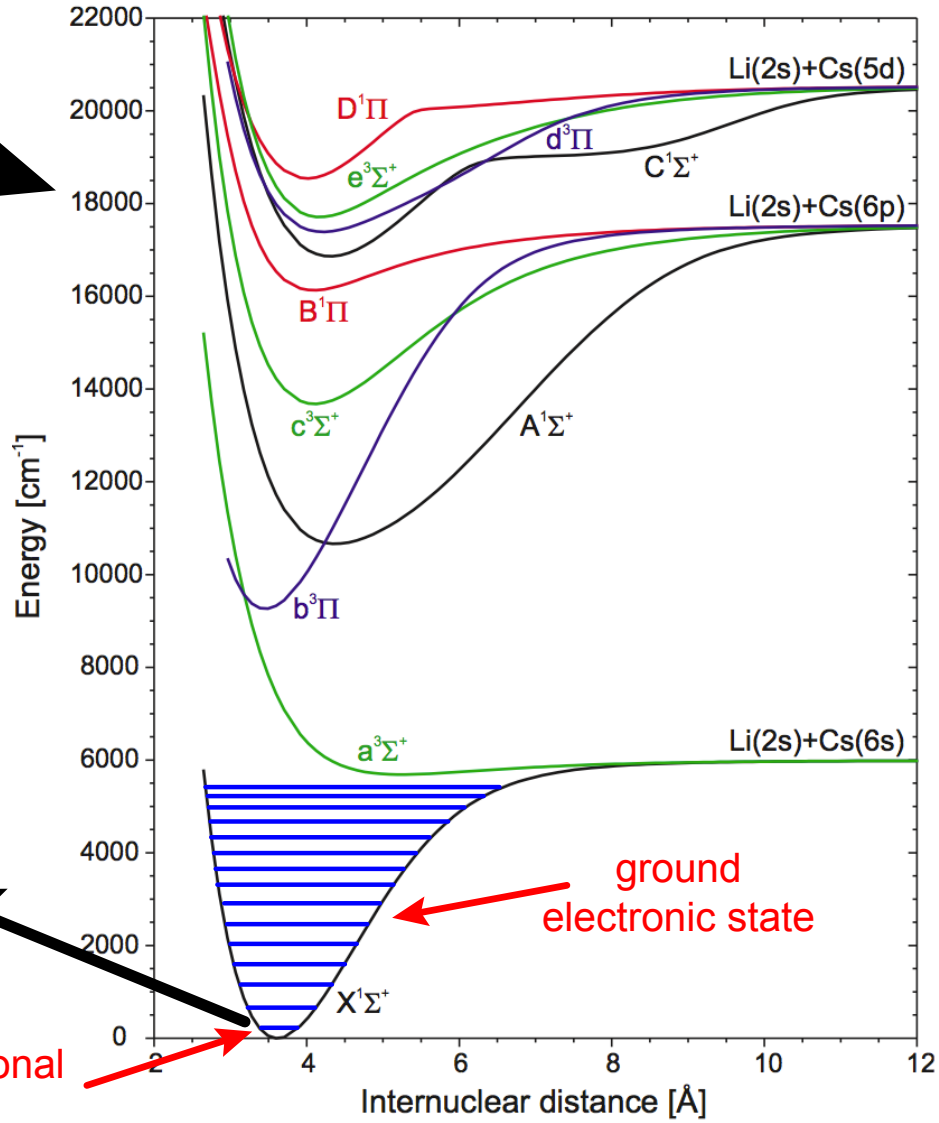
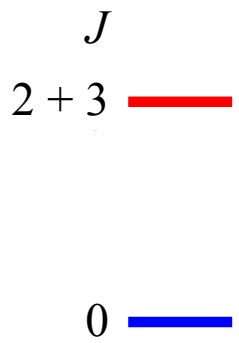


Effective two-level system

Excited state has a dipole moment
(interactions $V_{\text{dd}} \sim 1/r^3$)

Ground state has no dipole moment
(no interactions)



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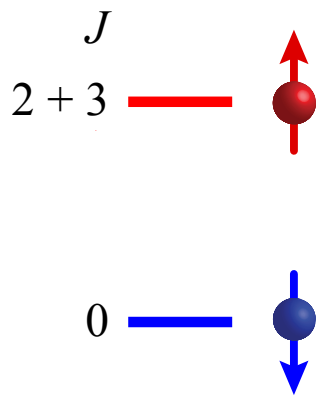
Effective spin system



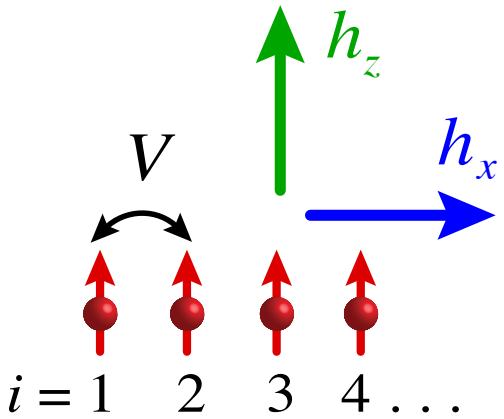
Spin crystal ⇒ molecular crystal

Transverse field

Longitudinal field

Spin-spin interaction

$$H = h_z \sum_i S_z^{(i)} + h_x \sum_i S_x^{(i)} + V \sum_{j<i} \frac{S_z^{(i)} S_z^{(j)}}{|i-j|^3}$$



Spin crystal ⇒ molecular crystal

Microwave intensity

~~Transverse field~~

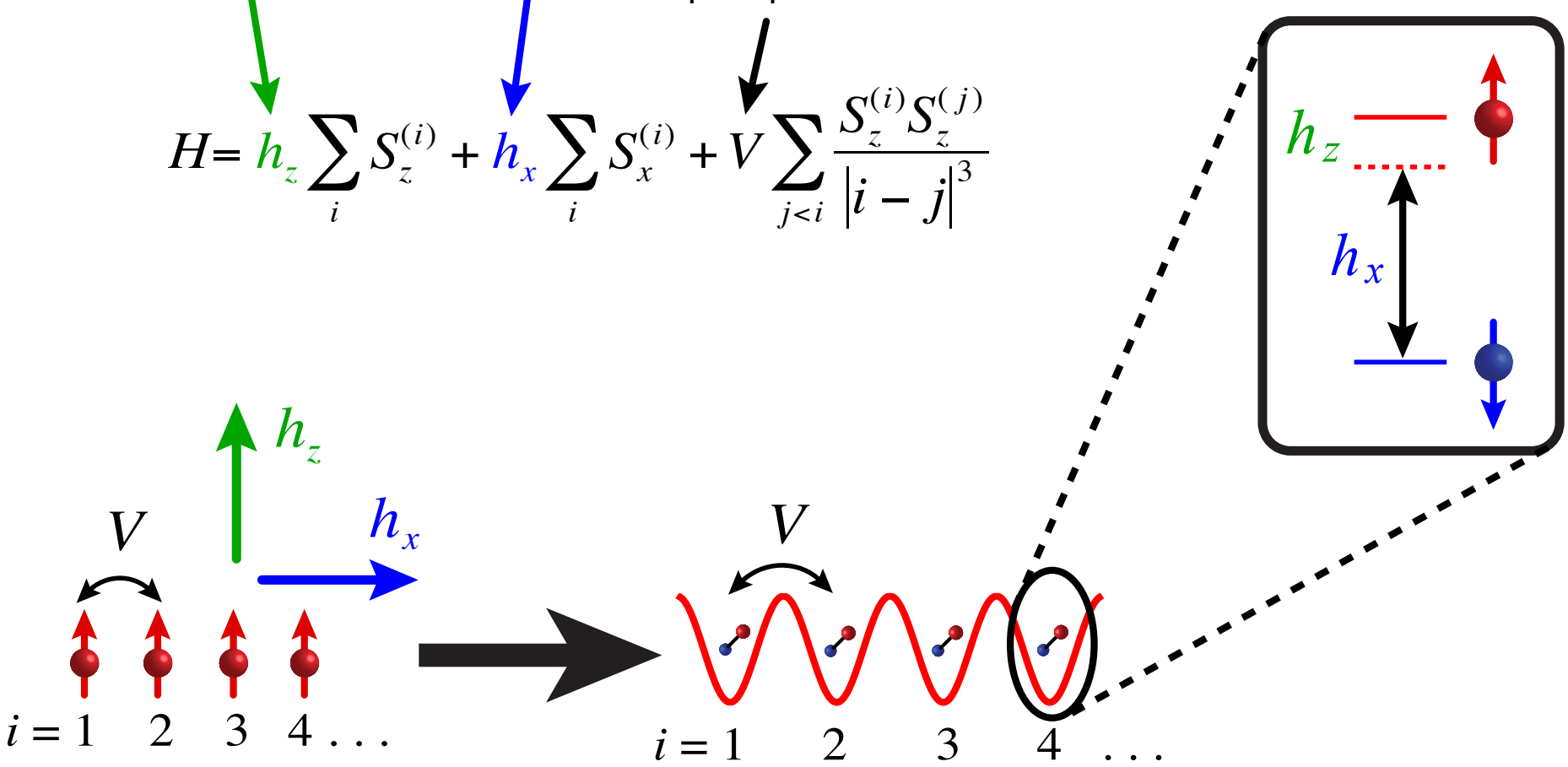
Microwave detuning

~~Longitudinal field~~

Dipole-dipole interaction

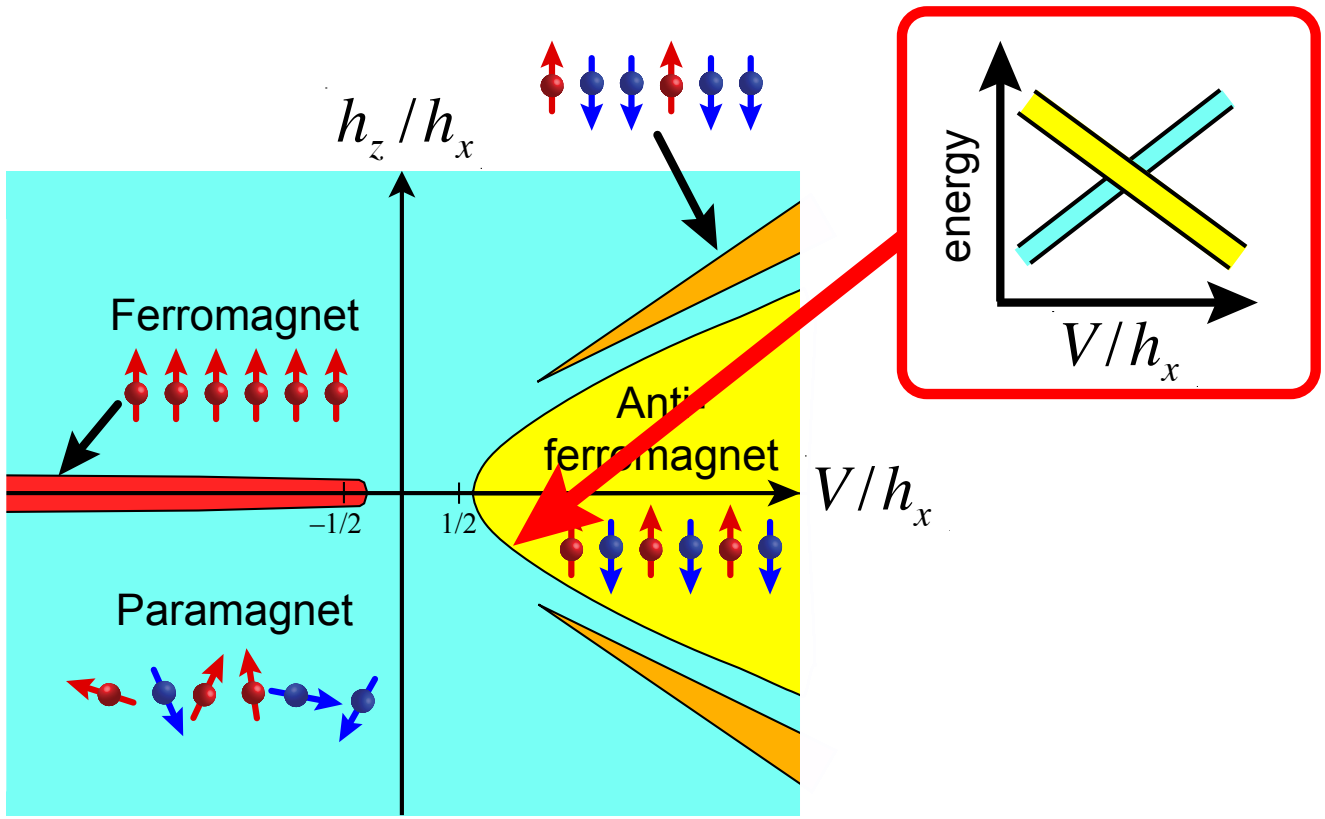
~~Spin spin interaction~~

$$H = h_z \sum_i S_z^{(i)} + h_x \sum_i S_x^{(i)} + V \sum_{j<i} \frac{S_z^{(i)} S_z^{(j)}}{|i-j|^3}$$



How to prepare phases of molecular crystals?

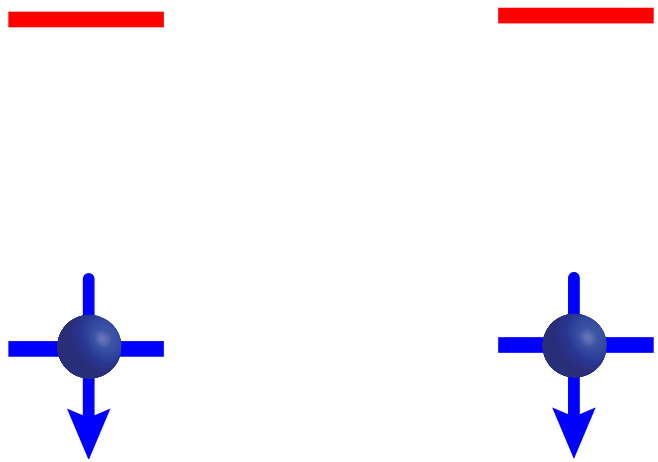
Adiabatic preparation is challenging: energy levels cross at phase transitions



Nonadiabatic preparation of molecular crystals is possible

Dipole blockade

Molecules close to each other cannot be excited at the same time:



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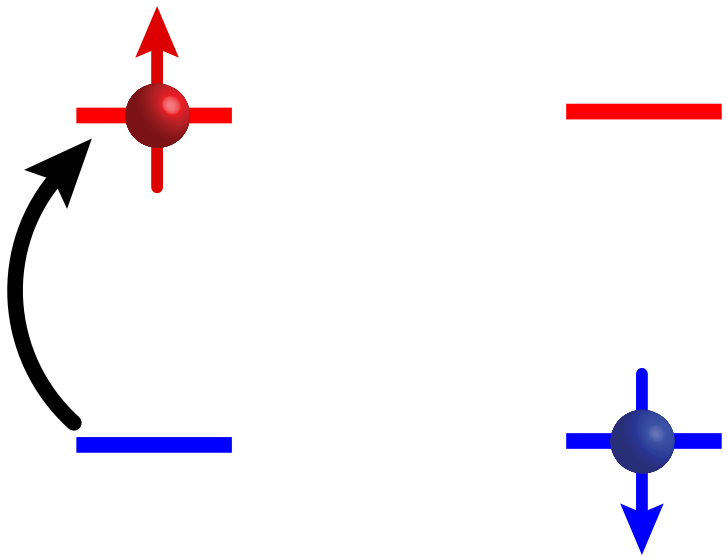

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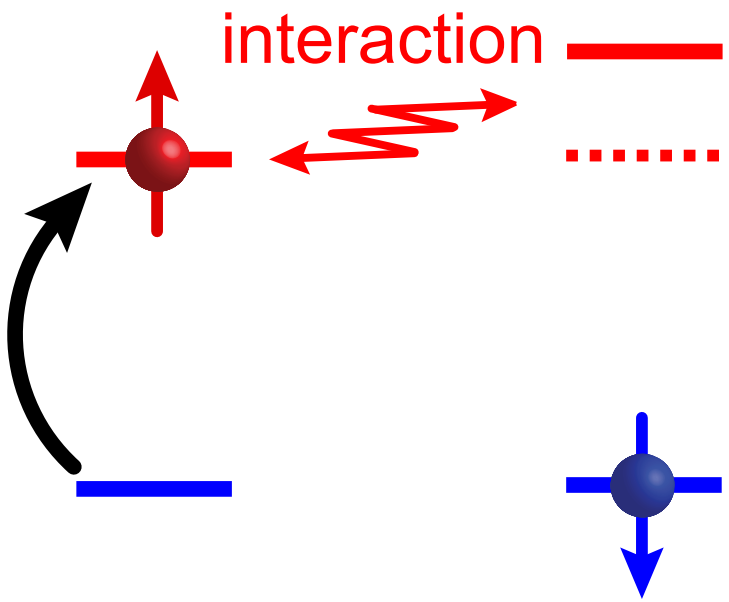
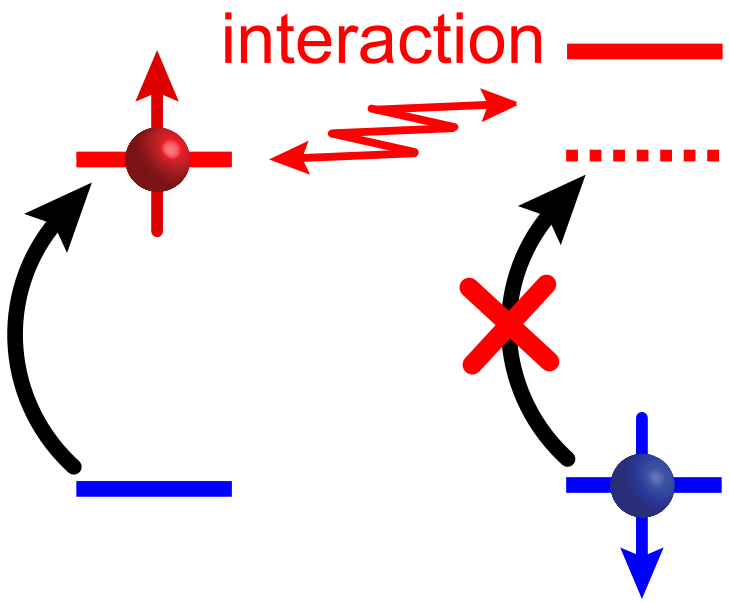


Dipole blockade

Molecules close to each other cannot be excited at the same time:

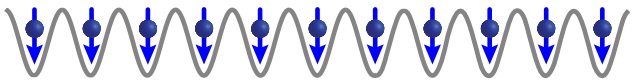


Distance-selective excitations!

Assembling molecular crystals out of “Lego-bricks”

No single-site addressing!

- Start: all molecules in the $\downarrow$ state



Assembling molecular crystals out of “Lego-bricks”

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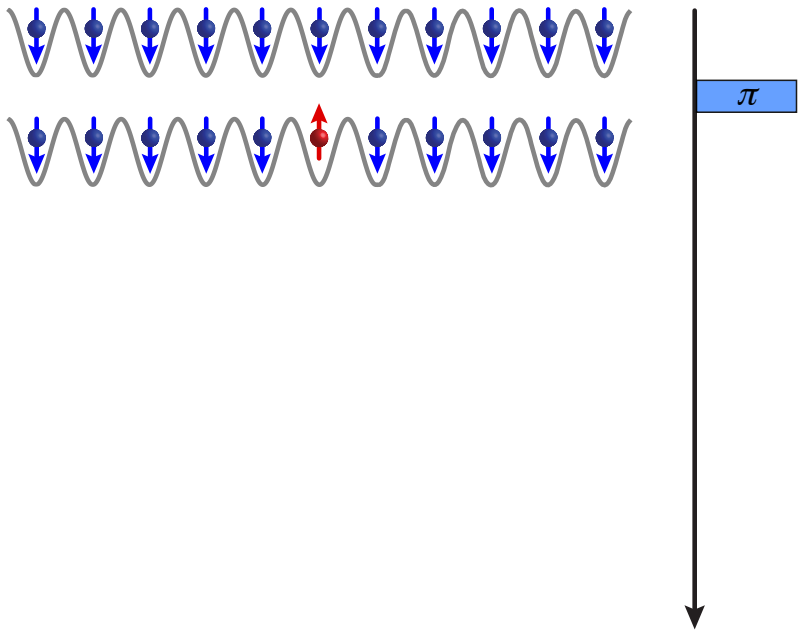
- Start: all molecules in the $\downarrow$ state
- Nucleate the phase: a far detuned pulse
  (flips one molecule **somewhere** in the lattice)



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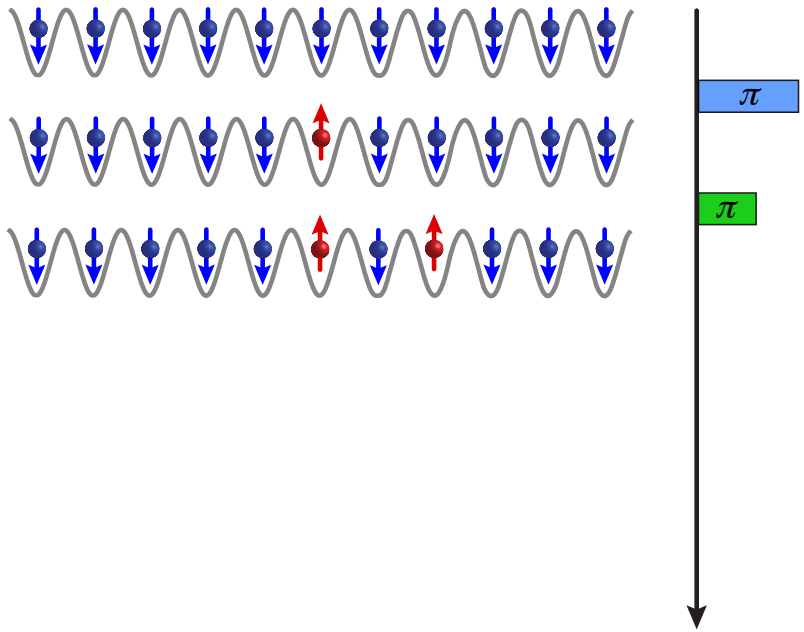

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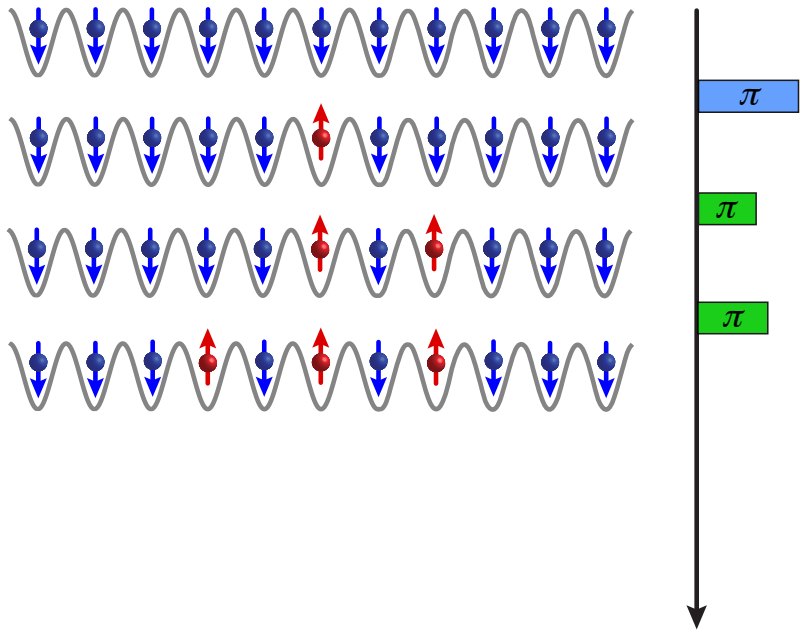

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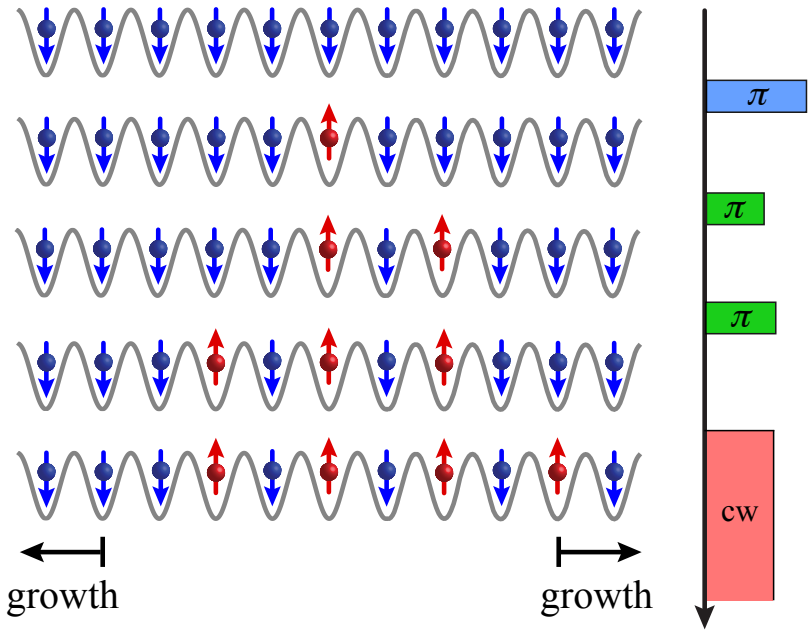
- Continuous microwave field:
  propagating the phase boundary



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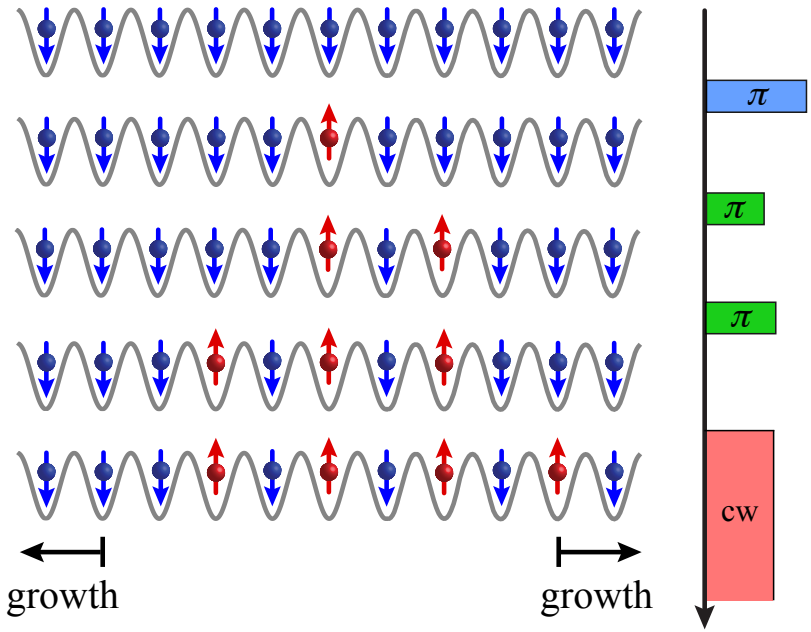
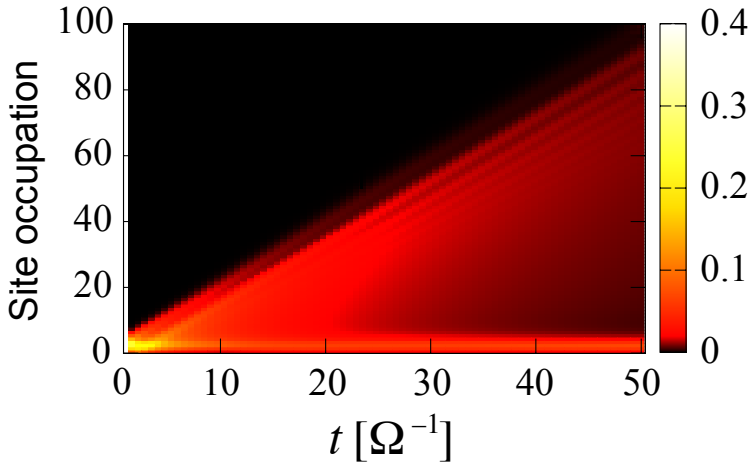


Size grows linearly in time!

In experiment (LiCs molecules) it’s possible:

- $\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow$ phase consisting of 1700 molecules
- $\uparrow\downarrow\downarrow\uparrow\downarrow\downarrow$ phase consisting of 1000 molecules

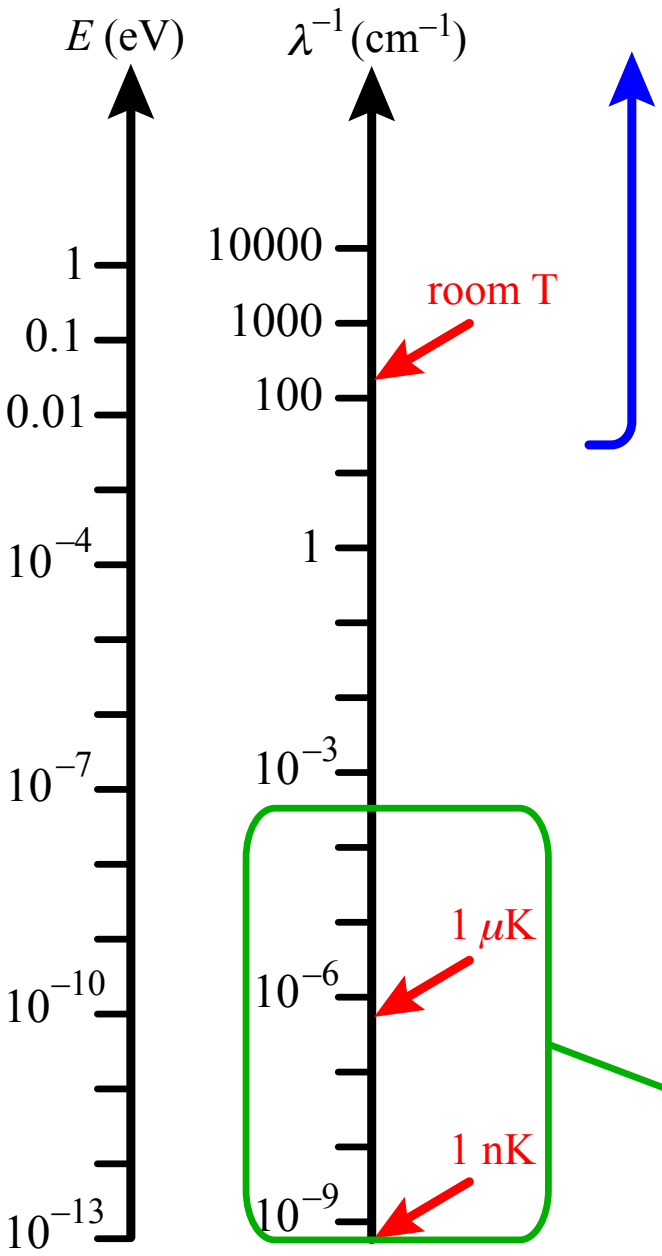


Summary: quantum simulation of spin crystals

- One can simulate spin-crystals with cold polar molecules
- Long lifetimes of rotational states allow to prepare large crystals nonadiabatically ($\gtrsim 1000$ molecules!)
- Experimental proposal: LiCs molecules on a 266 nm – spaced optical lattice
- Another possibility: microwave transitions between atomic Rydberg states (Charles Adams)

M. Lemeshko, R. V. Krems, H. Weimer, Phys. Rev. Lett. **109**, 035301 (2012)

Can we study open systems as well?

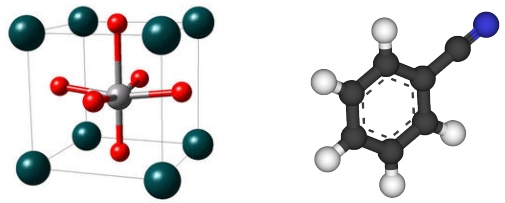


electrons in crystals

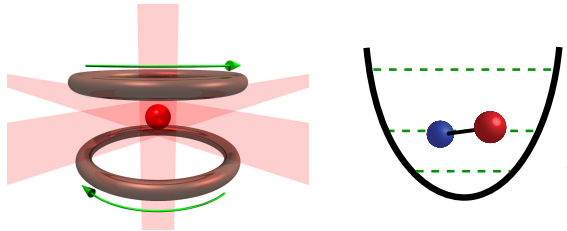
chemical bonds

vibrations in molecules and crystals

a lot of physics and chemistry happens here



slowing and trapping molecules



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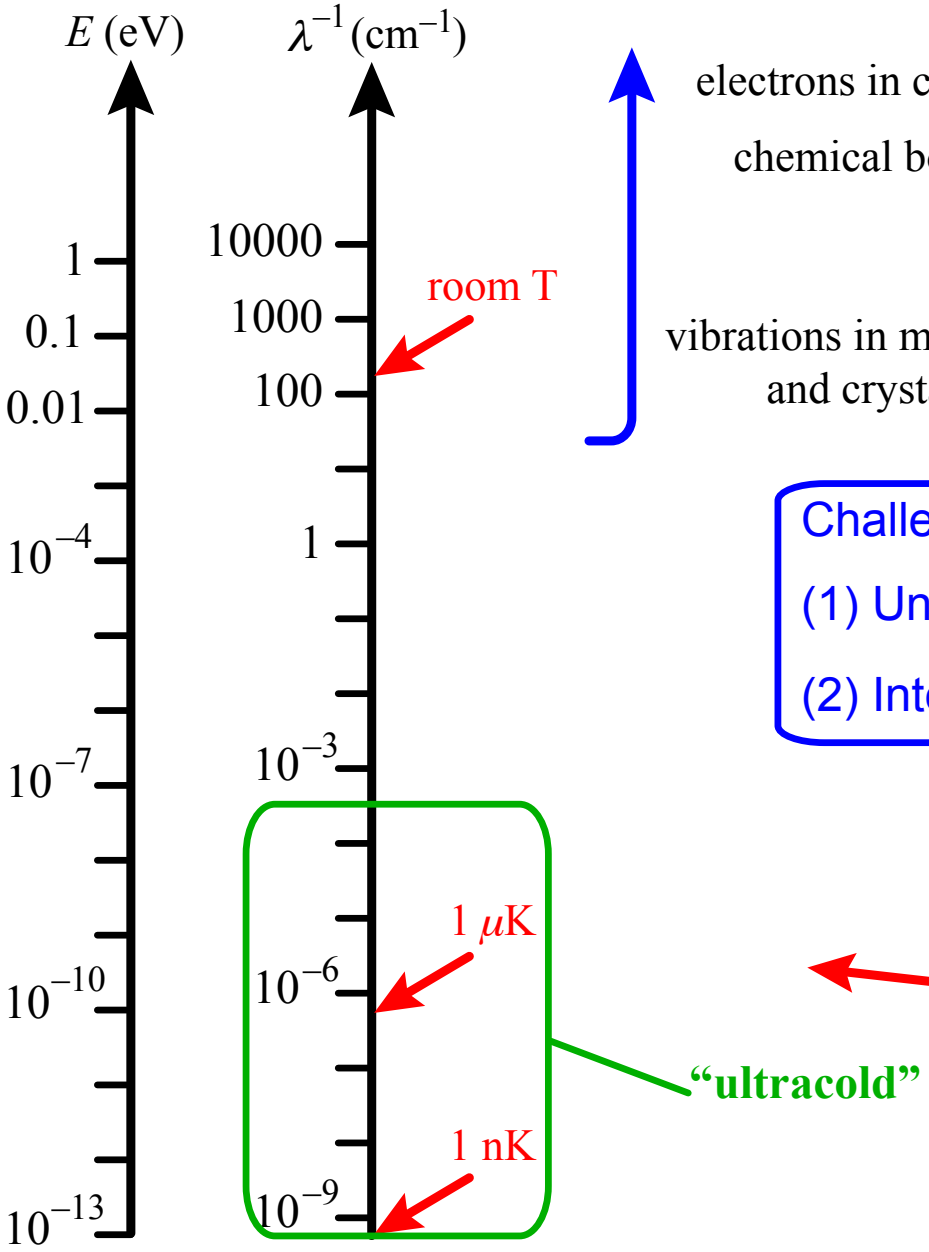


electrons in crystals

chemical bonds

vibrations in molecules and crystals

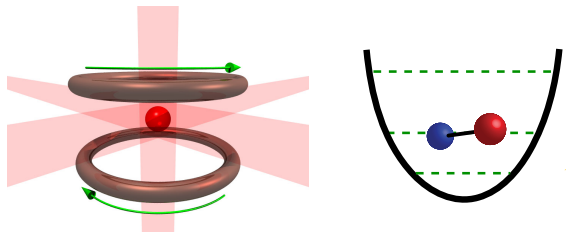
Most of these systems are open

Challenges:

(1) Unknown environments

(2) Interactions system-environment too complex

slowing and trapping molecules

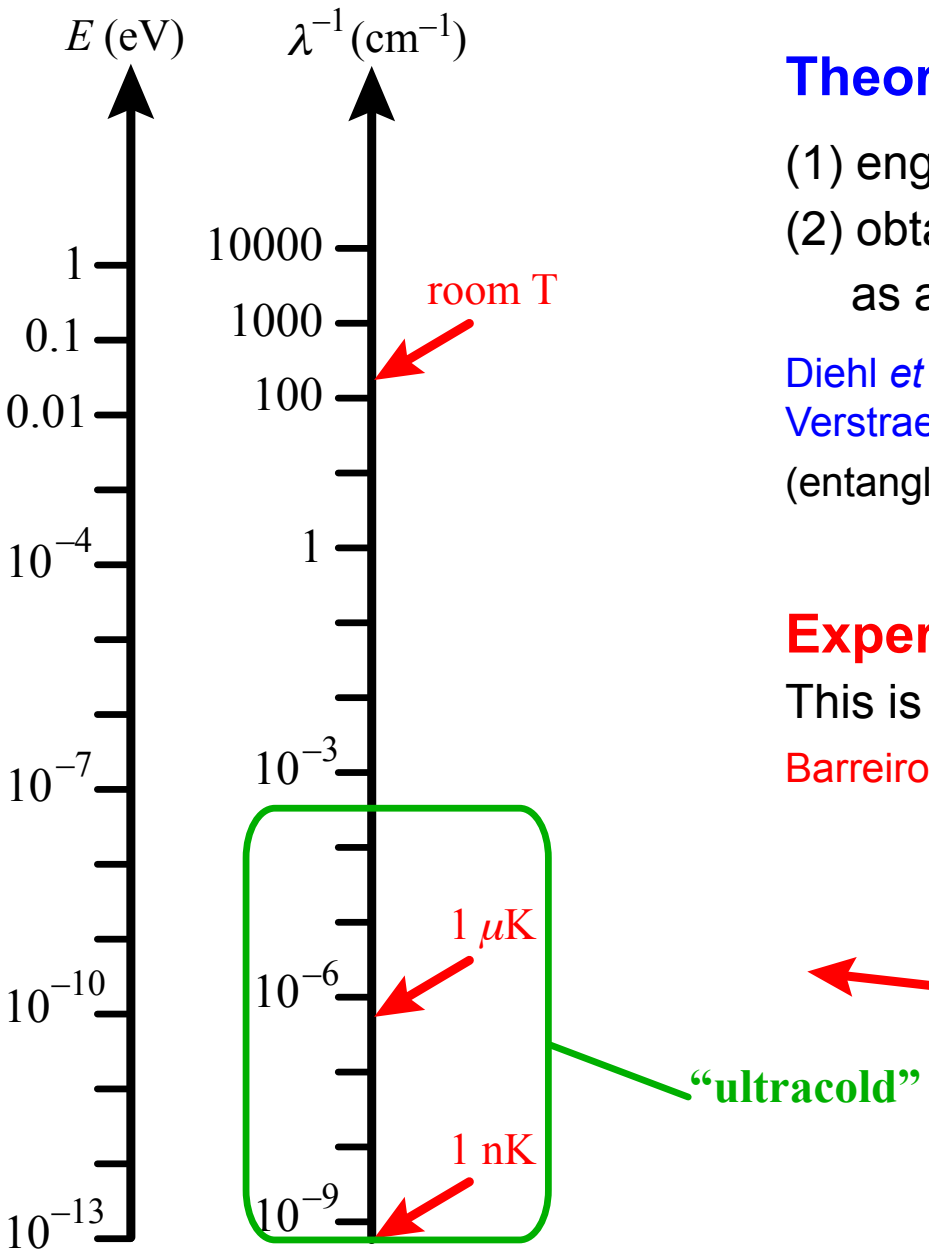


Dissipation leads to decoherence!

Usual approach in control of quantum processes:
decouple the system from the environment

Alternative approach:
can we use dissipation to achieve more control?

Using dissipation to prepare quantum states



Theoretical proposal:

(1) engineer the system and the environment

(2) obtain the required quantum state as a steady state of dynamics

Diehl *et al.*, Nature Phys. 4, 878 (2008);
Verstraete *et al.* Nature Phys. 5, 633 (2009)

(entangled states; ground states of spin Hamiltonians, . . .)

Experimental realization:

This is possible in controllable systems!

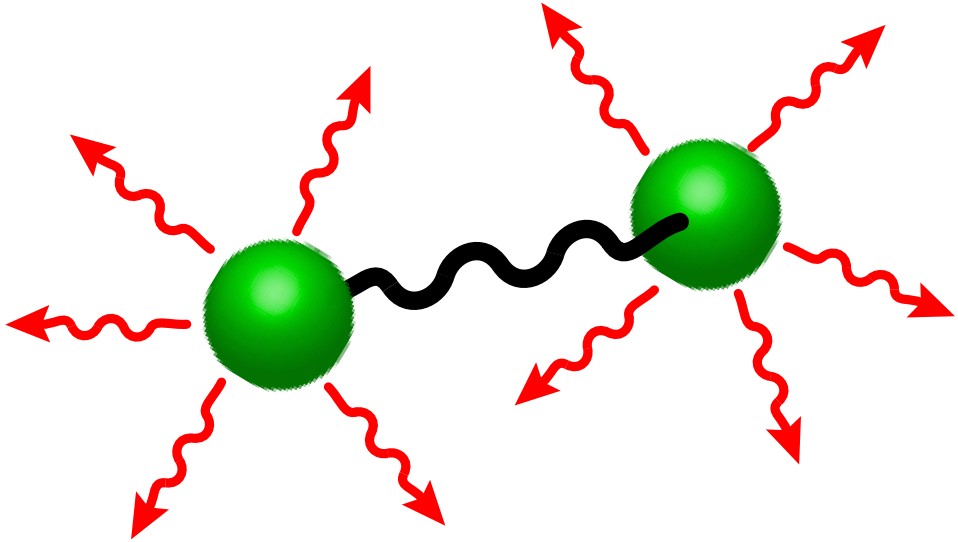
Barreiro *et al.*, Nature **470**, 486 (2011) (cold trapped ions)

Controllable systems

Dissipative preparation of quantum states:
new, rapidly developing field in physics

Can we use engineered dissipation to control
bonds between atoms and molecules?

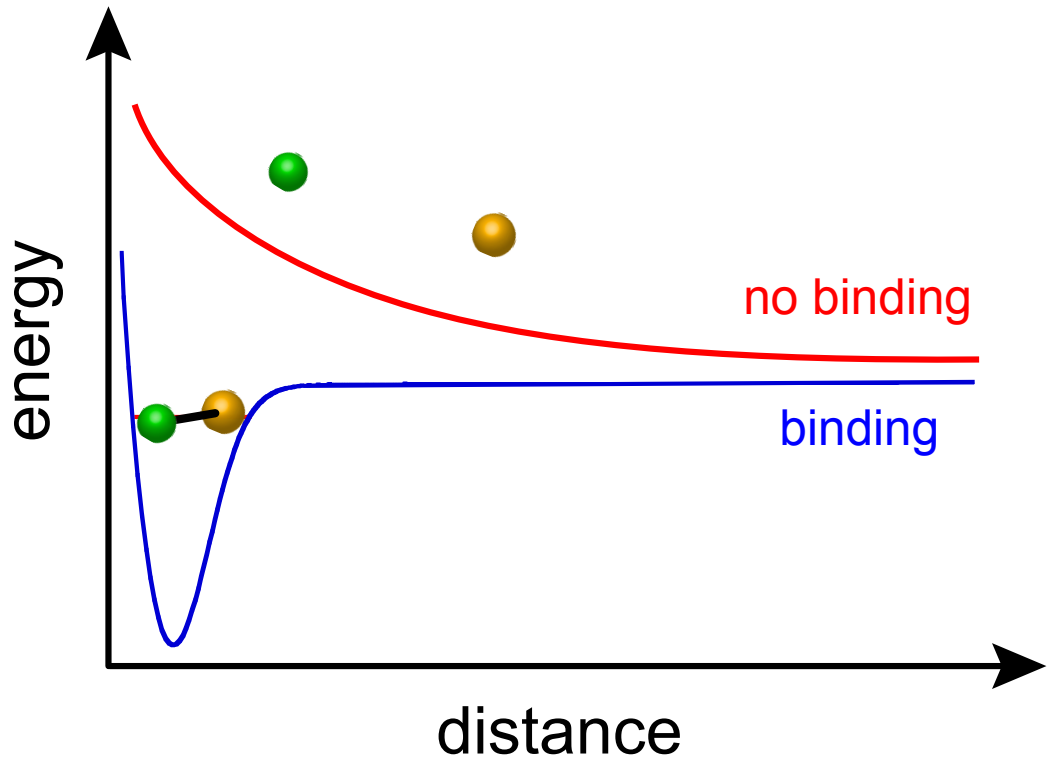
“Binding” of atoms by engineered dissipation



M. Lemeshko, H. Weimer, arXiv:1211.4035 (2012)

Binding of atoms and molecules

Conservative forces that result in a potential with a minimum at the equilibrium distance

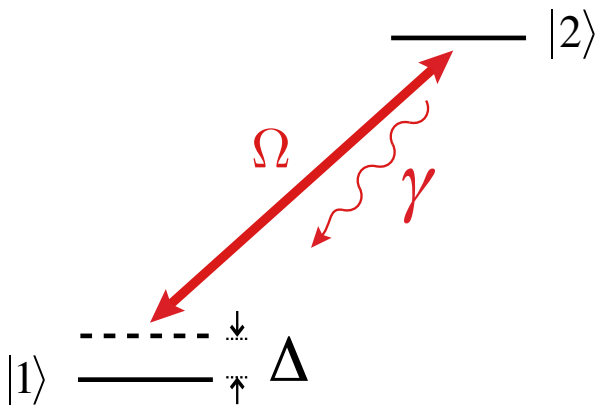


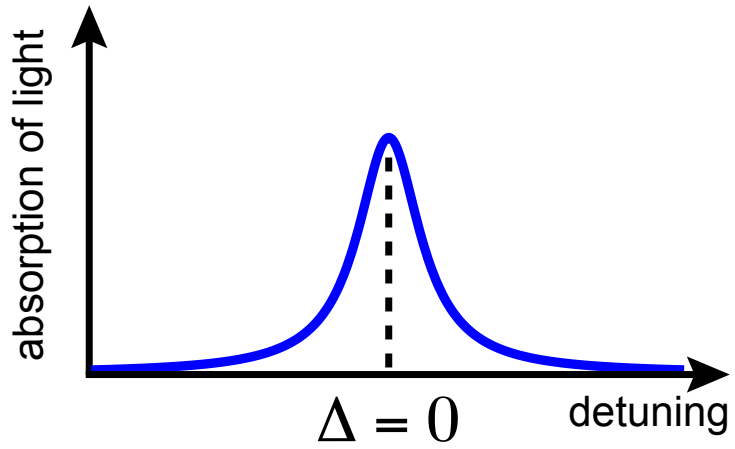
Can repulsive interactions plus dissipation keep atoms or molecules together?

A single atom: dark states

Open quantum system: atoms interacting with laser light

Dissipation: spontaneous emission of photons





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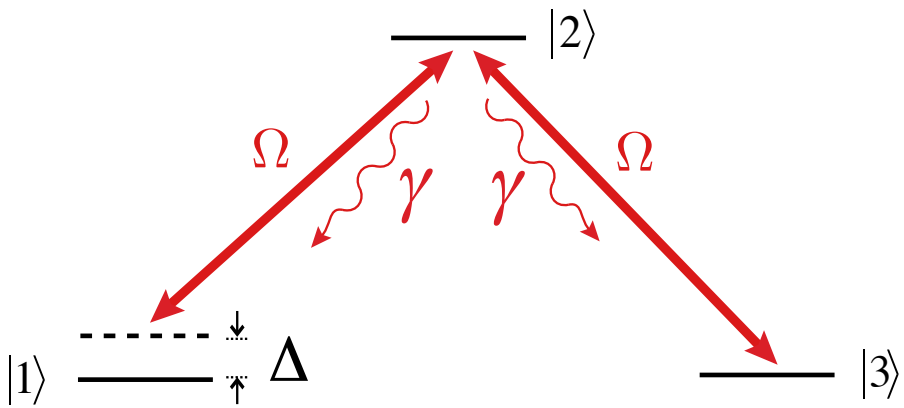
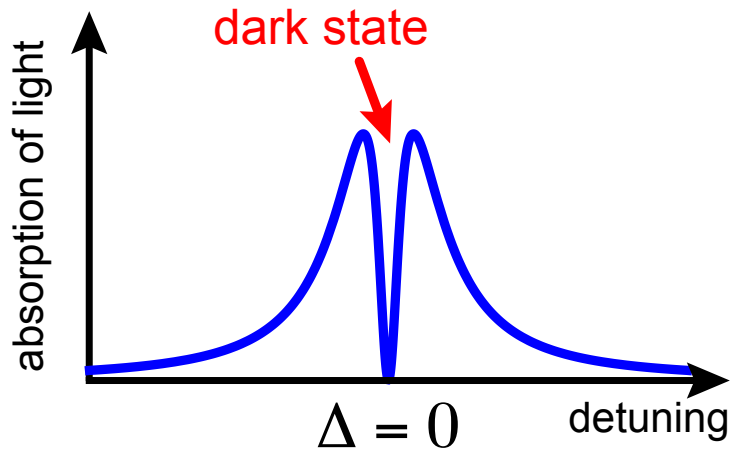
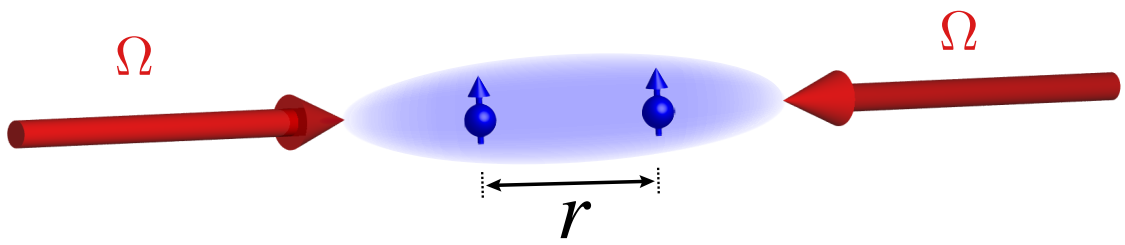


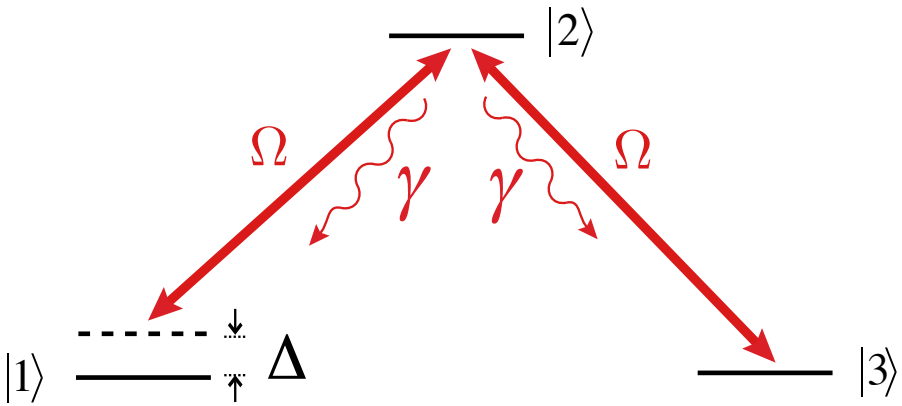


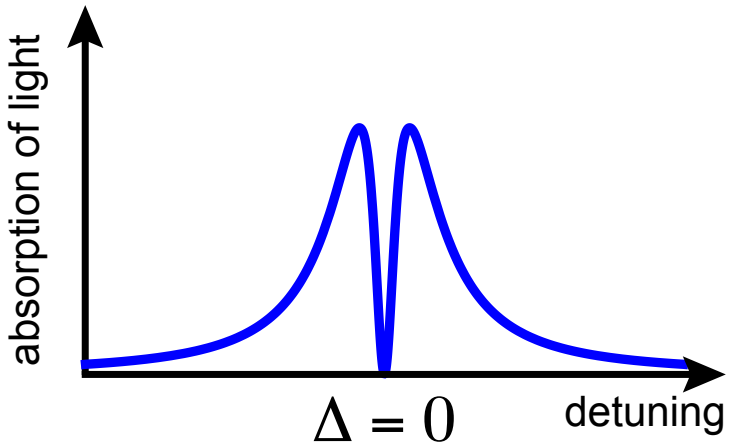
Interference leads to Coherent Population Trapping: $|\text{dark state}\rangle = |1\rangle - |3\rangle$

If $\Delta = 0$ atoms do not interact with lasers!

Two atoms in a 1D trap: distance-dependent dark states







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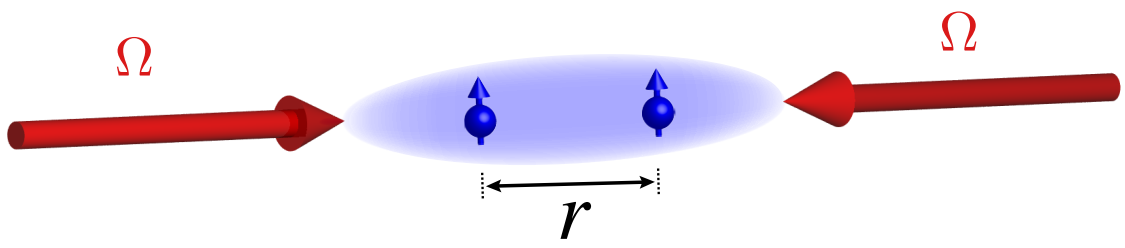

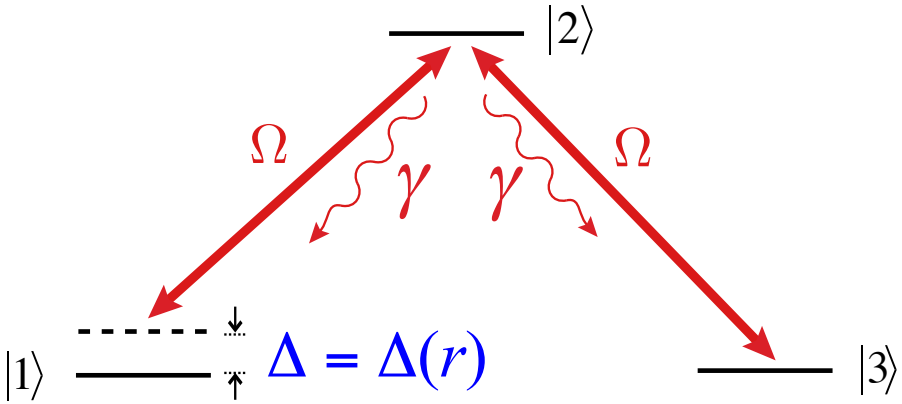

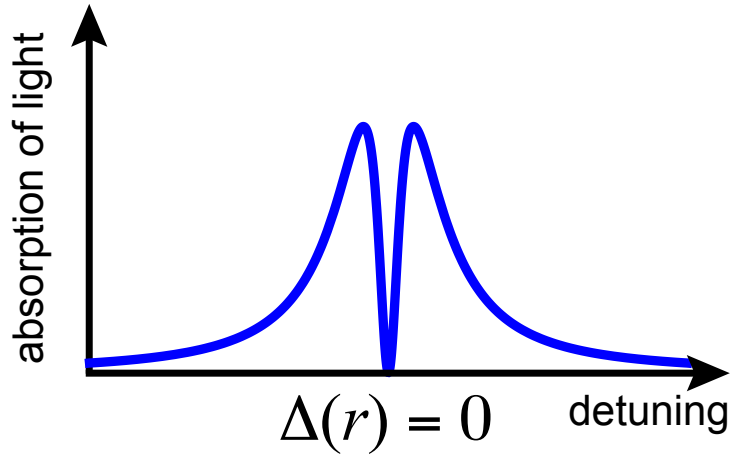

1. We provide state $|1\rangle$ with a dipole moment, atoms in $|1\rangle$ interact: $\Delta = \Delta(r)$

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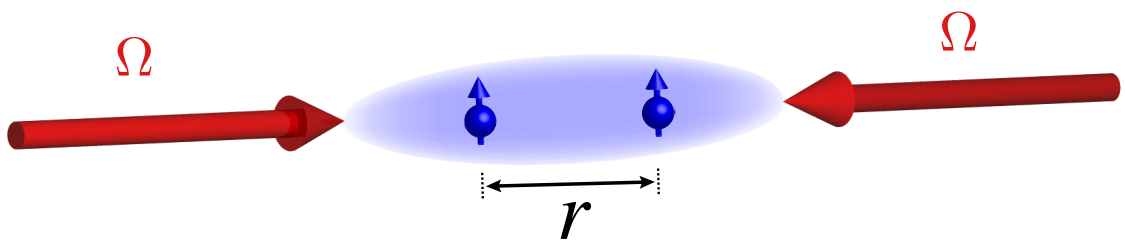
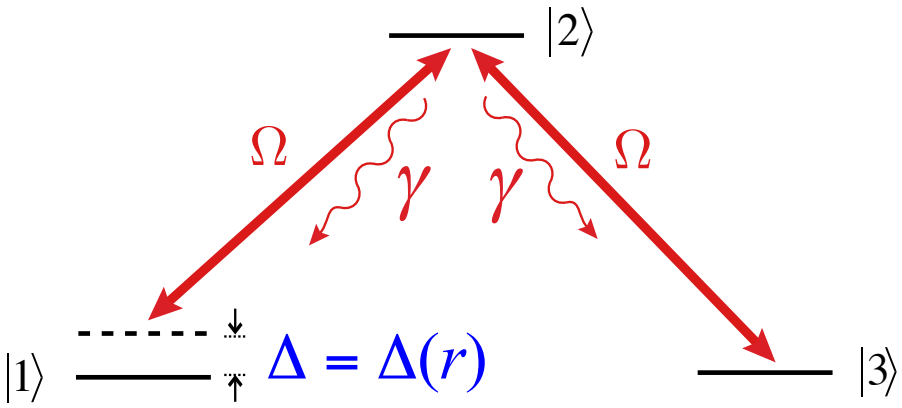
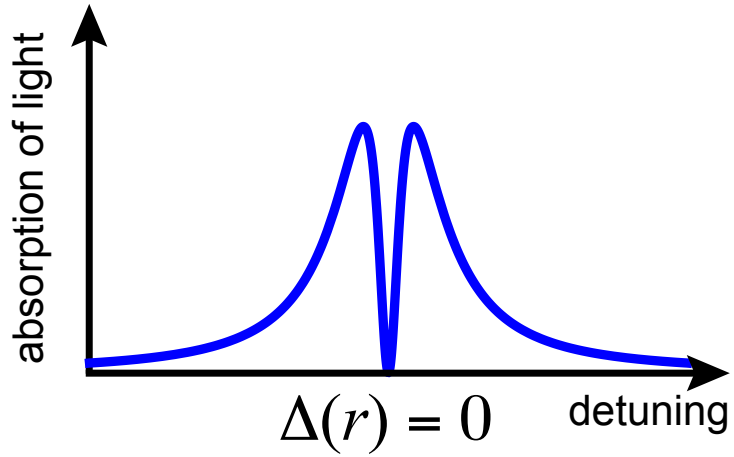
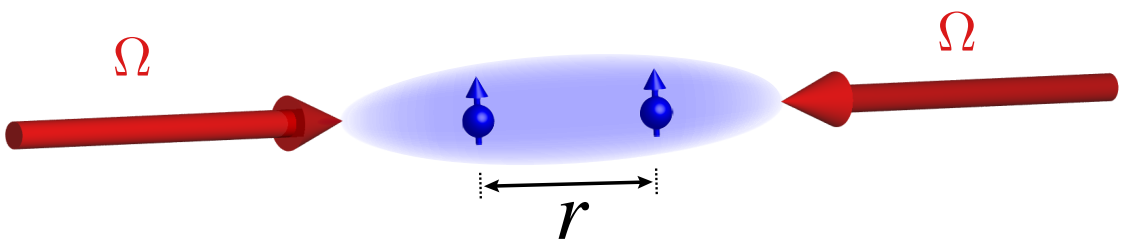


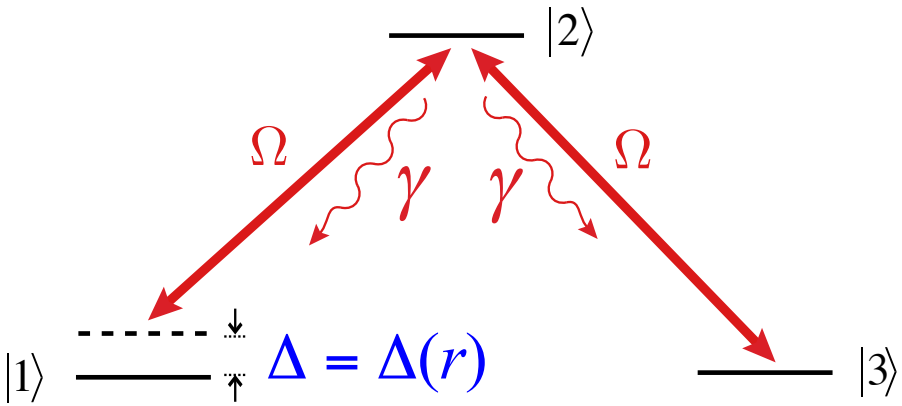


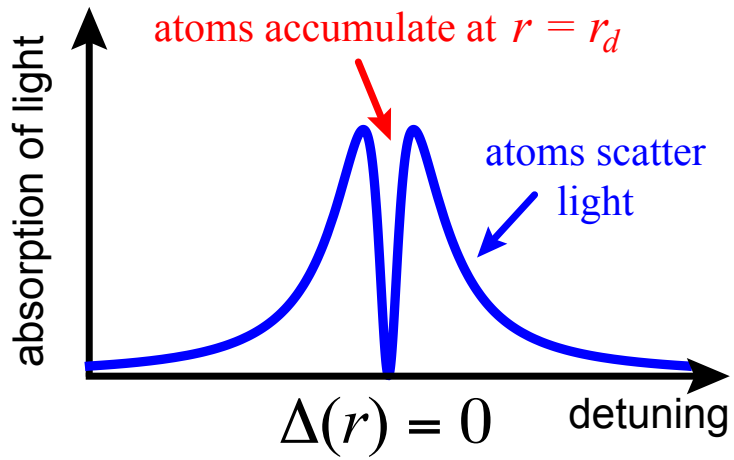


1. We provide state $|1\rangle$ with a dipole moment, atoms in $|1\rangle$ interact: $\Delta = \Delta(r)$
2. We choose the "dark distance" r_d by tuning laser frequencies ($\Delta(r_d) = 0$)

Two atoms in a 1D trap: distance-dependent dark states







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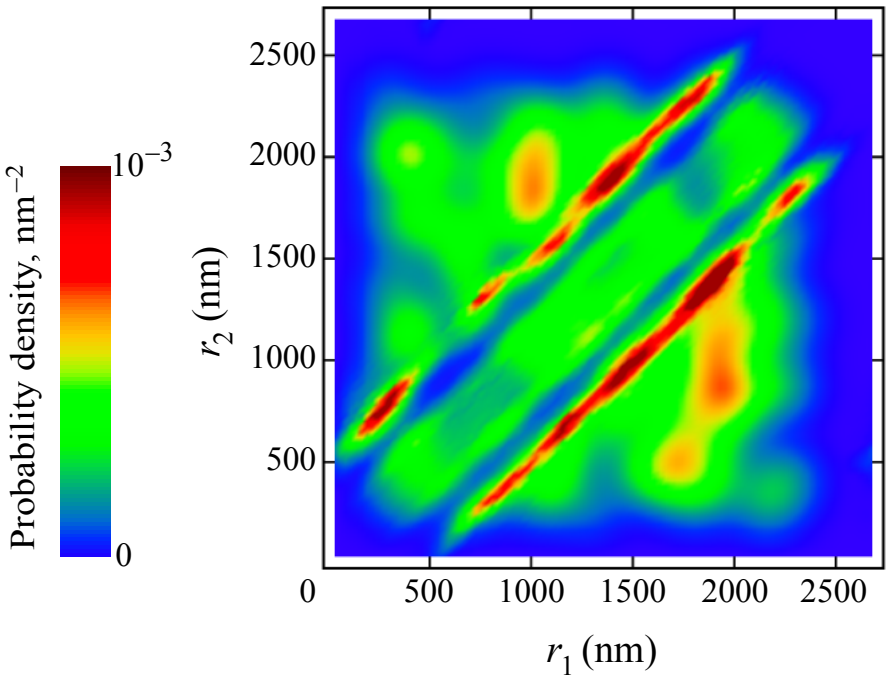
2. We choose the "dark distance" r_d by tuning laser frequencies ($\Delta(r_d) = 0$)
3. Population is accumulated at r_d – "dissipative bond" is forming

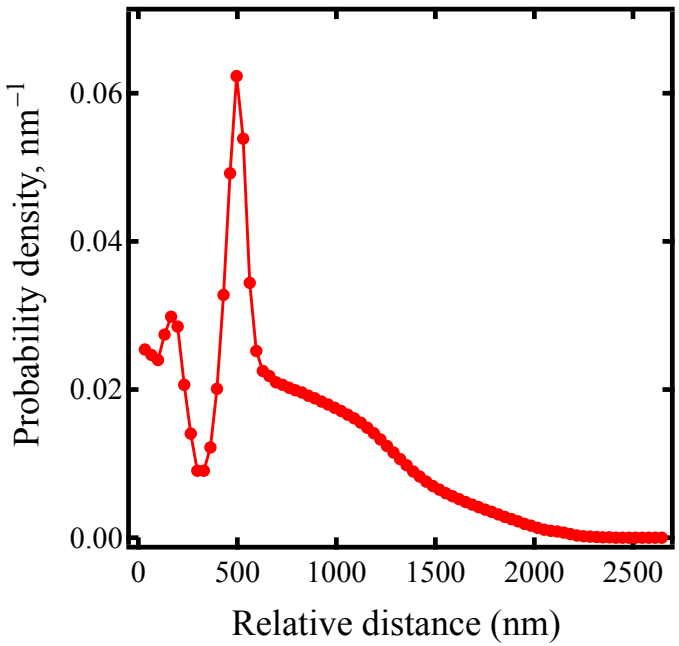
Example: Rydberg-dressed Cs atoms

Master equation is solved using the Stochastic Wavefunction Monte-Carlo Method

N^2-dimensional density matrix $\Rightarrow$ N-dimensional wavefunctions

Atoms bound at $r_d = 500$ nm after ~ 10 μs:

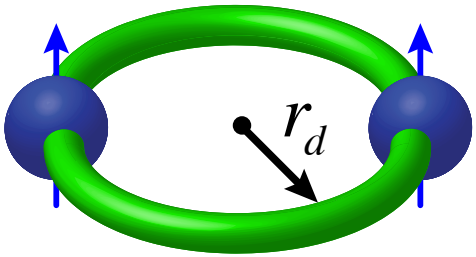




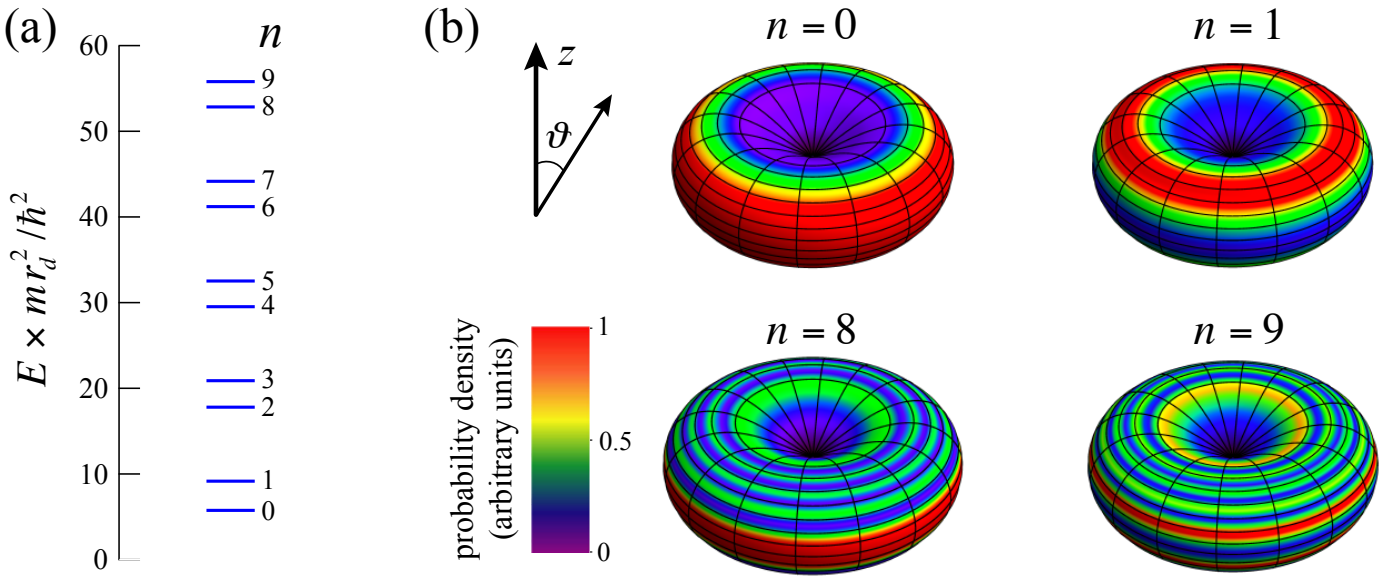
Lifetimes of ~ 0.1 s can be achieved. Similar results for ultracold SrF molecules

What happens in two and three dimensions?

2D: confinement to a ring



3D: confinement to a surface $r^3 = r_d^3(1 - 3\cos^2\vartheta)$; J_z – good quantum number



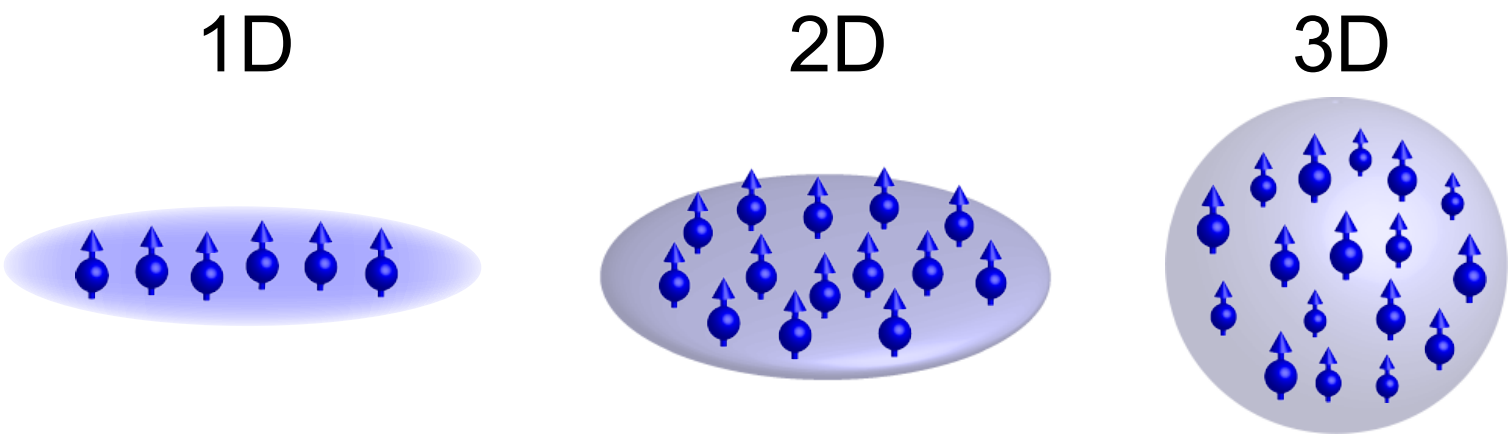
2D and 3D rotation can be studied spectroscopically!

Summary: “binding” by engineered dissipation

- Atoms or molecules can be “bound” using a combination of the repulsive dipole-dipole interaction and dissipation

  M. Lemeshko, H. Weimer, submitted (2012), arXiv:1211.4035

- Future directions: self-organization in many-body systems
  - Dissipative formation of “complexes” and “crystals”
  - Direct cooling atoms or molecules into strongly-interacting phases



Reviews that will appear soon:

M. Lemeshko, R. Krems, J. Doyle, S. Kais,

Manipulation of molecules with electromagnetic fields

(in the special issue of Molecular Physics that we are editing)

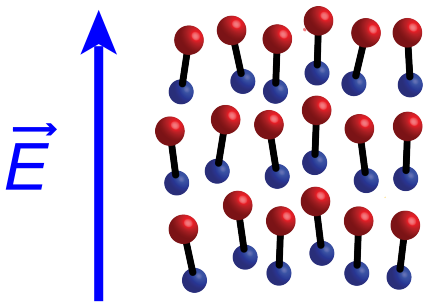
M. Lemeshko, J. Otterbach, H. Weimer,

Dissipative state preparation in open quantum systems

(in Journal of Physics B)

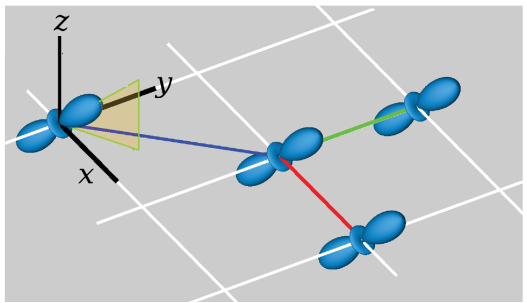
Other things we are thinking about

Field-sensing with cold molecules



S. Alyabyshev, ML, R. Krems, PRA **86**, 013409 (2012)

Quantum phases of quadrupolar Fermi gases



S. Bhongale, L. Mathey, E. Zhao, S. Yelin, ML, arXiv:1211.3317

Thank you for your attention!