Two interacting ultracold molecules in a trap: magnetic properties and quench dynamics

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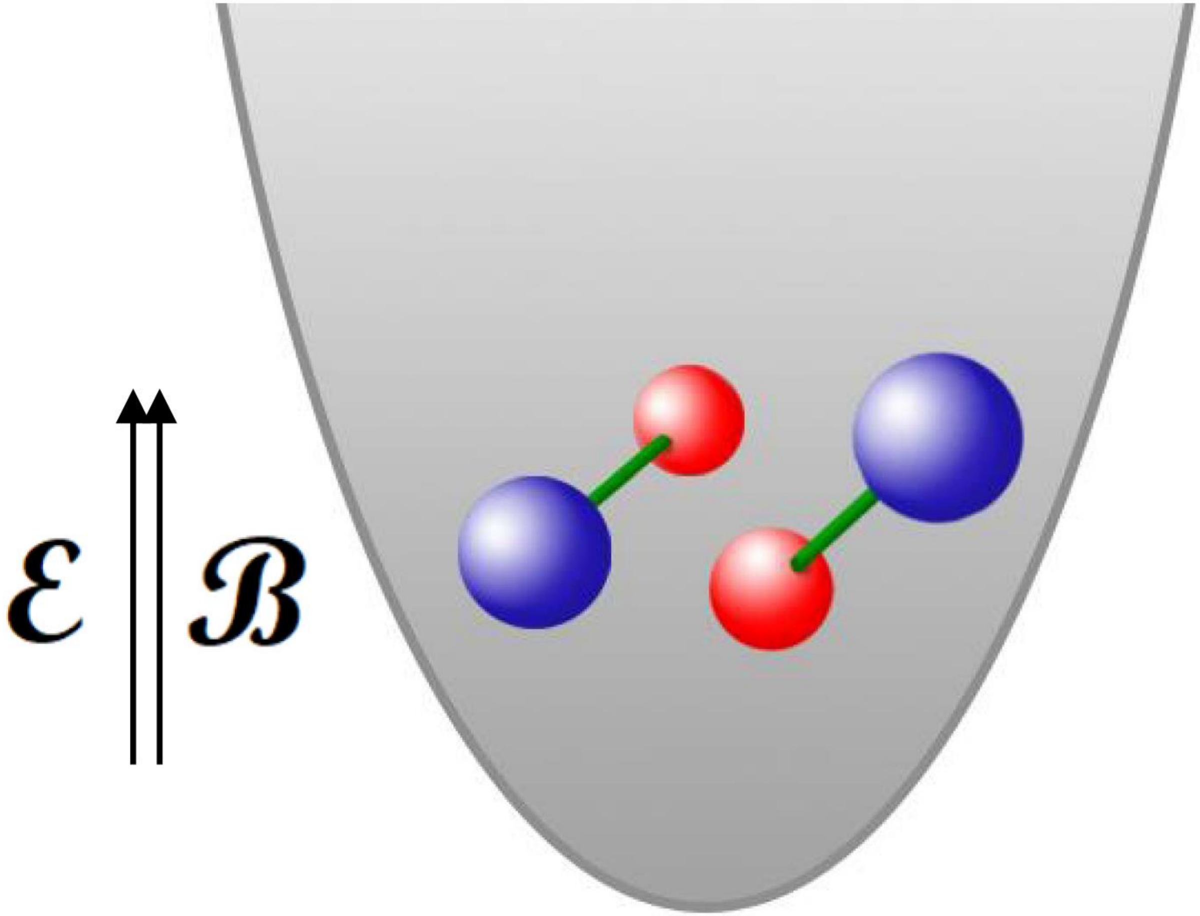

ICFO

FACULTY OF PHYSICS UNIVERSITY OF WARSAW

Outline

Ultracold molecules: state-of-the-art

Replacing atoms with molecules

- Rotational structure
- Intermolecular interactions

Results - highlights

- Anisotropic interaction
- Magnetic properties
- Quench dynamics

Plans, outlook, conclusions

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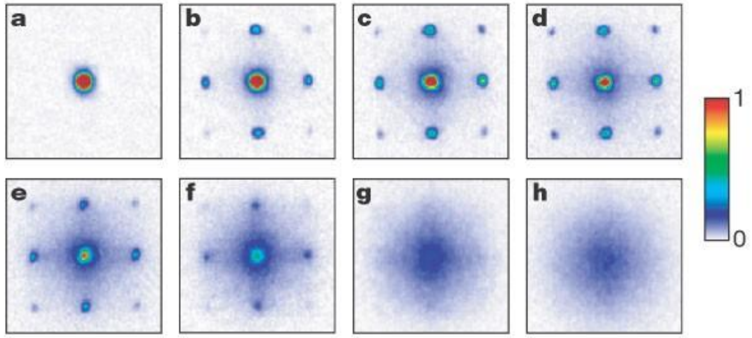
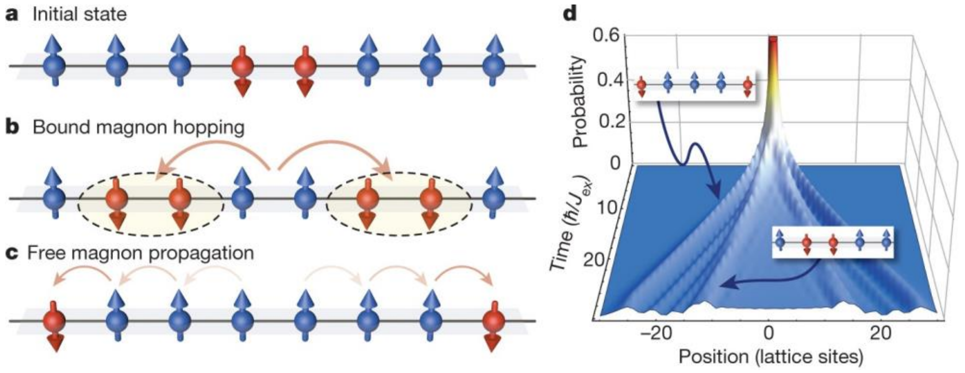
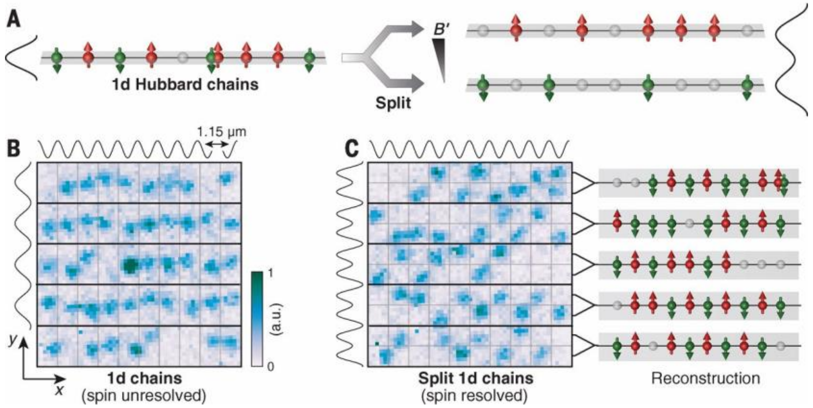
Many-body physics with ultracold atoms



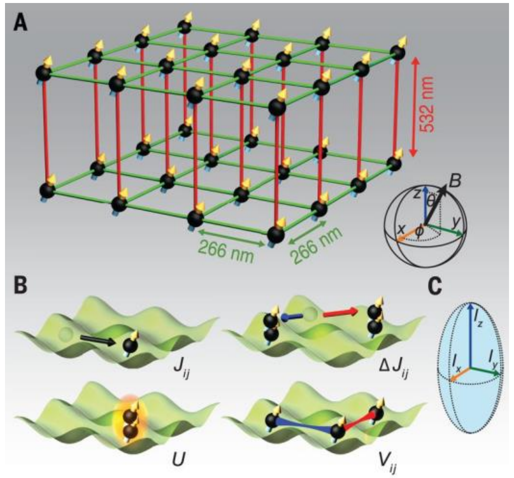
Greiner *et al*. Nature, 415, 2002



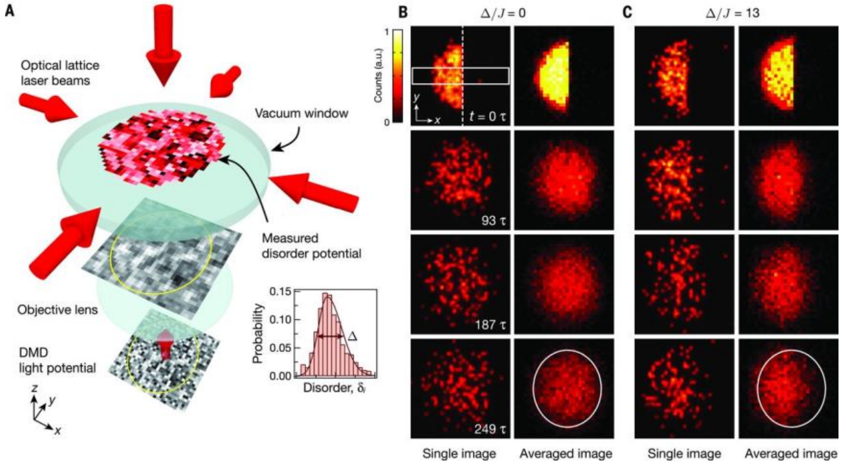
Fukuhara *et al*. Nature, 502, 2013



Boll *et al*. Science, 353, 2016

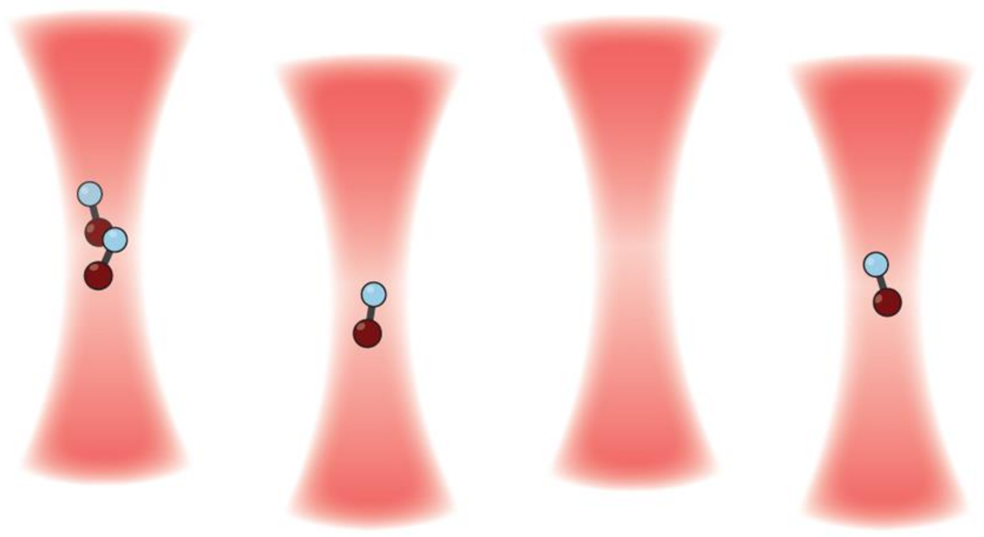


Baier *et al*. Science, 352, 2016

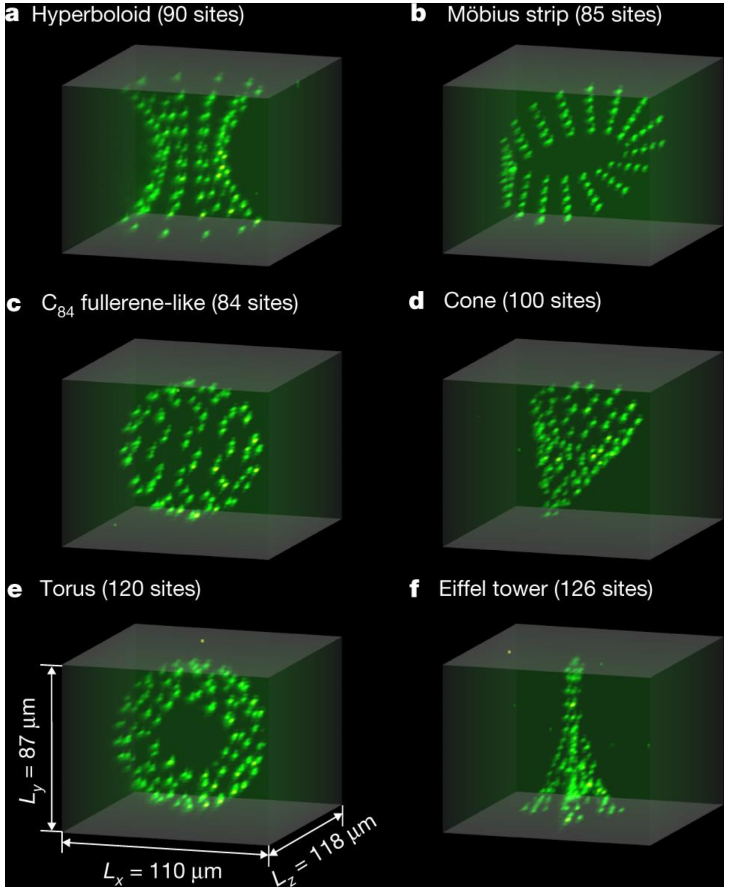


J. Choi *et al*. Science, 352, 2016

Quantum control at a single-particle level



Science **365**, 1079 (2019)



Science **354**, 1024 (2016)

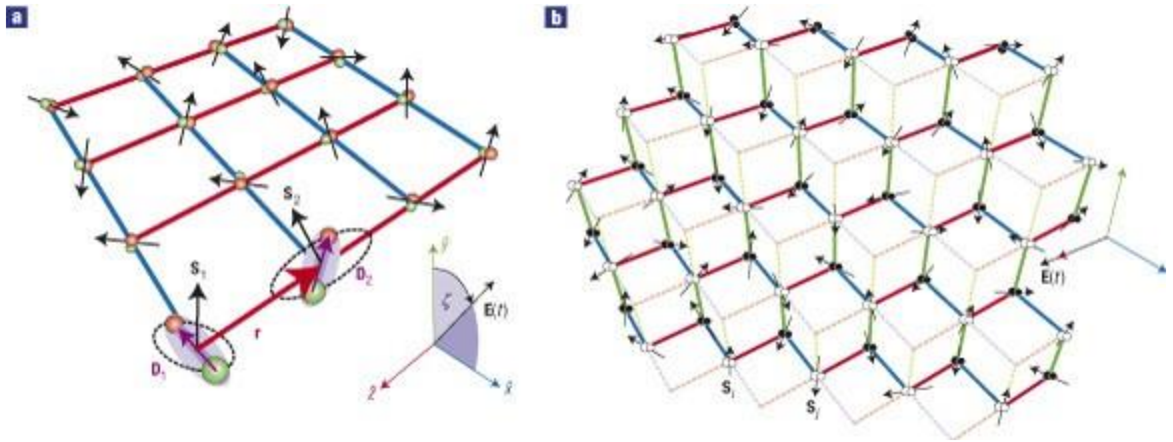
Nature **561**, 79 (2018)

Replacing atoms with molecules

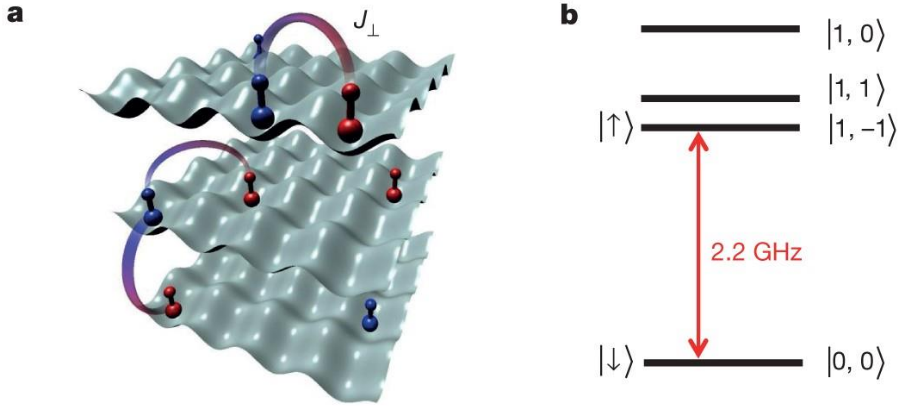
- Isotropic and short-range interactions
- Magnetic dipole moment
- Electronic structure, fine and hyperfine structure

- **Anisotropic** and **long-range** interactions
- Magnetic **+ electric dipole moment**
- Electronic, fine and hyperfine **+ rotational, vibrational structure**

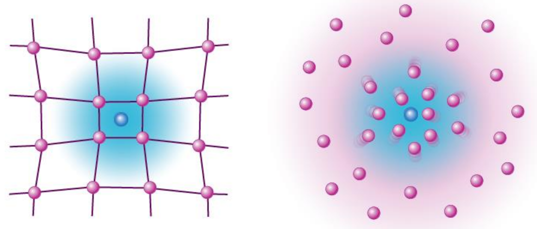
Molecular promises



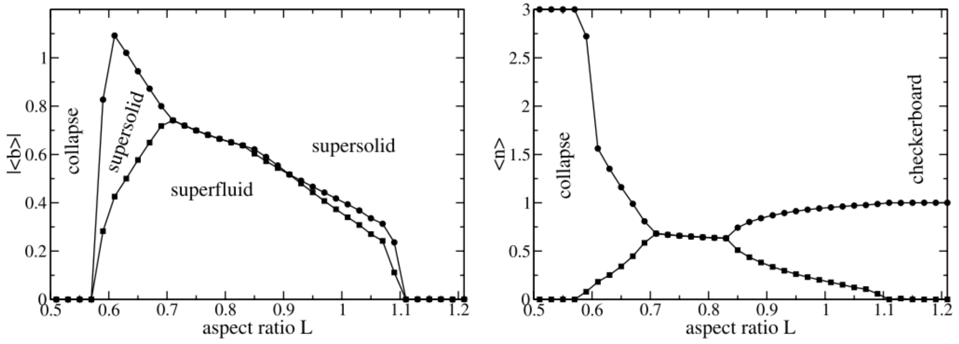
Micheli, Brennen, & Zoller. Nat. Phys., **2**, 341, 2006



Yan *et al.* Nature, **501**, 521, 2013



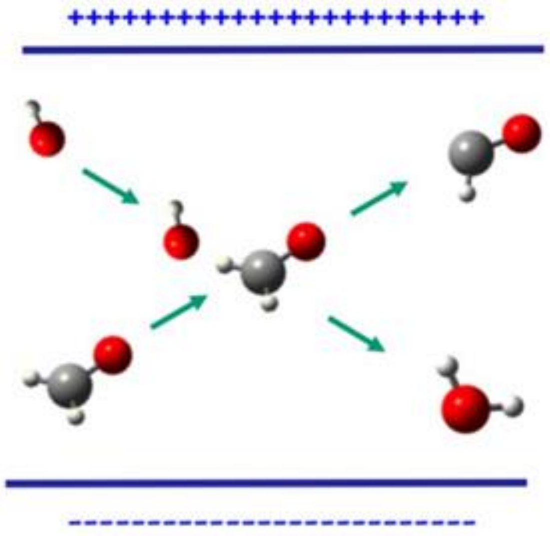
e.g. Herrera *et al.* Phys. Rev. Lett., **110**, 223002, 2013



Góral, Santos & Lewenstein. Phys. Rev. Lett., **88**, 170406, 2002

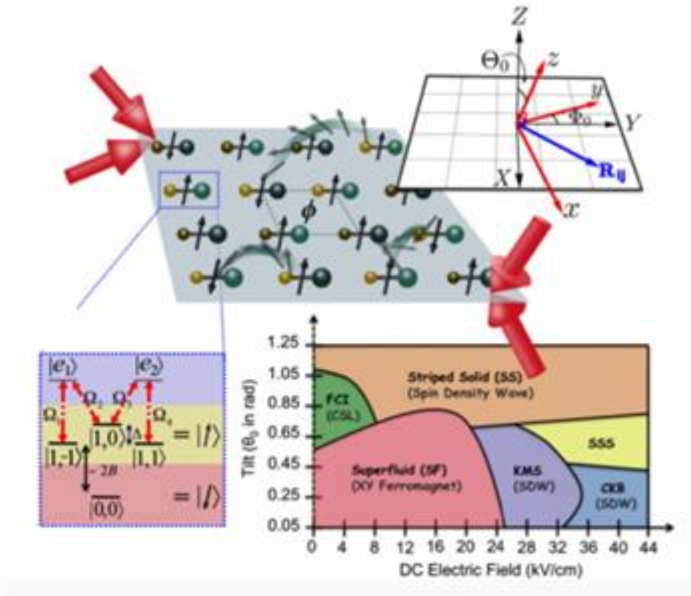
Molecular promises

Ultracold chemistry



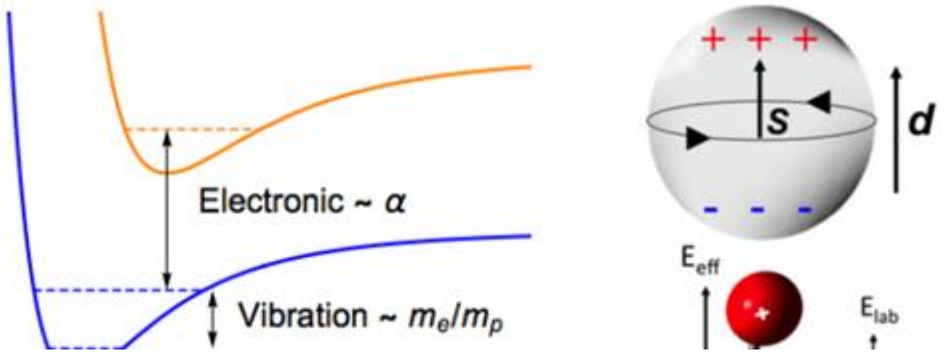
Science **327**, 853-857 (2010)
Nature Phys. **7**, 502-507 (2011)

Quantum many-body physics



Phys. Rev. Lett. **110**, 185302 (2013)

Precision measurements



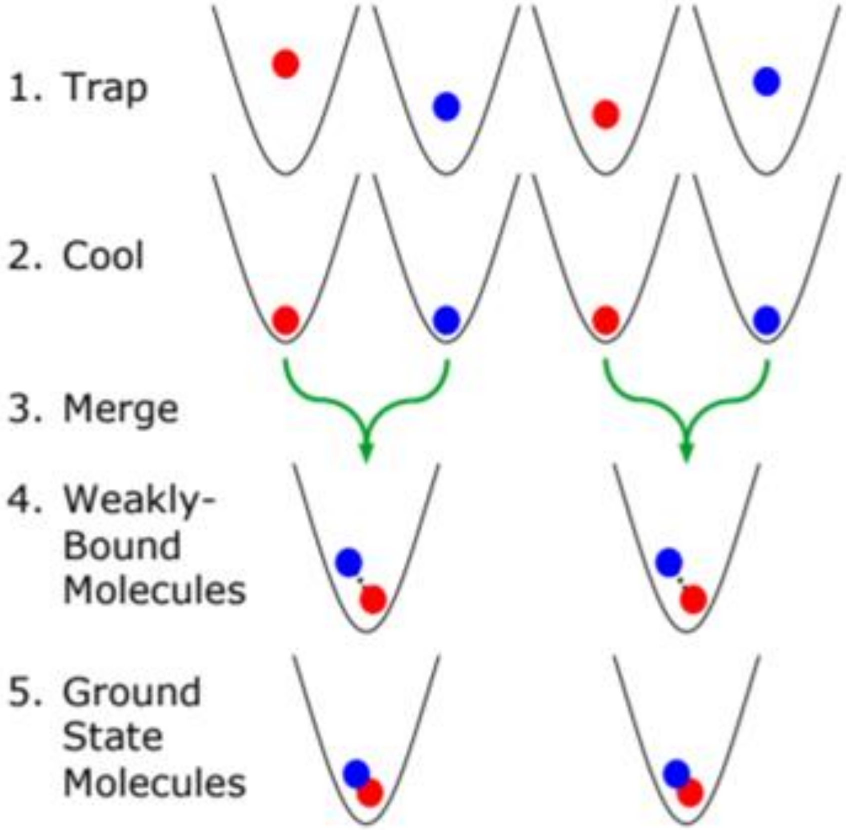
Nature **473**, 493-496 (2011)
Science **343**, 269-272 (2014)

Towards full control over molecules

- Bottom-up approach

  Ni group: NaCs
  Wuhan group: RbRb

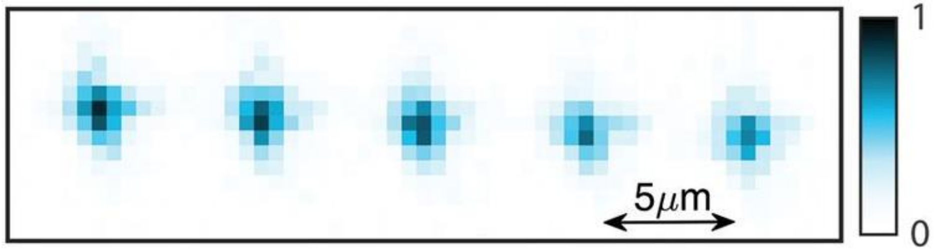
  Science **360**, 900 (2018)
  Science **370**, 331 (2020)



Towards full control over molecules

- Laser cooling of molecules, then loading to traps

  Doyle/Ketterle/Ni: CaF



Phys. Rev. Lett. **119**, 103201 (2017)
Science **365**, 1156 (2019)

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- Quench dynamics

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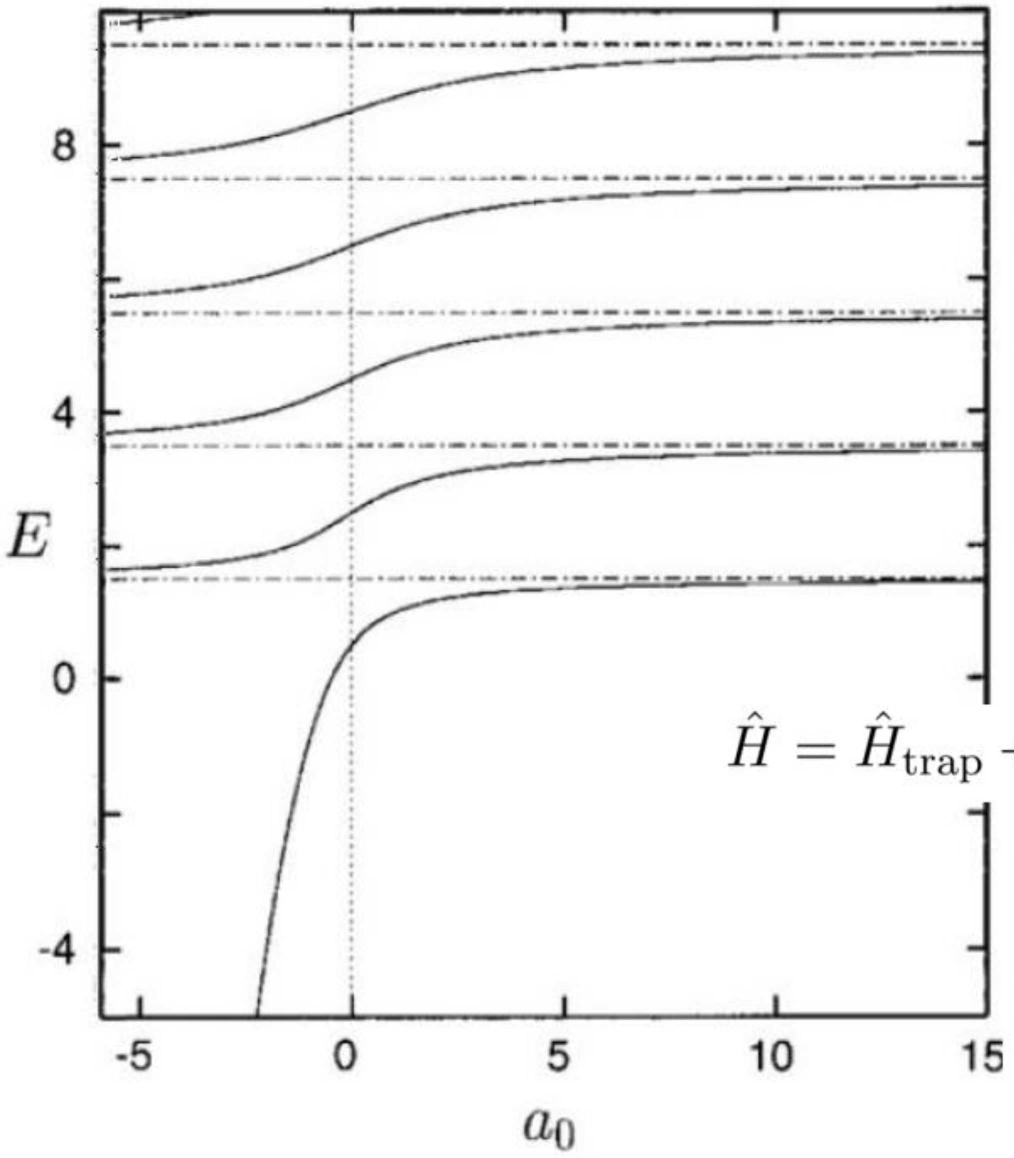
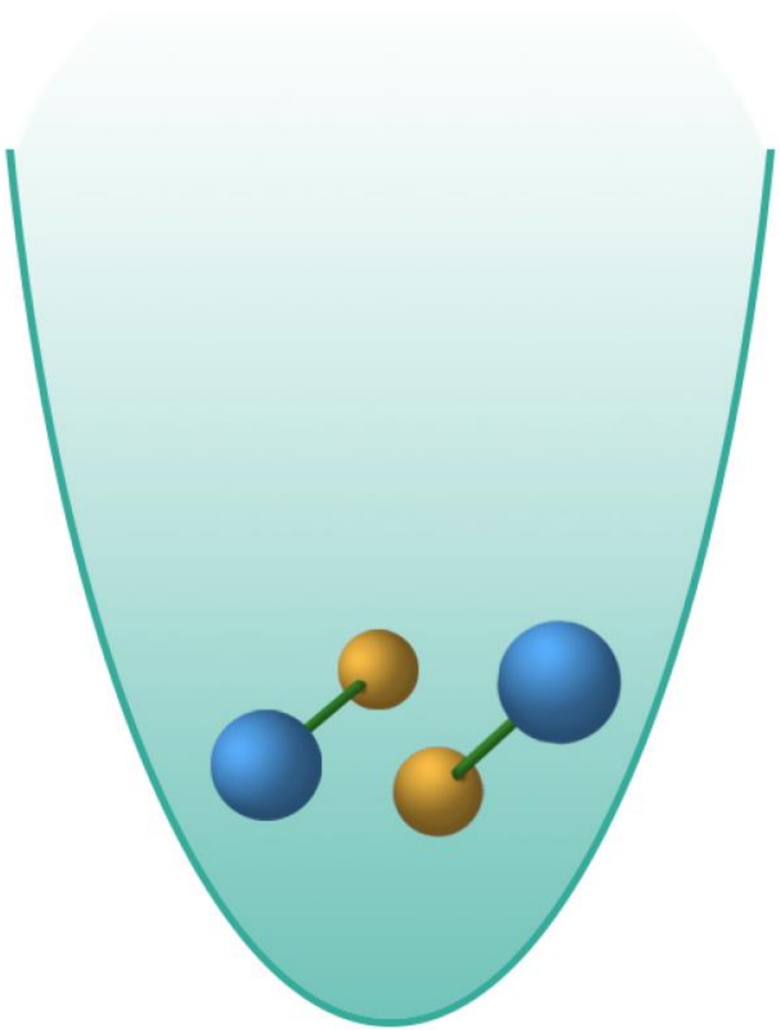
Isotropic intermolecular interaction

Results for two ultracold atoms



$$\hat{H} = \hat{H}_{\text{trap}} + \underbrace{g_0 \delta(z_1 - z_2) \hat{P}_0}_{\hat{H}_{\text{iso}}}$$

Found. Phys. **28**, 549–559 (1998)



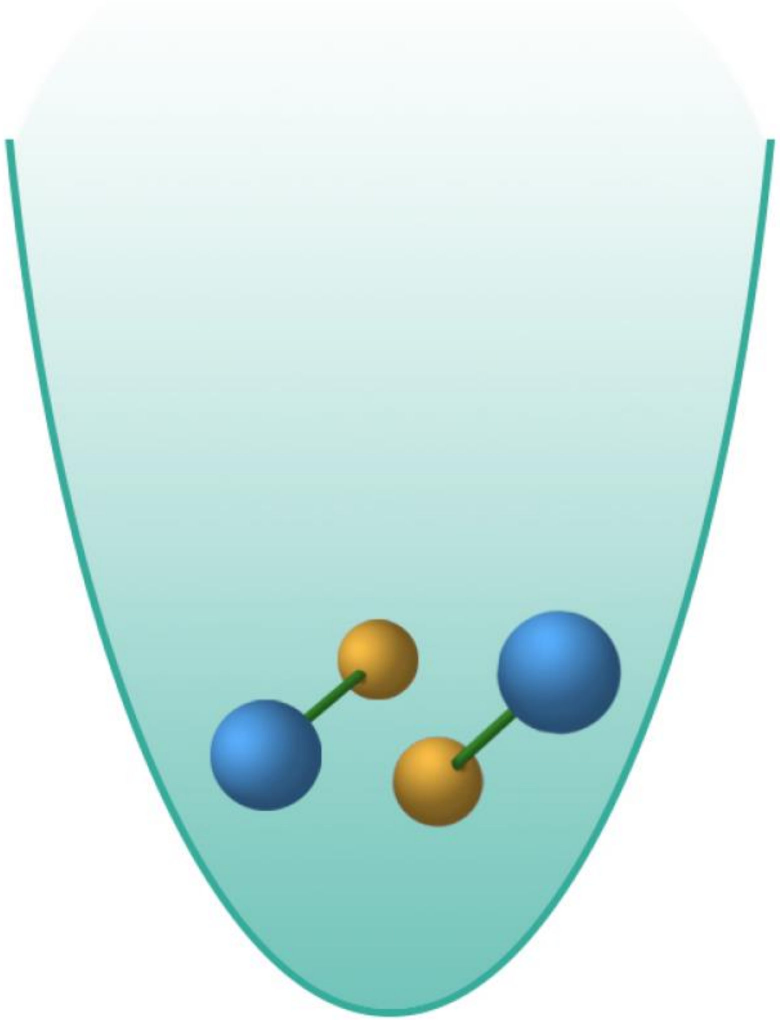
Molecular model

$$\hat{H} = \hat{H}_{\text{trap}} + \hat{H}_{\text{mol}} + \hat{H}_{\text{field}} + \hat{H}_{\text{int}}$$

Basis set:

$|n\rangle \, |J, M_J, j_1, j_2\rangle \, |s_1, m_{s_1}\rangle \, |s_2, m_{s_2}\rangle \equiv |\alpha\rangle$

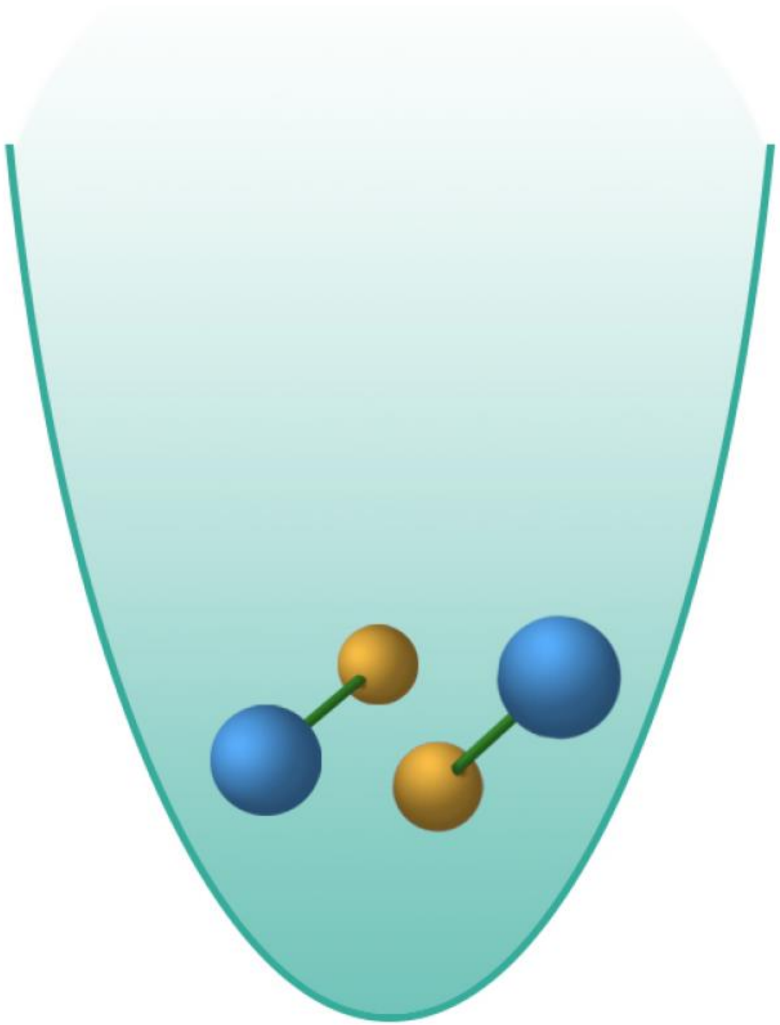
Exact diagonalization!



Molecular model

$$\hat{H} = \boxed{\hat{H}_{\text{trap}}} + \hat{H}_{\text{mol}} + \hat{H}_{\text{field}} + \hat{H}_{\text{int}}$$

$$\hat{H}_{\text{trap}} = \sum_{i=1}^{2} \frac{\hat{p}_i^2}{2m} + \sum_{i=1}^{2} \frac{1}{2} m\omega z_i^2$$

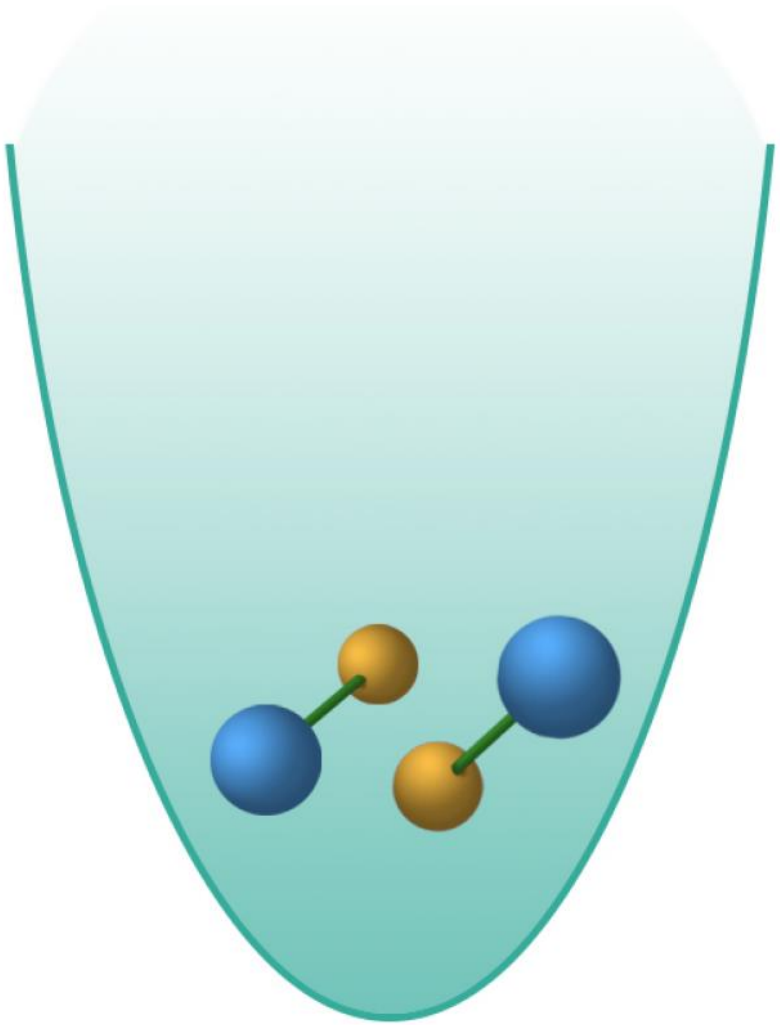


Molecular model

$$\hat{H} = \hat{H}_{\text{trap}} + \boxed{\hat{H}_{\text{mol}}} + \hat{H}_{\text{field}} + \hat{H}_{\text{int}}$$

$$\hat{H}_{\text{rot}} = \sum_{i=1}^{2} B\,\hat{\mathbf{j}}_i^2\,,$$

$$\hat{H}_{\text{spin-rot}} = \sum_{i=1}^{2} \gamma\,\hat{\mathbf{s}}_i \cdot \hat{\mathbf{j}}_i\,,$$

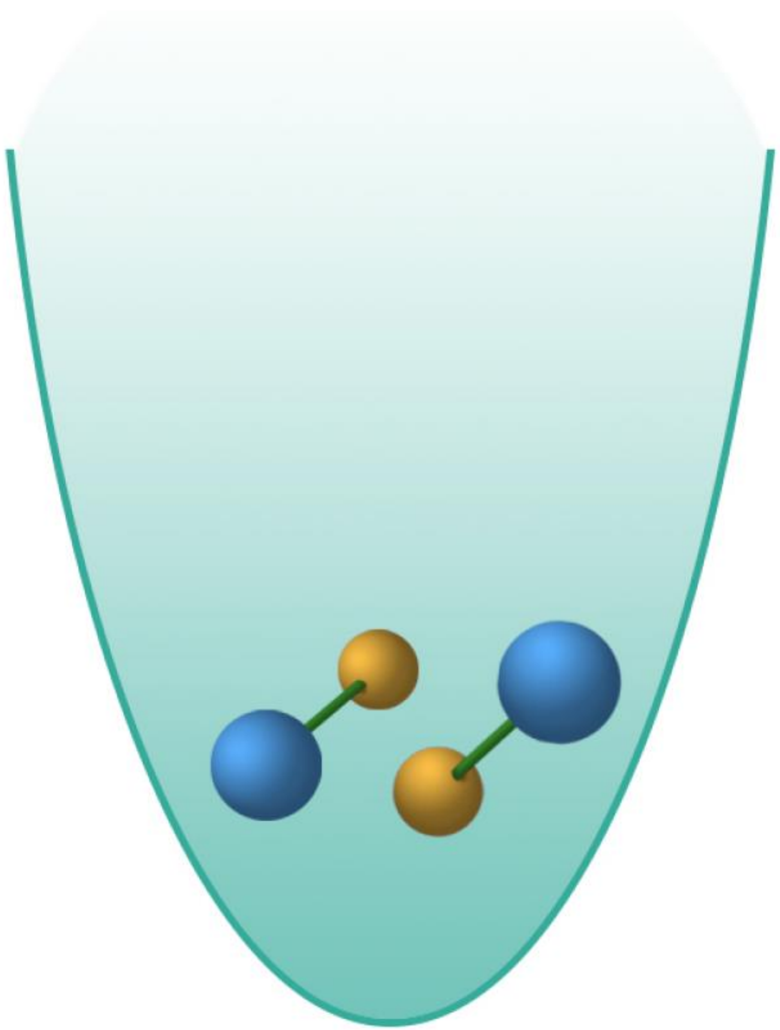


Molecular model

$$\hat{H} = \hat{H}_{\text{trap}} + \hat{H}_{\text{mol}} + \boxed{\hat{H}_{\text{field}}} + \hat{H}_{\text{int}}$$

$$\hat{H}_{\text{Stark}} = -\sum_{i=1}^{2} \hat{\mathbf{d}}_i \cdot \mathcal{E}\,,$$

$$\hat{H}_{\text{Zeeman}} = 2\mu_B \sum_{i=1}^{2} \hat{\mathbf{s}}_i \cdot \mathcal{B}$$



Molecular model

$$\hat{H} = \hat{H}_{\text{trap}} + \hat{H}_{\text{mol}} + \hat{H}_{\text{field}} + \boxed{\hat{H}_{\text{int}}}$$

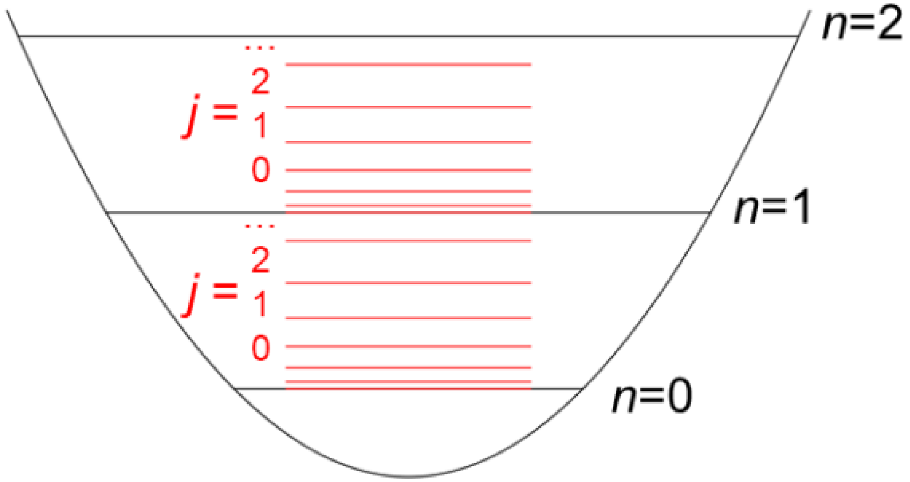
$$\hat{H}_{\text{iso}} = \sum_{\alpha} g_0 \delta(z_1 - z_2) \hat{P}_0 \,,$$

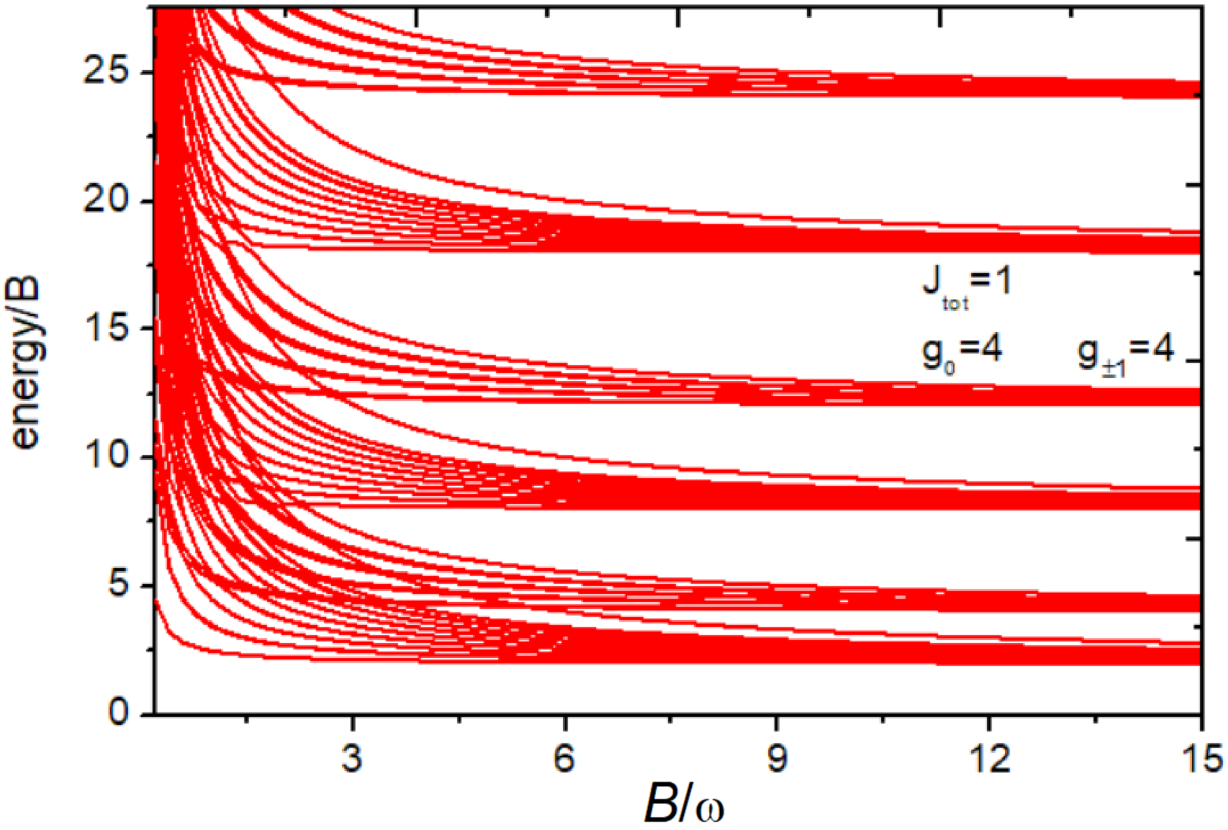
$$\hat{H}_{\text{aniso}} = \sum_{\alpha \neq \alpha'} g_{\pm 1} \delta(z_1 - z_2) \hat{P}_{\pm 1}$$

$$\text{with } \hat{P}_0 = |J, M, j_1, j_2\rangle \langle J, M, j_1, j_2|$$

$$\hat{P}_{\pm 1} = |J, M, j_1 \pm 1, j_2\rangle \langle J, M, j_1, j_2 \mp 1| + \text{H.c.}$$

Choice of rotational constant determines the importance of molecular structure in the problem





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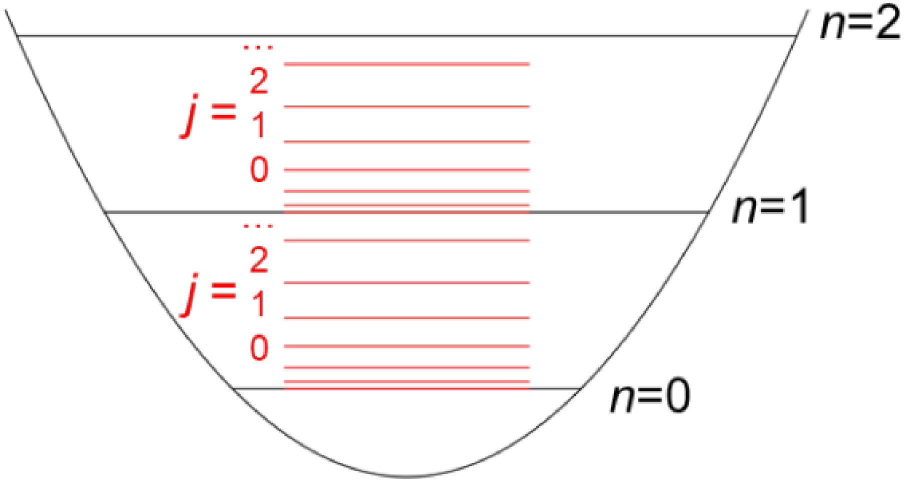

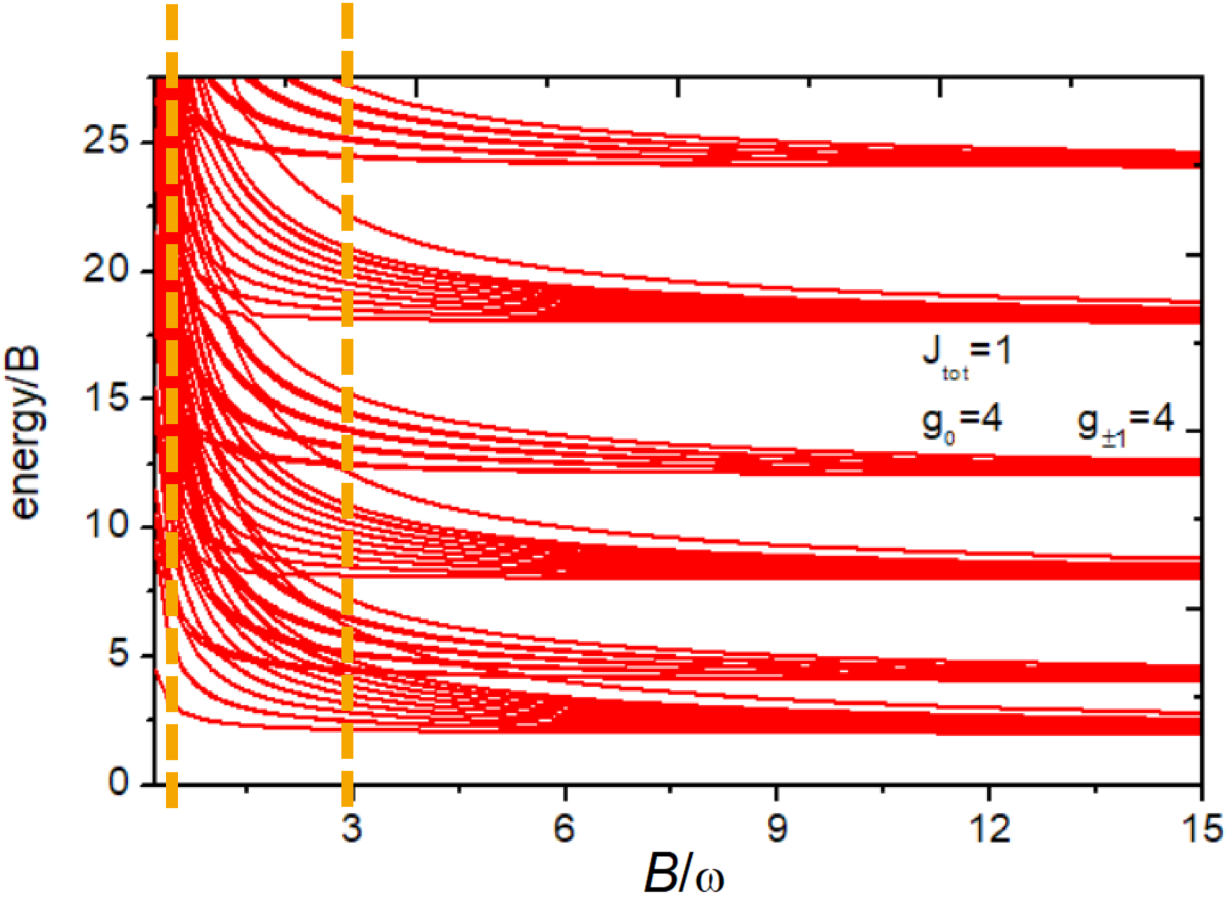

- B = 0.3 ω and 3 ω
- typical experiments B / ω >> 1

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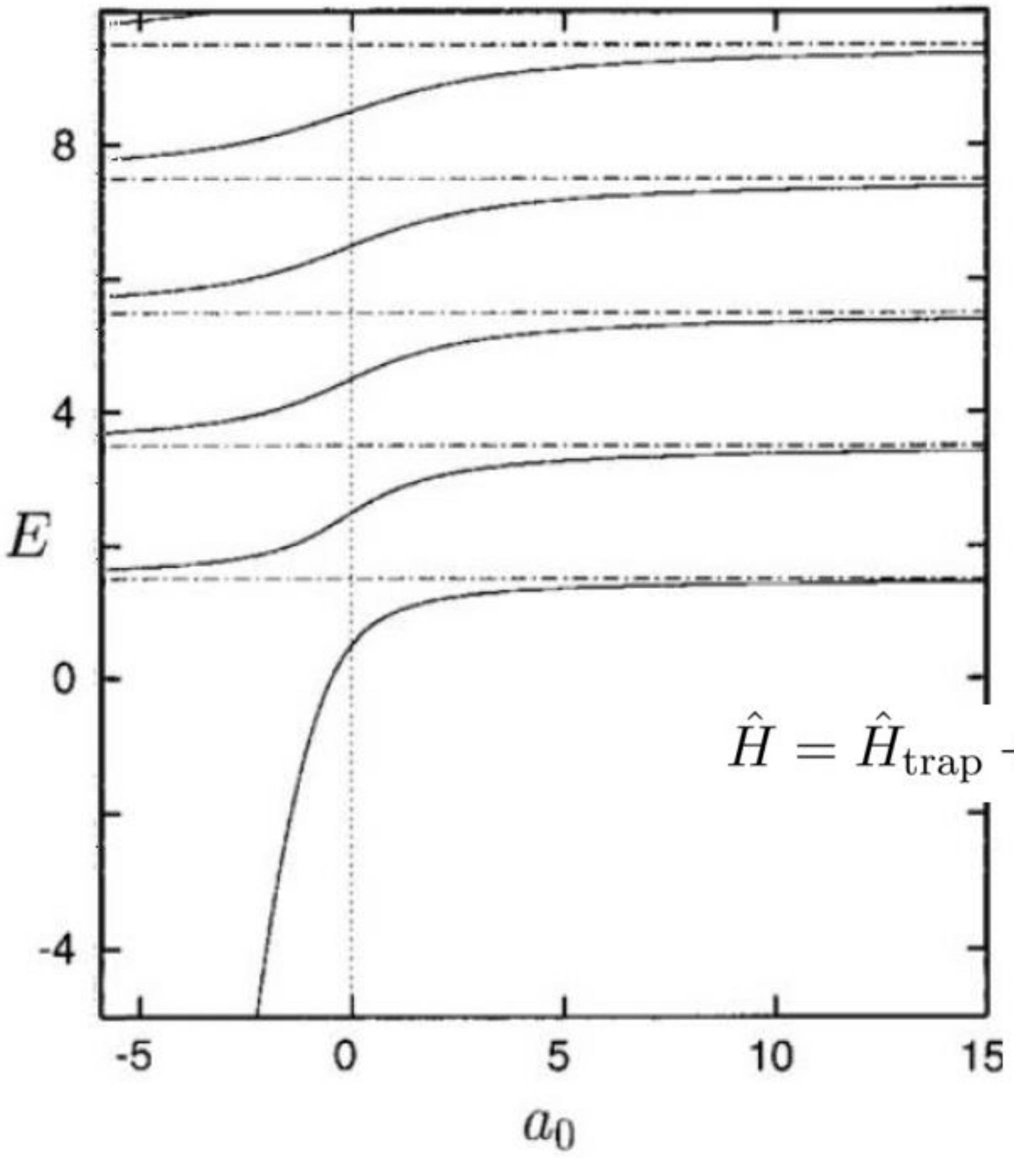

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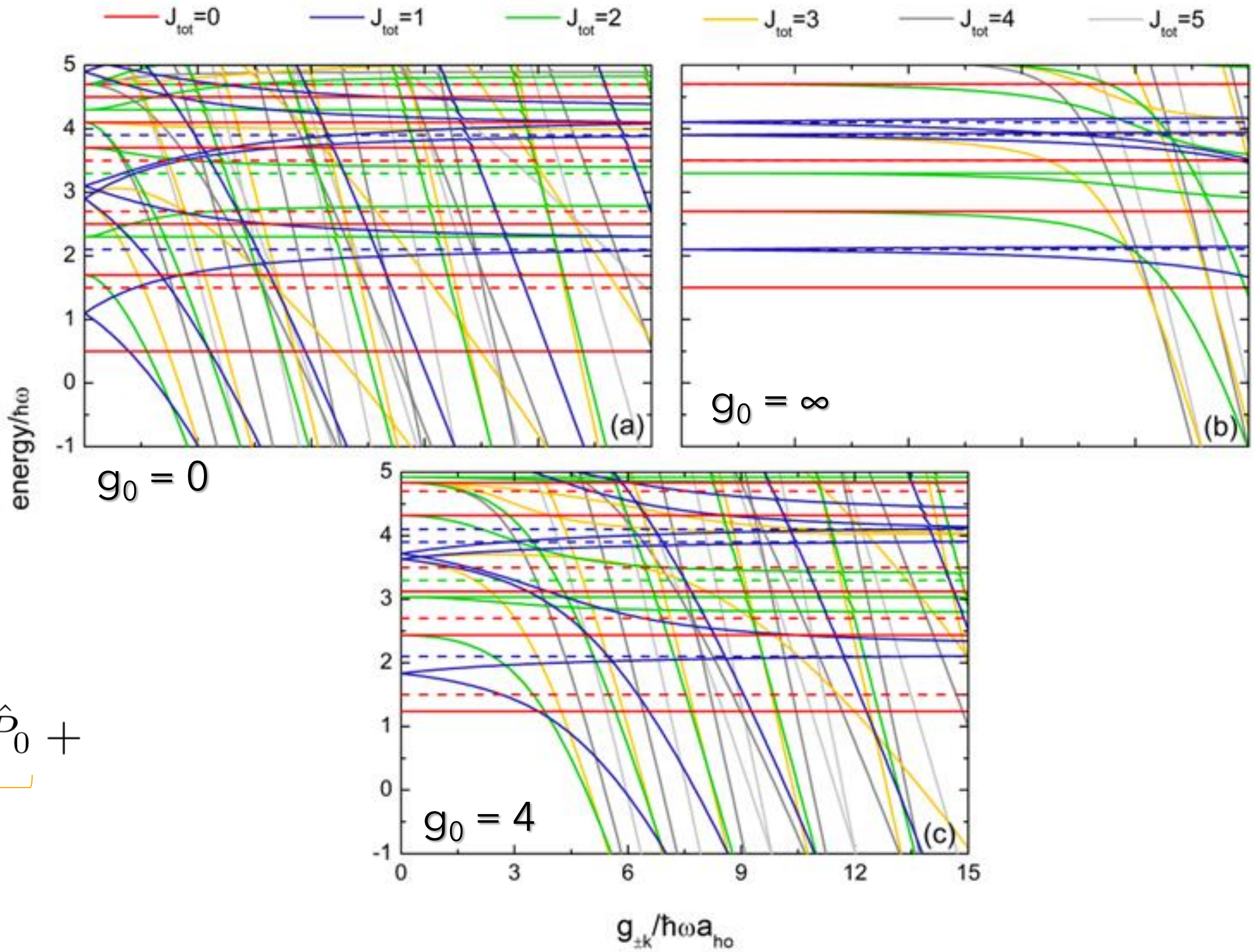
Found. Phys. **28**, 549–559 (1998)

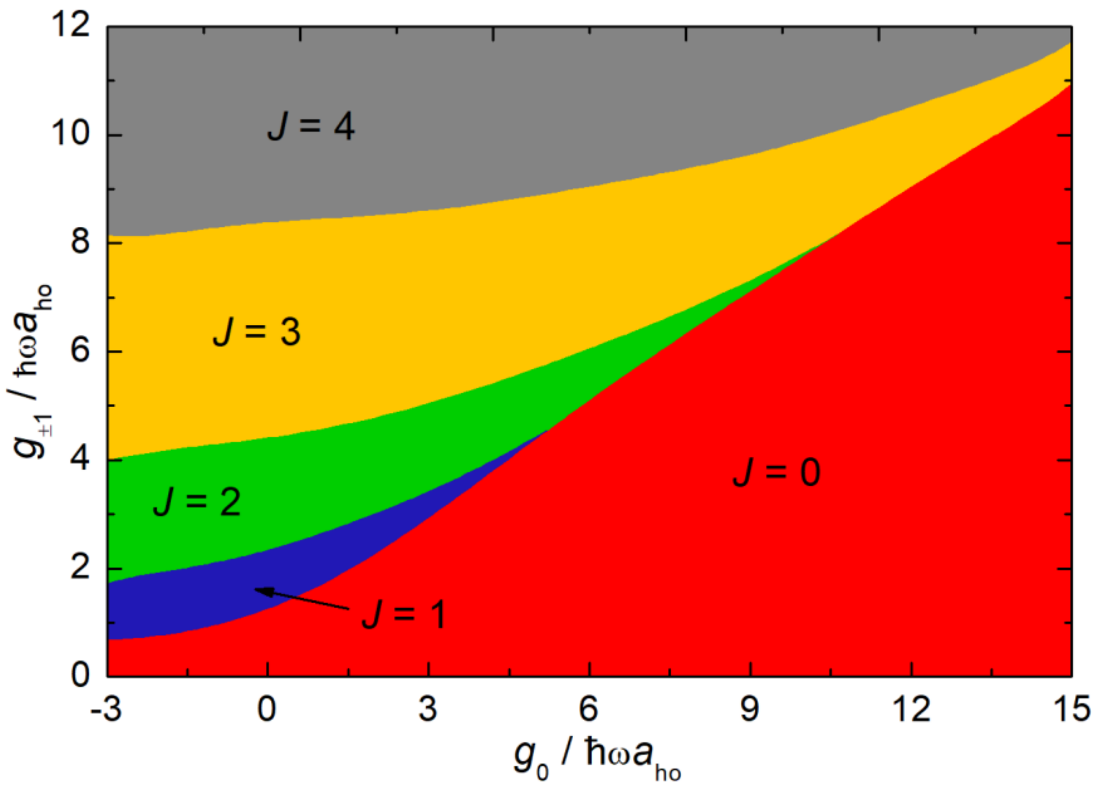
Anisotropic intermolecular interaction

- ❖ Molecular effect
- ❖ Tonks-Girardeau regime
- ❖ Ground state with $J_{tot} \neq 0$!

$$\hat{H} = \hat{H}_{\text{trap}} + \hat{H}_{\text{rot}} + \underbrace{g_0 \delta(z_1 - z_2)\hat{P}_0}_{\hat{H}_{\text{iso}}} + \underbrace{+\sum_k g_{\pm k}\delta(z_1 - z_2)\hat{P}_{\pm k}}_{\hat{H}_{\text{aniso}}}$$

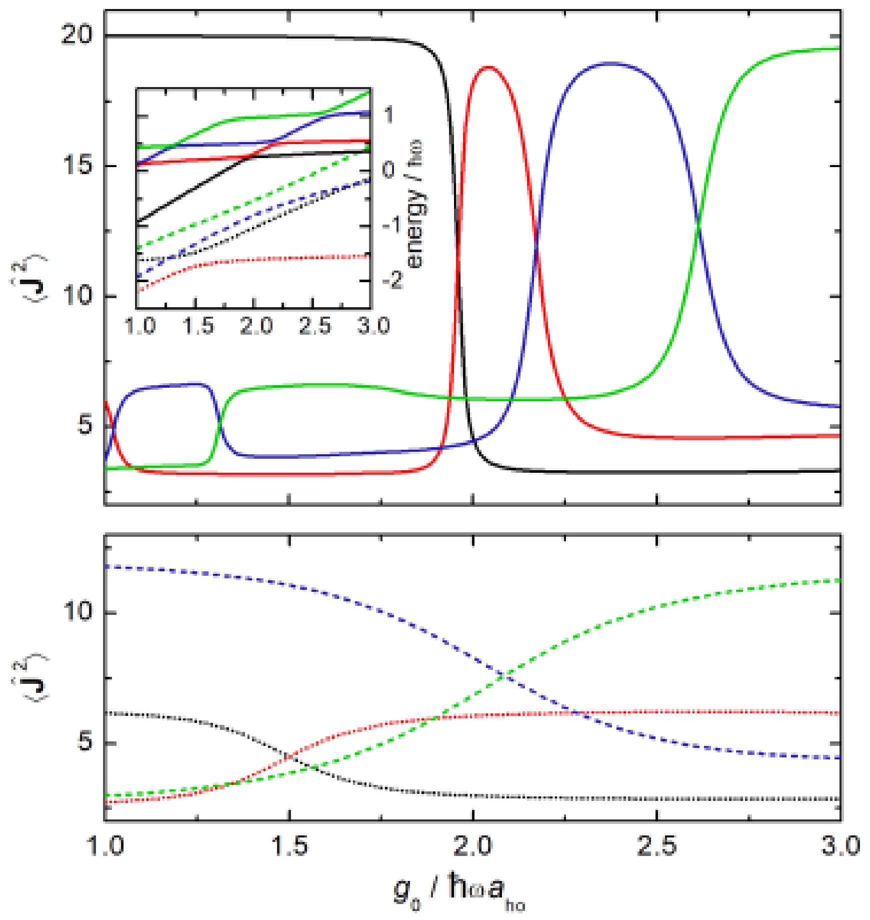


Ground state with $J_{tot} \neq 0$!



Total rotational momentum
of the ground state
as a function of the isotropic (g_0)
and anisotropic ($g_{\pm 1}$)
interaction strength

Total rotational angular momentum can be pumped into the system with external electric field!

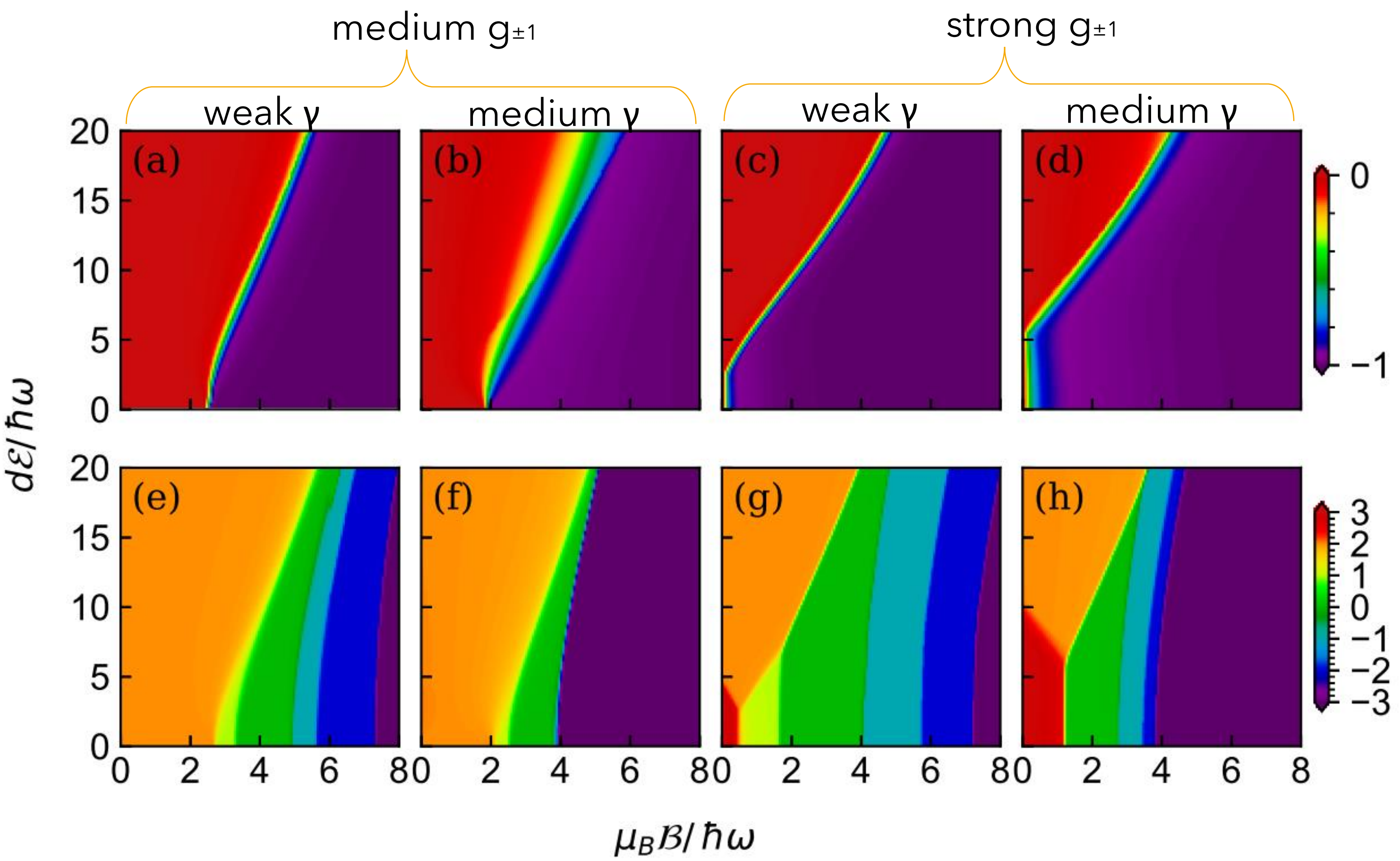


$$d\mathcal{E} = 2.5\,\hbar\omega$$

Mean values of the square of the total rotational angular momentum operator for selected eigenstates as a function of the isotropic (g_0) interaction strength

Magnetization can be controlled with external fields!

Electric E vs. magnetic field B strength magnetization diagrams



spin 1/2
(M_{tot} = 0)

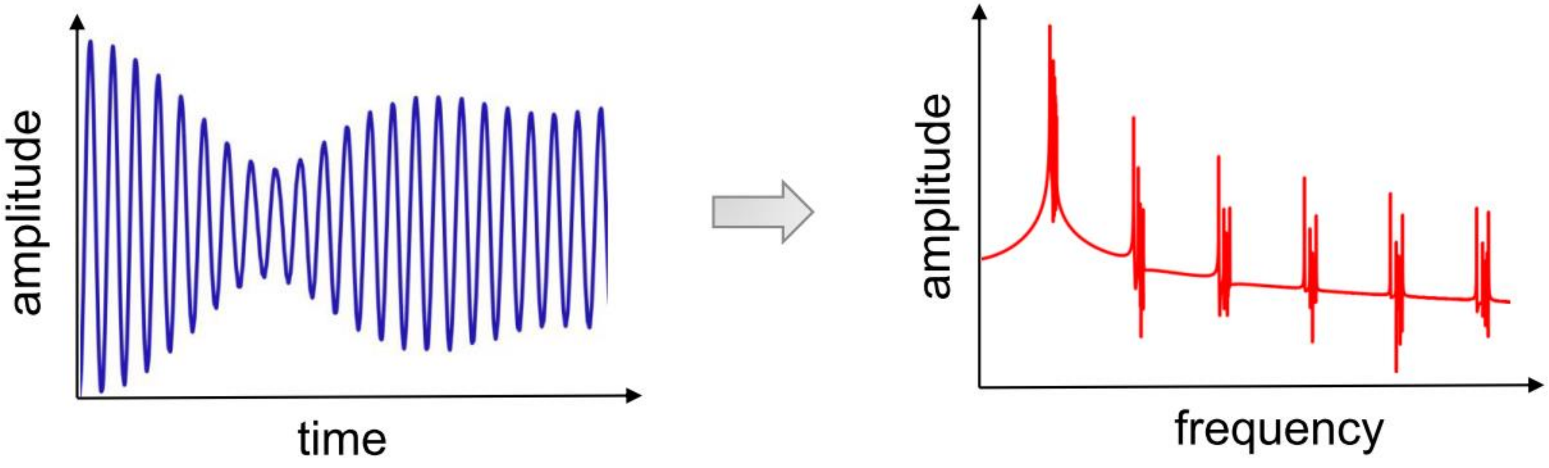
spin 3/2
(M_{tot} = 2)

γ - spin-rotation coupling

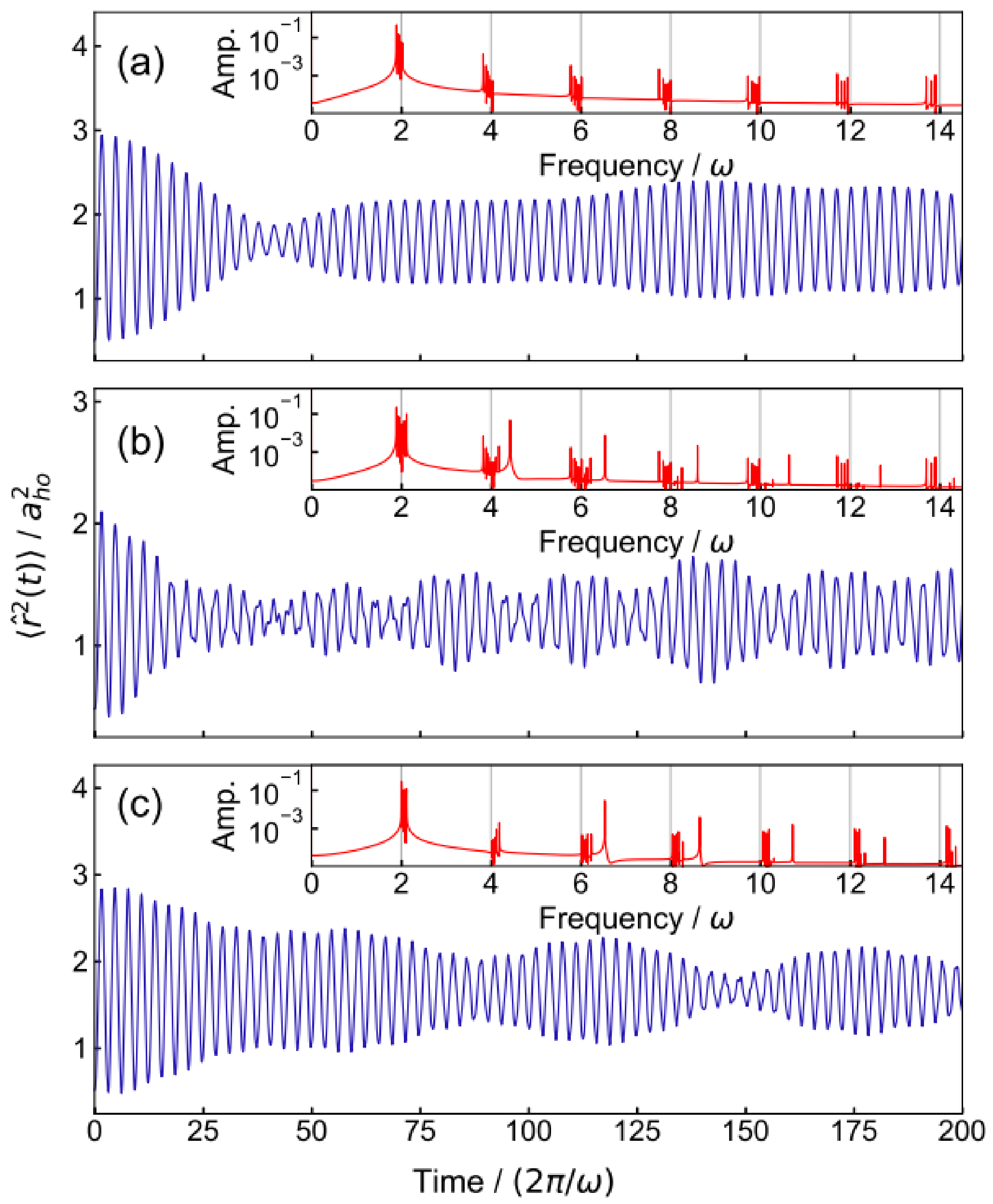
$g_{\pm1}$ - anisotropic interaction strength

How to extract molecular properties?

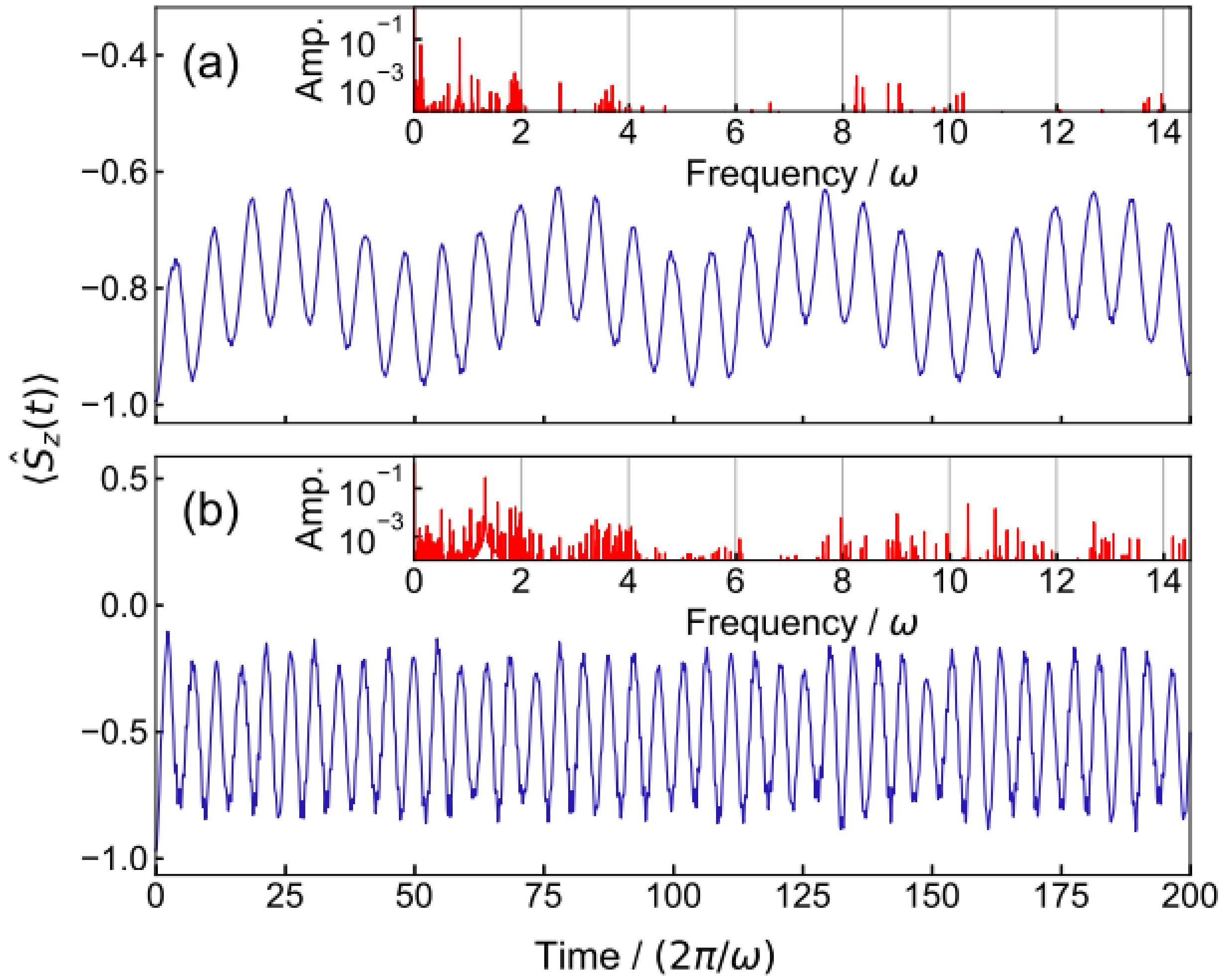
quench



Iso- and anisotropic interaction



Spin-rotation coupling



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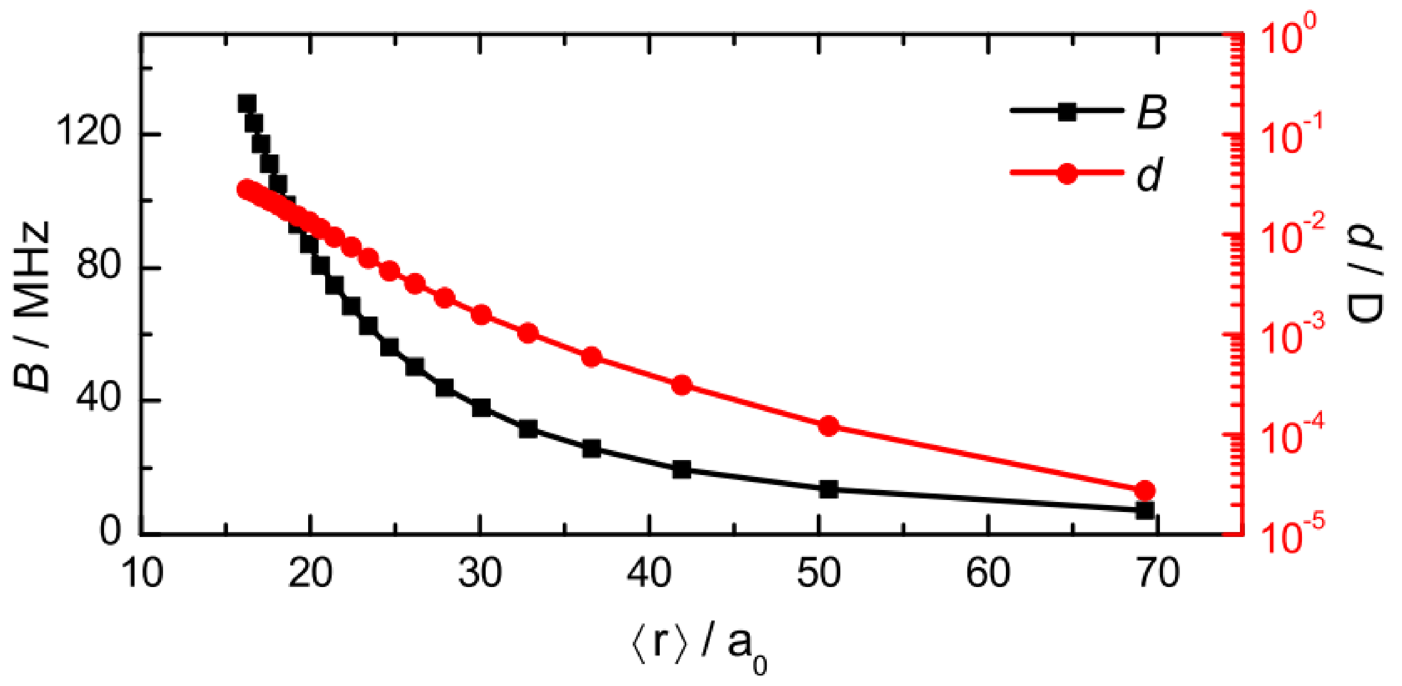
Summary

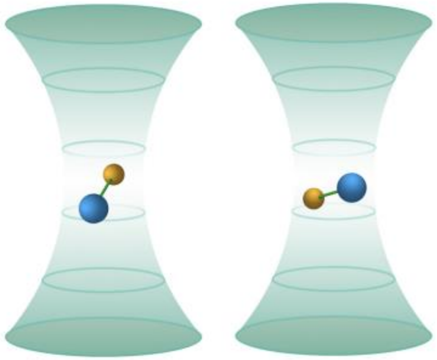
- ❖ Molecular means: rotational structure, anisotropic interactions, and spin-rotation coupling
- ❖ Anisotropic interaction brings down the states with high rotational angular momenta
- ❖ We can control magnetic properties with external electric field
- ❖ Quench dynamics can reveal the molecular properties of the system

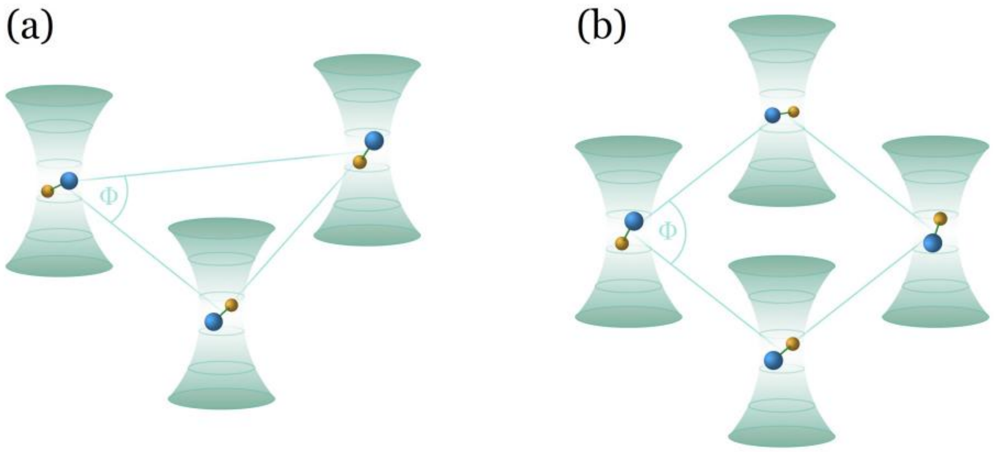
Experimental feasibility

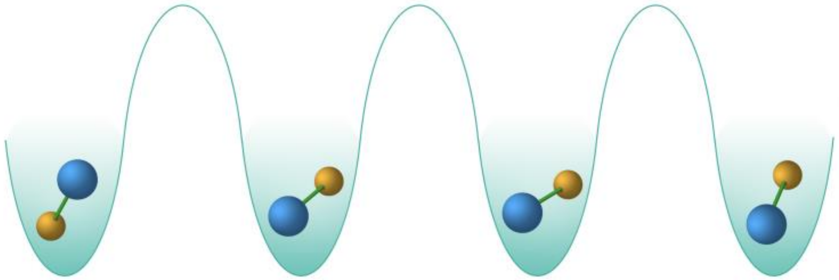


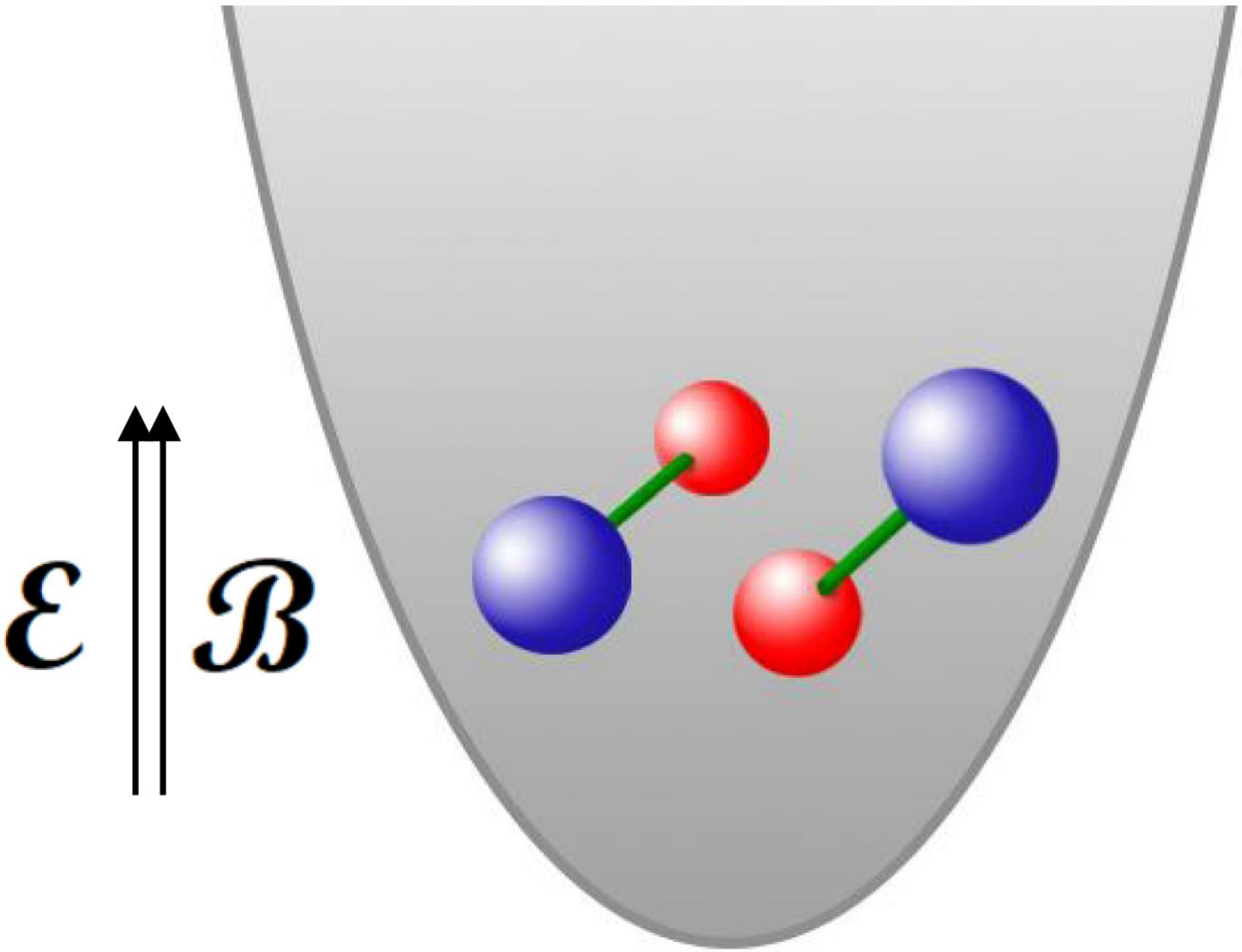
Science **366**, 1111 (2019)

Plans and possible extensions









Thank you for your attention!

Code available at: http://doi.org/10.5281/zenodo.3985911

A. Dawid, M. Lewestein, M. Tomza. 2018. Phys. Rev. A **97**, 063618 (arXiv:1804.09168)
A. Dawid, M. Tomza. 2020. Phys. Chem. Chem. Phys. In press (arXiv:2010.11899)