Dipole-dipole interactions between atoms for many-body physics and quantum information

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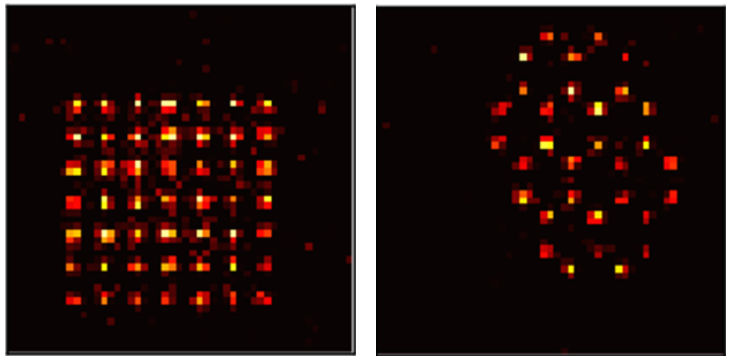
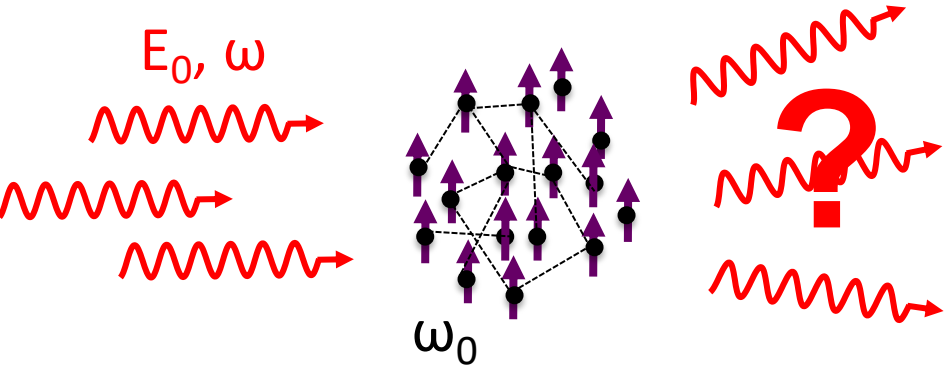
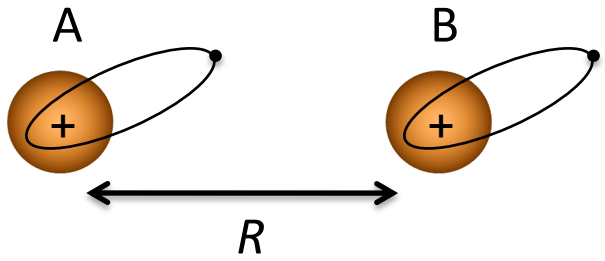
Dipole interactions for QIP and many-body physics





Rydberg interactions



Interactions between
light-induced dipoles

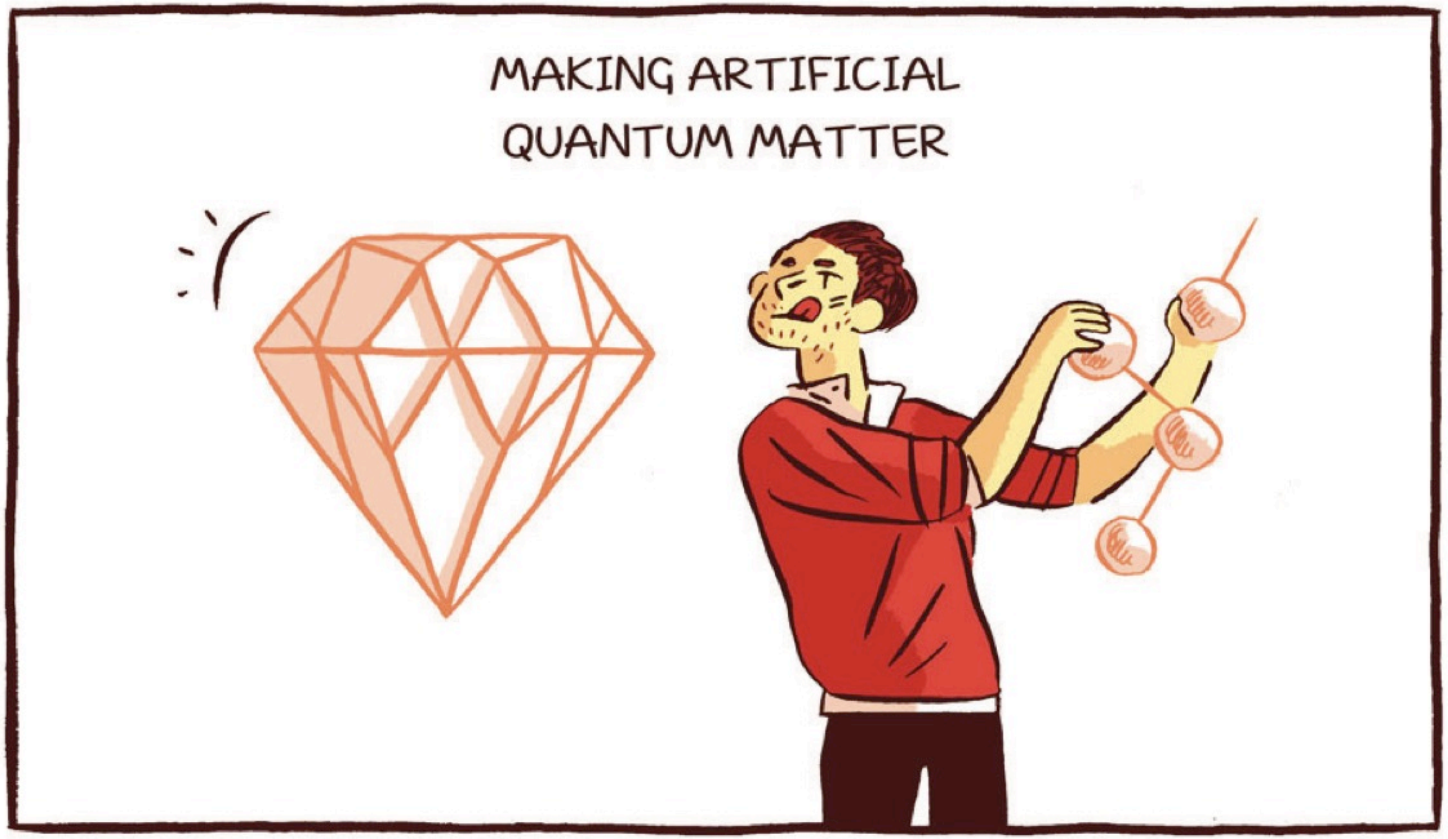
Van der Waals $\frac{C_6}{R^6}$

resonant $\frac{C_3}{R^3}$

See: A. Asenjo-Garcia
R. Kaiser

Our Goal

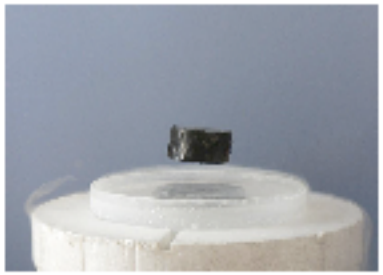
(as many groups…)

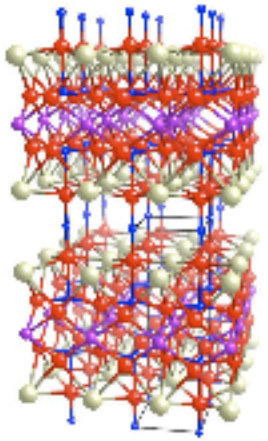


Héloïse Chochois, for Labex PALM

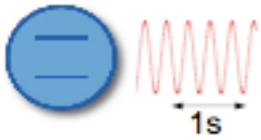
Quantum state engineering: create controlled quantum states

Many-body physics





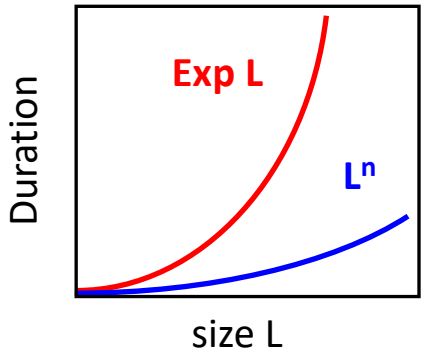
Quantum metrology



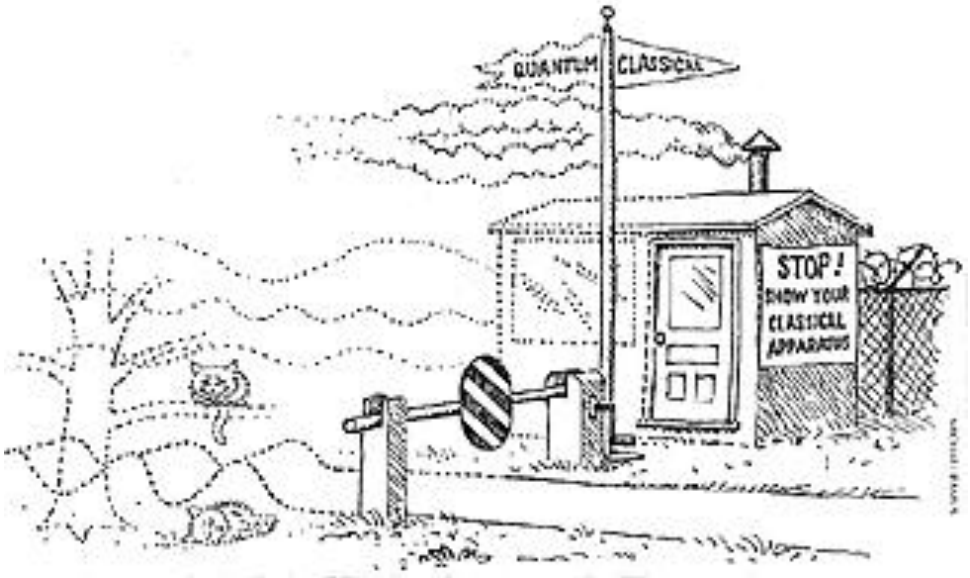
$$\frac{\Delta\nu}{\nu_0} \propto \frac{1}{\sqrt{N}} \quad \text{qu. states} \quad \frac{\Delta\nu}{\nu_0} \propto \frac{1}{N}$$

Quantum information

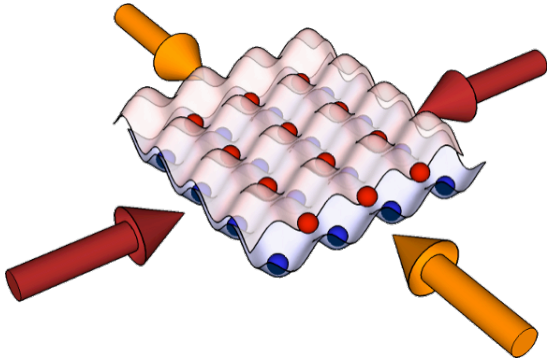
Message



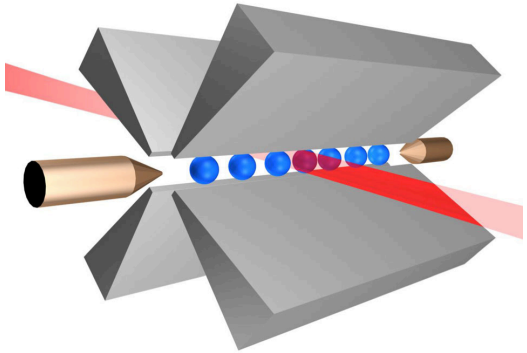
Transition quantum / classical



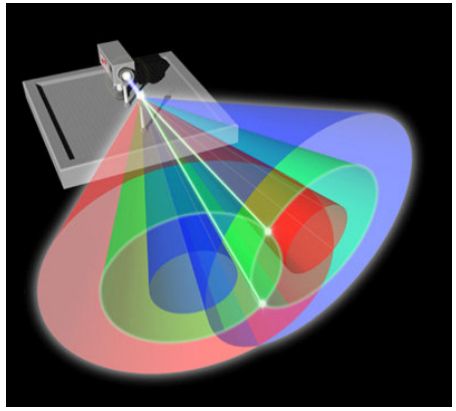
Quantum state engineering with individual systems



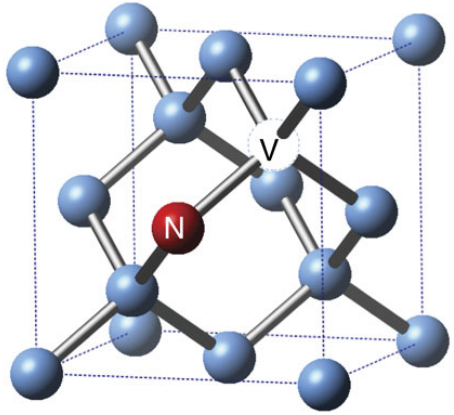
Neutral atoms



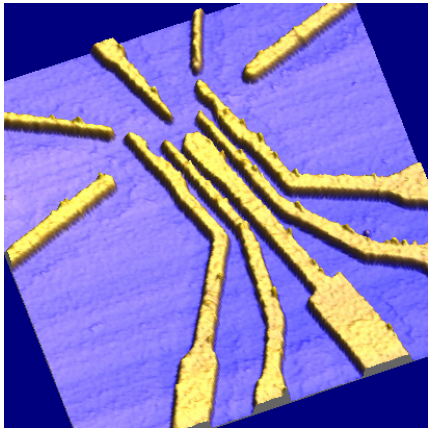
Trapped ions



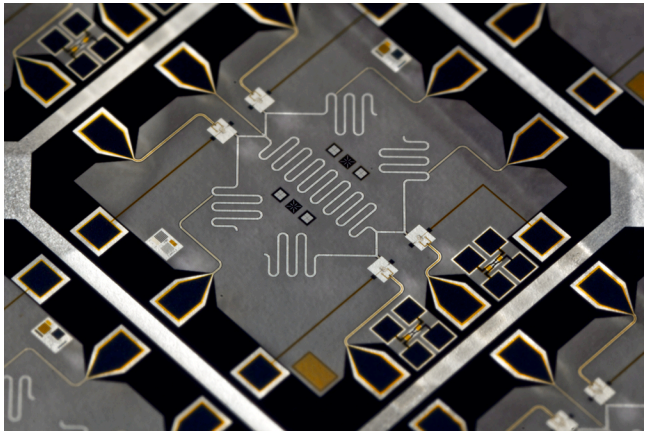
Photons



NV centers

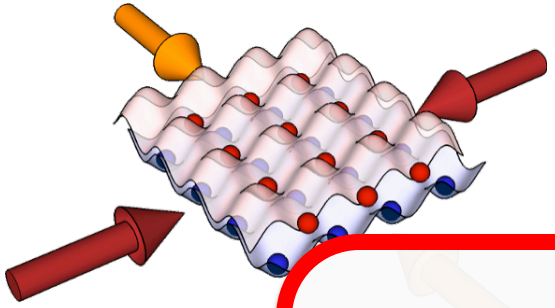


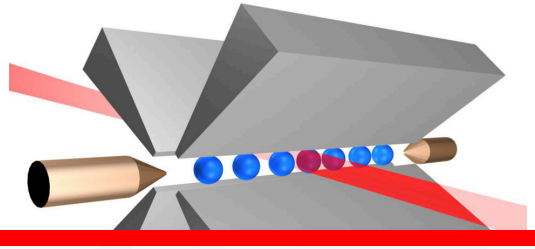
Quantum dots

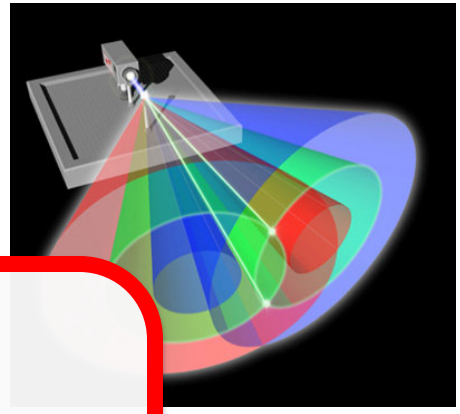


Superconducting qubits

Quantum state engineering with individual systems



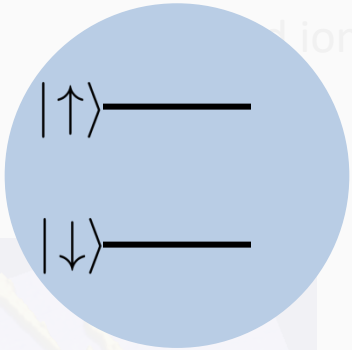




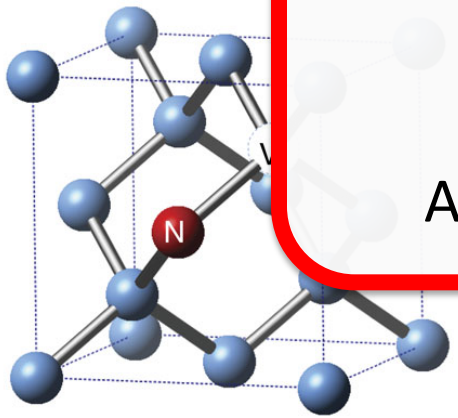
Neutral atoms

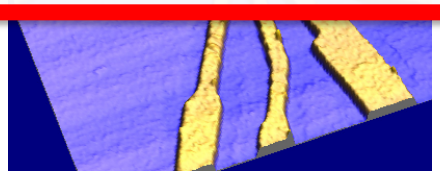
Photons

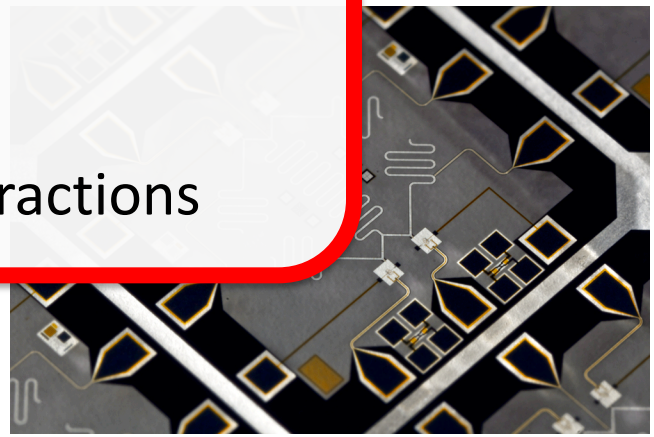
Two-level systems to encode a spin:



Addressable + controlled interactions





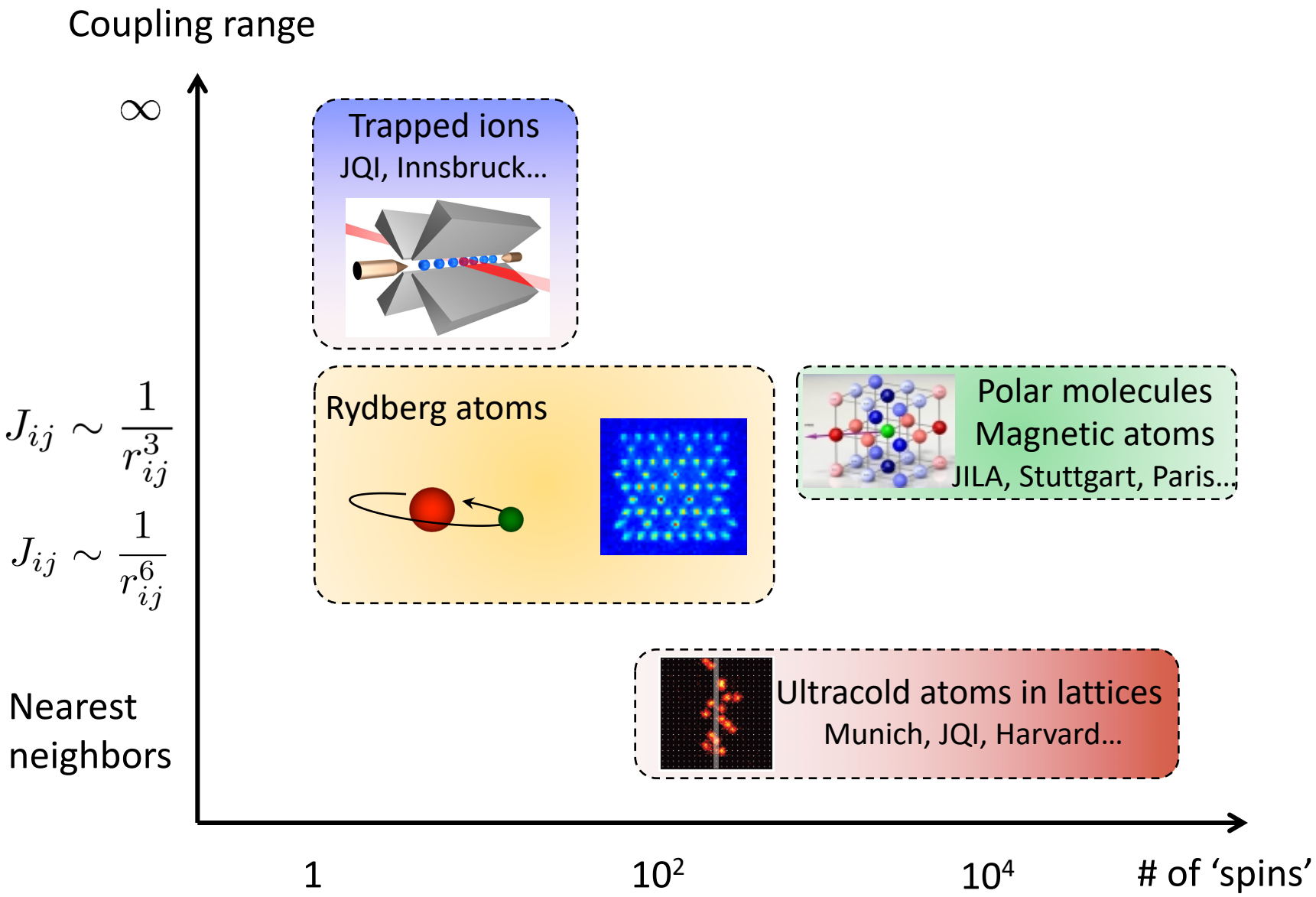


NV centers

Quantum dots

Superconducting qubits

Platforms in AMO physics



See e.g. Hazzard *et al.*, PRA **90**, 063622 (2014)

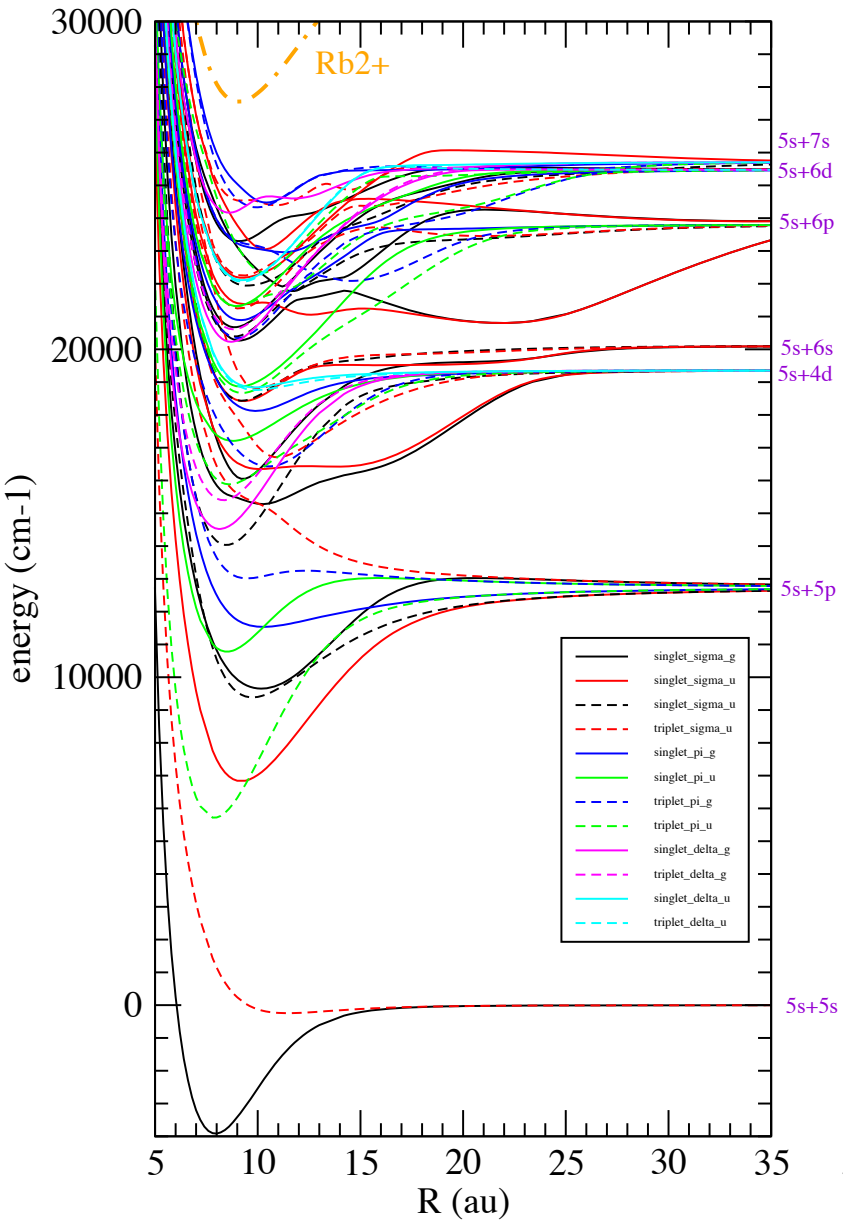
Outline

Lecture 1: Dipole-dipole interaction between atoms

Lecture 2: Basics of Rydberg physics. Arrays of cold atoms. Rydberg blockade & QIP

Lecture 3: Many-body physics with Rydberg atoms

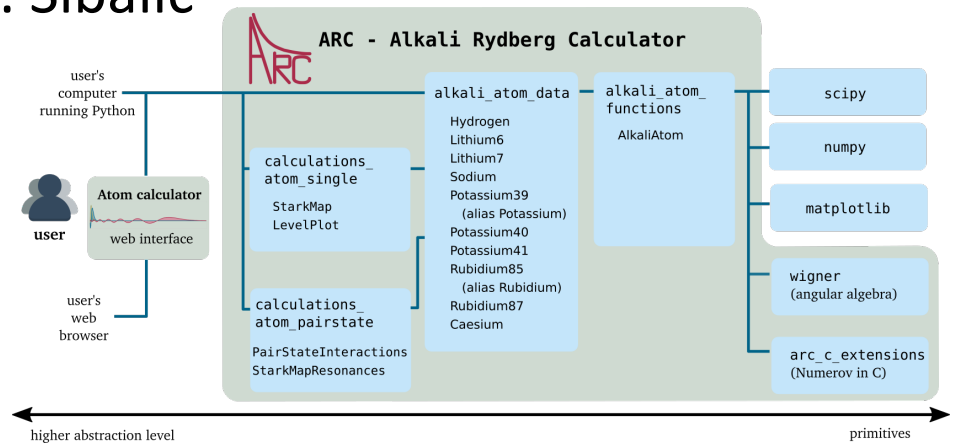
Molecular potentials Rb_2



O. Dulieu, LAC

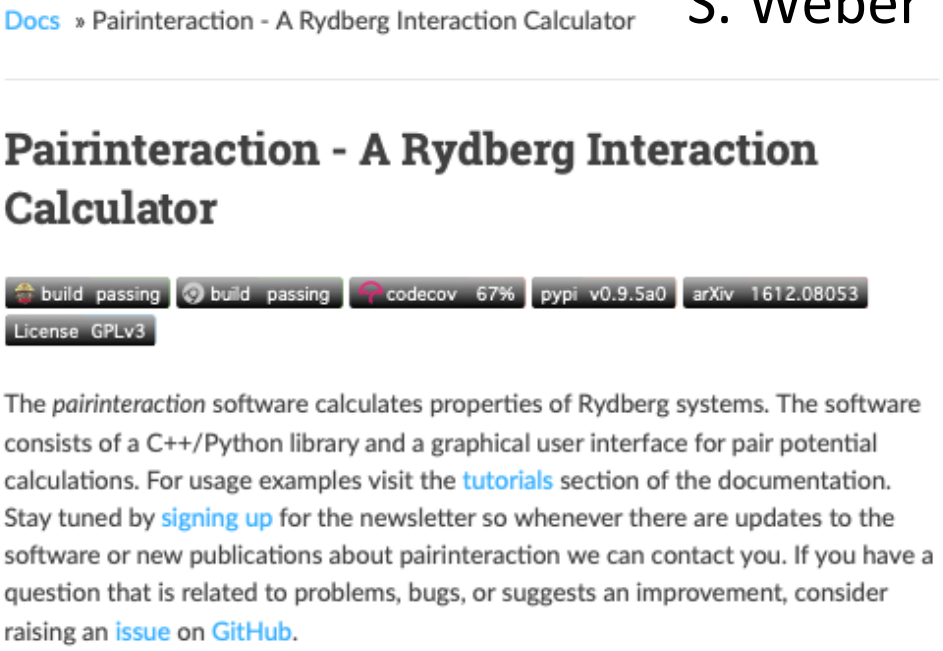
On-line interaction calculator

N. Sibalic



https://arc-alkali-rydberg-calculator.readthedocs.io/en/latest/

S. Weber



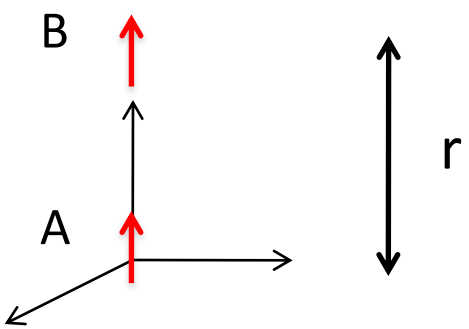
https://pairinteraction.github.io/pairinteraction/sphinx/html/index.html

Sub- and super radiant states (linear dipoles)

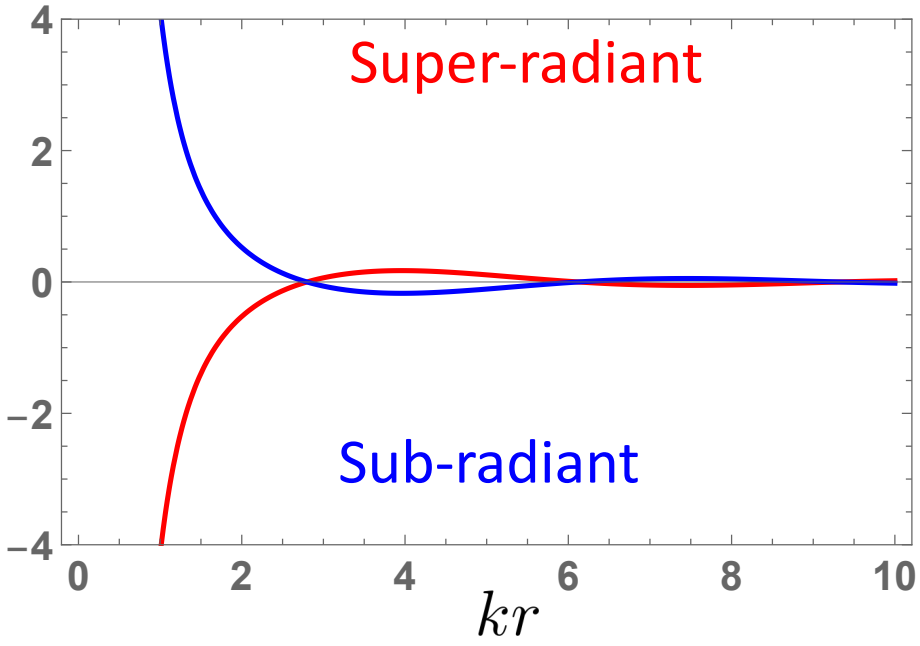
$$V_{A,B} = 2\,\Re[V_{\rm dd}]$$

$$\Gamma_{A,B} = \Gamma - 2\,\Im[V_{\rm dd}]$$

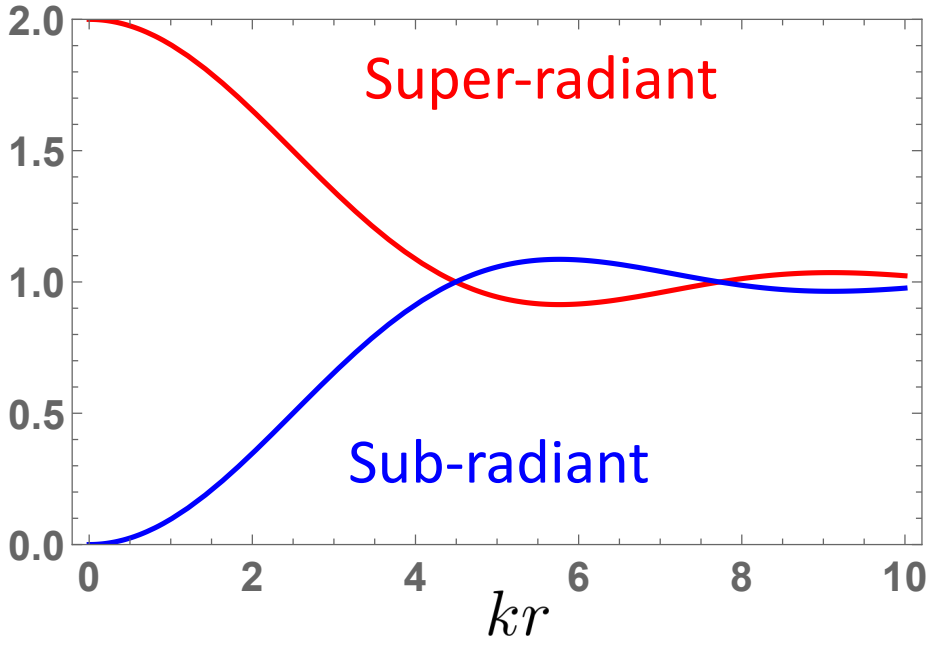
θ = 0



$V_{A,B}/\Gamma$



$\Gamma_{A,B}/\Gamma$

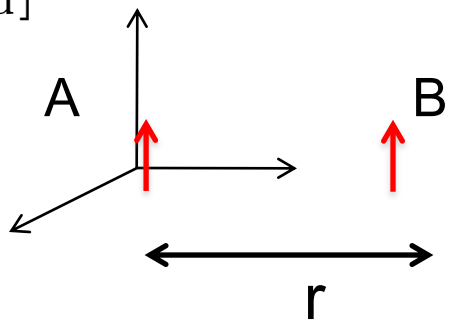


Sub- and super radiant states (linear dipoles)

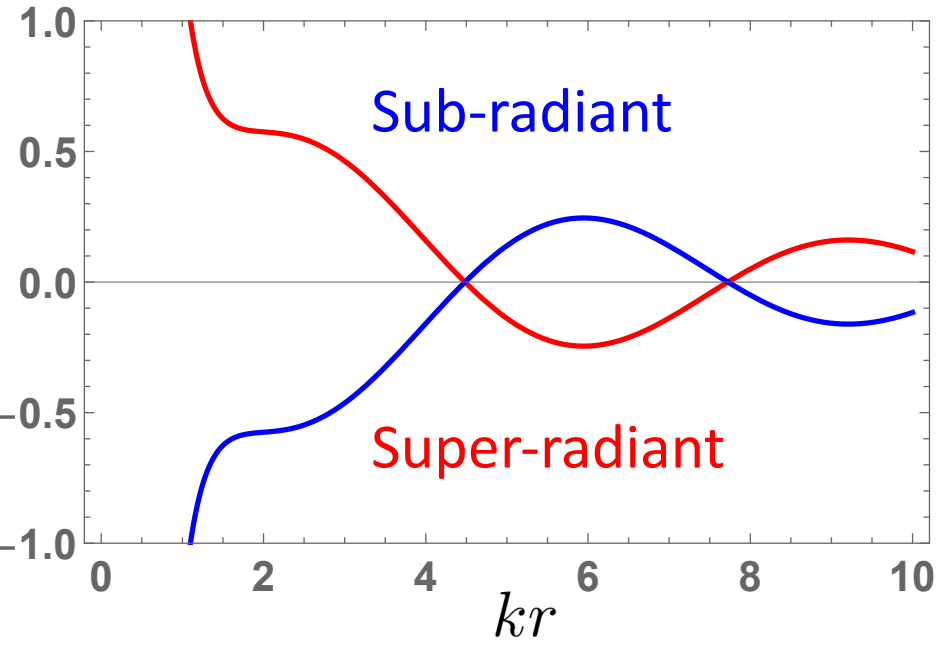
$$V_{A,B} = 2\,\Re[V_{\rm dd}]$$

$$\Gamma_{A,B} = \Gamma - 2\,\Im[V_{\rm dd}]$$

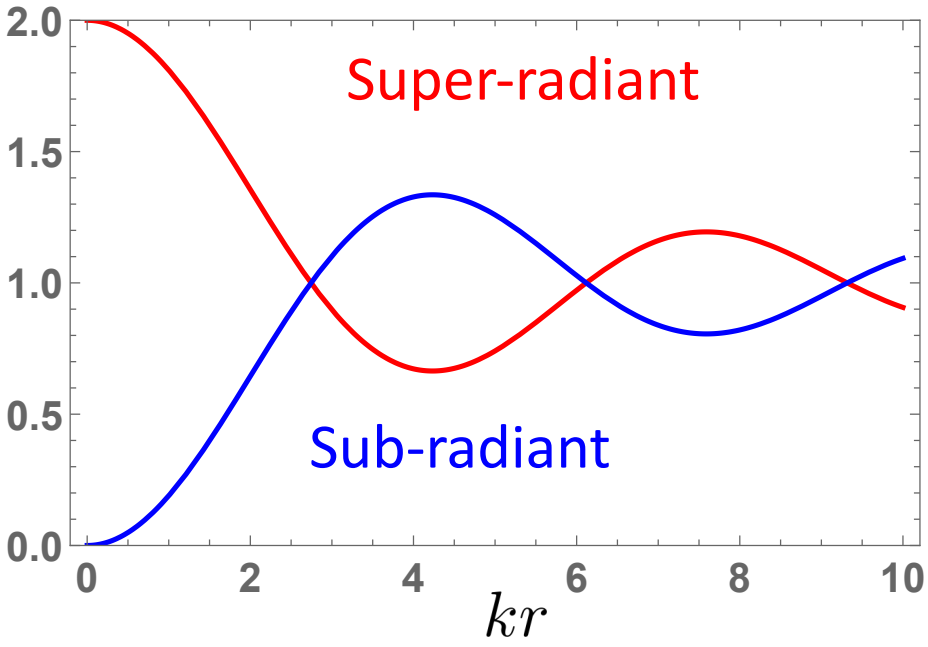
$\theta = \pi/2$



$V_{A,B}/\Gamma$



$\Gamma_{A,B}/\Gamma$



Near-field vs. far-field = coherent vs. collective dissipation

$$V_{\rm dd} = -\frac{d_{eg}^2 k^3}{4\pi\epsilon_0} e^{ikr}\left[\left(\frac{1}{(kr)^3} - \frac{i}{(kr)^2}\right)(3\cos^2\theta - 1) + \frac{\sin^2\theta}{kr}\right]$$

$kr \ll 1$

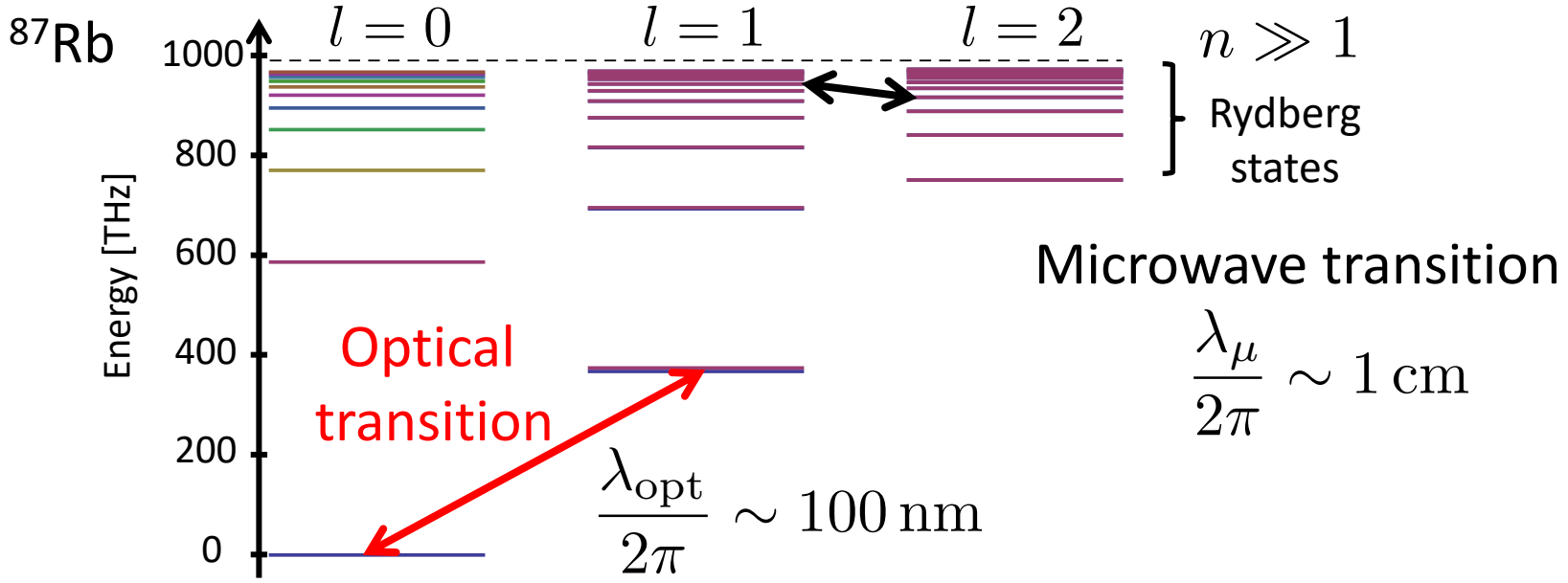
$$V_{\rm dd} \sim \frac{d_{eg}^2}{r^3} \gg \hbar\Gamma$$

$\Rightarrow$ "**coherent**" interaction

$kr \gtrsim 1$

$$V_{\rm dd} \sim \frac{\hbar\Gamma}{kr} \sim \hbar\Gamma$$

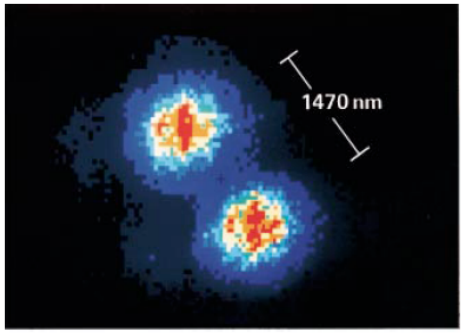
$\Rightarrow$ **Dissipative** spin models

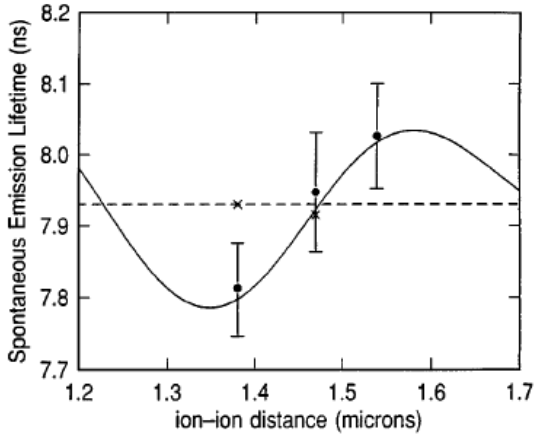


Resonant dipole interaction: observations of the eigenmodes

1. **Far field (R = 2 λ)**: Modification of lifetime Ba^+, $6S_{1/2} - 6P_{3/2}$

DeVoe, Brewer,
PRL **76**, 2049 (1996)





2. **Near field (R = 0.02 λ)**: spectroscopy of 2 Terrylene molecules

Hettich,
Science **298**, 385 (2002)