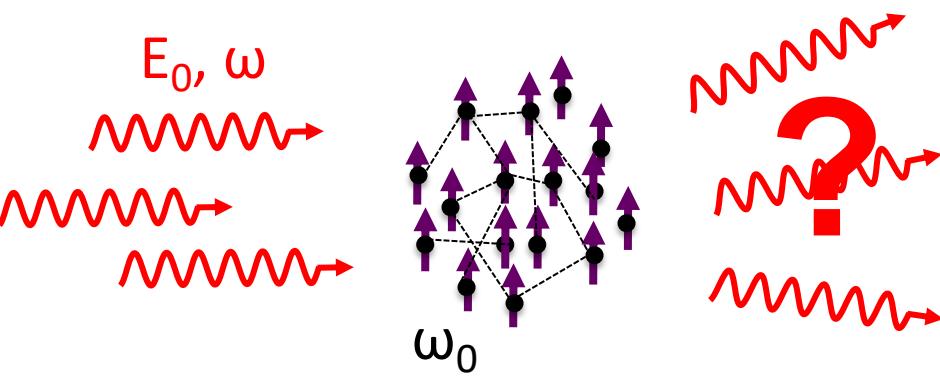
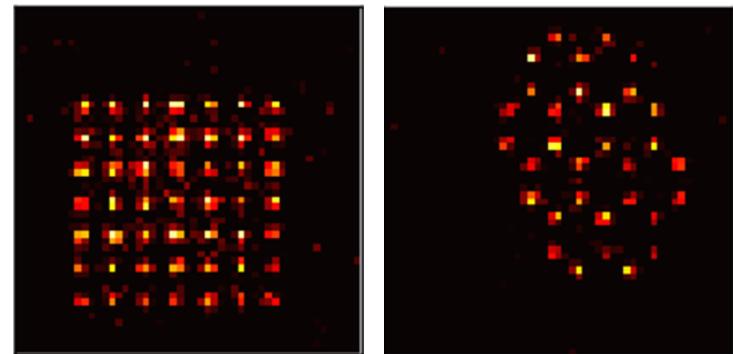


Dipole-dipole interactions between atoms for many-body physics and quantum information

Antoine Browaeys

*Laboratoire Charles Fabry,
Institut d'Optique, CNRS, FRANCE*

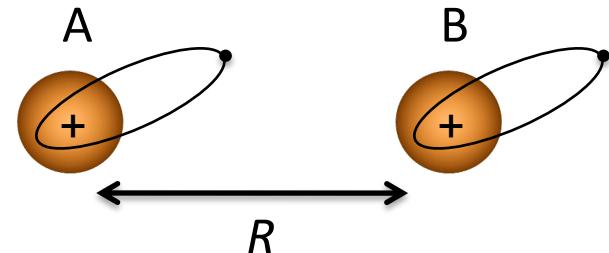
Dipole interactions for QIP and many-body physics



Interactions between
light-induced dipoles

See: A. Asenjo-Garcia
R. Kaiser

Rydberg interactions



Van der Waals

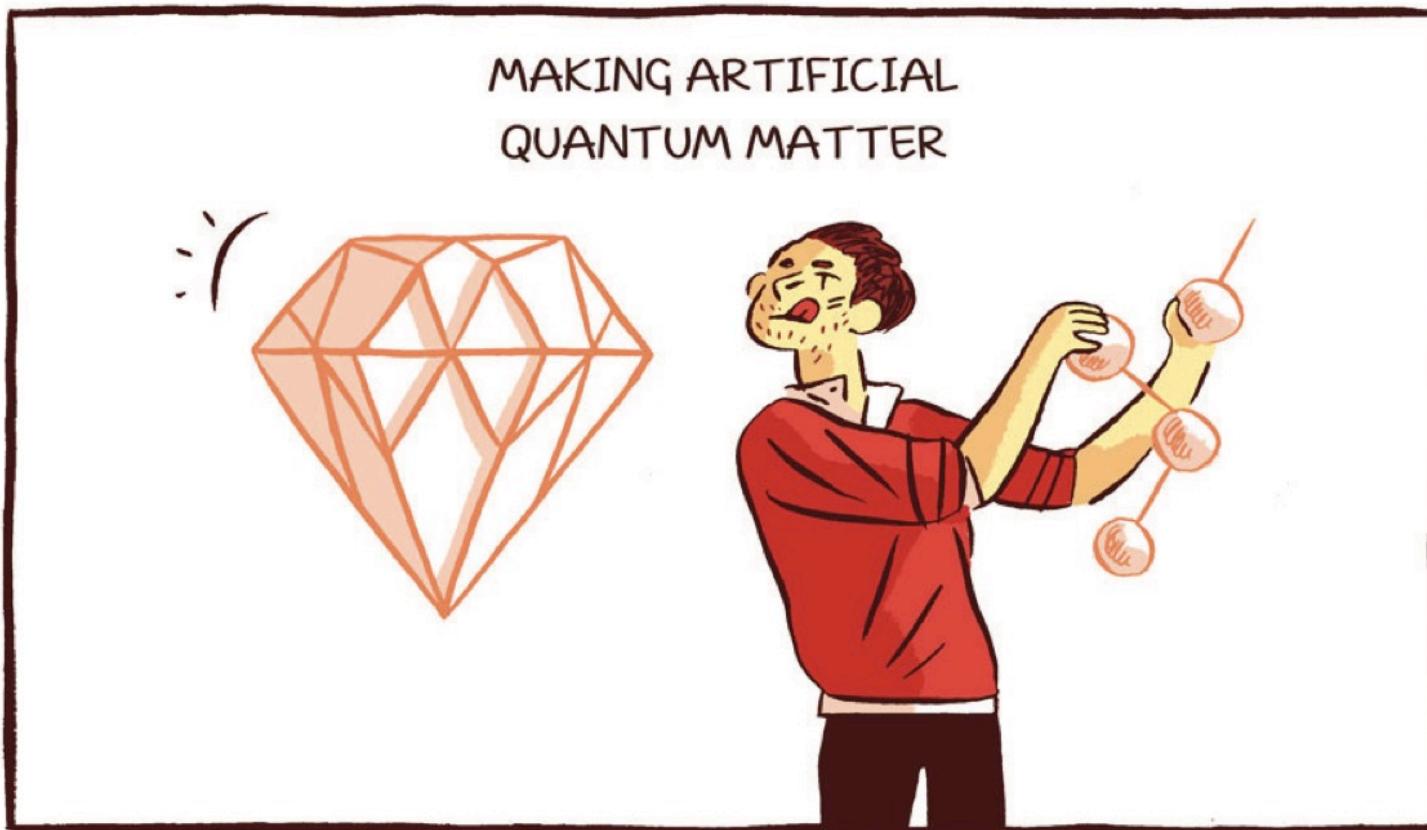
$$\frac{C_6}{R^6}$$

resonant

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

Our Goal

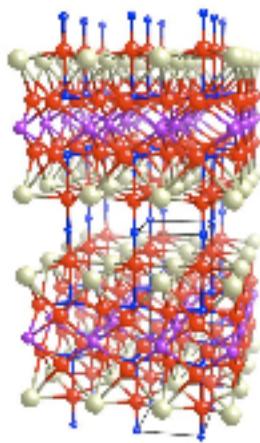
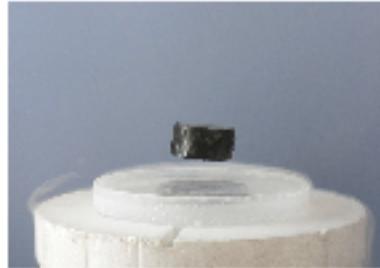
(as many groups...)



Héloïse Chochois, for Labex PALM

Quantum state engineering: create controlled quantum states

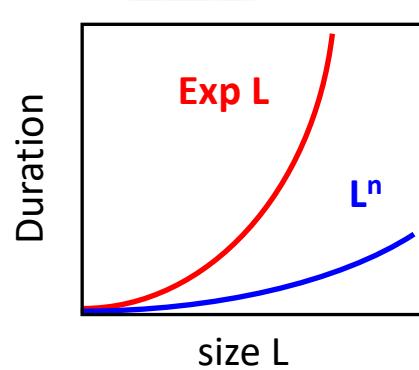
Many-body physics



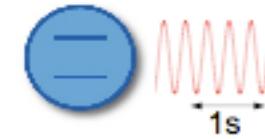
Quantum information



Message

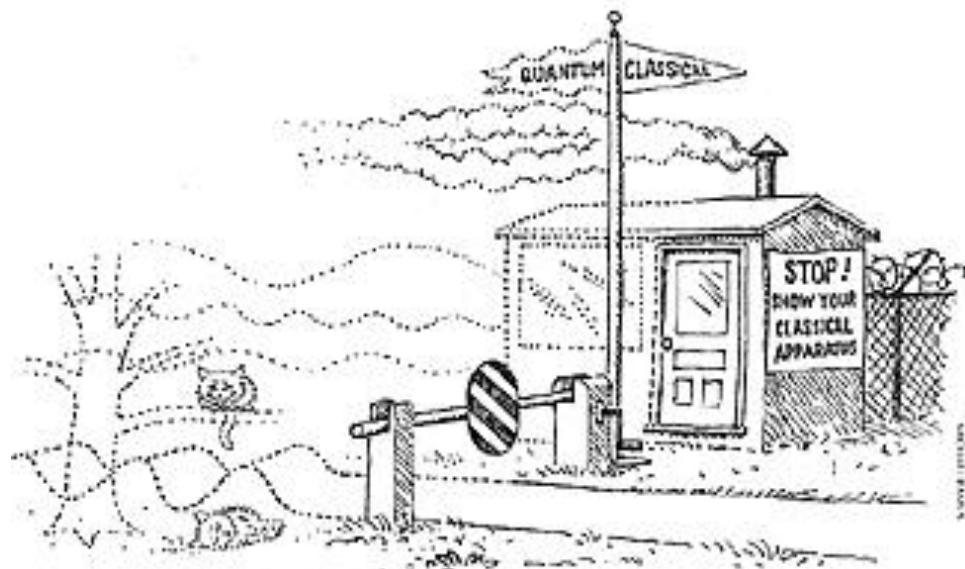


Quantum metrology

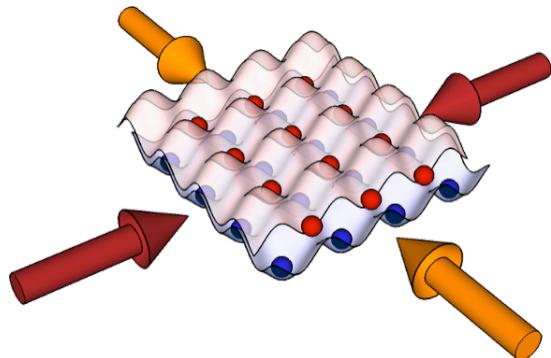


$$\frac{\Delta\nu}{\nu_0} \propto \frac{1}{\sqrt{N}} \xrightarrow{\text{qu. states}} \frac{\Delta\nu}{\nu_0} \propto \frac{1}{N}$$

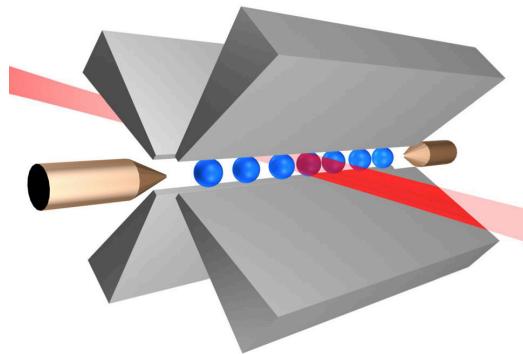
Transition quantum / classical



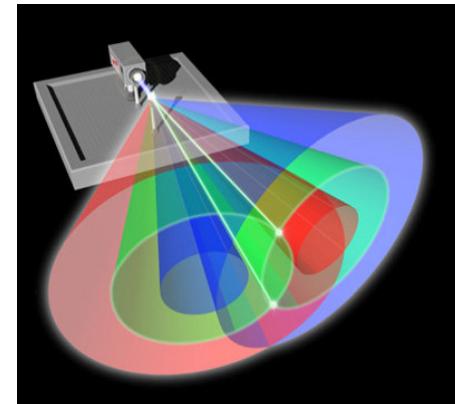
Quantum state engineering with individual systems



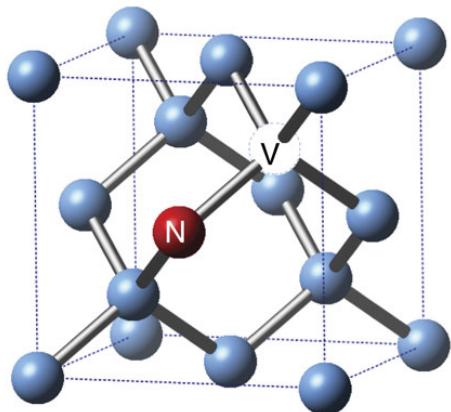
Neutral atoms



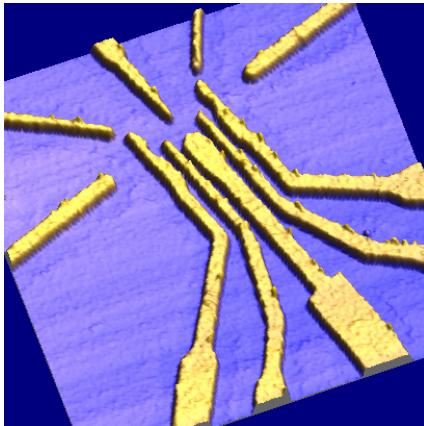
Trapped ions



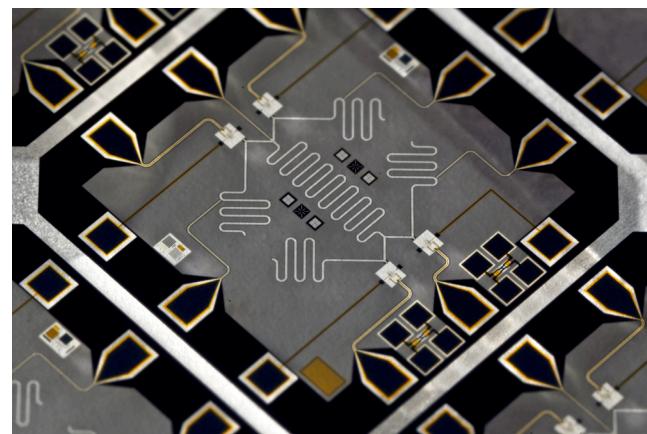
Photons



NV centers

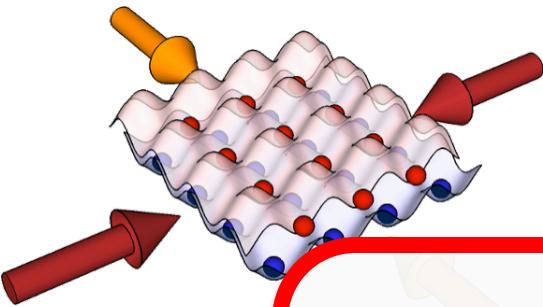


Quantum dots

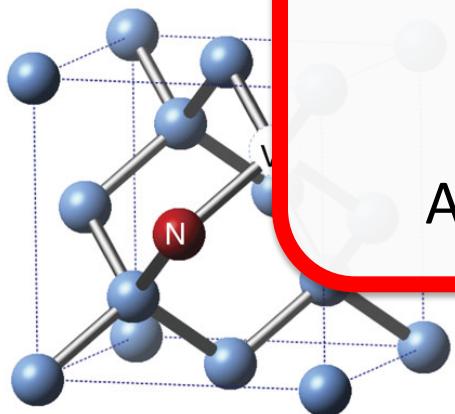


Superconducting qubits

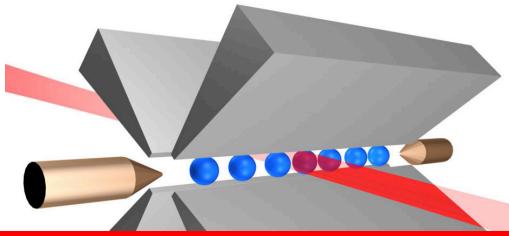
Quantum state engineering with individual systems



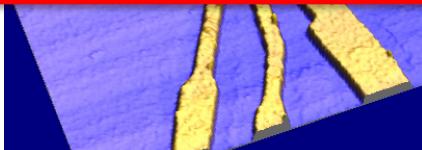
Neutral atoms



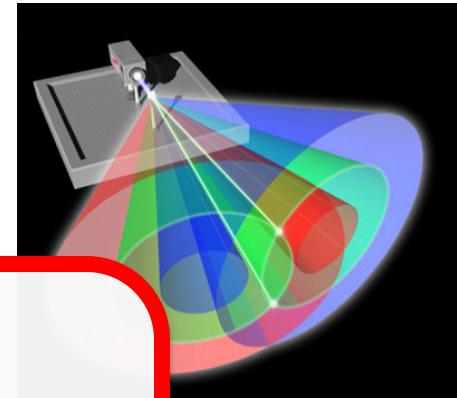
NV centers



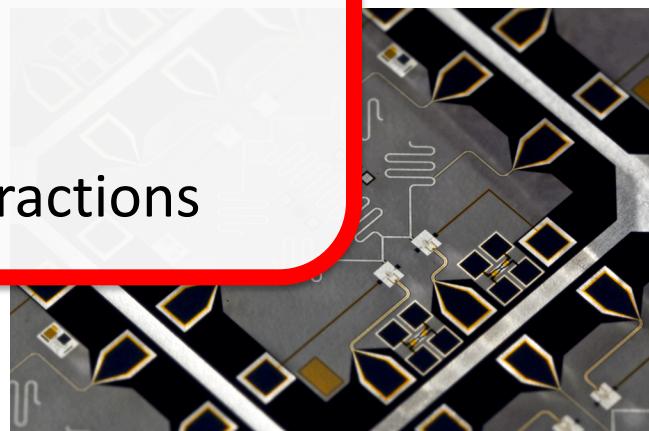
Ions



Quantum dots

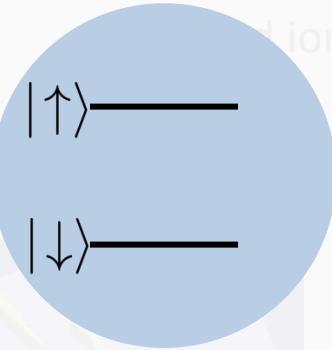


Photons



Superconducting qubits

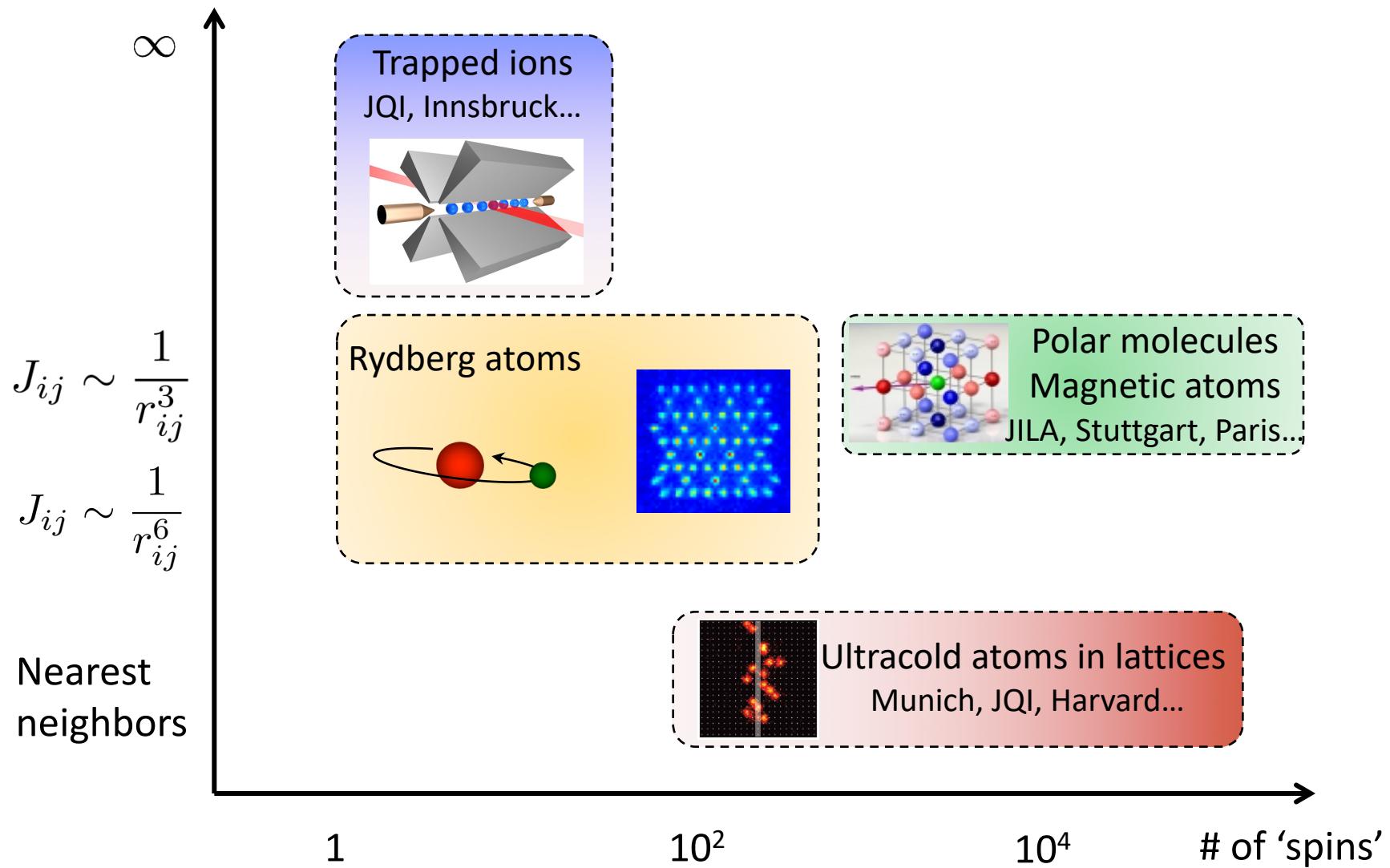
Two-level systems to encode a spin:



Addressable + controlled interactions

Platforms in AMO physics

Coupling range



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

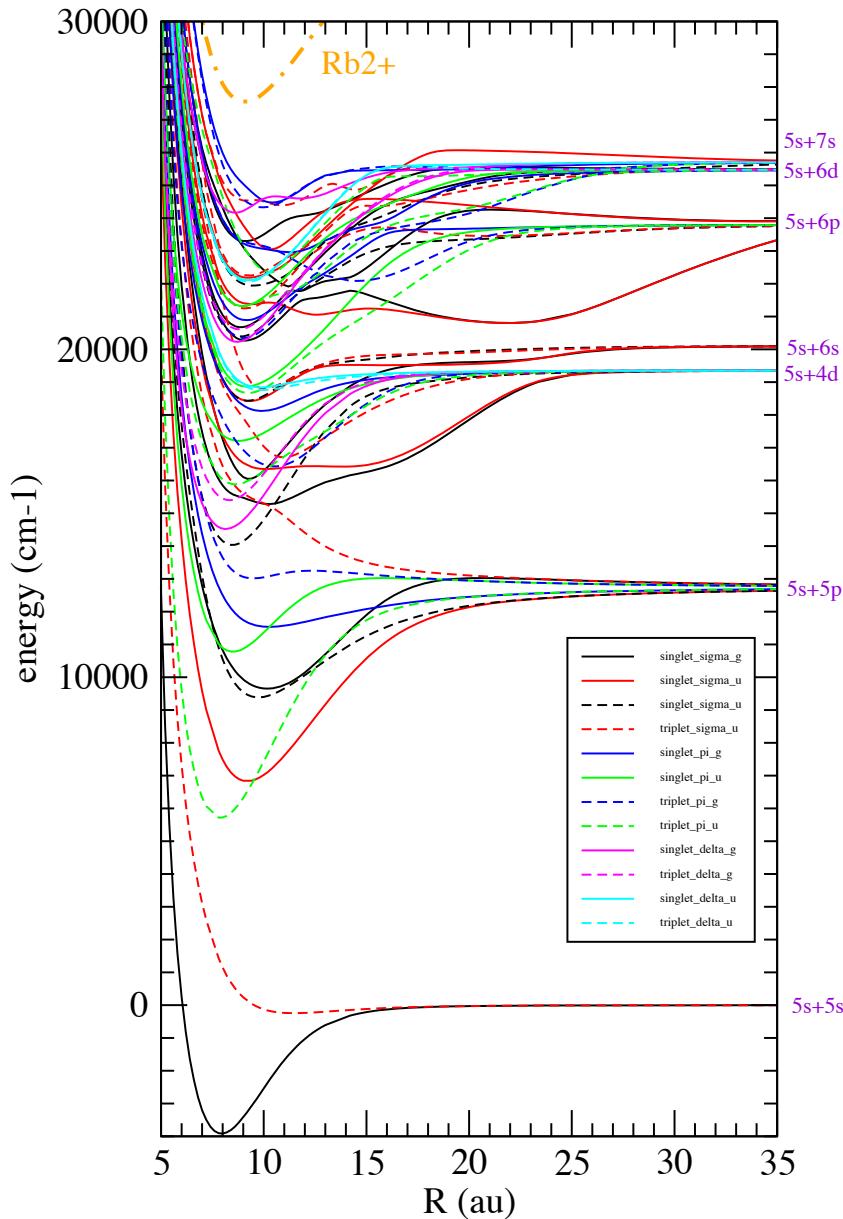
Outline

Lecture 1: Dipole-dipole interaction between atoms

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

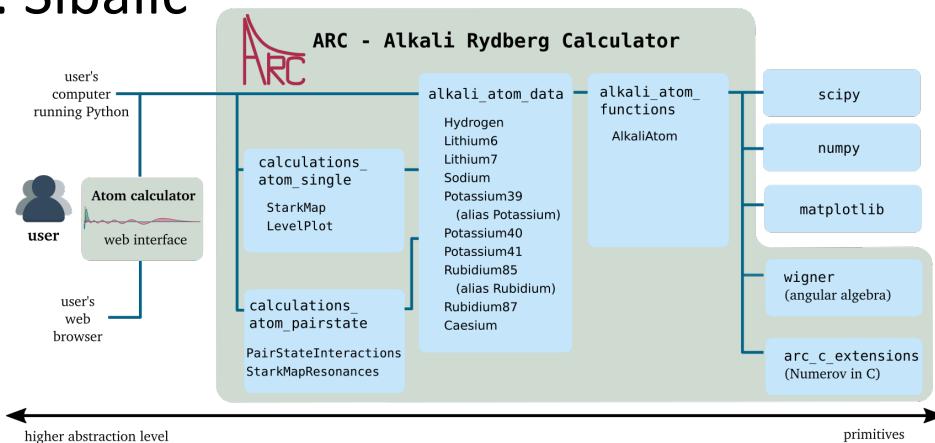
Lecture 3: Many-body physics with Rydberg atoms

Molecular potentials Rb₂



On-line interaction calculator

N. Sibalic



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

[Docs](#) » Pairinteraction - A Rydberg Interaction Calculator

S. Weber

Pairinteraction - A Rydberg Interaction Calculator



The *pairinteraction* software calculates properties of Rydberg systems. The software consists of a C++/Python library and a graphical user interface for pair potential calculations. For usage examples visit the [tutorials](#) section of the documentation. Stay tuned by [signing up](#) for the newsletter so whenever there are updates to the software or new publications about pairinteraction we can contact you. If you have a question that is related to problems, bugs, or suggests an improvement, consider raising an [issue](#) on [GitHub](#).

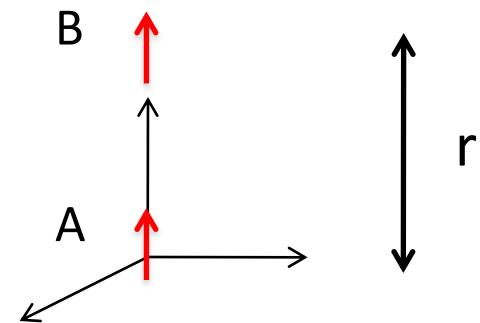
<https://pairinteraction.github.io/pairinteraction/sphinx/html/index.html>

Sub- and super radiant states (linear dipoles)

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

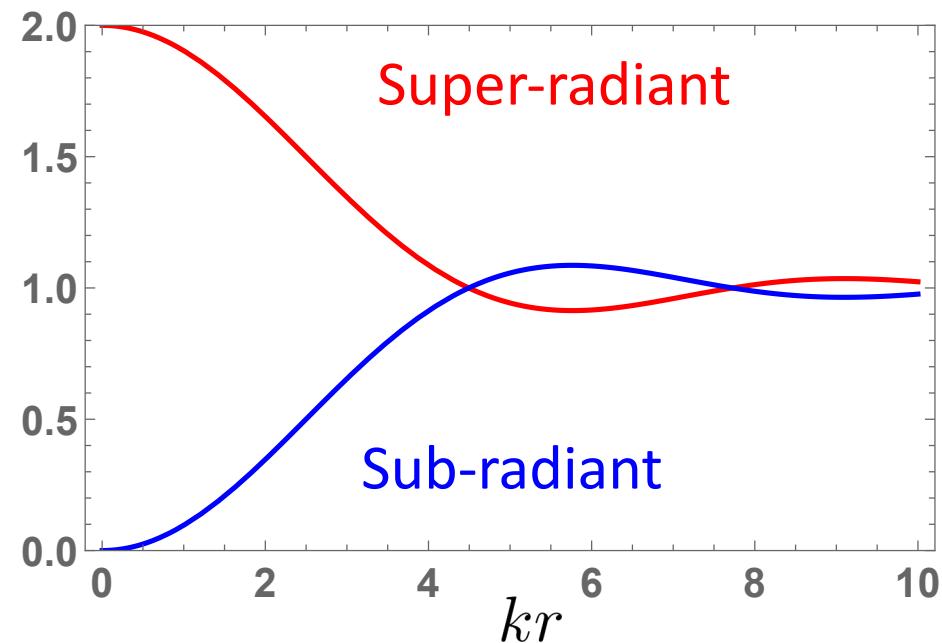
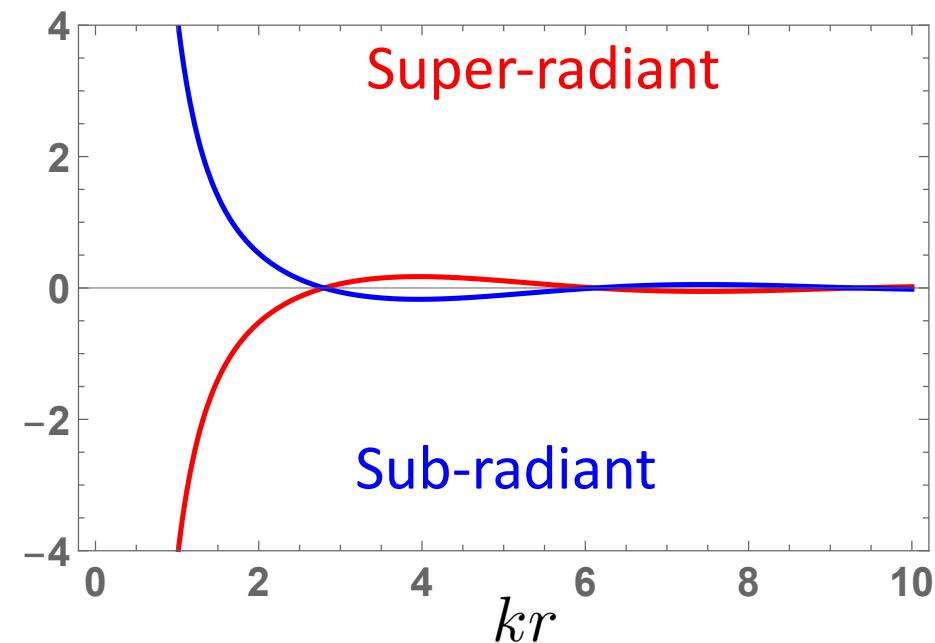
$$\theta = 0$$

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



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

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

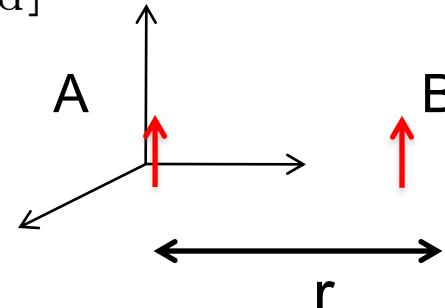


Sub- and super radiant states (linear dipoles)

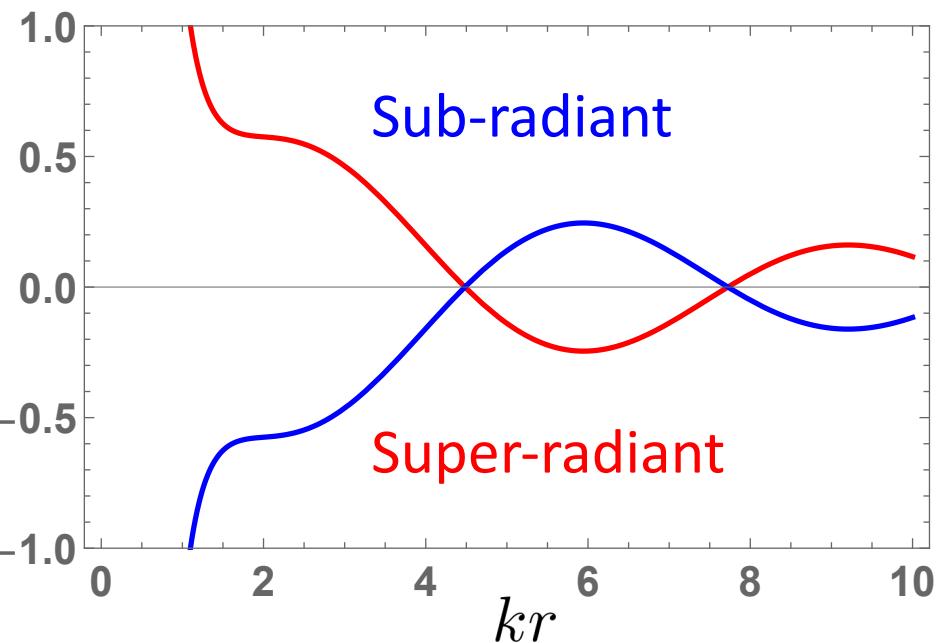
$$V_{A,B} = 2 \Re[V_{dd}]$$

$$\theta = \pi/2$$

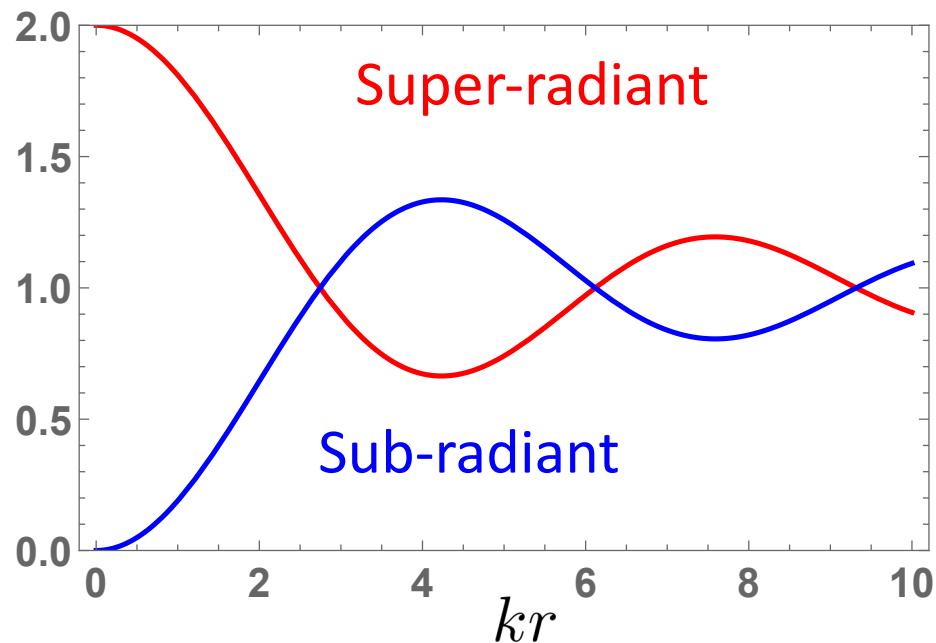
$$\Gamma_{A,B} = \Gamma - 2 \Im[V_{dd}]$$



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



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



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

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

$$kr \ll 1$$

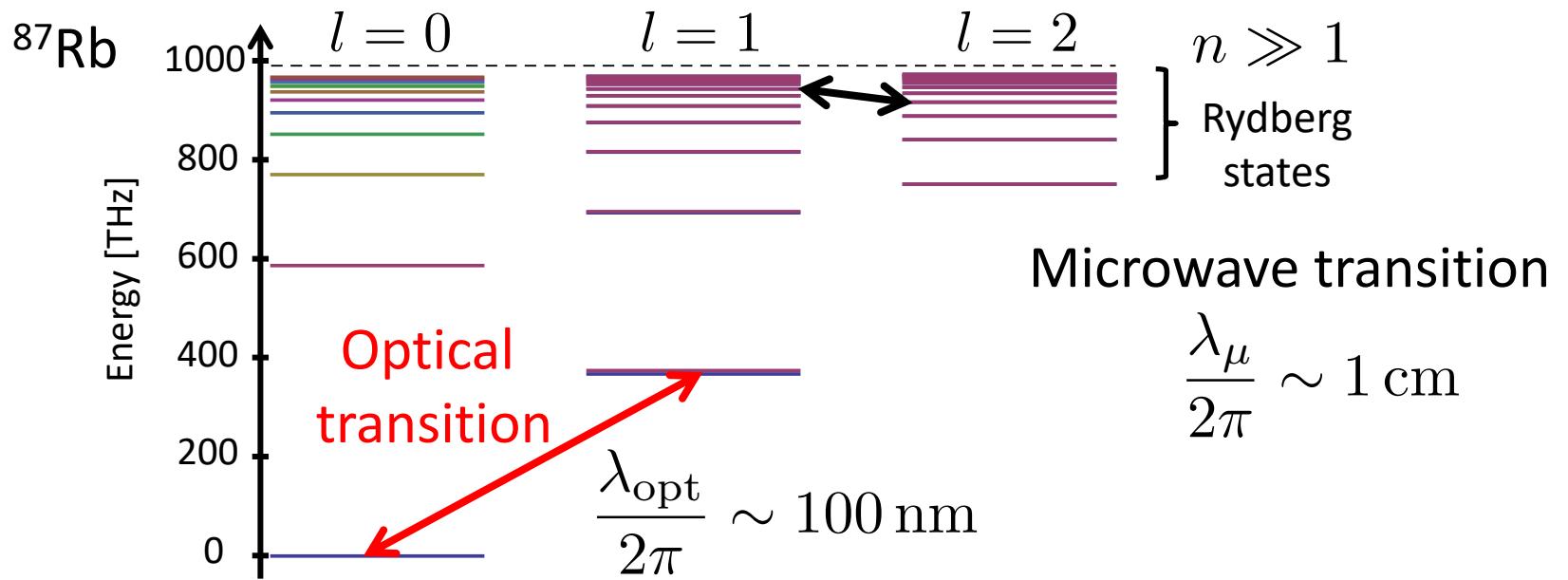
$$V_{dd} \sim \frac{d_{eg}^2}{r^3} \gg \hbar\Gamma$$

$$kr \gtrsim 1$$

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

⇒ “coherent” interaction

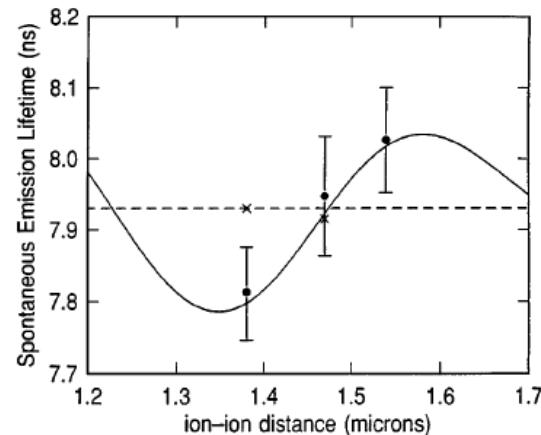
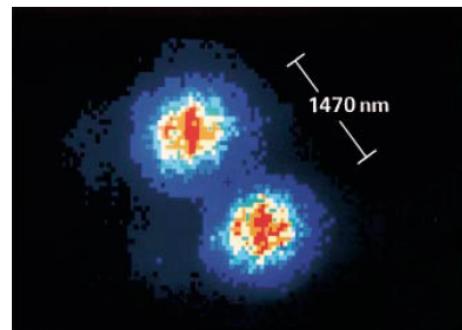
⇒ **Dissipative** spin models



Resonant dipole interaction: observations of the eigenmodes

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

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



2. Near field ($R = 0.02 \lambda$): spectroscopy of 2 Terrylene molecules

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

