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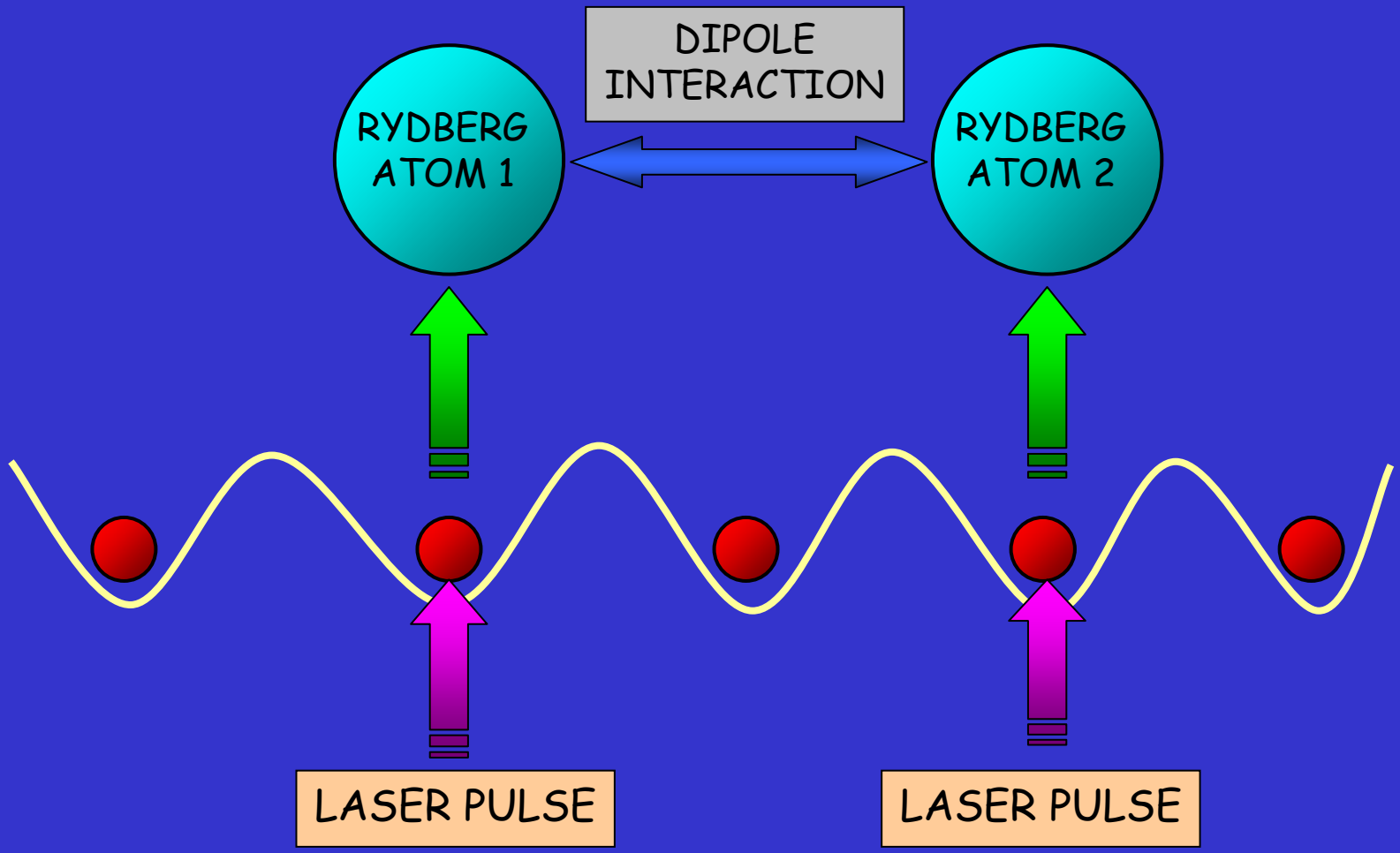
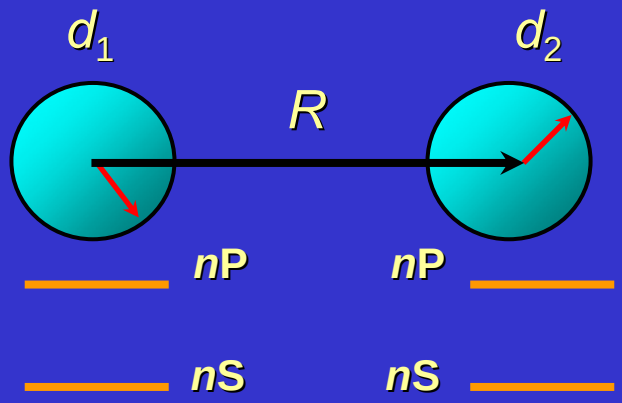
Implementation of quantum logic gates with Rydberg atoms

QUANTUM GATES WITH COLD ATOMS TRAPPED IN OPTICAL LATTICES



Principal quantum numbers: limitation by collisions



$$\hat{H}_{dd} = \frac{1}{4\pi\varepsilon_0}\left[\frac{\hat{\mathbf{d}}_1\hat{\mathbf{d}}_2}{R^3} - \frac{3\left(\hat{\mathbf{d}}_1\mathbf{R}\right)\left(\hat{\mathbf{d}}_2\mathbf{R}\right)}{R^5}\right]$$

Dipole moment: $d = e\,r$ $\qquad \langle r \rangle = a_0\{3n^2 - L(L+1)\}/2$

No collisions: $R > 10\,\langle r \rangle$

$$n_{max} \sim \sqrt{\frac{R}{15\,a_0} + \frac{L(L+1)}{3}}$$

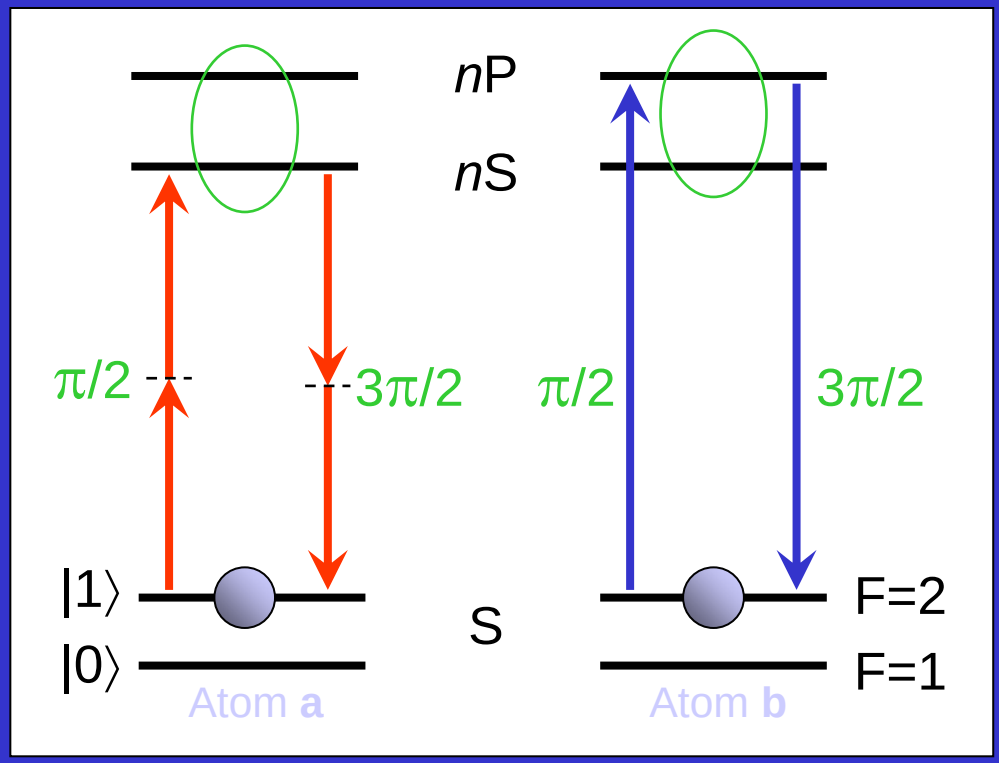
Individual addressing: $R > 1\ \mu m$

CO_2-laser lattice: $R \approx 5\ \mu m$

Low-L states: $n_{max} \sim 70$

Time of single quantum operation

Conditional Quantum Phase Gate $|ab\rangle \rightarrow \exp(i\Phi\delta_{a1}\delta_{b1})\,|ab\rangle$



$\Psi(t) = |SP\rangle \cos(V_{dd}t/\hbar) - i\,|PS\rangle \sin(V_{dd}t/\hbar)$

$\Phi = \pi$ at $T = \pi\hbar / V_{dd}$

For $n = 50$ and $R \approx 5$ μm

T~50 ns **V_{dd}/h ~10 MHz**

Laser pulses must be short $\tau < 5$ ns!

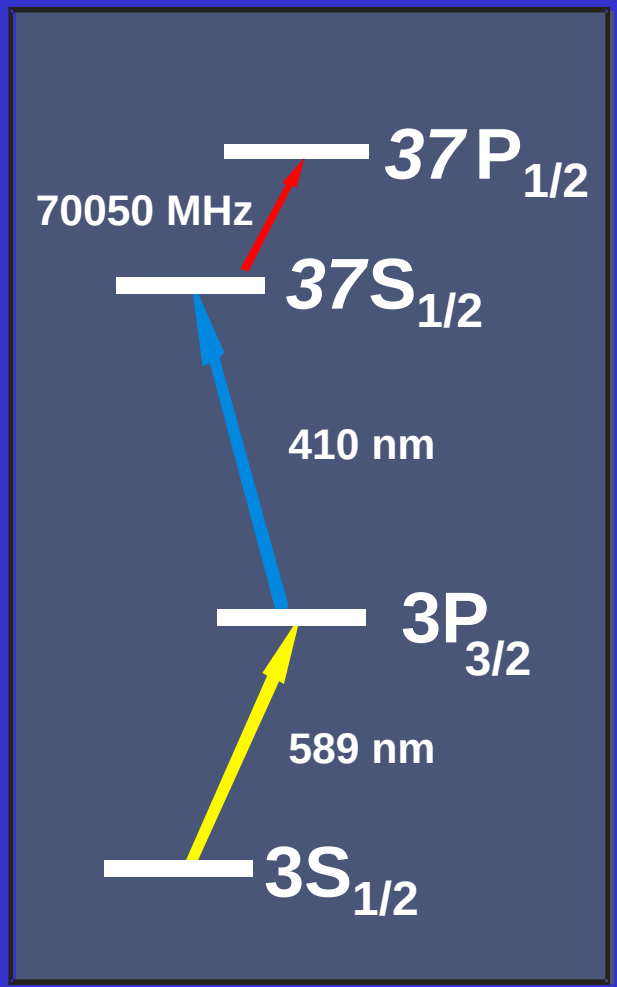
Probability of excitation: $W \sim n^{-3}$

n=50 τ= 5 ns: P_{laser} ~ 0.5 W/atom

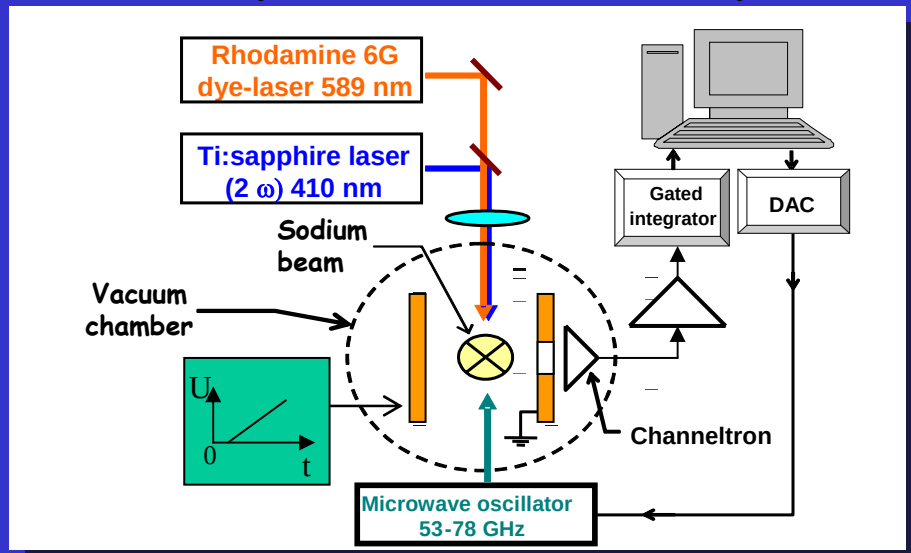
OPTIMIZATION: $n \approx 30£35$ $T \approx 500$ ns $\tau \approx 50$ ns P_{laser} ~ 1 mW/atom

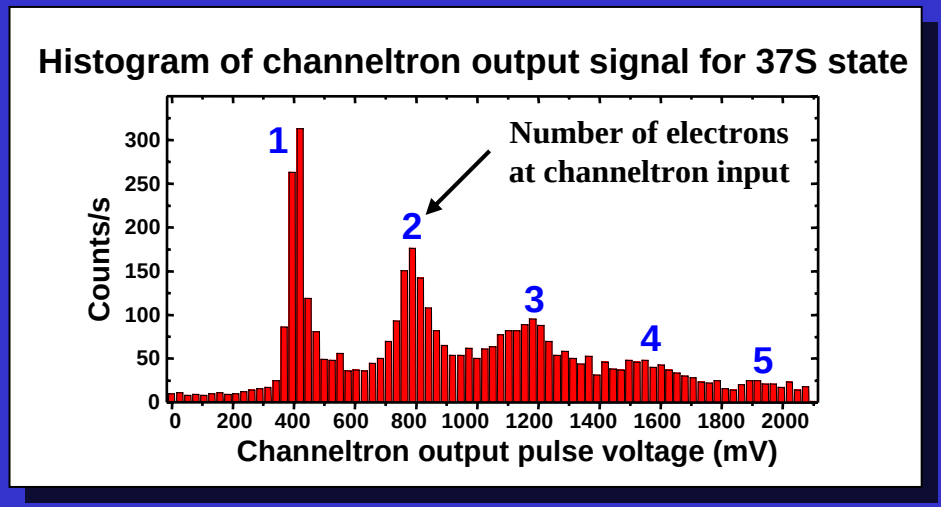
MICROWAVE SPECTROSCOPY OF MULTI-ATOM EXCITATIONS OF Na

Laser excitation

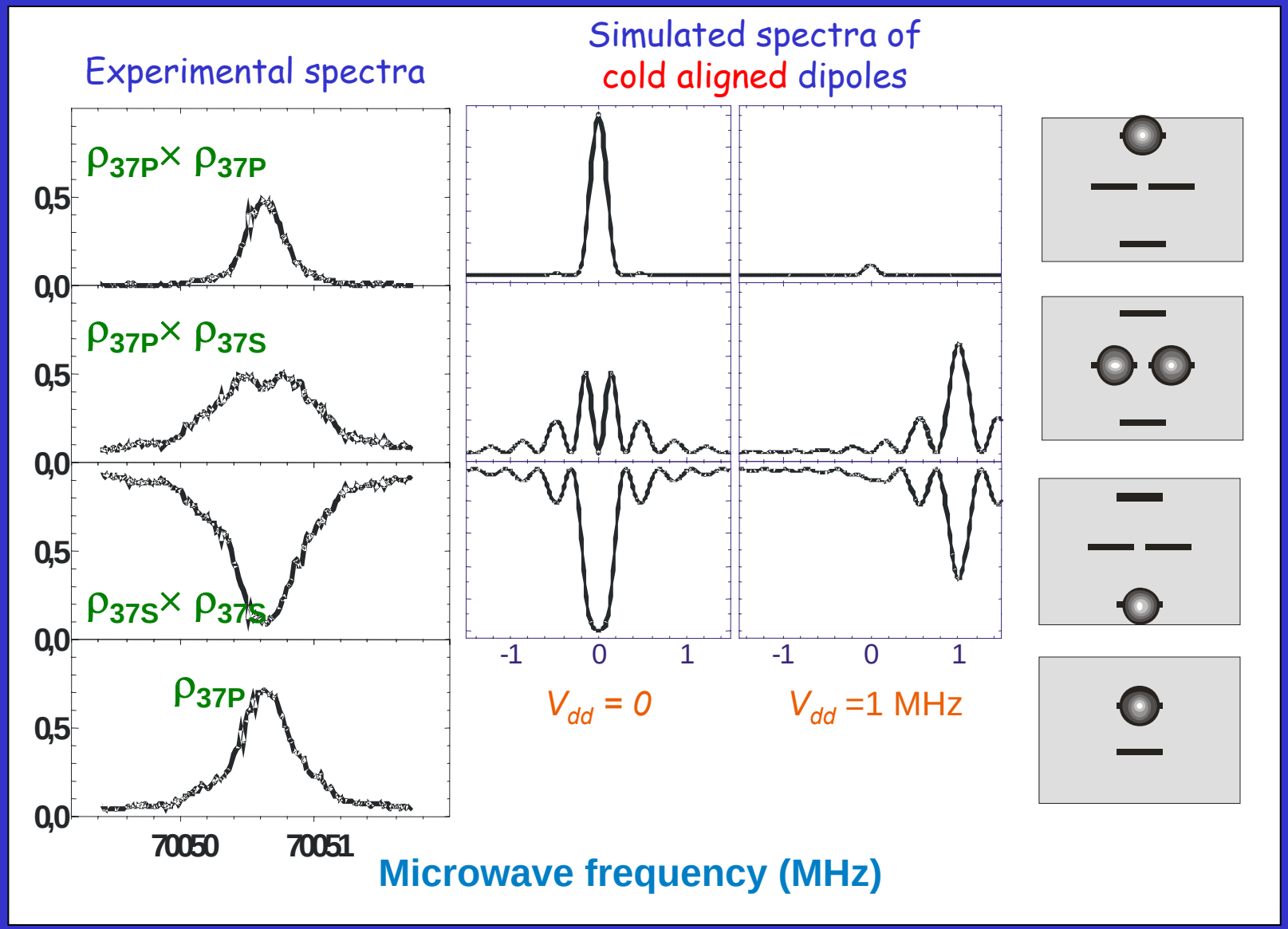


Experimental setup

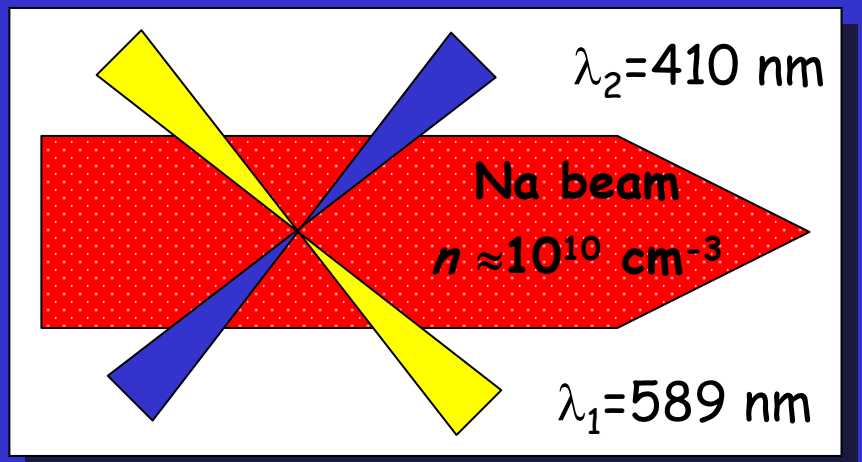




Two-atom spectra of one-photon transition $37S_{1/2}$-$37P_{1/2}$



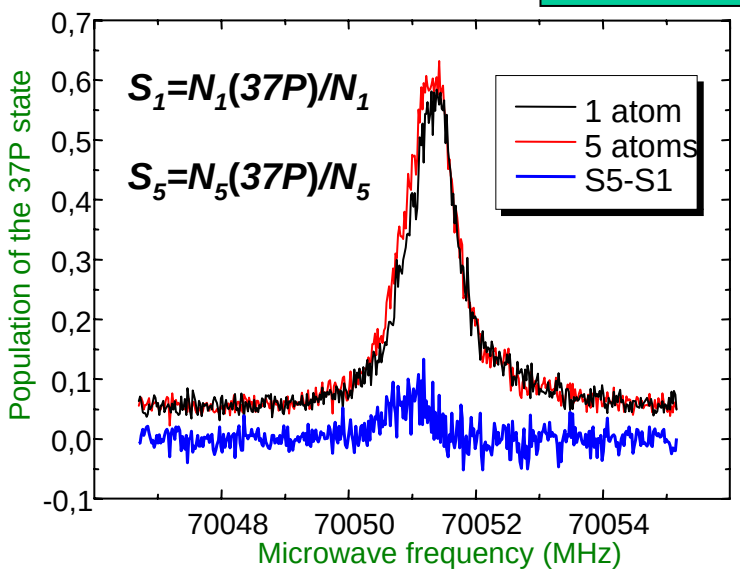
Experiment for hot random Na dipoles

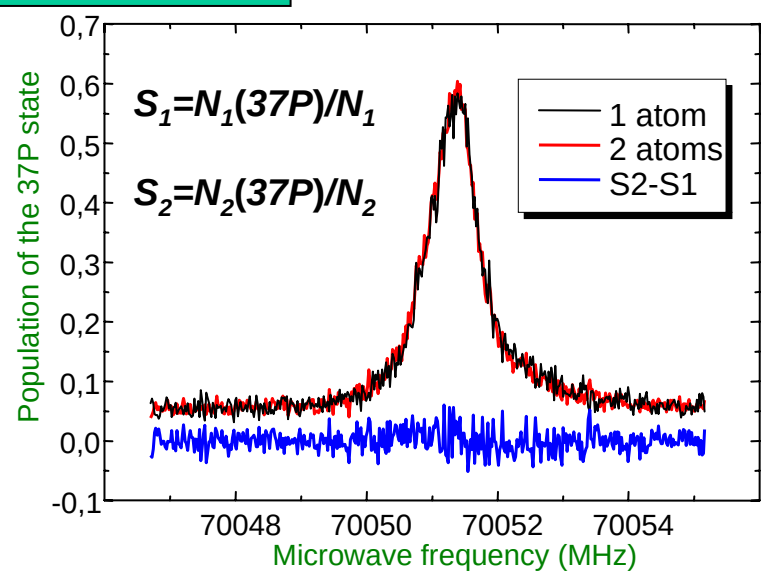


- Pulsed lasers at λ_1 and λ_2
- 25-35 μm laser beam waists
- 15 μm average distance between Rydberg atoms
- 300 m/s average relative velocity
- 50 ns average interaction time

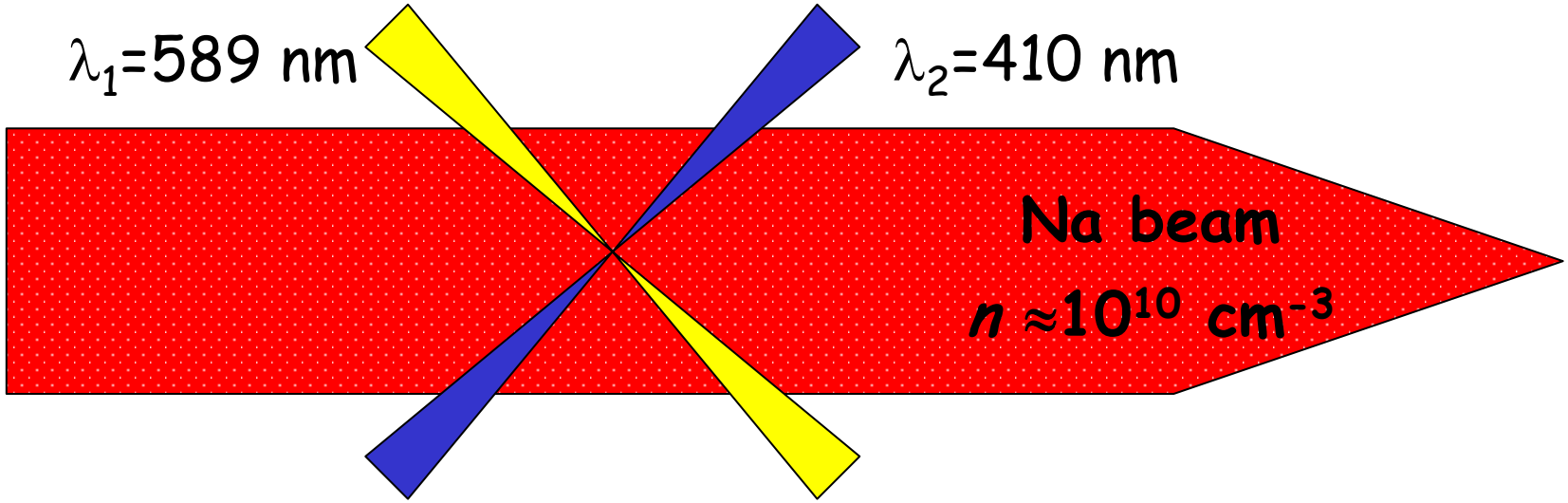
Microwave spectra for randomly moving dipoles

$37S_{1/2} \rightarrow 37P_{1/2}$ transition



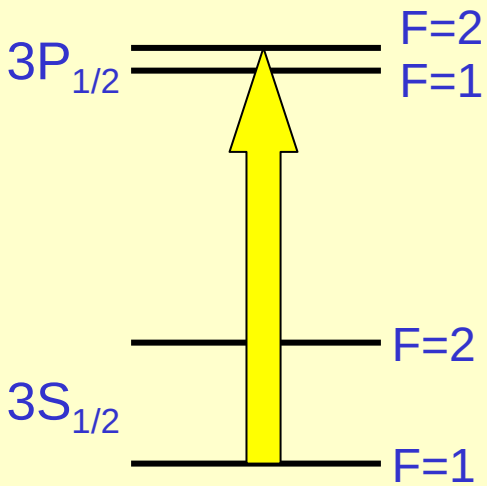


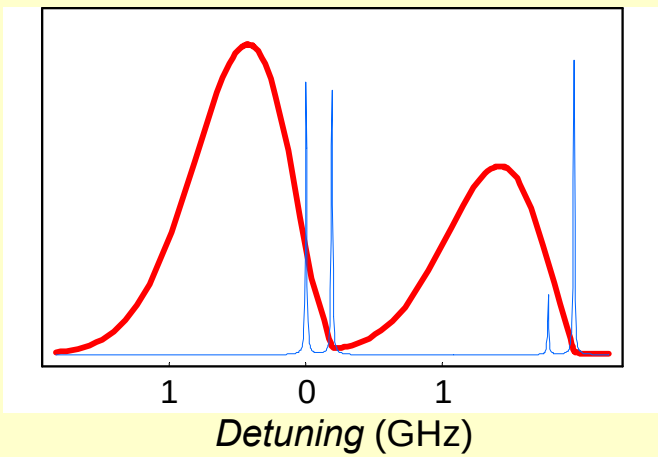
In progress: Experiment with velocity selected dipoles



- CW laser at λ_1
- Pulsed laser at λ_2
- 20 μm laser beam waists
- 10 μm average distance between Rydberg atoms
- 500 ns average interaction time

Velocity selection: V=600±30 m/s





SUMMARY

- Rydberg atoms are a promising tool for quantum information processing with neutral atoms.
- The principal quantum numbers $n \sim 30 \div 35$, interatomic distances ~ 5 μm, exciting laser pulses ~ 50 ns, and ~ 500 ns time of dipole-dipole interaction seem to be optimal to realize a two-qubit quantum phase gate in optical lattices of cold alkali atoms.
- Microwave spectroscopy of Rydberg atoms in the atomic beam helps reveal the populations and interactions in a quasi-molecule formed by a few atoms.
- Preliminary experimental data demonstrate the signatures of dipole-dipole interaction between five close Rydberg atoms in the atomic beam and point towards further experiments with velocity selected and cold atoms.