Photonic phase-gate using Rydberg atoms and Microwaves

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Aim

Design a quasi-deterministic phase gate for photonic qubits using cold Rydberg atoms

EIT + Rydbergs

allow storage of single excitations in an atomic cloud and provide strong nonlinear interactions [1-4,7]

Separate storage and interactions

using microwaves and an auxiliary state to prevent loss.

Nonlocal character

of the blockade might allow circumvention of conventional limitations to local (Kerr-like) nonlinearities [7-9]

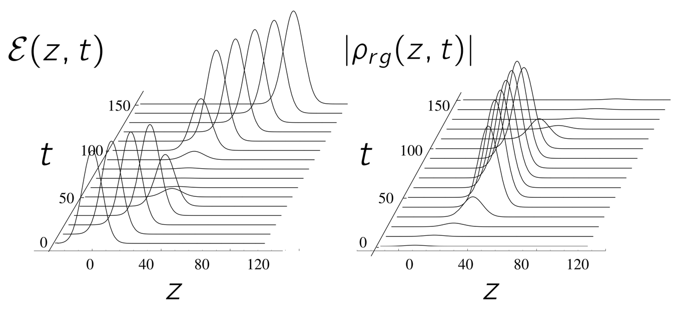
Storage and retrieval

dual rail photonic qubits → EIT → atomic excitations (polaritons)

Using **electromagnetically induced transparency** (EIT), **photonic qubits are coherently mapped** into a spin wave (polariton) [14,15] with Rydberg content.

$$\Psi(z,t) = \cos\theta\,\mathcal{E}(z,t) - \sin\theta\sqrt{N}\rho_{rg}(z,t)e^{i\Delta kz}$$

light — atomic excitation



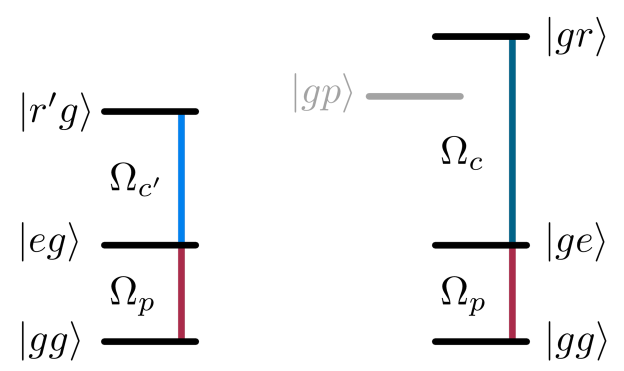
$n_{gr} \propto \frac{1}{\Omega_c^2}$ Group index

$\tan^2\theta = n_{gr} - 1$

Polaritons involve **Rydberg levels with strong interactions**, which stores each photon as a **collective excitation**.

$$|r\rangle = \sum_i^N e^{i\phi_i}|r_i\rangle$$

The summation is carried out over states with a single excitation $|r_i\rangle = |g...r_i...g\rangle$



Noninteracting level system for the control (left) and target (right) states in the inner region.

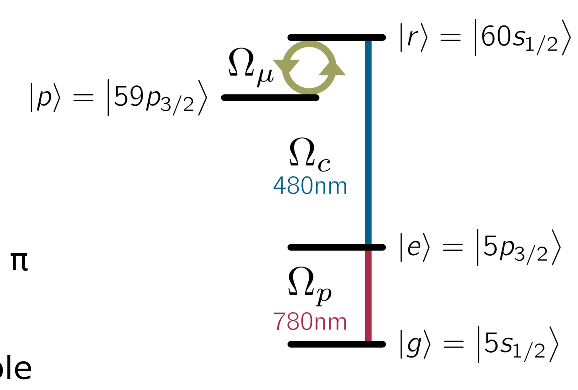
Microwave driving

Drive a 2π rotation in the target qubit through an auxiliary state

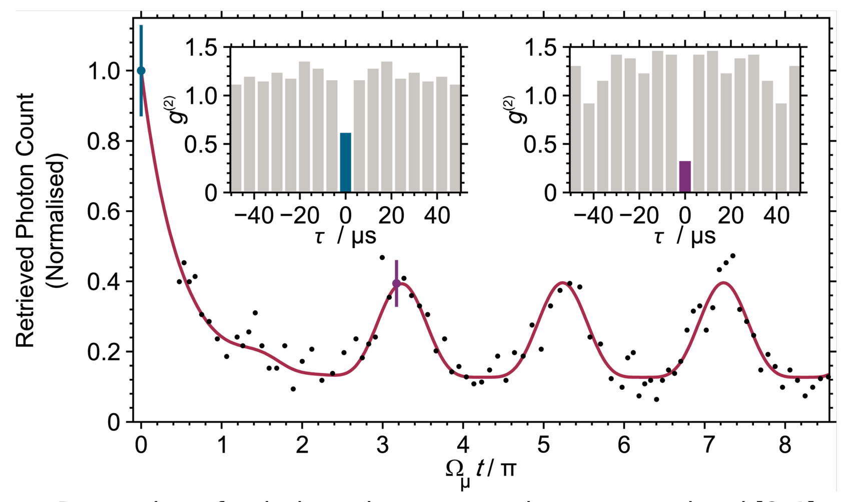
$$|p\rangle = \sum_i^N e^{i\phi_i}|p_i\rangle \qquad |p_i\rangle = |g...p_i...g\rangle$$

In the non-interacting case, it that adds a global (boring) π phase shift to the wavefunction.

However, microwaves turn on resonant dipole-dipole interactions between stored polaritons [4].



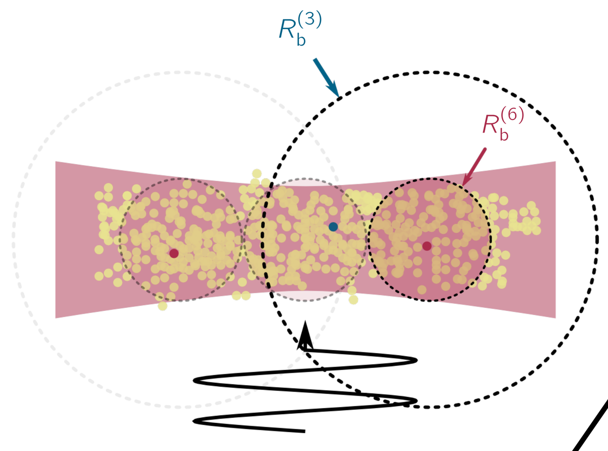
The strength of the microwave driving affects the interactions between neighbouring polaritons.

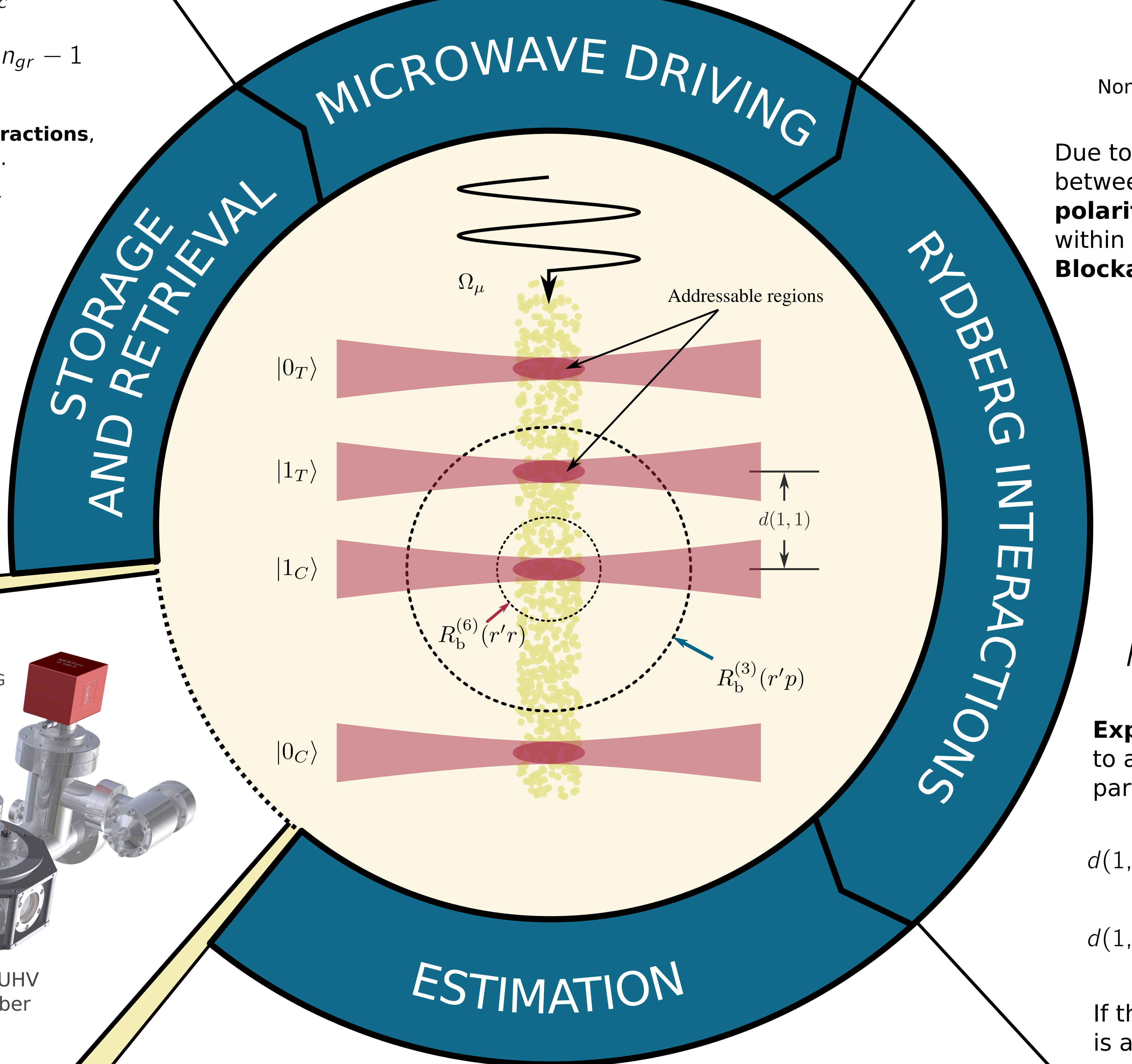


Processing of polaritons happens at the quantum level [2-4]

$R_b^{(6)}$ Coherence length of vdW interaction

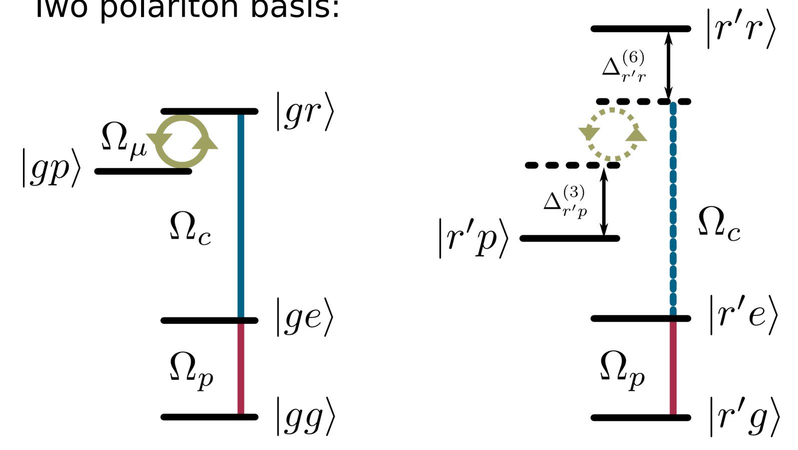
$R_b^{(3)} = \sqrt[3]{\frac{C_3}{\Omega_\mu}}$ Microwave-induced



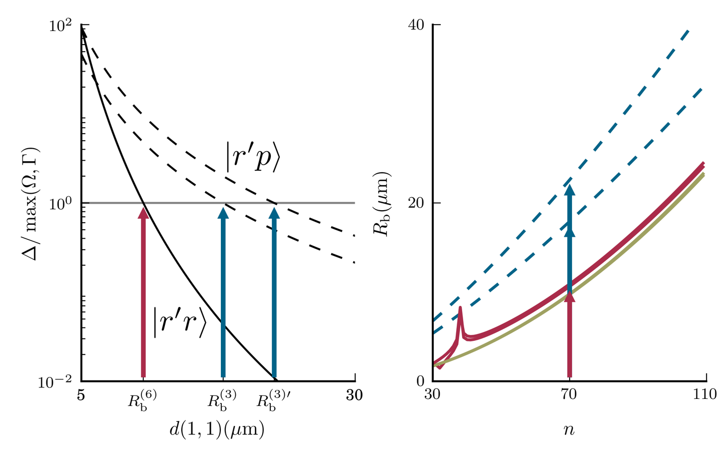


Rydberg interactions

Two polariton basis:



Due to the strong dipole-dipole interactions between Rydberg levels**, excitation of multi-polariton states is shifted out of resonance** within a certain region characterized by the **Blockade radius** R_b.



$$R_b^{(n)} = \sqrt[n]{\frac{C_n}{\Omega}}$$

$C_6 \propto n^{11}$ van der Waals

$C_3 \propto n^4$ resonant dipole-dipole

Exploit the control given by microwaves to add a conditional π phase shift to the $|1,1\rangle$ part of the wavefunction.

$d(1,1) > R_b^{(6)}(r'r)$ — If they are too close, vdW interactions prevent the storage of the two excitations.

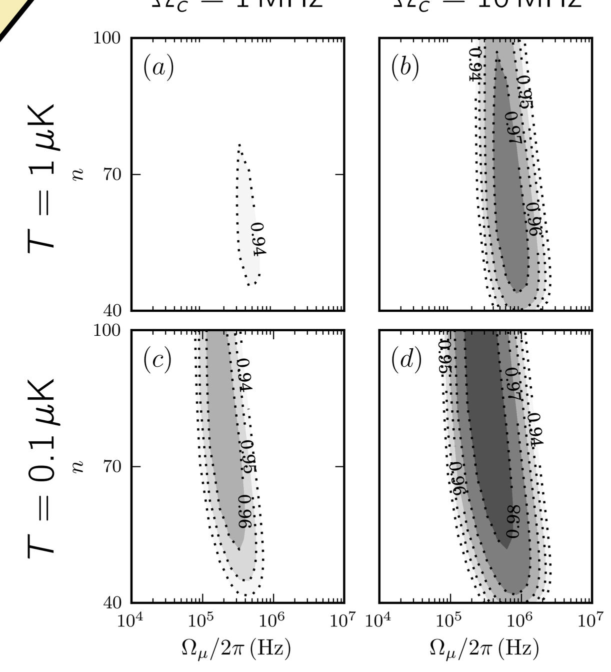
$d(1,1) \ll R_b^{(3)}(r'p)$ — If they are too far apart, resonant dipole-dipole interactions do not prevent the rotation

If these conditions are fulfilled, the operation is a **controlled-z phase gate**

$$\begin{array}{ccc} & (2\pi)_\mu & \\ |1\rangle|1\rangle & & |1\rangle|1\rangle \\ |1\rangle|0\rangle & & -|1\rangle|0\rangle \\ |0\rangle|1\rangle & & -|0\rangle|1\rangle \\ |0\rangle|0\rangle & & -|0\rangle|0\rangle \end{array}$$

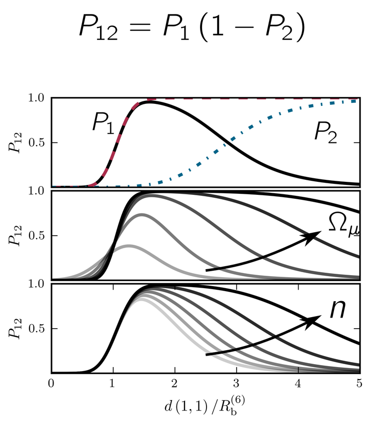
Estimation

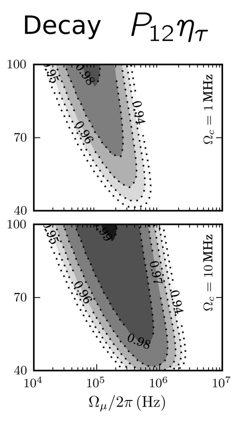
$$P = P_1(1-P_2)\eta_\tau\eta_\mu$$



Look at the success probability of two phenomena in the interaction region:
P_1 - population of the state $|1_C, 1_T\rangle = |r'r\rangle$ given a Rydberg excitation in the control site
P_2 - probability to drive a 2π transition through $|1_C, 1_T\rangle = |r'p\rangle$

The probability of success is then given by $P_{12} = P_1(1-P_2)$



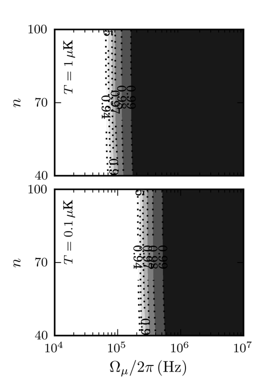


Motional dephasing [16]

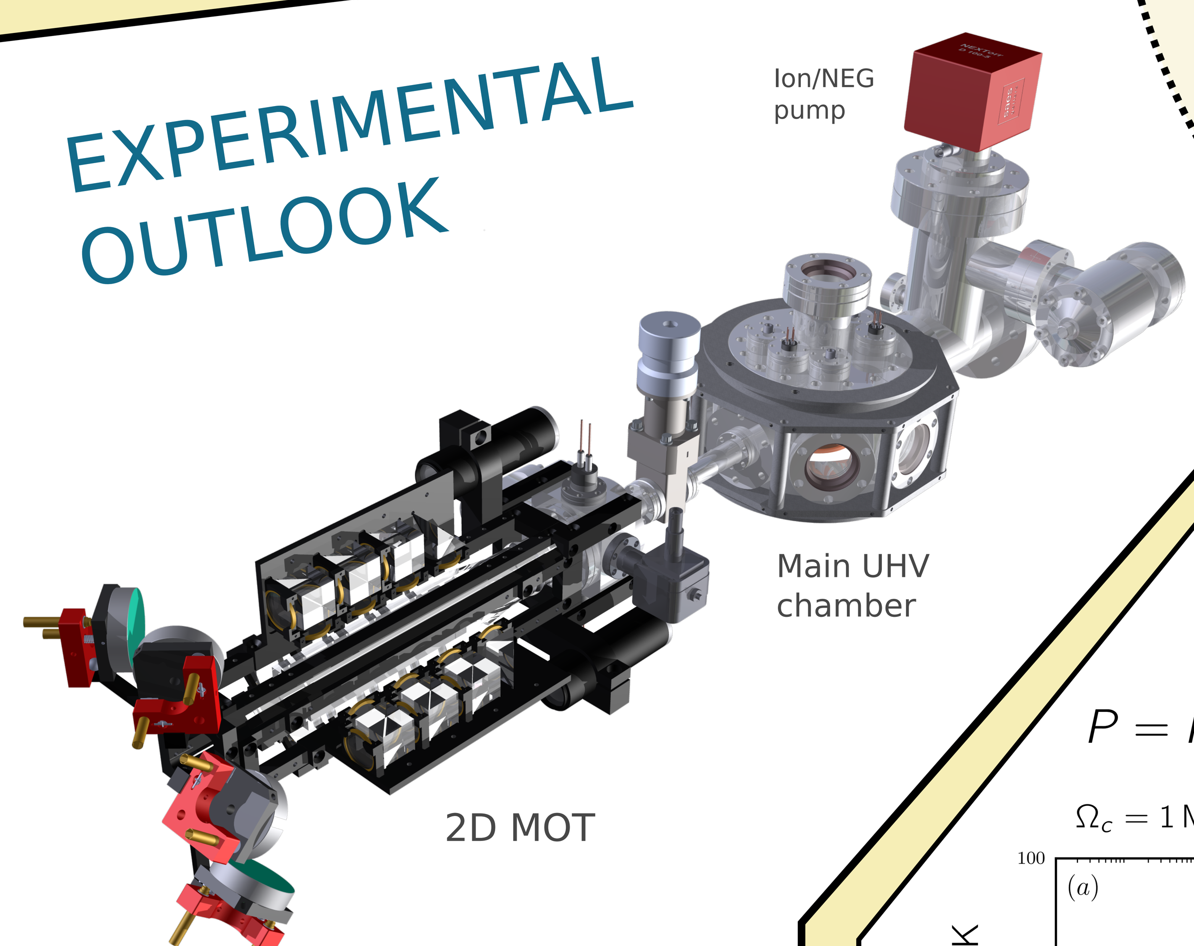
$$\eta_m = \frac{e^{-\epsilon t^2/\zeta^2}}{(1+t^2/\xi^2)^2}e^{-\frac{t^2/\zeta^2}{1+t^2/\xi^2}}$$

ξ Atoms moving in/out of the region

ζ Atoms moving within the spin-wave grating



Experimental outlook



- Higher repetition rates thanks to efficient 2D MOT loading
- Higher magnetic field gradients for compressed MOT phase to increase atomic density in dipole trap.
- In-vacuum high NA lenses to address individual polaritons with tightly focused beams
- Built-in microwave control

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